Experiments at Future *pp* Colliders

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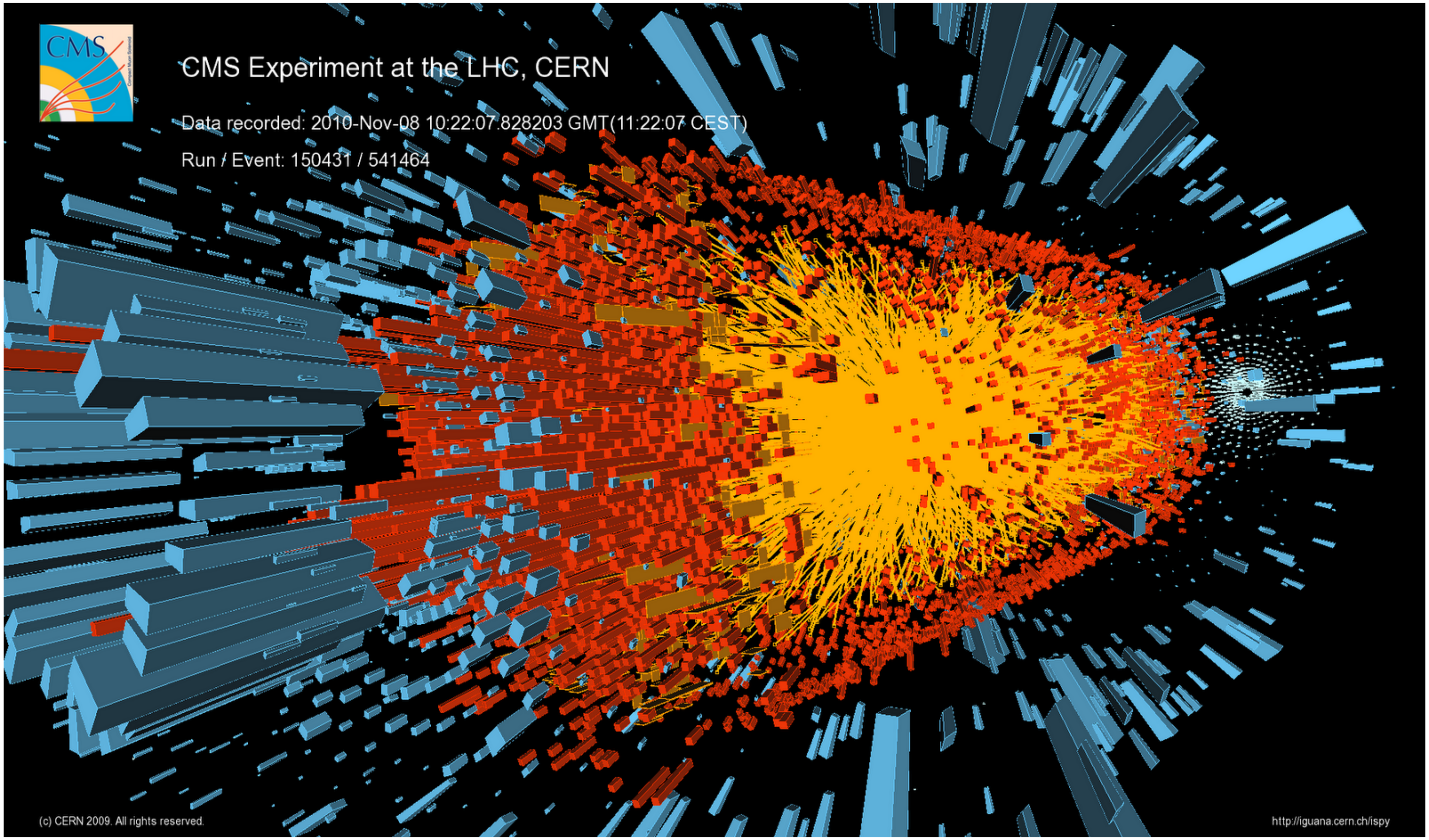
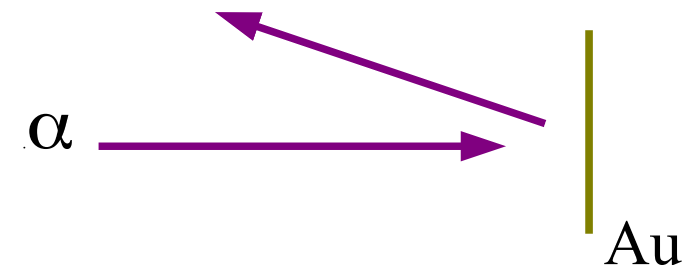


Workshop on the Future of High Energy Physics
Hong Kong University of Science & Technology,
January 19, 2015

Why Build Accelerators?
From Atoms to Quarks

- Scattering of probe particles off matter to investigate substructure, i.e. "look inside"
- Rutherford did it, shooting a particles at a gold foil, to tell us the structure of the atom (1911)

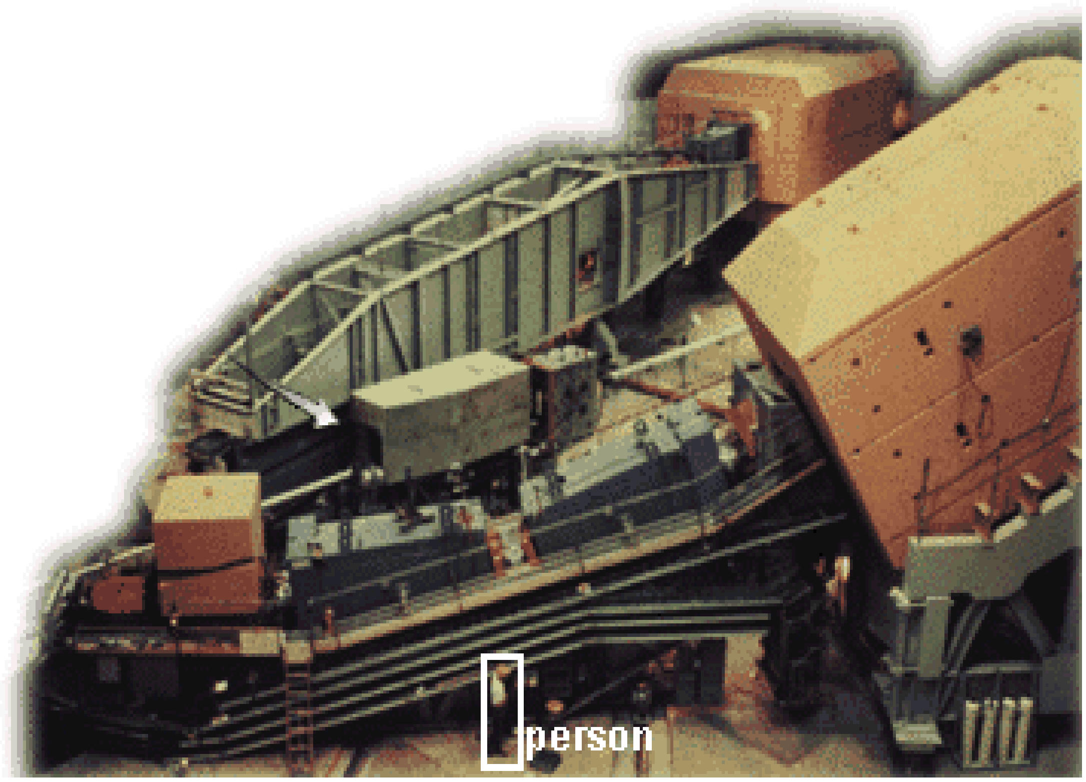
Quantum mechanics: $\Delta r \sim h / \Delta p$



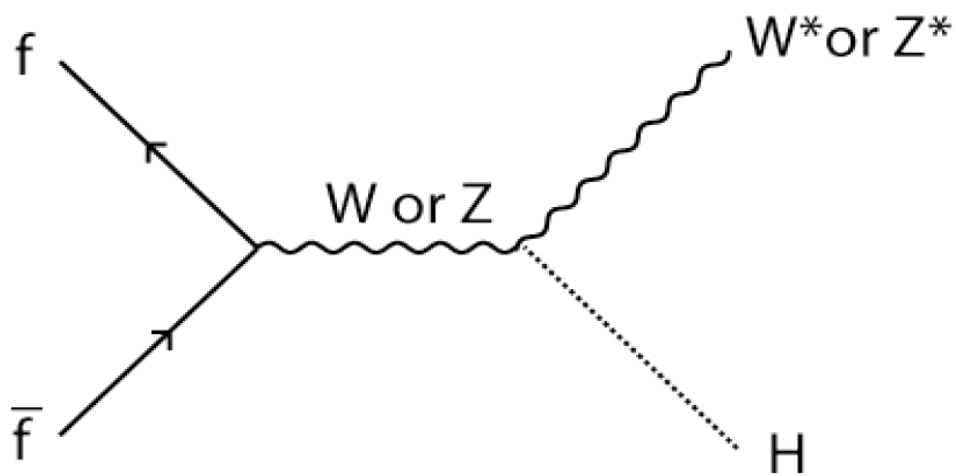
	Radius	Accelerator energy
atom	10^{-10} m	10 electron-volts (eV)
nucleus	10^{-15} m	10^{6} eV (MeV)
proton, neutron	10^{-18} m	10^{9} eV (GeV)
quarks	$<10^{-18}$ m	> GeV

A Century of Particle Physics

- Quark constituents of nucleons established in high energy electron scattering experiments at SLAC, 1966-1978
  - Point-like particles explain high scattering rate at large energy and angle



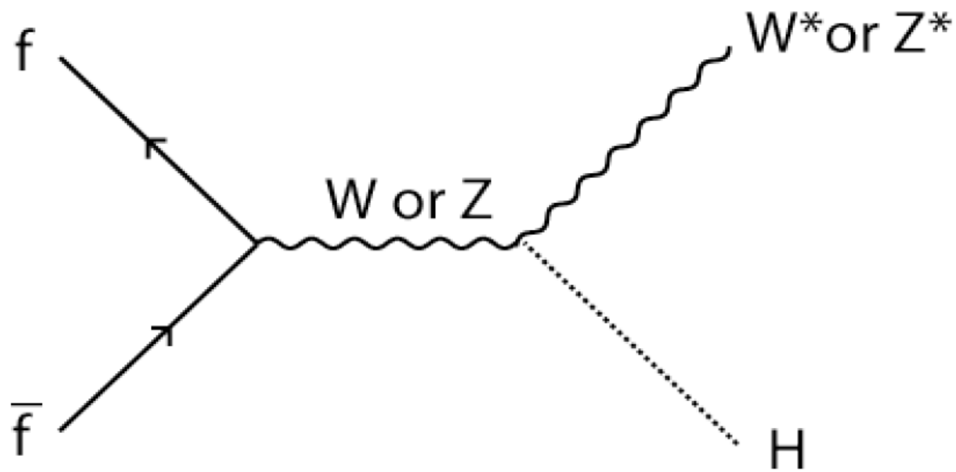
Why Collider Physics ?



W, Z decay to electrons, muons and/or neutrinos

- First order of business from Uncertainty Principle:
  - To probe small-distance phenomena we must scatter particles at high energy
  - What is the center-of-mass energy of a fixed target collision?
    - $(P_{beam} + P_{target})^2 = [\,(p,0,0,p) + (M,0,0,0)\,]^2 = p^2 + 2pM + M^2 - p^2 \sim 2pM$
    - => collision energy in center-of-mass frame = $\sqrt{(2pM)}$
    - Where p is the energy of the beam and M is the mass of the target
    - To obtain 1 TeV of COM frame energy, and proton target (~1 GeV), need 500 TeV beam energy

Why Collider Physics ?



W, Z decay to electrons, muons and/or neutrinos

- First order of business from Uncertainty Principle:
  - To probe small-distance phenomena we must scatter particles at high energy
  - What is the center-of-mass energy of a collider configuration?
    - $(P_{beam1} + P_{beam2})^2 = [\ (p_1,0,0,p_1) + (p_2,0,0,-p_2)\ ]^2 = (p_1 + p_2)^2 - (p_1 - p_2)^2 \sim (2p)^2$
    - => collision energy in COM-frame is $2p$, where $p_1 = p_2 = p$
    - To obtain 100 TeV of COM frame energy, need 50 TeV beams

Hadron Colliders

- Intersecting Storage Rings at CERN (proton-proton and later proton-antiproton collider) with maximum COM energy of 62 GeV: the first pp and p-pbar collider
  - Studied charged and neutral particle production
  - Development of "stochastic cooling" to reduce both the transverse size of the beam and reduce the energy spread (Nobel Prize for Simon Van der Meer): critical for future proton-antiproton colliders
- Super Proton Synchrotron (maximum beam energy of 450 GeV) at CERN, was also used as a proton-antiproton collider at COM energy of 630 GeV
  - Discovery of W and Z bosons via direct production and decay into leptons
- Tevatron at Fermilab (1.8 → 1.96 TeV proton-antiproton collider)
  - Discovery of top quark
- Large Hadron Collider at CERN (7 → 8 → 13 TeV proton-proton collider)
  - Discovery of Higgs boson

Cross Section

Detector

$$N_{observed} = \Delta t \times \mathrm{L} \times \varepsilon \times \mathrm{A} \times \sigma + \mathrm{B}$$

$

Machine

Background

Physical Cross Section

L is the Luminosity

$\varepsilon \times \mathrm{A}$ is the efficiency X acceptance

B is the Background

σ is the cross section

The Cross Section will be the same for
any experiment with the same physical conditions

Unit of Cross Section is area
essentially the effective scattering size for the process

Thanks to H. Schellman

Detector Goals in a Nutshell

- Maximize A x ε: all detectable particles
  - should be detected and over as much of the angular phase space as possible
  - And be well-measured over as much of their energy spectrum as possible (or of most importance to the interesting signals)
- Leptons of interest: electrons, muons and τ-leptons
- Photons
- Quarks and gluons hadronize to jets of particles
- *b*-quarks are special and need to be distinguished from other jets

- Undetectable particles like neutrinos and Dark Matter can only have their transverse momentum sum inferred
  - Catch all visible momentum
  - Impose transverse momentum conservation
  - Hermeticity is important

Detector Goals in a Nutshell (2)

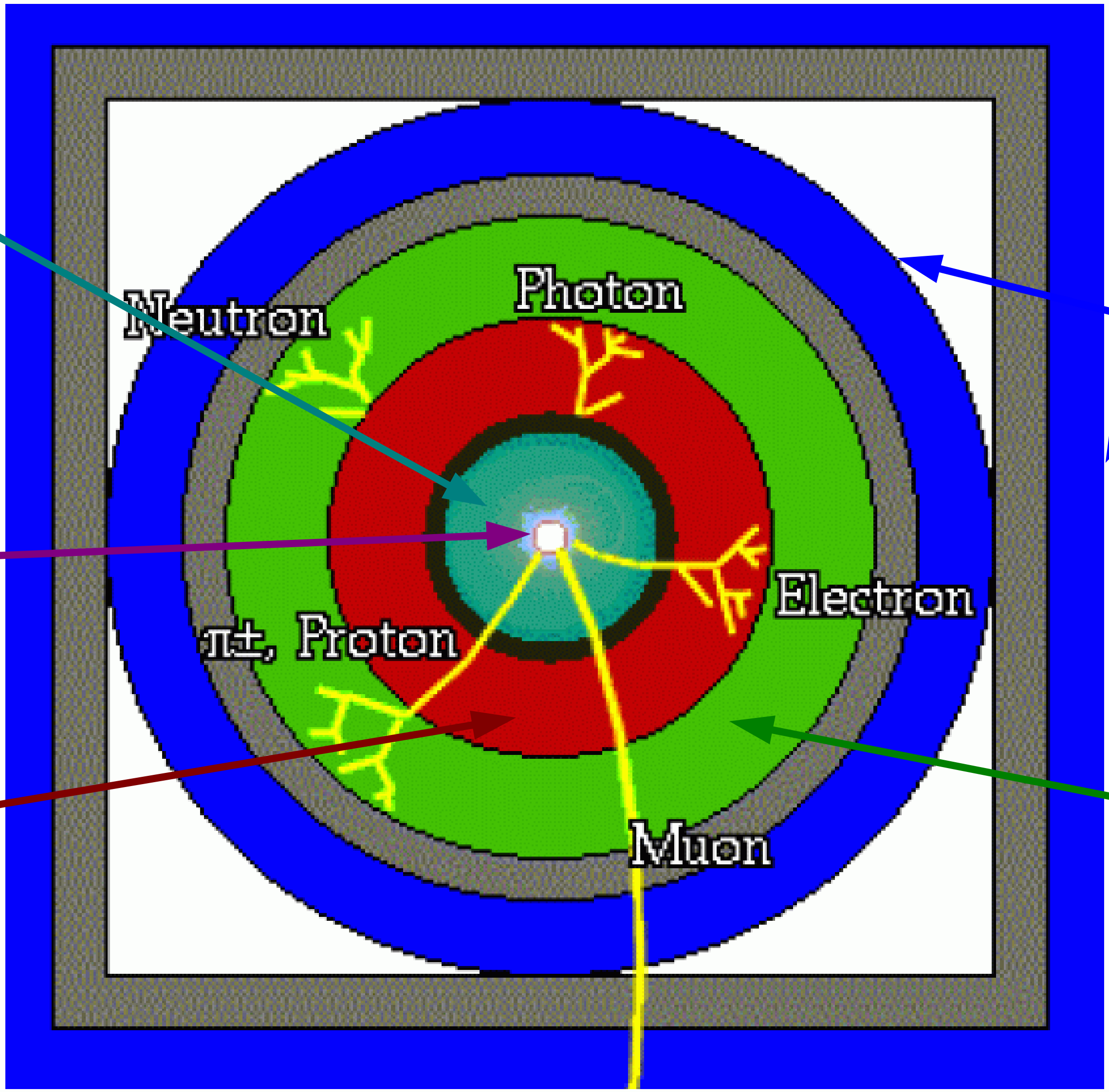
- Minimize B: reducible backgrounds from mis-identified particles
  - High rate of fragmentation pions, kaons, and photons misidentified as prompt electrons, photons and muons
  - Generic jets mis-identified as *b*-quark jets
  - Electrons and generic jets mis-identified as **τ**-leptons
  - Energy resolution of detected particles, or missed visible energy due to missing instrumentation, leads to fake missing p_T signature
  - Hermetic detectors have become very important

