Experiments at Future *pp* Colliders

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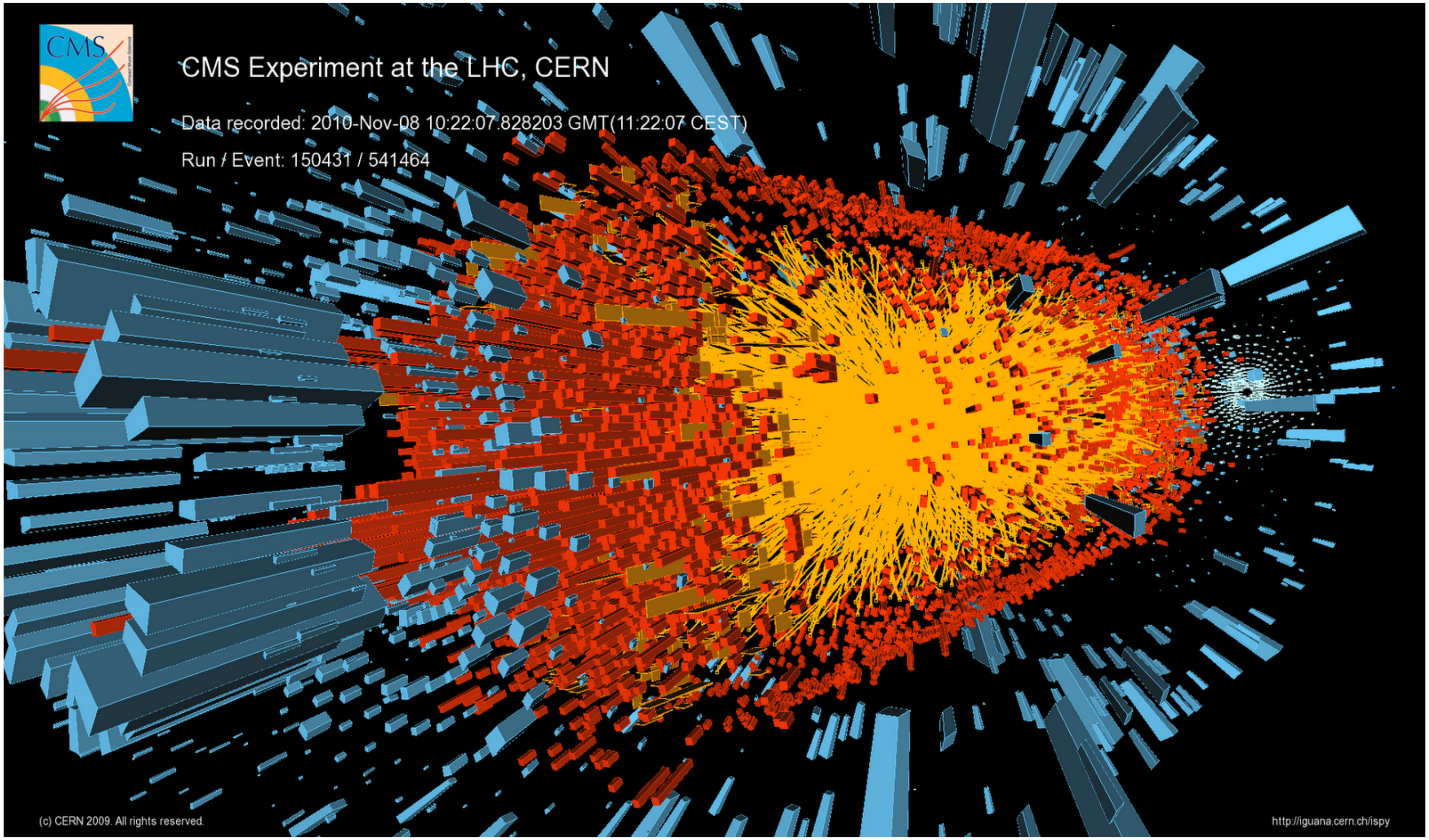


Workshop on Probing the EWPT
Amherst Center for Fundamental Interactions
September 17, 2015

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 τ2leptons
  - 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