- Maximize Δt x L: enable data-taking in high instantaneous luminosity environment
  - Large number of particles from additional (uninteresting) pp collisions
    - Can confuse/obfuscate the particles from the interesting collision
  - Total exposure of sensors to radiation flux scales with integrated luminosity and falls off with distance from collision point
    - Radiation damage causing degradation of sensor efficiency and increasing noise

Particle Detection

Drift chamber:
reconstuct particle
trajectory by sensing
ionization in gas
on high voltage wires

Silicon detector:
reconstuct particle
trajectory by sensing
ionization in planar
silicon sensors
(diodes)

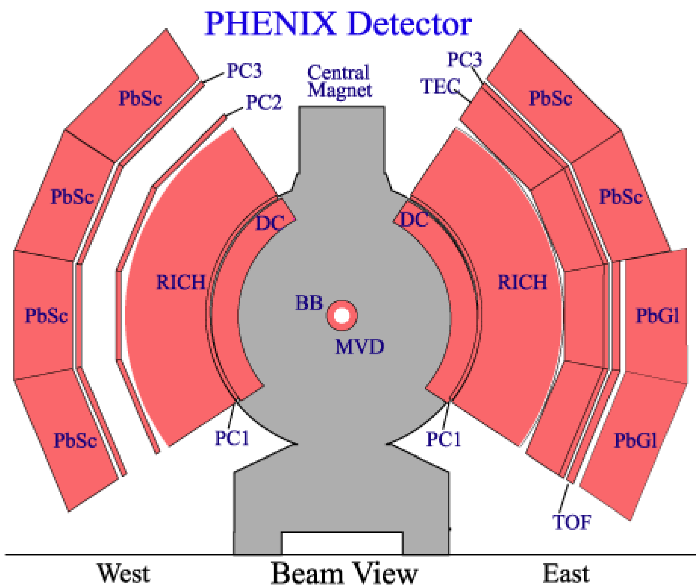


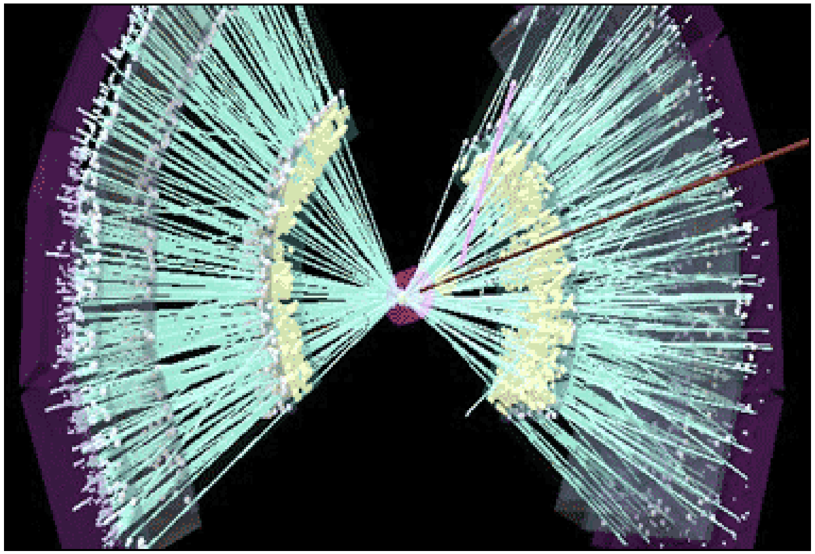
Muon chambers:
detect penetrating
particles behind
shielding

Electromagnetic
(EM) calorimeter:
metal sheets cause
e/γ shower, sense
light or charge

Hadronic
calorimeter:
metal sheets
cause hadronic
showers, sense
scintillator light
or charge

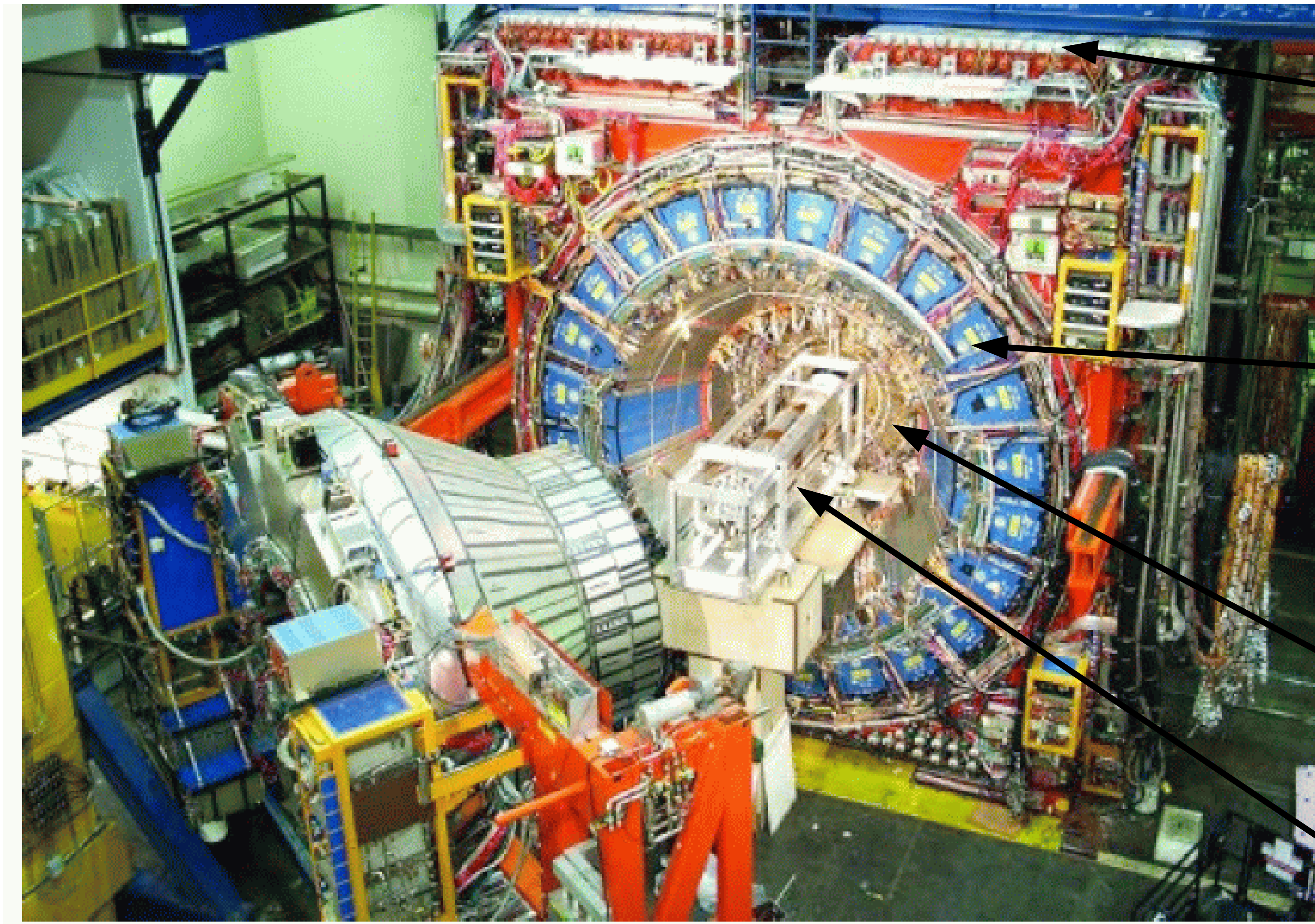
non-4π detectors (uncommon)



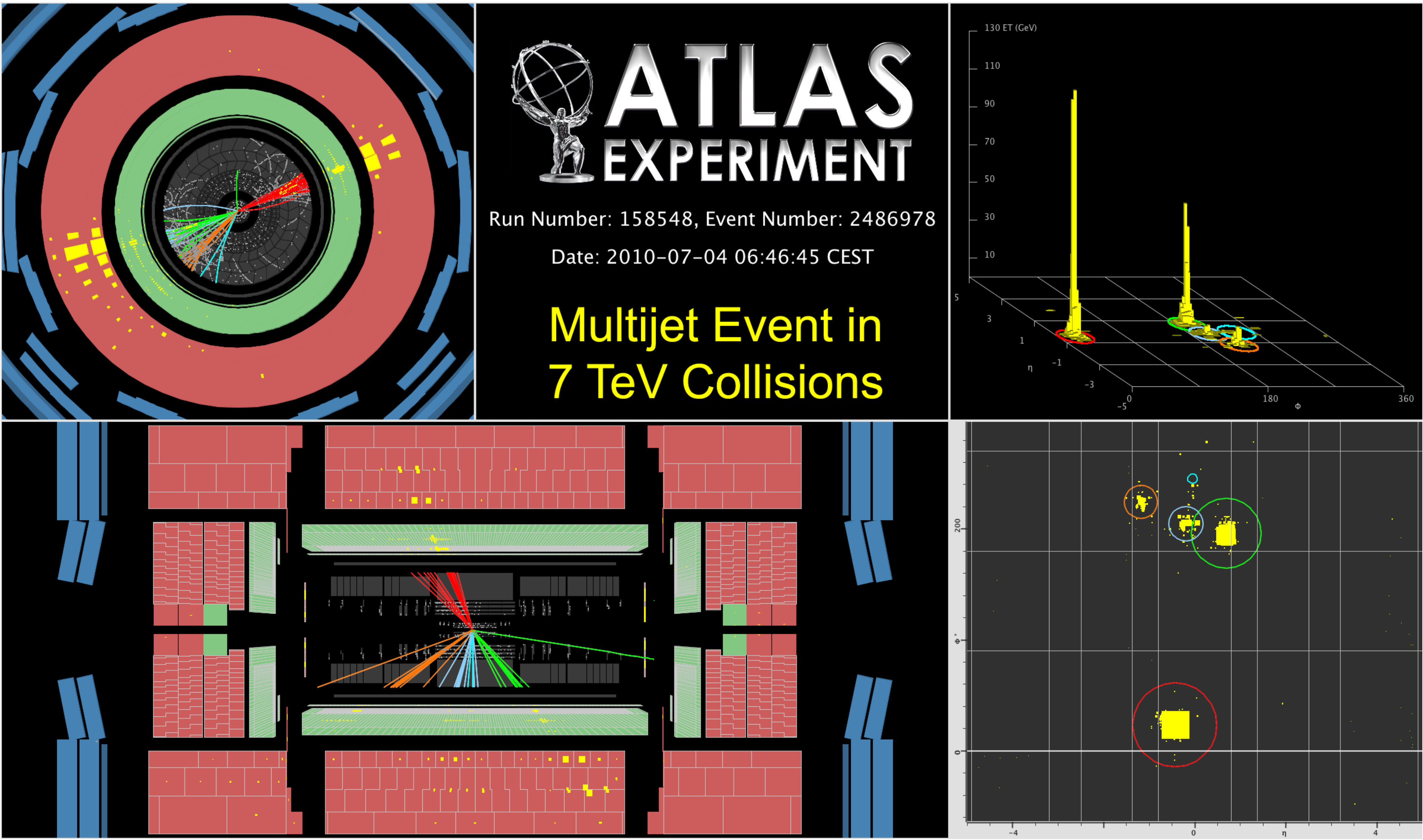


Intersecting Storage Rings (CERN) and C0 experiment at Fermilab Tevatron also had non-4π detectors

Collider Detector at Fermilab (CDF)



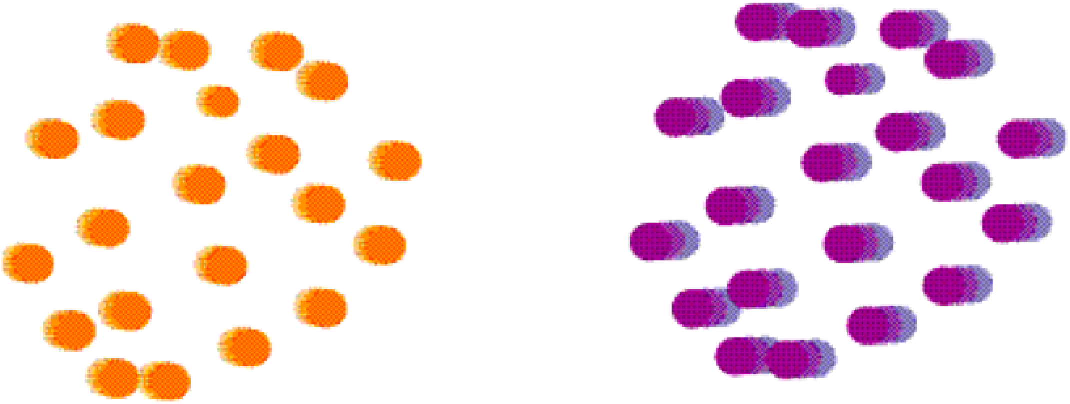
Particle Detection



Collider Luminosity and Sensor Timing

Luminosity is a measure of how often protons/antiprotons get close enough to interact

$$L = f\,\frac{n_1 n_2}{4\pi\, s_x s_y}$$



f= beam crossing frequency

50 ns → 25 ns at LHC

n= protons/bunch

s = transverse beam size

L ~ 10^{34} crossings/cm^2/sec

Reducing pileup by reducing *n* requires increasing *f* => faster detectors

Reducing *s* is not easy for the accelerator

Thanks to H. Schellman

Sensing Ionization Energy Loss

Detection of charged particles

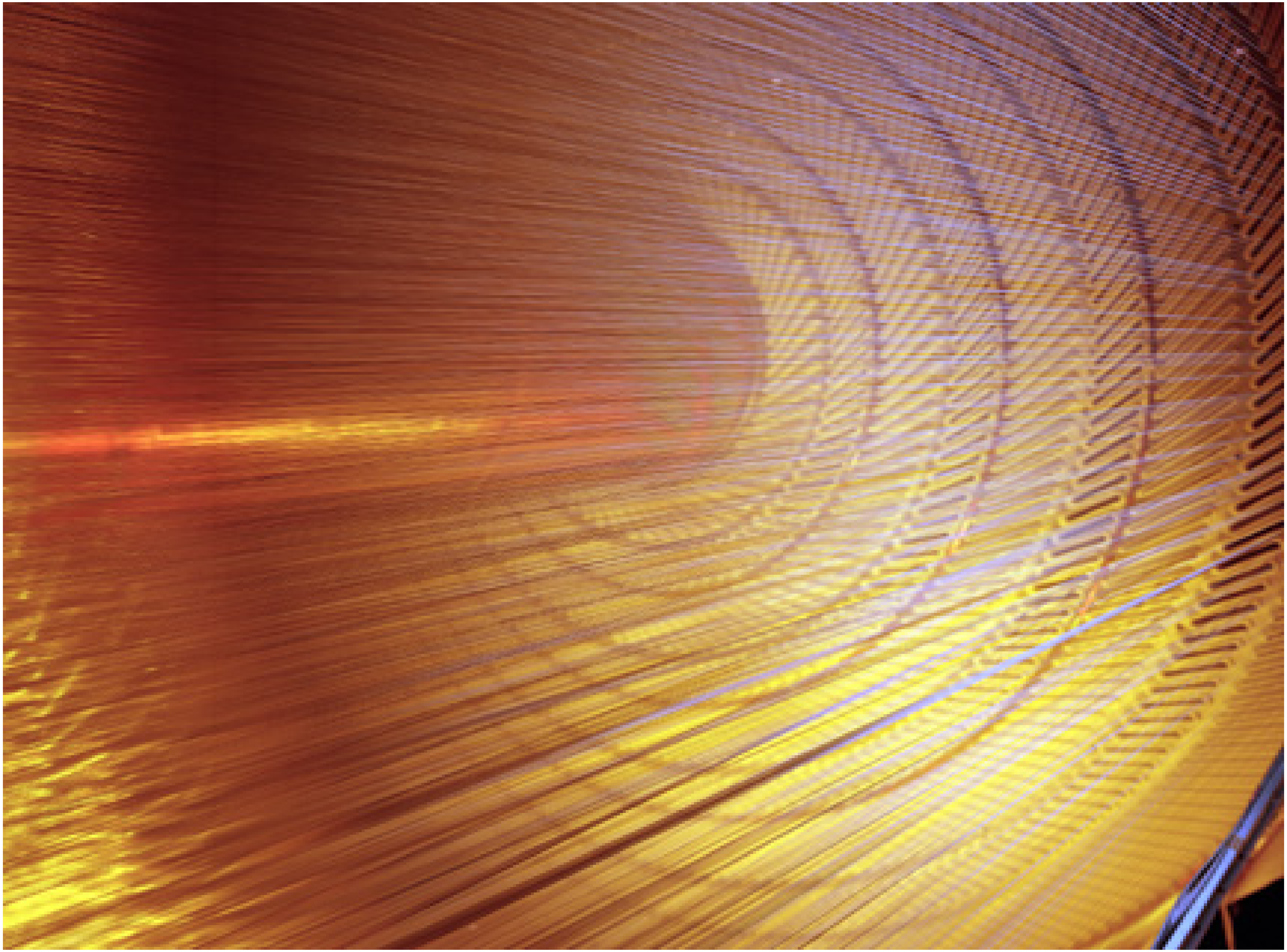
When a relativistic charged particle passes through matter, it knocks electron out of atoms as it passes by. This is what we call 'Energy Loss' and it is reasonably independent of the particle or material type.

$$dE/dx \sim 2 \text{ MeV/cm} \times \rho \text{ [gr/cm}^3\text{]}$$

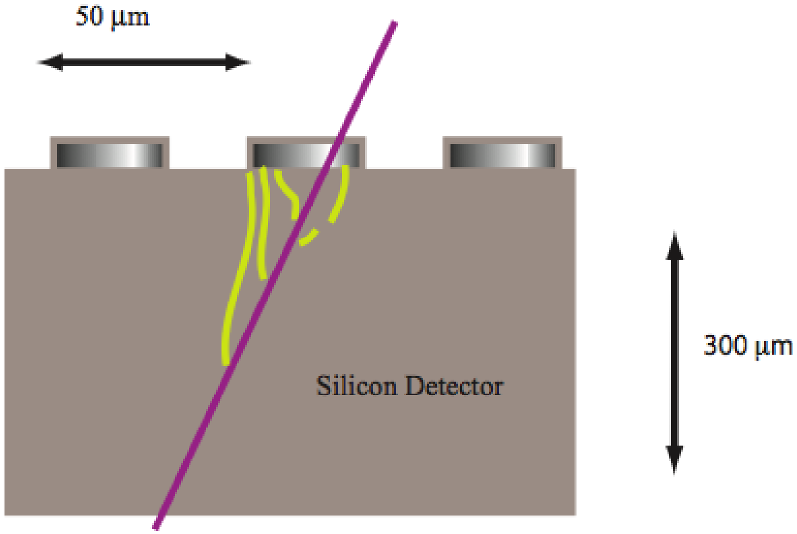
this energy shows up as low energy electrons and photons and can be detected optically or electronically.

Magnetic Tracking

CDF Run1 Tracking Chamber (1985-95)



ATLAS Silicon Tracker

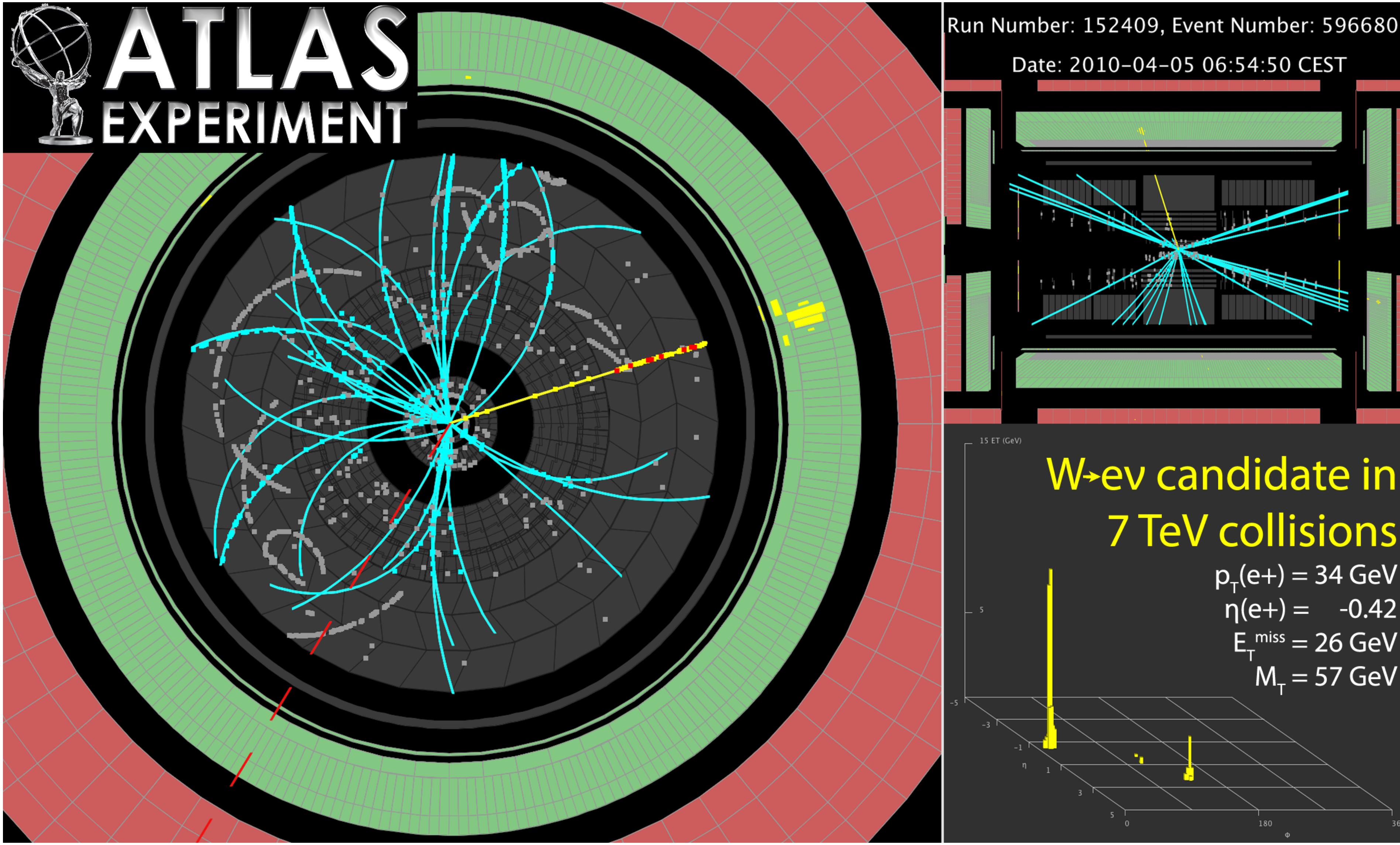


Detect ~2000 e in a 350 µm thick detector

Can measure x,y, z to 10-20 µm

Magnetic Tracking

B field →



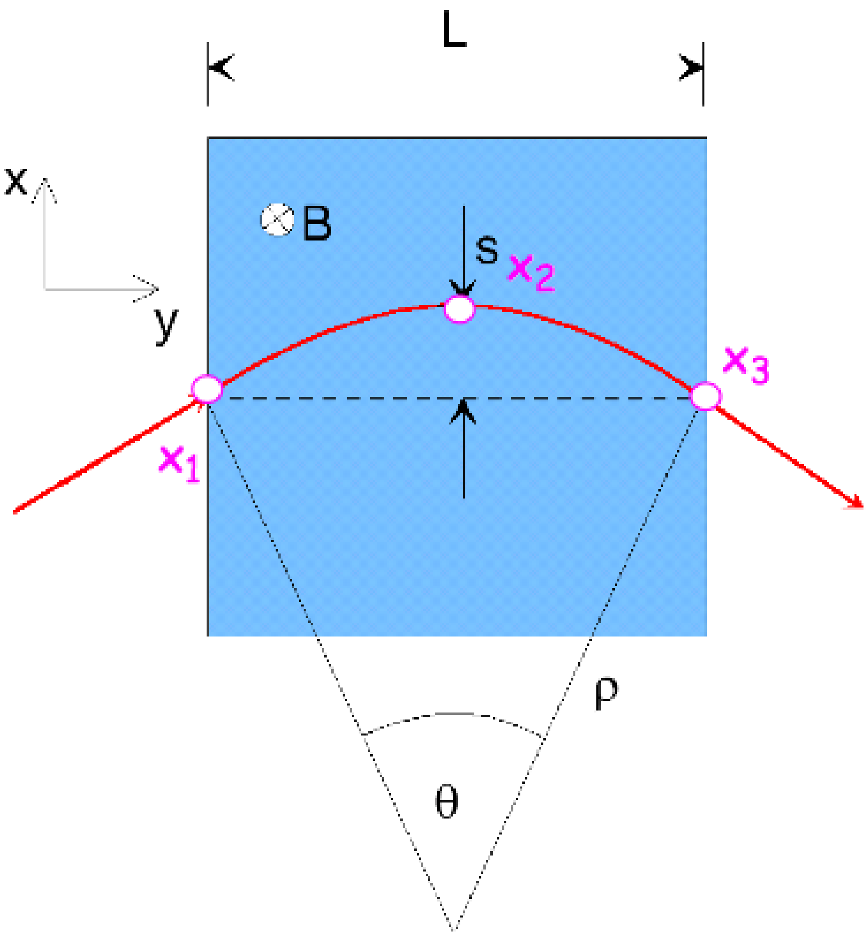
Fit the helical trajectory in the longitudinal magnetic field

=> Extract position, direction and momentum of charged particles

Tracker Design – the heart of the experiment

Momentum is determined by measurement of track curvature $\kappa = 1/\rho$ in B field:

Measure sagitta s of the track. For the momentum component transverse to B field:



$$p_T = qB\rho$$

Units: $p_T[\mathrm{GeV}] = 0.3B[\mathrm{T}]\rho[\mathrm{m}]$

$$\frac{L/2}{\rho} = \sin\frac{\theta}{2} \approx \frac{\theta}{2} \text{ (for small } \theta) \Rightarrow \theta \approx \frac{L}{\rho} = \frac{0.3B \cdot L}{p_T}$$

$$s = \rho\left(1 - \cos\frac{\theta}{2}\right) \approx \rho\left(1 - \left(1 - \frac{1}{2}\frac{\theta^2}{4}\right)\right) = \rho\frac{\theta^2}{8} \approx \frac{0.3}{8}\frac{L^2 B}{p_T}$$

Thanks to Carsten Niubuhr

Relative Momentum Error

For 3 points the relative momentum resolution is given by: $\frac{\sigma(p_T)}{p_T} = \frac{\sigma_s}{s} = \sqrt{\frac{3}{2}}\sigma_x \cdot \frac{8p_T}{0.3BL^2}$

- degrades linearly with transverse momentum
- improves linearly with increasing B field
- improves quadratically with radial extension of detector

In the case of N equidistant measurements according to Gluckstern [NIM 24 (1963) 381]:

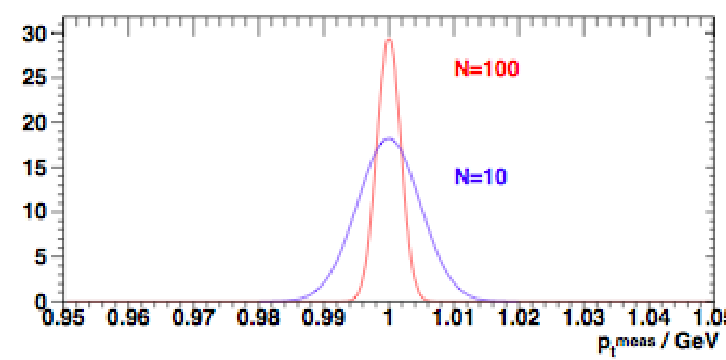
$$\boxed{\frac{\sigma(p_T)}{p_T} = \frac{\sigma(\kappa)}{\kappa} = \frac{\sigma_x \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{(N+4)}}}$$

(for $N \geq 10$, curvature $\kappa = 1/\rho$)

Example: For $p_T = 1\,\mathrm{GeV}$, $L = 1\,\mathrm{m}$, $B = 1\,\mathrm{T}$, $\sigma_x = 200\,\mu\mathrm{m}$ and $N = 10$ one obtains:

$\frac{\sigma(p_T)}{p_T} \approx 0.5\%$ for a sagitta $s \approx 3.8\,\mathrm{cm}$

Important track detector parameter: $\frac{\sigma(p_T)}{p_T^2}$ $(\%/\mathrm{GeV})$