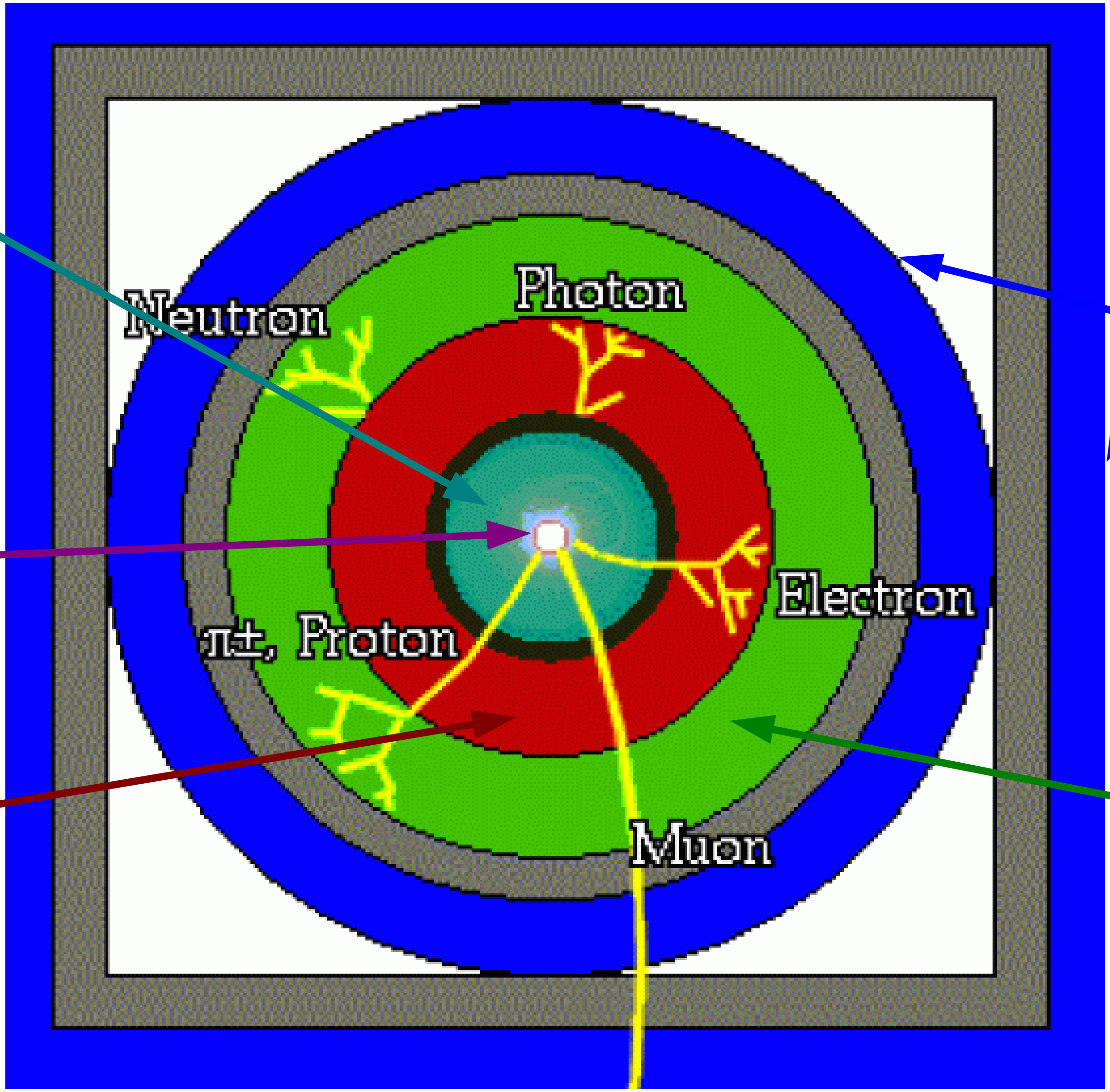
- Maximize Δt x *L*: enable data-taking in high instantaneous luminosity environment
  - Large number of particles from additional (uninteresting) pp collisions
    - Can confuse/obfuscate the particles from the interesting collision
  - Total exposure of sensors to radiation flux scales with integrated 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)