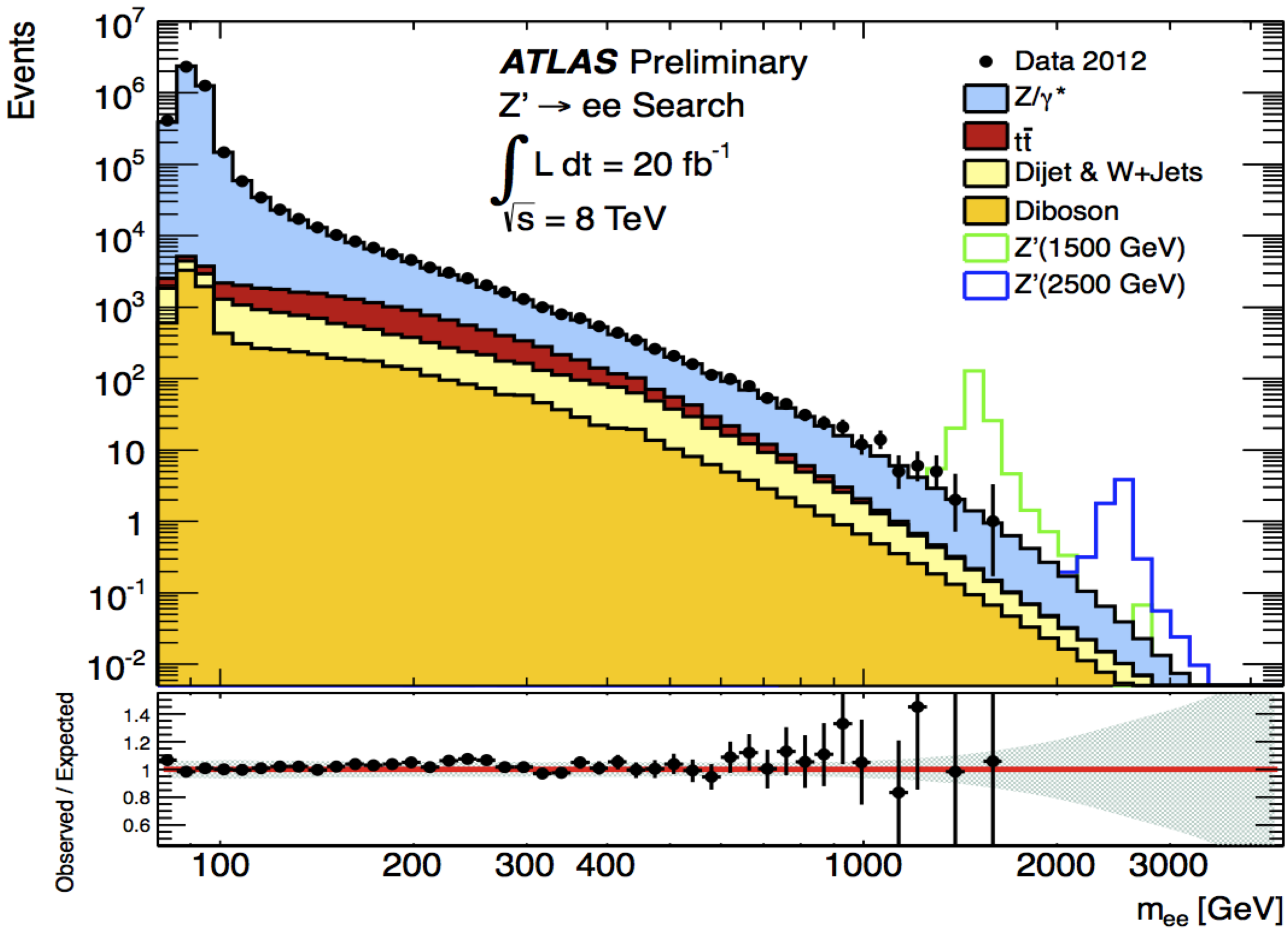


CDF achieved 0.015% with ~90 drift chamber hits, consistent with this example

Thanks to Carsten Niubuhr

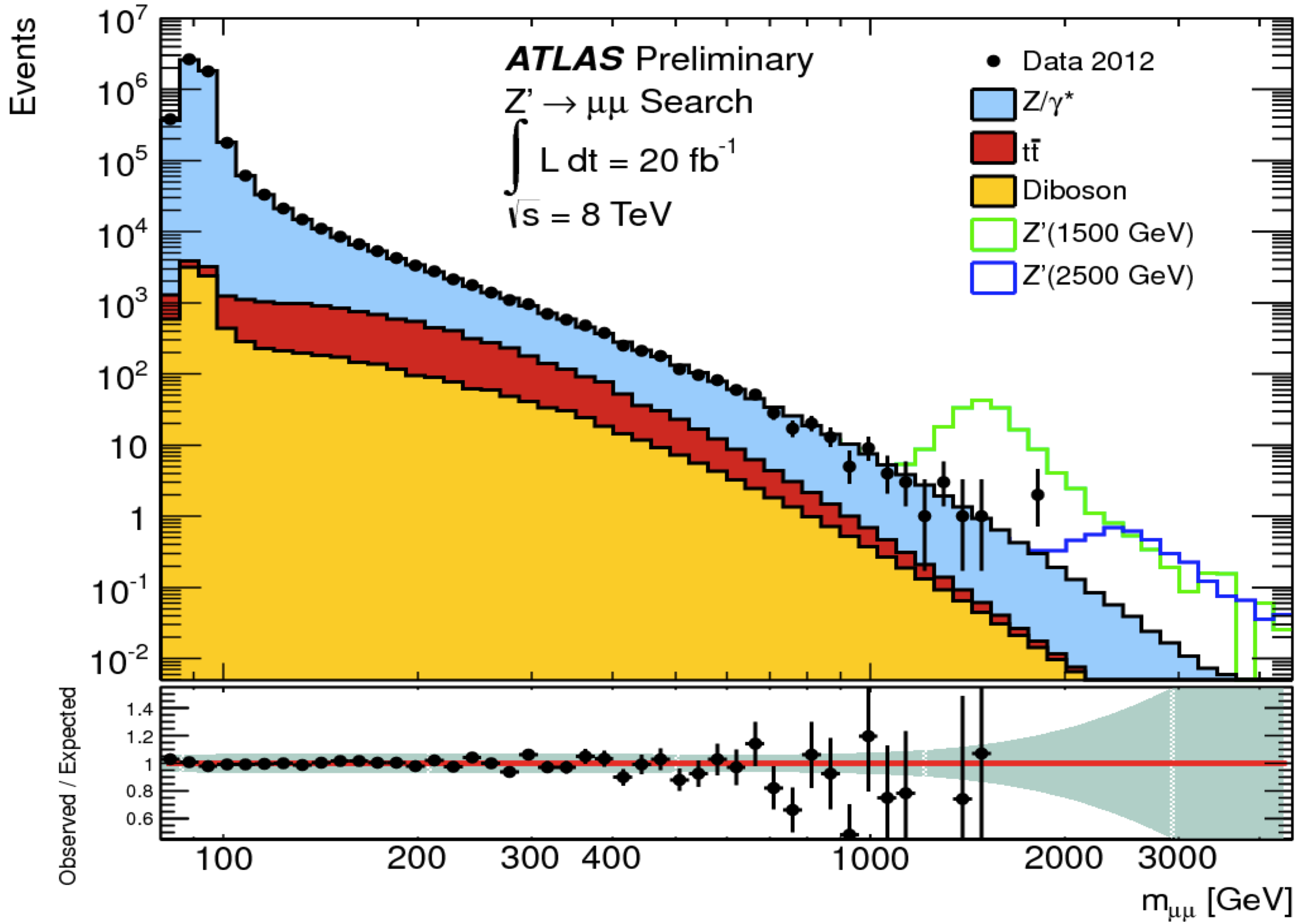
Dielectron Mass Spectrum

Multi-TeV masses probed at LHC



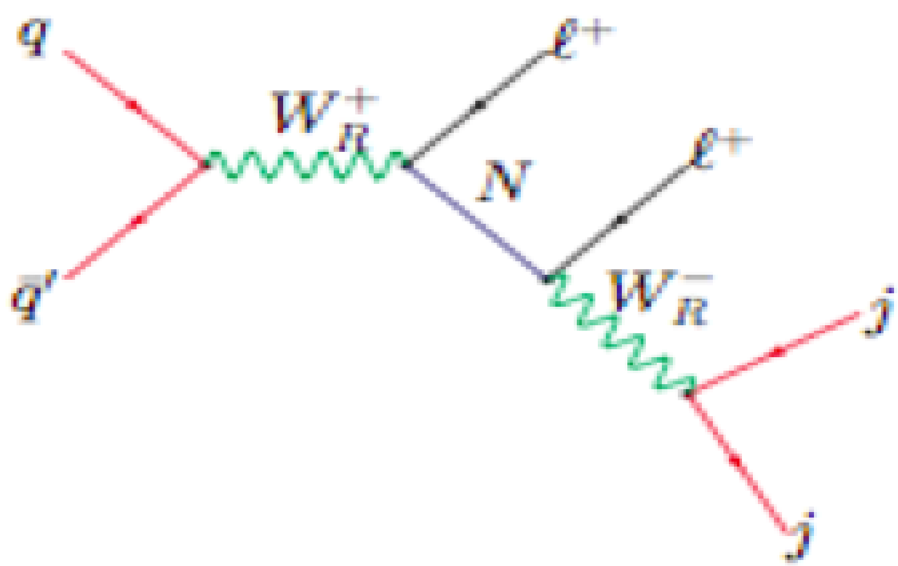
Dimuon Mass Spectrum

Multi-TeV masses probed at LHC



Demands on p_T Resolution

- High-mass dimuon resonances most demanding on tracker momentum resolution
- If universal coupling to leptons, dielectron channel is reliable
- Non-universal couplings plausible:
  - Higgs mechanism: additional Higgs bosons with $H \rightarrow \mu\mu$
  - Left-right seesaw model of neutrino masses



$$N \rightarrow l^{\pm} jj$$

(Keung, Senjanovic'83)

  - Prudent to maintain muon p_T resolution (%) from LHC to 7x higher p_T

Maintaining Fractional p_T Resolution

- Resolution gain with number of hits on track is slow (improves as $\sqrt{N}$)
- Resolution improves linearly with BL^2 ~ stored magnetic field energy in tracker
- Resolution improves linearly with hit resolution

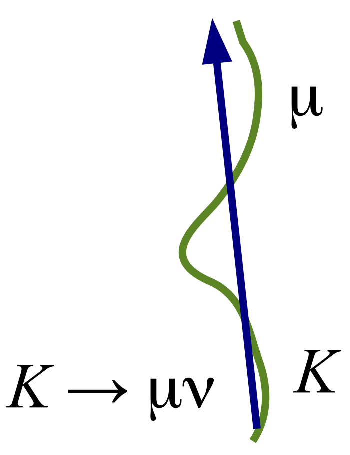
Three tracker/magnet geometries being considered:

- see Dr. Marcello Mannelli's talk at Fermilab's "Next Steps in the Energy Frontier – Hadron Collider" Workshop

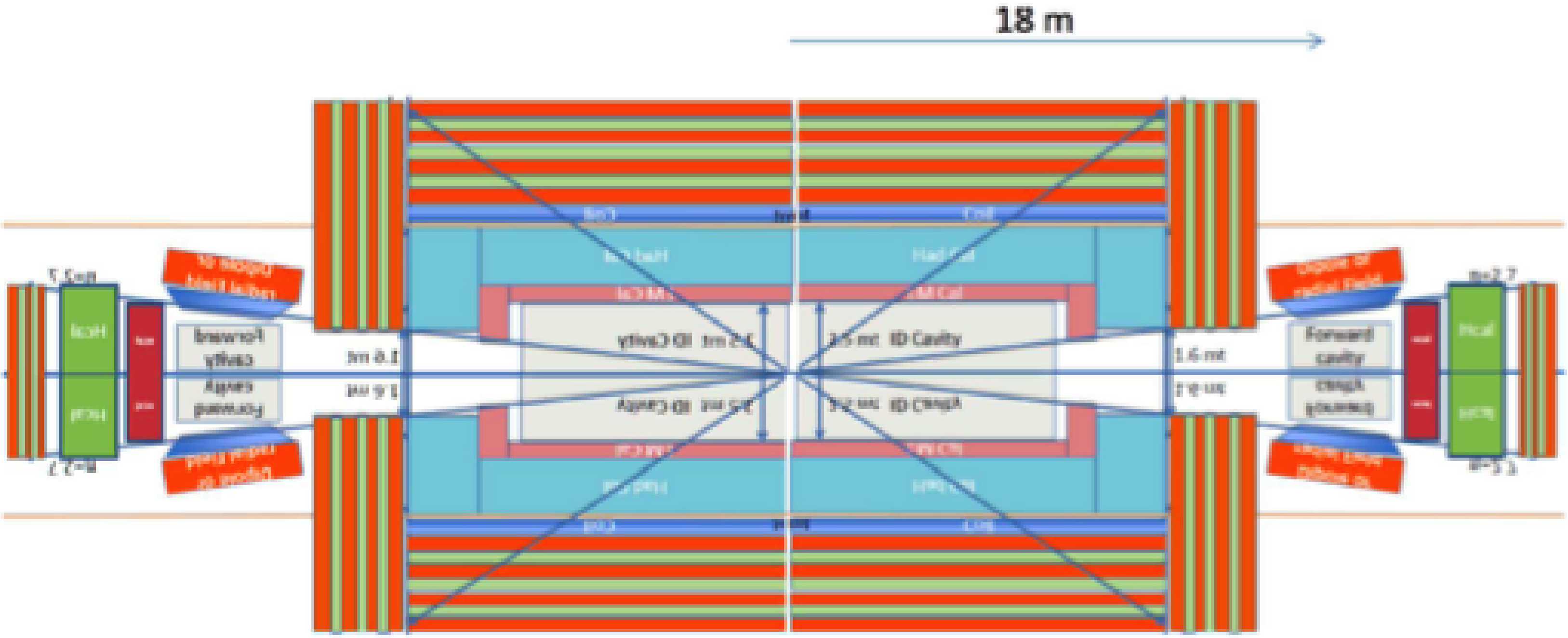
https://indico.fnal.gov/conferenceOtherViews.py?view=standard&confId=7864

Stored energy in the tracker magnetic field in the 50-100 GJ range (similar to ITER)

Need to measure muon momentum after shielding, to eliminate mis-measured decays-in-flight with very high reconstructed p_T

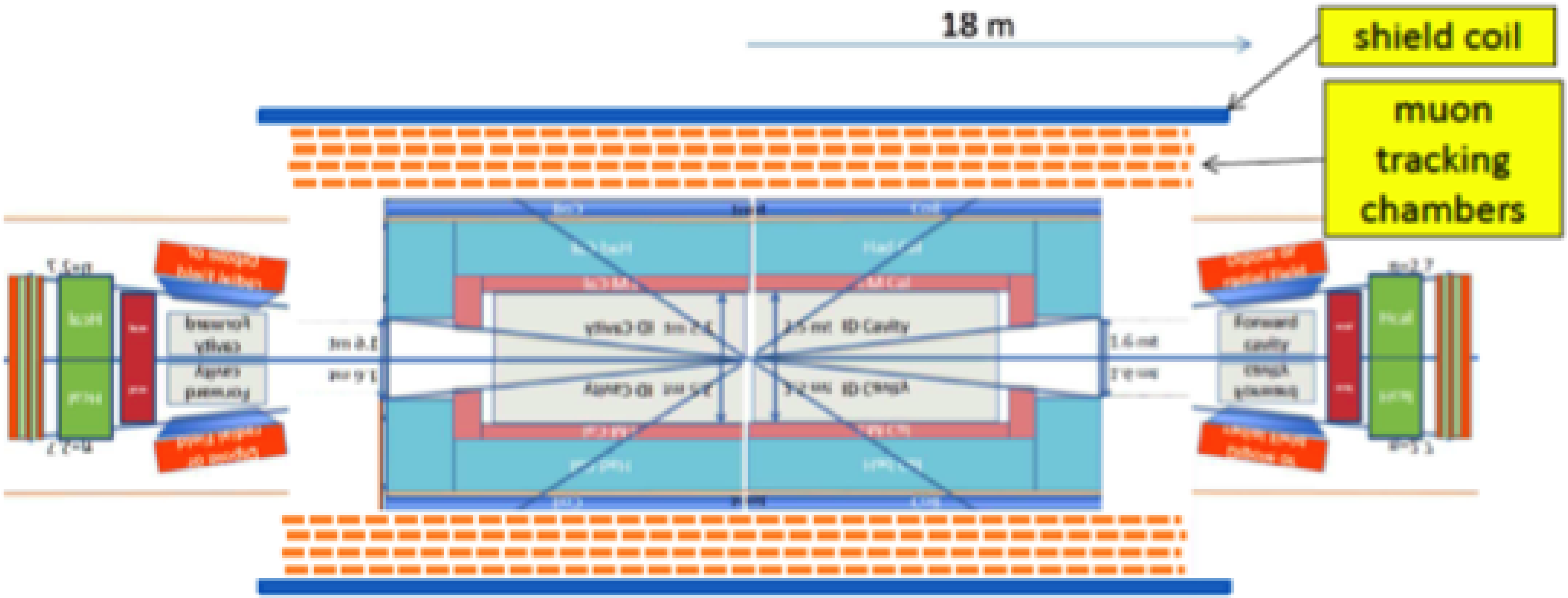


2. Option 1: Solenoid-Yoke + Dipoles (CMS inspired)



- **Solenoid:** 10-12 m diameter, 5-6 T, 23 m long
  + massive Iron yoke for flux shielding and muon tagging.
- **Dipoles:** 10 Tm with return yoke placed at z≈18 m.
  Practically no coupling between dipoles and solenoid.
  They can be designed independently at first.

2. Option 2: Twin Solenoid + Dipoles

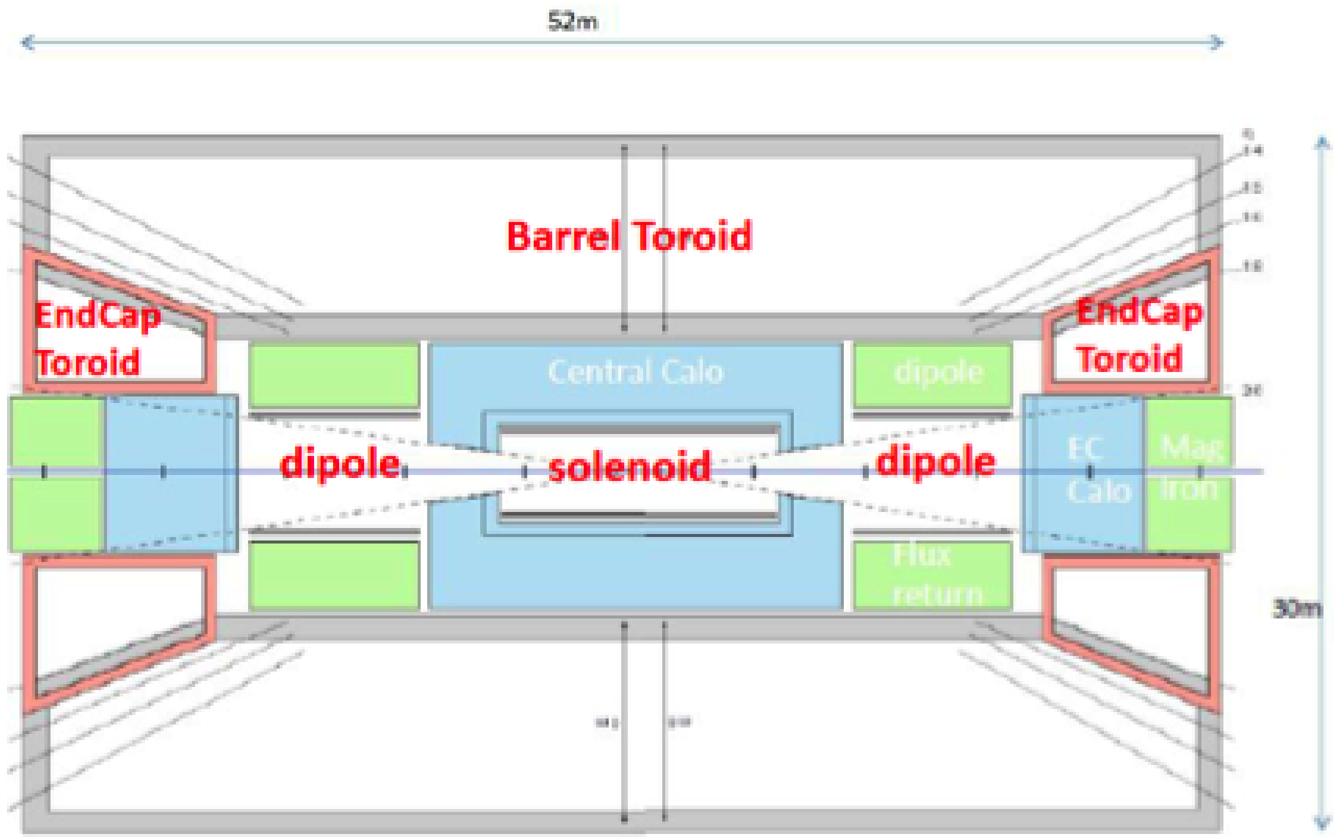


Twin Solenoid: a 6 T, 12 m dia x 23 m long main solenoid + an active shielding coil

Important advantages:

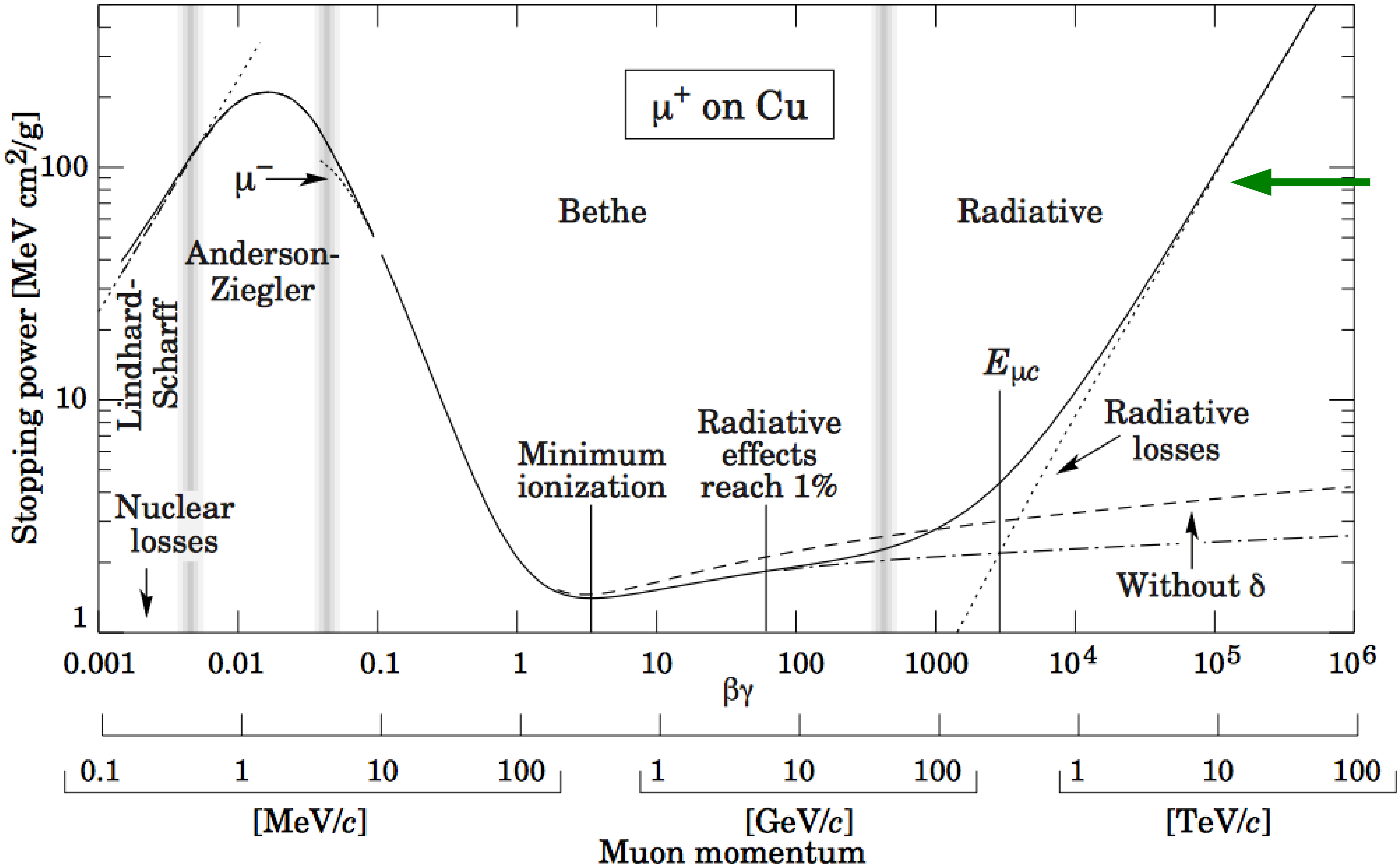
- ✓ **Nice Muon tracking space:** area with 2 to 3 T for muon tracking in 4 layers.
- ✓ **Very light:** 2 coils + structures, ≈ 5 kt, only ≈ 4% of the option with iron yoke!
- ✓ **Much smaller:** system outer diameter is significantly less than with iron .

2. Option 3: Toroids + Solenoid + Dipoles (ATLAS +)



- 1 Air core Barrel Toroid with 7 x muon bending power $B_z L^2$.
- 2 End Cap Toroids to cover medium angle forward direction.
- 2 Dipoles to cover low-angle forward direction.
- Overall dimensions: 30 m diameter x 51 m length (36,000 m^3).

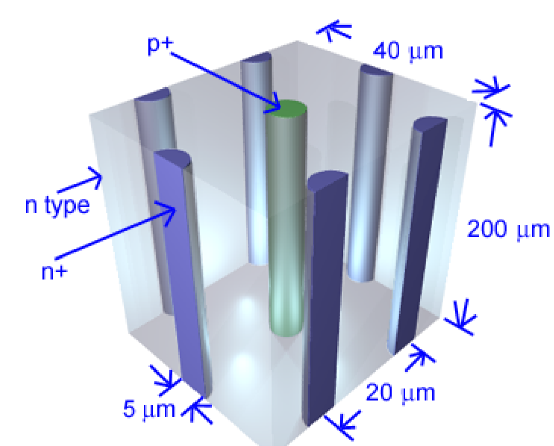
High Energy Muon Bremsstrahlung



- For a ~10 TeV muon, average energy loss ~ 1 GeV / cm ~ 16 GeV / interaction length ~ 200 GeV in hadronic calorimeter, with long tailed distribution

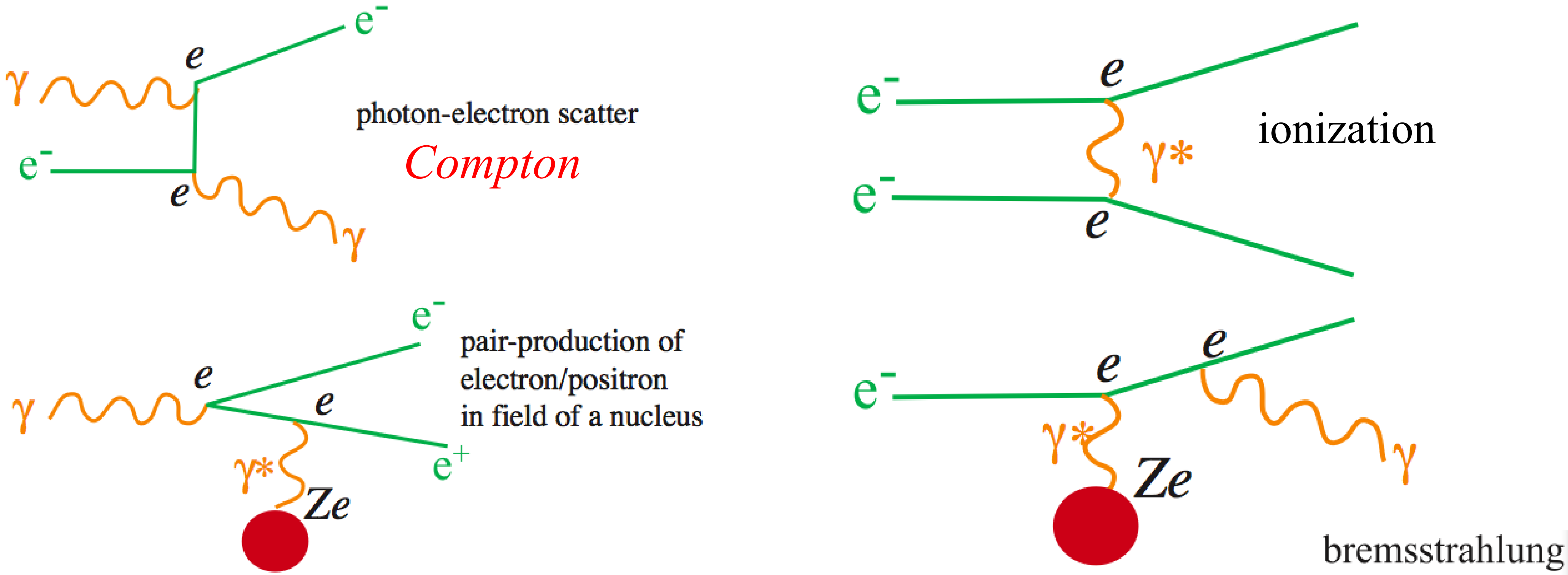
Improving Hit Resolution

- Smaller pixels with silicon sensors have multiple advantages
  - Improved hit resolution linearly improves momentum resolution at high p_T
  - Higher granularity improves two-track resolving power
    - Helps resolve close-by tracks and maintain track reconstruction efficiency in
      - high-density environment (inside boosted jets)
      - High-occupancy environment (pileup at high L)
- Issues:
  - Higher readout rate required
  - Power may be dominated by inter-pixel capacitance, which does not reduce with pixel size
    - More pixels => more power
- Potential solutions (3D electronics etc) under discussion



Calorimetry

Photon and Electron Detection

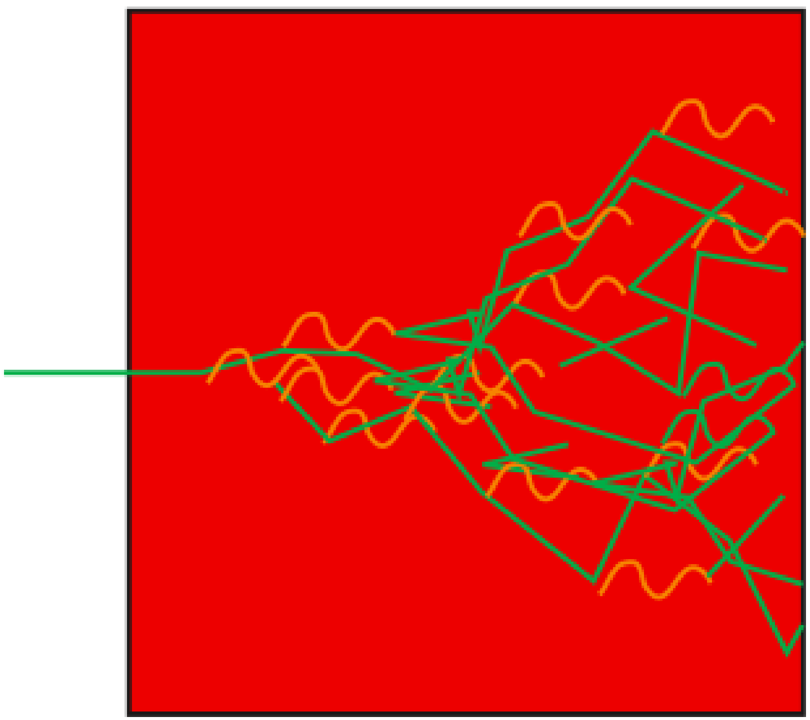


At high energy and for high-Z material, energy loss by pair-production and bremsstrahlung dominates.

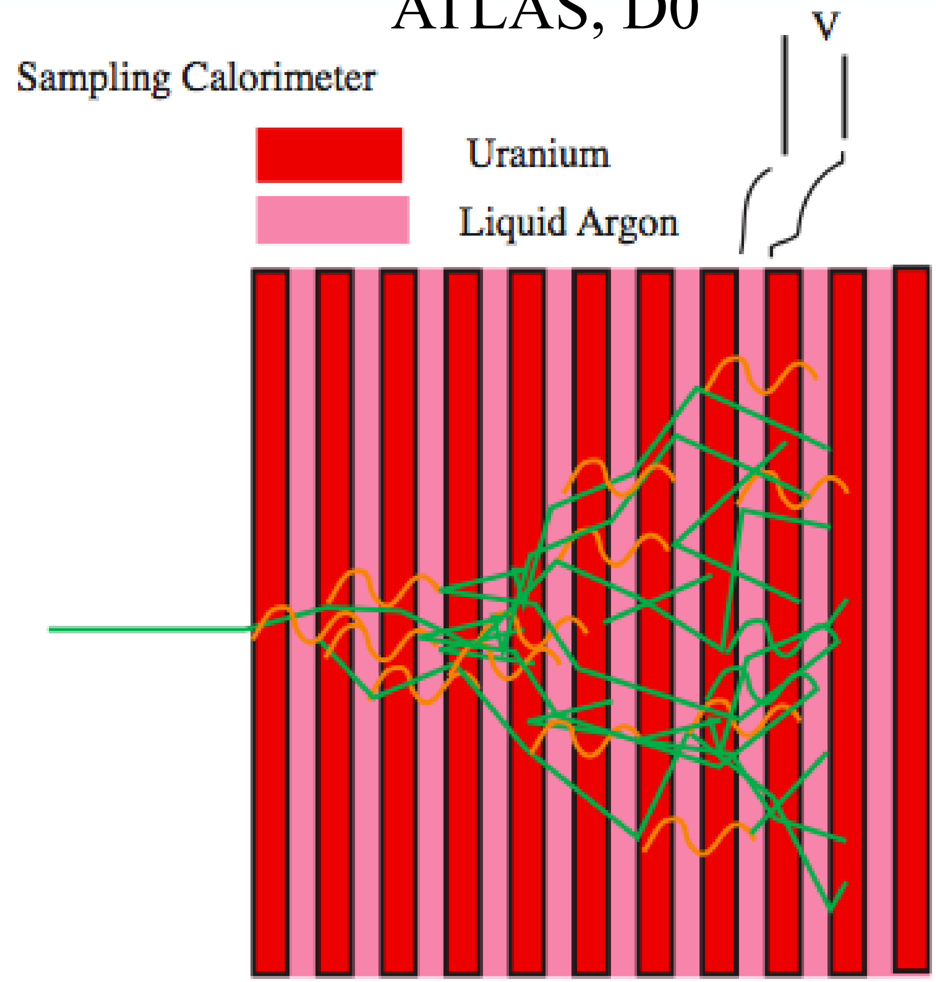
Cross sections scale as lepton mass^{-2} : bremsstrahlung is small for incident muons

Photon and Electron Detection

Total absorption calorimeter
e.g. lead glass, BGO, lead tungstate (CMS)



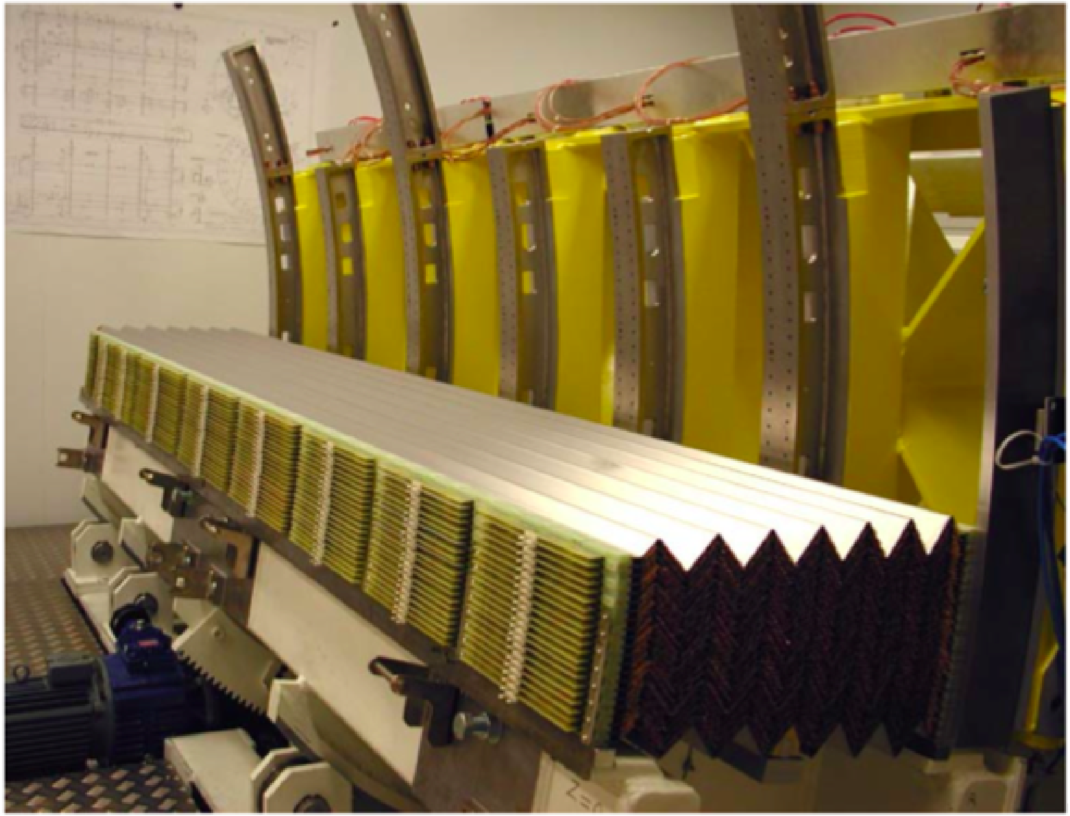
ATLAS, D0

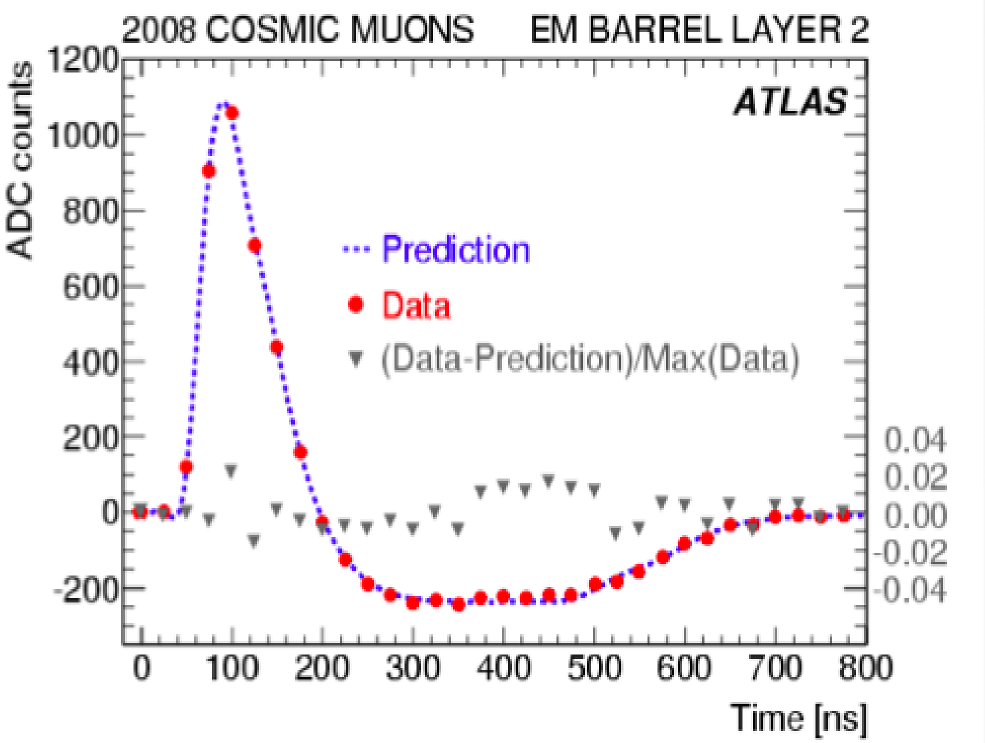


Cascade of electrons and photons due to repeated pair-production and bremsstrahlung

Collect light or electric charge deposited by the shower electrons and photons

Accordion Sampling Calorimeter





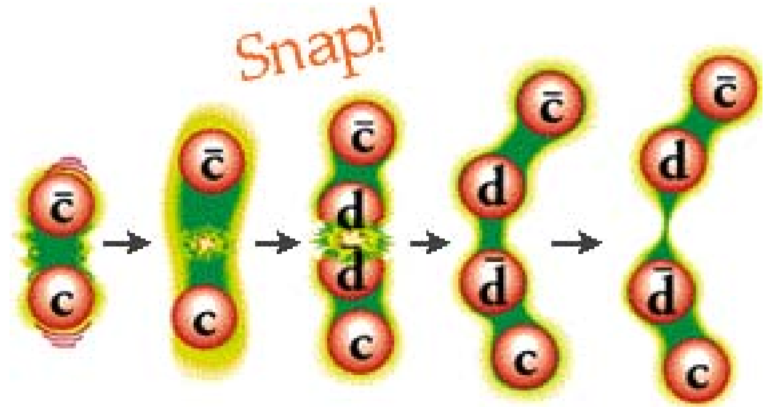
ATLAS L-Ar accordion calorimeter allows fast pulse-shaping

Benefits of noble-liquid calorimeter: stable gain, uniform response, ease of segmentation, radiation-hard

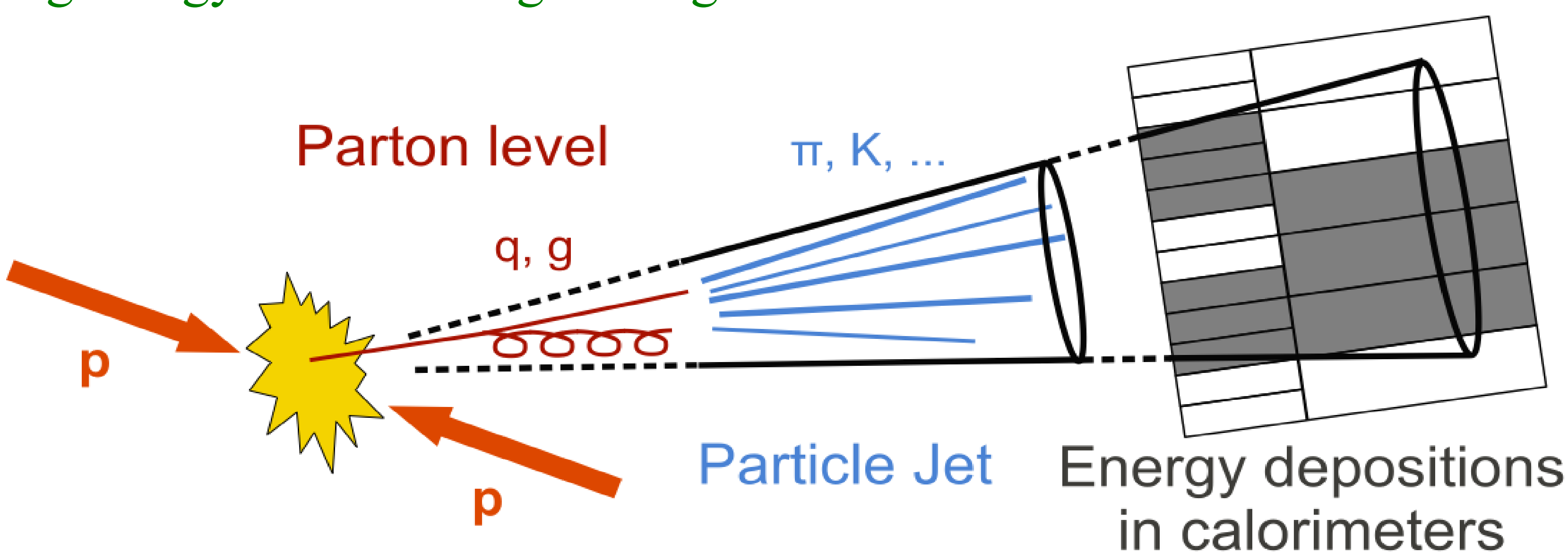
Complications: cryogenic requirements, liquid purity, long drift time, out-of-time pileup effects

Vice-versa for crystal calorimeters

Hadronic Shower



- Due to confining effect of strong force, colored quarks/gluons cannot separate:
  - gluon "string" connecting them generates the confining potential $U \propto distance$
  - String breaks with new quarks/antiquarks created from the vacuum when string energy becomes large enough

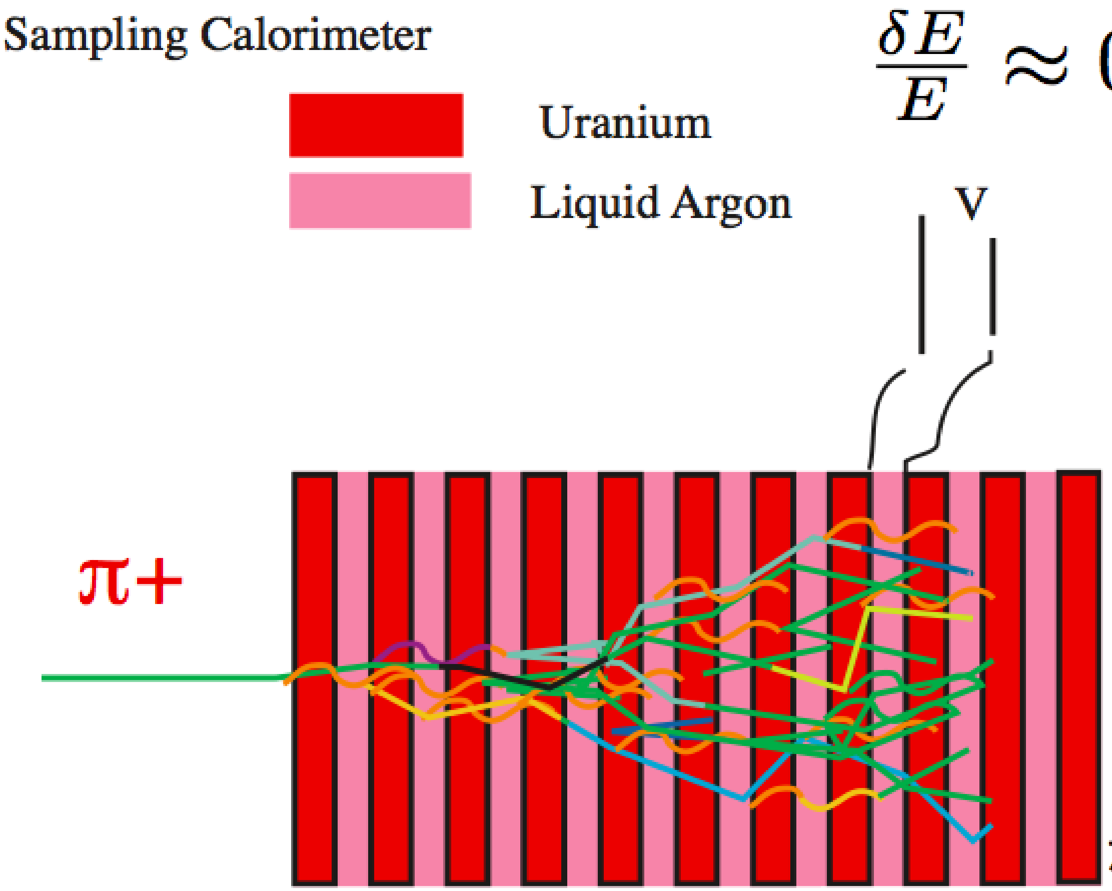


Hadronic Calorimeter

- Strong interactions of hadrons with atomic nuclei generates a cascade of particles
  => hadronic shower

- Shower fluctuations are larger than in the electron/photon case: neutrinos, neutrons, nuclear spallation products, hadronic vs electromagnetic ($\pi^0 \rightarrow \gamma\gamma$) fraction ...

$$\frac{\delta E}{E} \approx 0.50 \frac{1}{\sqrt{(E, GeV)}}$$



Requirements at 100 TeV collider

The detector has to cover wide range of signatures

- Detection of high mass states
  - Dijet resonances or compositeness, $M_{q^*} \sim 50$ TeV
  - Z' or W' to leptons, $m_{Z'} \sim 30$ TeV
  - → Deeper calorimeters, higher dynamic range
- Precision measurements of the Higgs boson properties, and Higgs in BSM production
  - Precision lepton/photon in complex events, b, c, tau tagging
  - → at least comparable to CMS/ATLAS in EM resolution and PID
- Vector boson fusion and scattering
  - Forward jets → more forward coverage, up to $\eta=6$
- Boosted jets from Z, W, top and H
  - Jet substructures
  - → More granular calorimeters

Thanks to Hong Ma

Calorimeter Geometry Issues

- Conveniences for going to higher energy:
  - Shower depth for full containment grows as log(E)
  - Energy resolution improves as $\sqrt{E}$

- Issues:
  - Dynamic range of electronics readout required scales linearly with collider energy
  - Granularity is a KEY issue: all decay products will be boosted closer together
    - 5 TeV resonance $\rightarrow$ HH $\rightarrow$ 4 τ produces 1 TeV τ-lepton
      - Photons within τ-jet are separated by ~1 mm
      - τ-leptons from Higgs separated by ~5 mm
    - 30 TeV resonance $\rightarrow$ *tt*, top decay products separated by ~1 cm
  - Tracking particles inside jets can be crucial
  - exploit particle flow algorithms to the fullest, push experience from CMS and ILC detector design effort

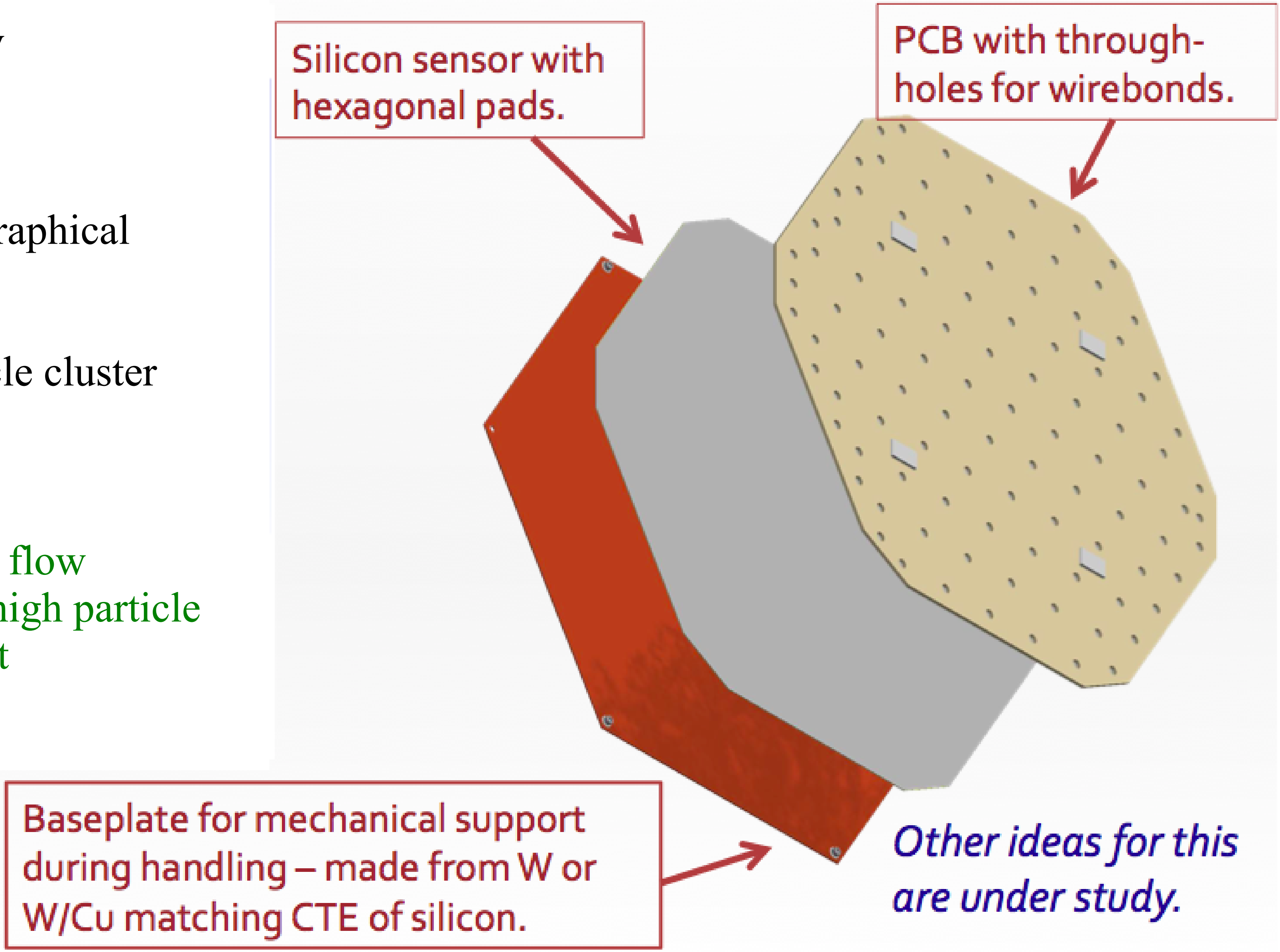
Proposal – Silicon High Granularity Calorimeter

Good cluster energy resolution

Very detailed topographical information

Excellent two particle cluster resolving power

Suitable for particle flow reconstruction in a high particle density environment



Thanks to R. Rusack, ECFA 2014

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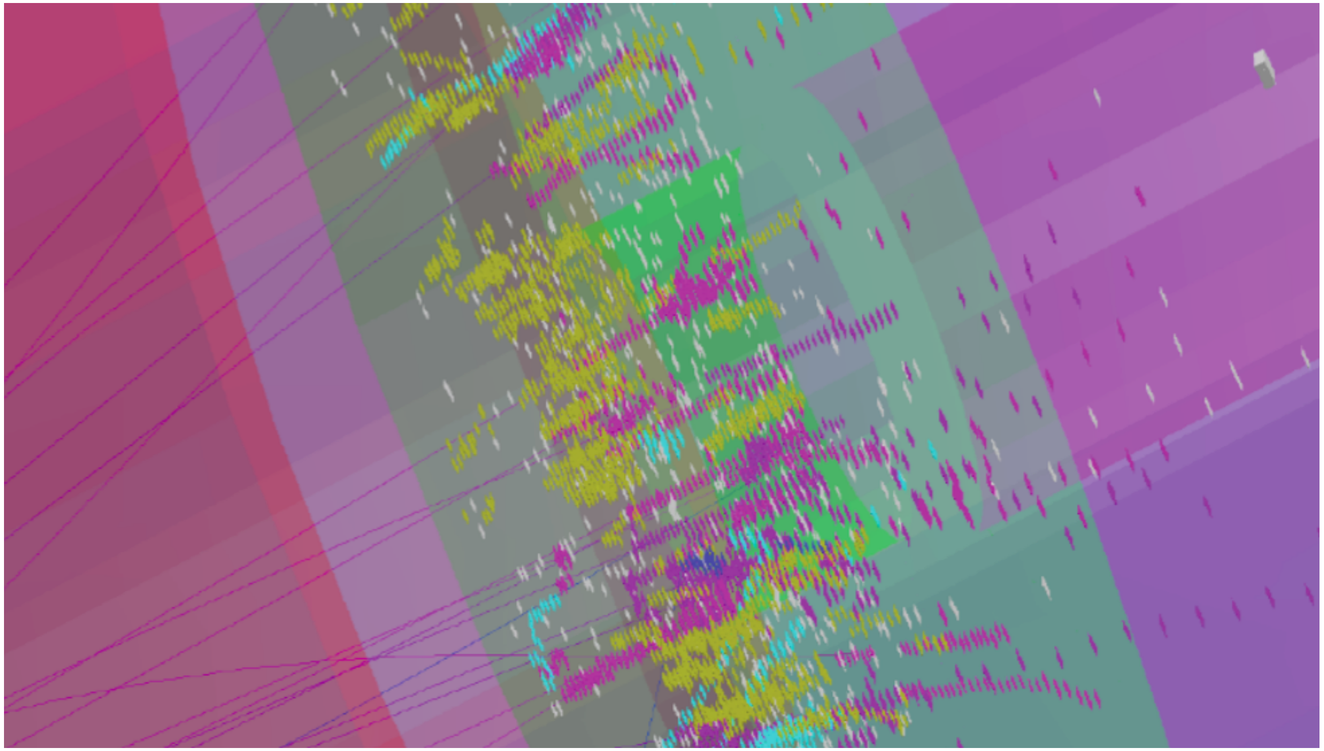
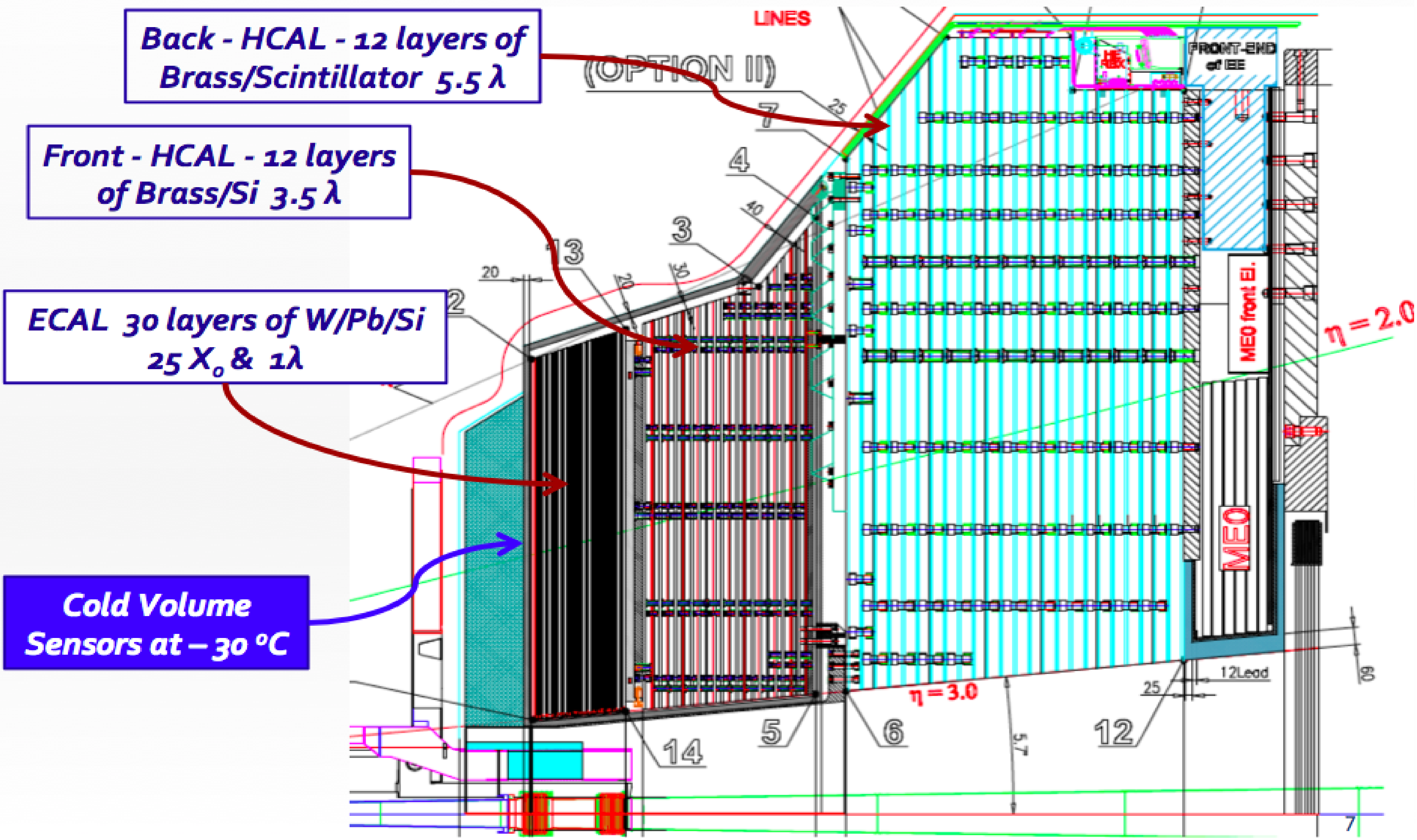


Thanks to R. Rusack, ECFA 2014

Proposal – Si-HGC for CMS Endcap

CMS Calorimeter Concept



Thanks to R. Rusack, ECFA 2014

b-tagging

b-tagging

The speed of light is

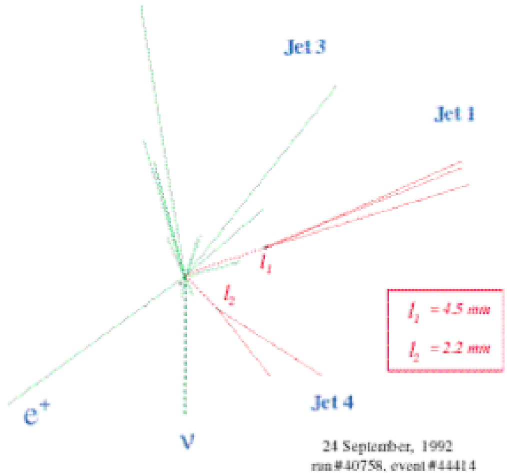
3×10^{8} m/sec

For a particle travelling at 'c'

1 nsec ~ 1 foot.

SVX Display

CDF



Example:

B meson as a lifetime in rest frame of τ

$= 1.5 \times 10^{-12}$ sec

and mass of ~ 5 GeV/c^2

$N(t) = N_0 e^{-t/\tau}$ in rest frame

a 50 GeV B meson has $\gamma = 10$

and time-dilated lifetime of

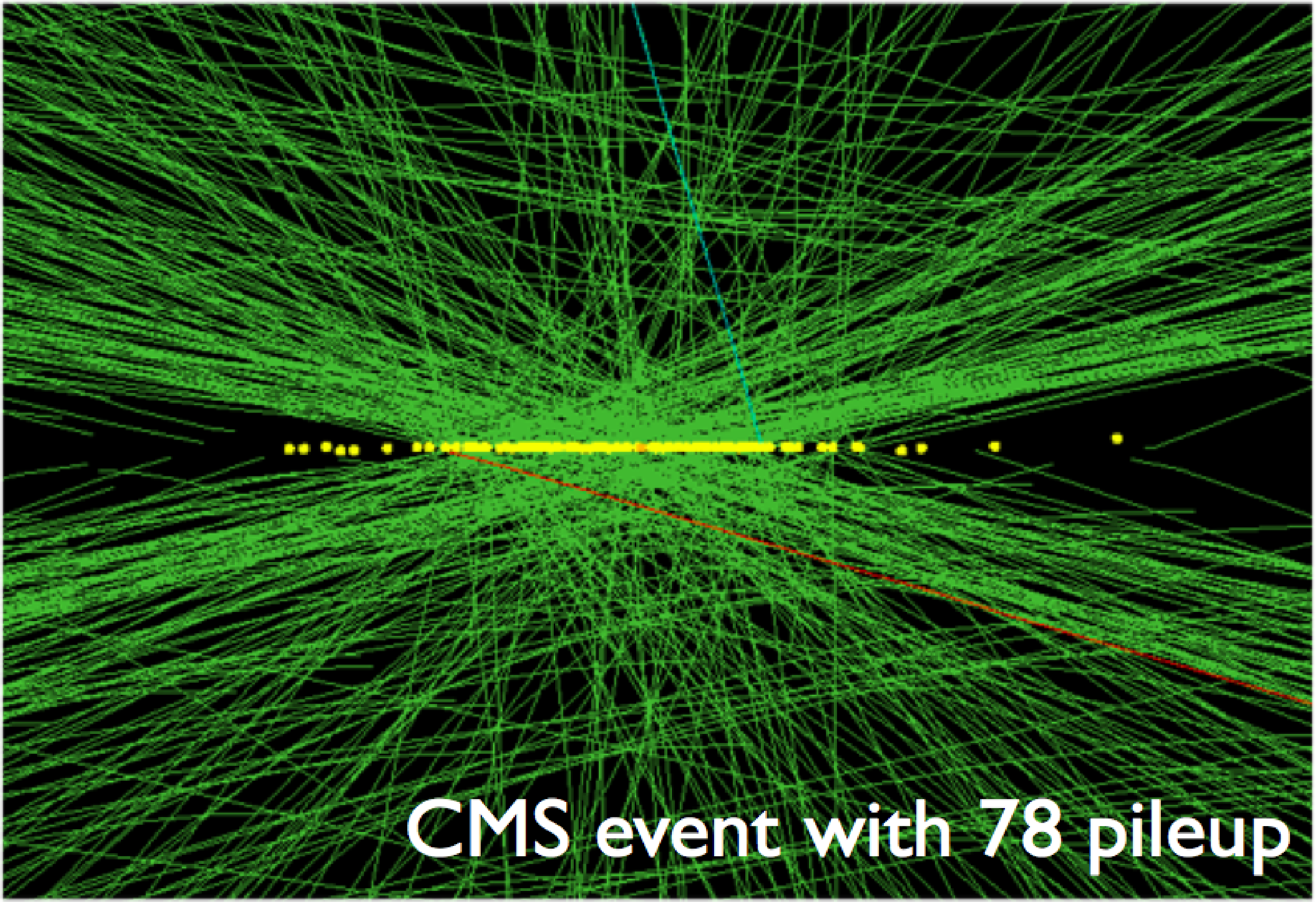
$t = \gamma\tau \sim 1.5\text{x}10^{-11}$ sec

It will travel ~4.5 mm on average.

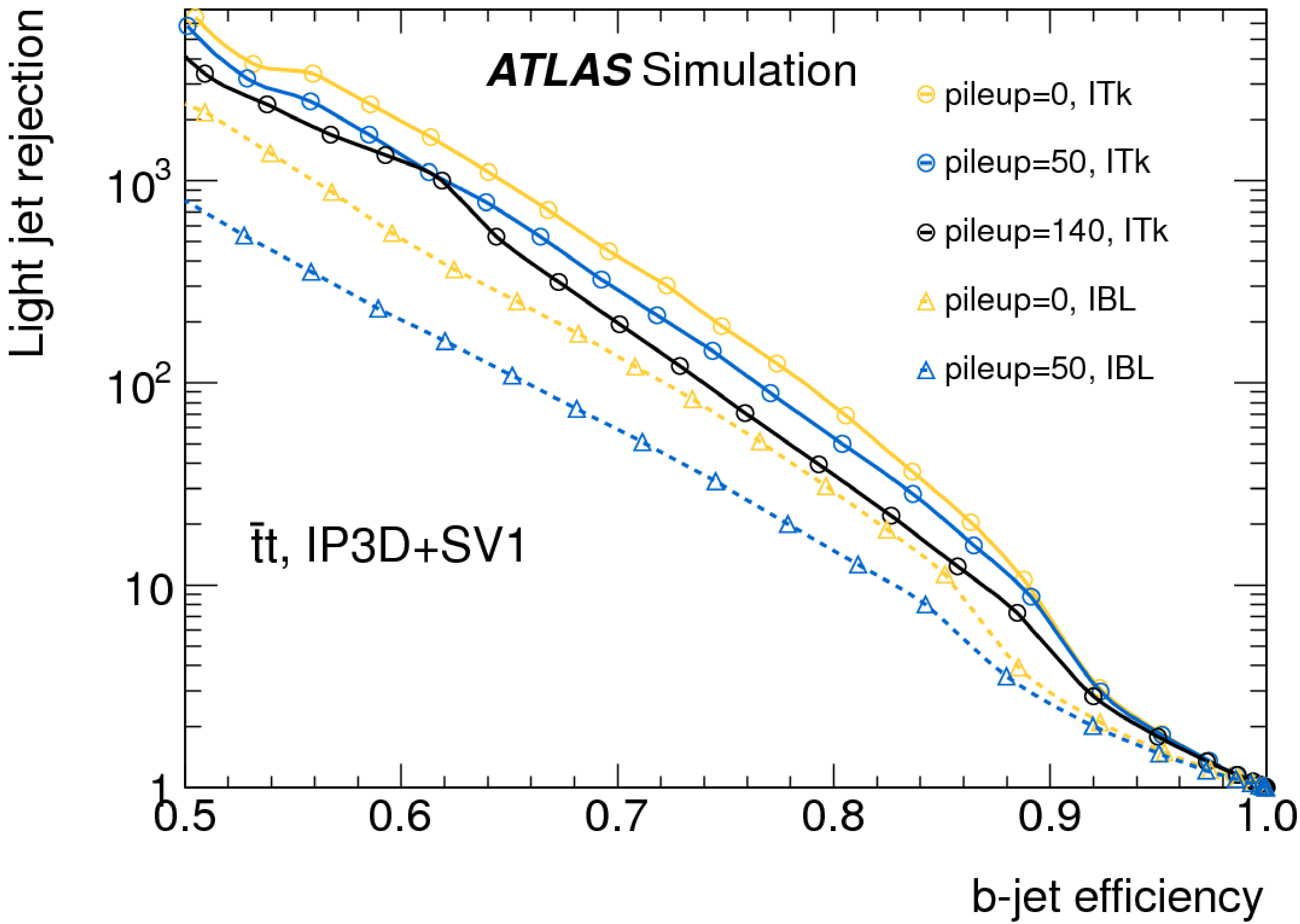
Thanks to H. Schellman

CMS Barrel Pixel detector

Multiple *pp* Interactions (pileup)



Design Performance for HL-LHC



IBL = current, ITk = HL-LHC design (3 → 4 pixel layers, smaller pixels)

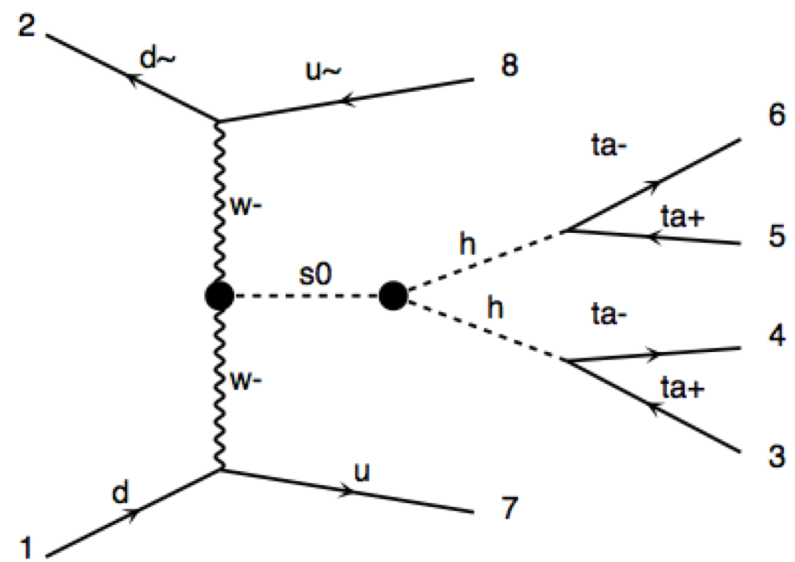
Forward rapidity coverage

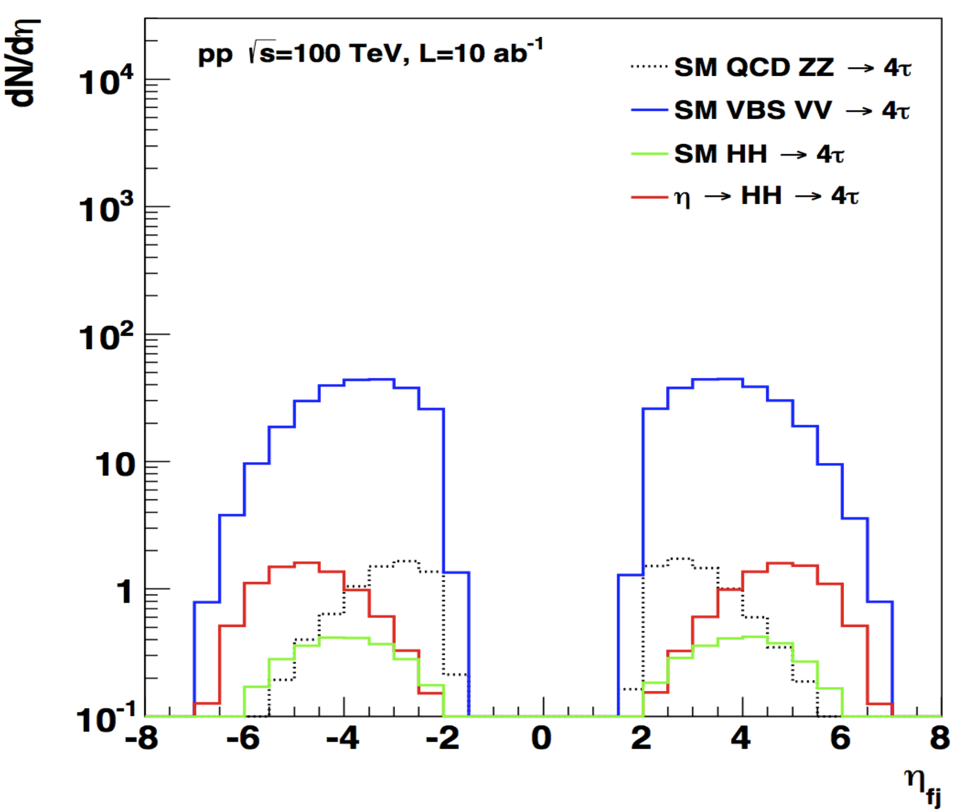
Why is the Higgs Boson So Light?

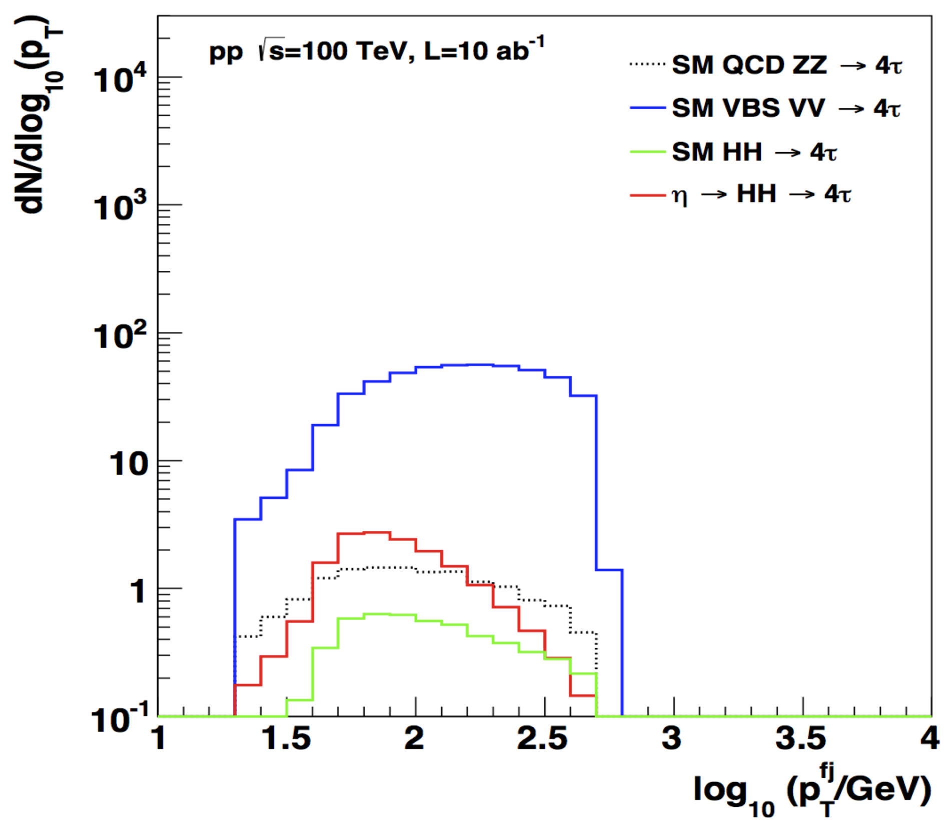
- Old idea: Higgs doublet (4 fields) is a Goldstone mode generated from the spontaneous breaking of a larger global symmetry
  - Higgs boson and W_L, Z_L are all Goldstone bosons from, eg. Spontaneously breaking global SO(5) → SO(4)
  - Examples: Holographic Higgs, Little Higgs models...
  - Electroweak vev "*v*" is small compared to SO(5) breaking scale "*f*"

- Vector boson scattering topology
  - Quarks emit longitudinal vector bosons which interact with new (presumably strong) dynamics
  - Quarks scatter by small angle in the forward direction

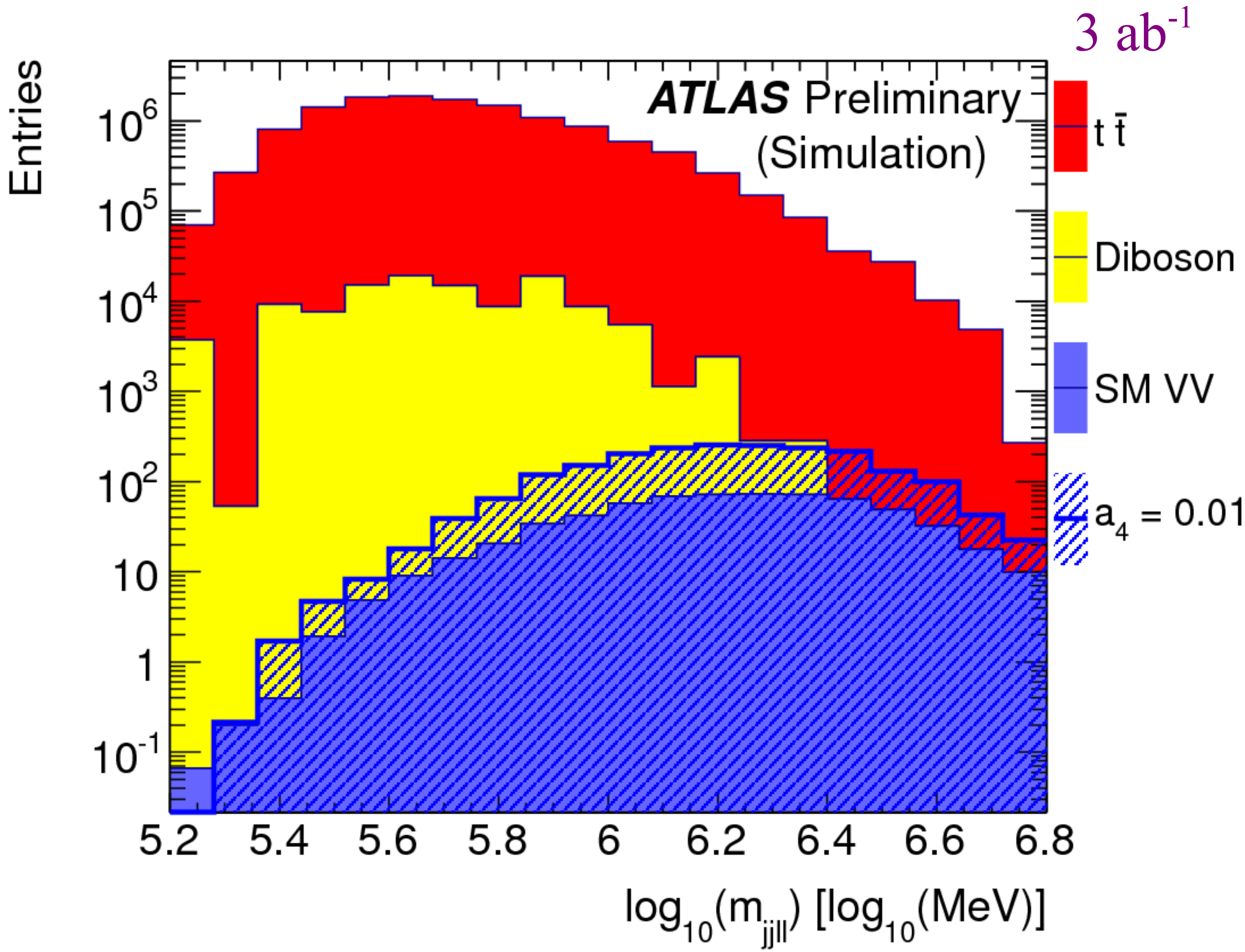
Vector Boson Scattering







VV → WW Scattering



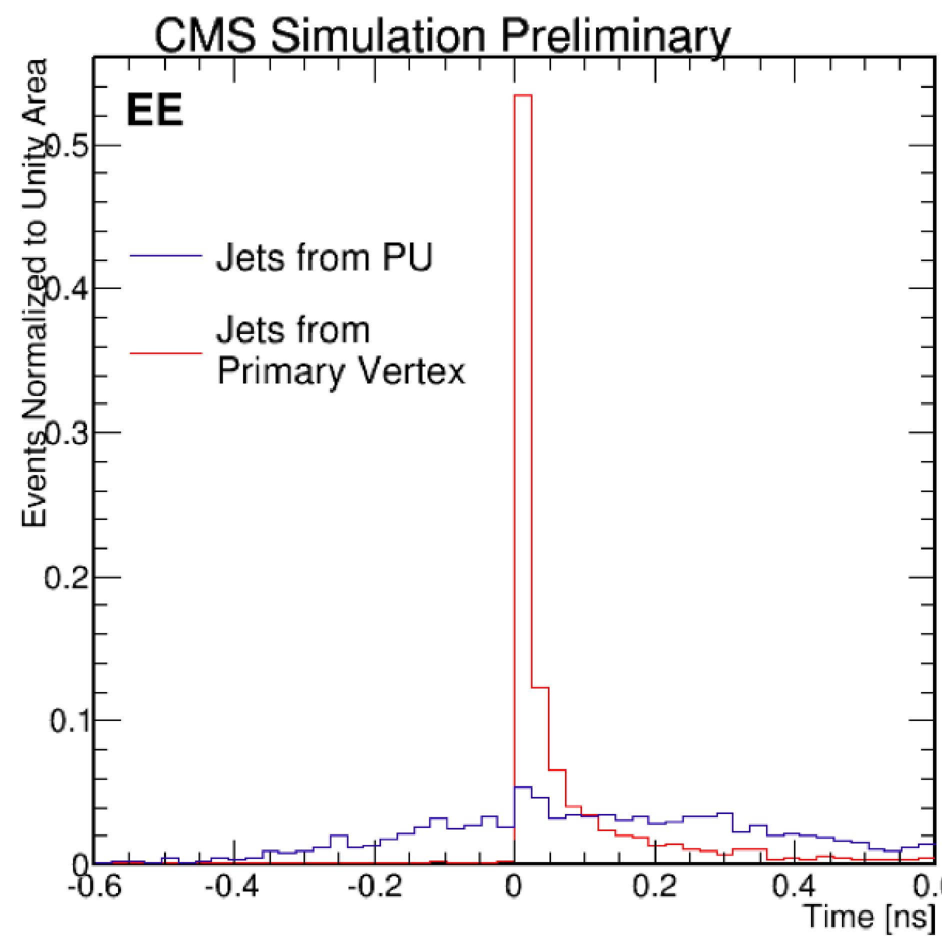
For W^+W^- final state in VBS, *tt* background is problematic

Forward *b*-tagging can veto *tt* to reduce it to a managable level

Timing

ECAL Clean-up using Timing

- **Effect of timing cut** on ΣE_T^{ECAL} variable
  - sum of all ECAL hits with E > 1GeV.
- O(30 ps) resolution detector simulated
- Require ECAL timing (time-of-flight subtracted) within a **90 ps window**
- Most of the **PU extra energy gone**
  - able to almost recover no PU conditions
- Timing-based selection looks **promising for high PU environment**



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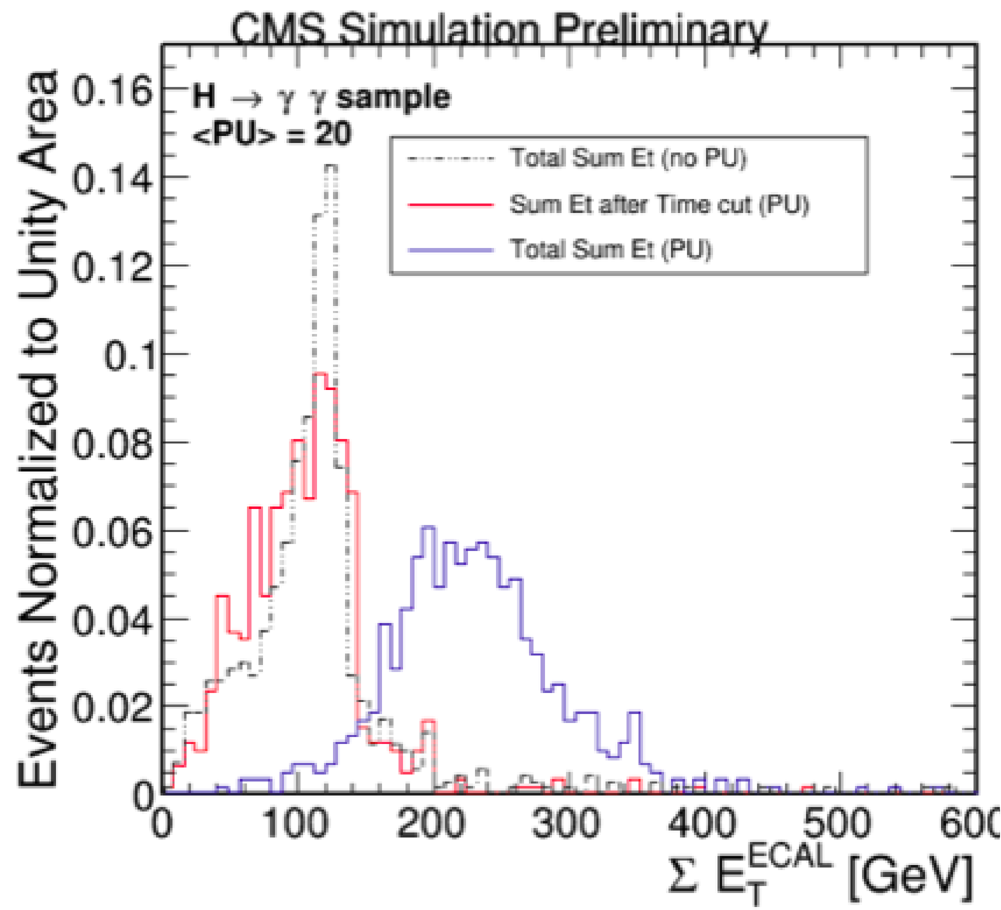
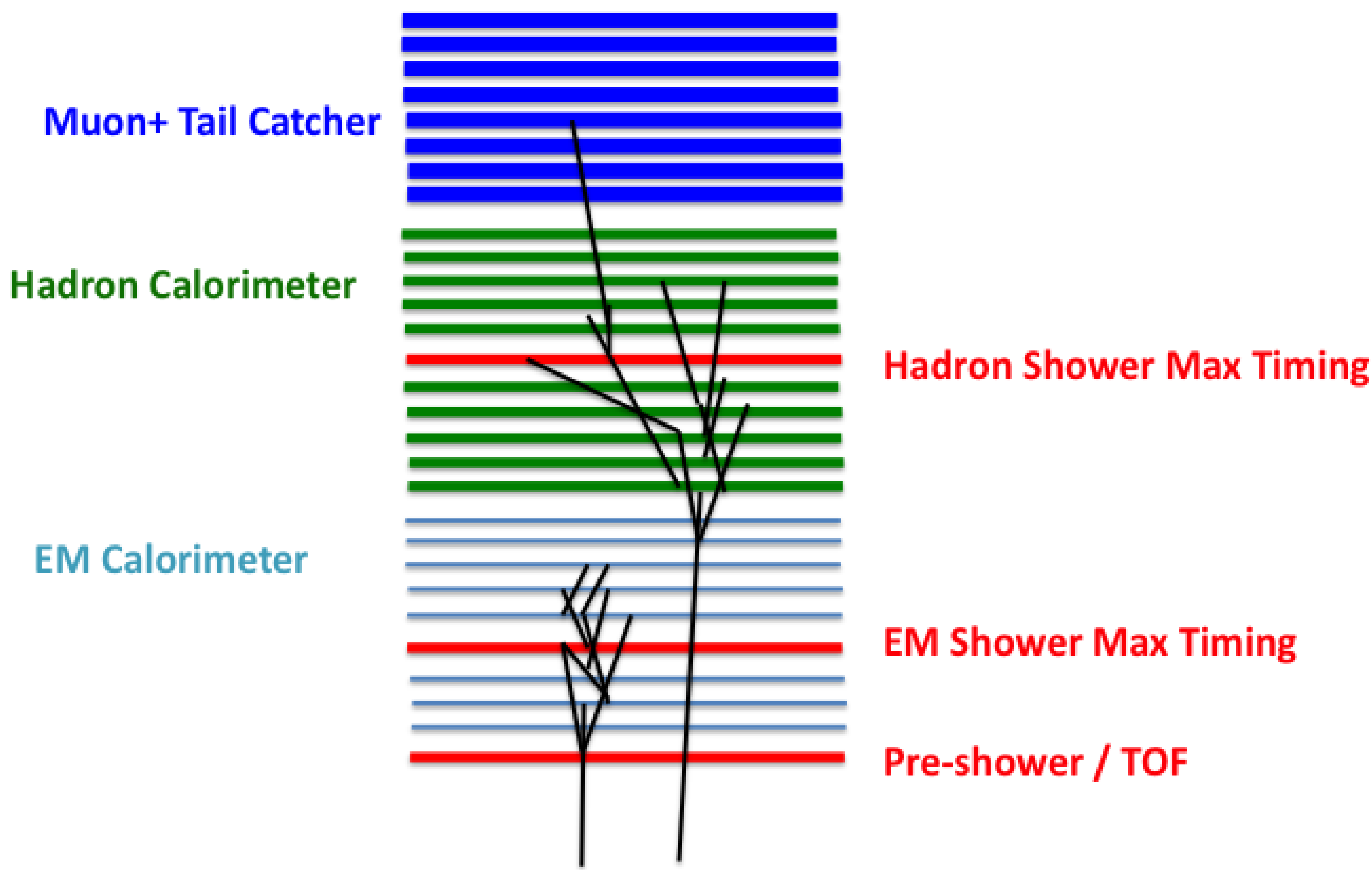


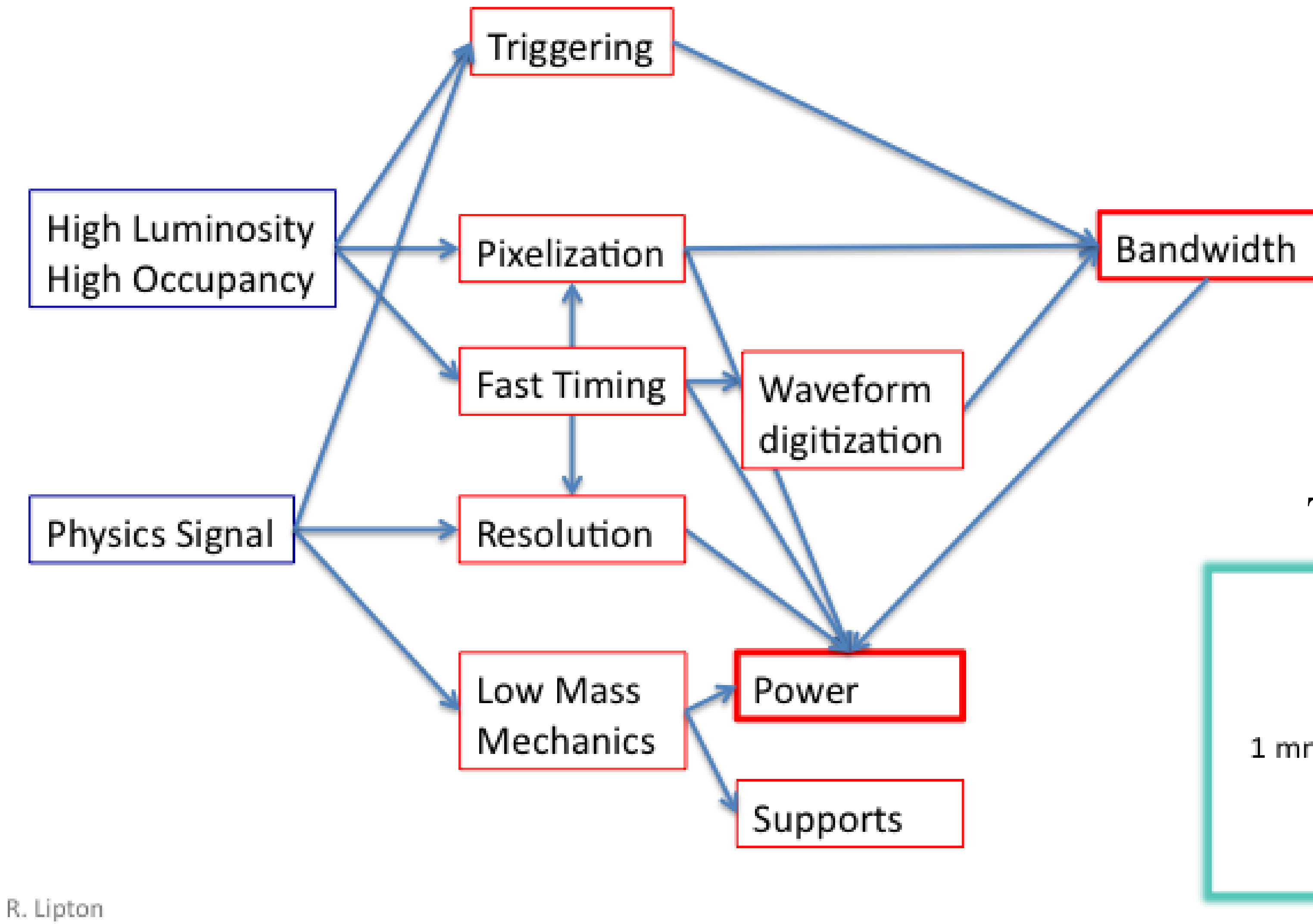
A Strawman Design:
Sampling Calorimeters INtegrated with Timing (SCINT)



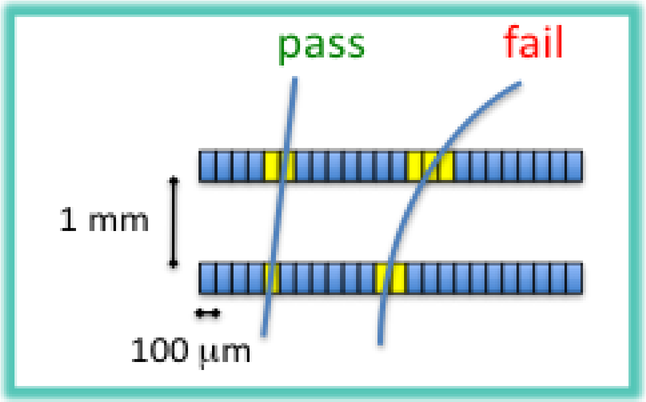
Eric Ramberg, Fermilab Workshop talk

Summary

Whole Picture – The Drivers



Track triggering



Radiation damage:

0.01 ab^{-1} (Tevatron) → 0.3 ab^{-1} (LHC) → 3 ab^{-1} (HL-LHC) → 10+ ab^{-1} ?

Summary

- Entering new regime on all fronts
  - Accelerator physics and design
  - Detector technology and design
- Completion of the Standard Model and its consistency with all data implies
  - Energy scale of new physics is less well-defined now than when LHC/SSC were designed
  - We must prepare for a broader range of possible new physics
- Detectors will need to be more capable on all fronts
  - Faster
  - Much higher resolution
  - Much higher granularity
  - Much more forward-detection capability
  - Much higher bandwidth, smarter triggers
- Substantial knowledge & experience on detector design will be gained from HL-LHC upgrade