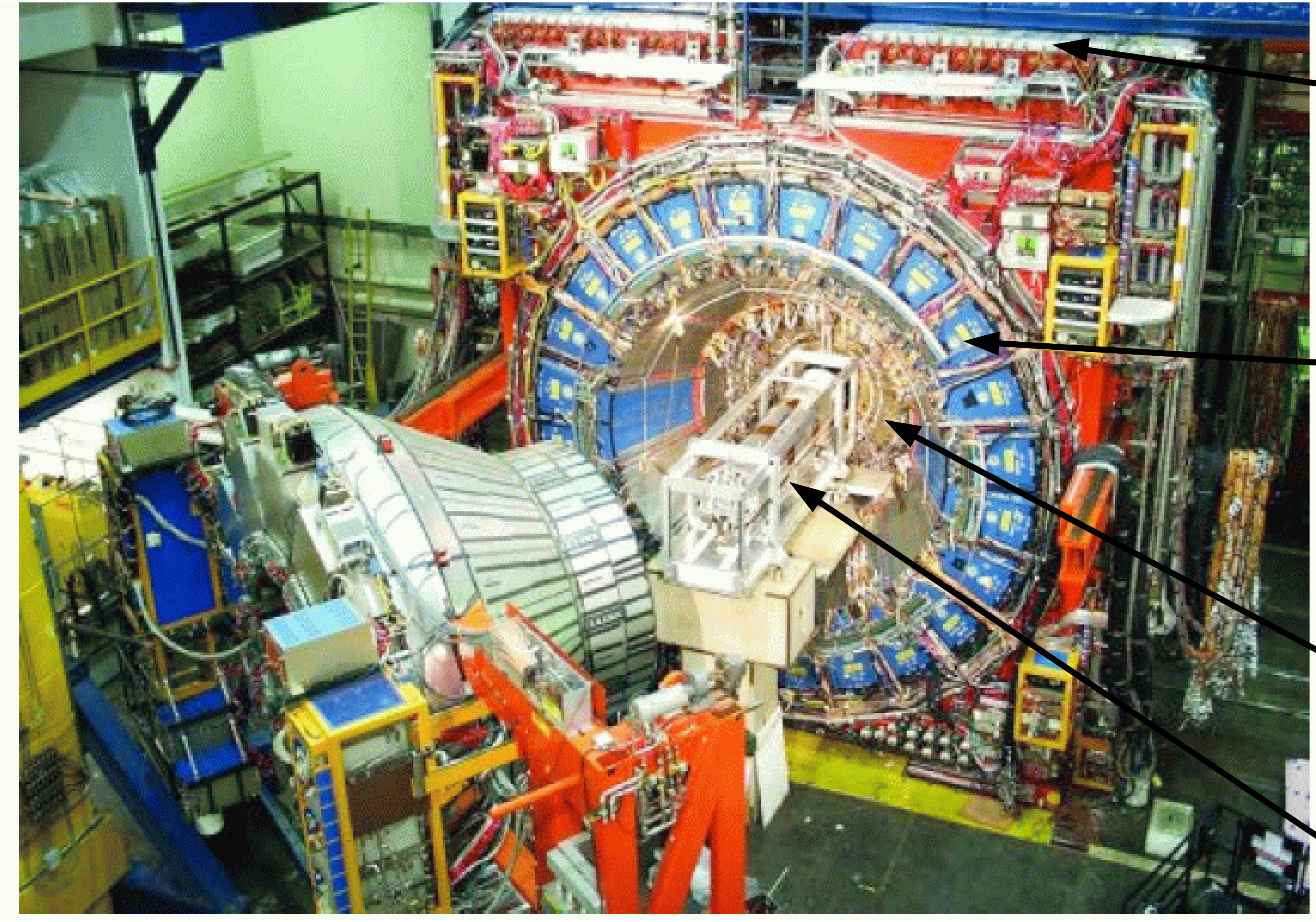
Electromagnetic (EM) calorimeter: metal sheets cause *e*/γ shower, sense light or charge



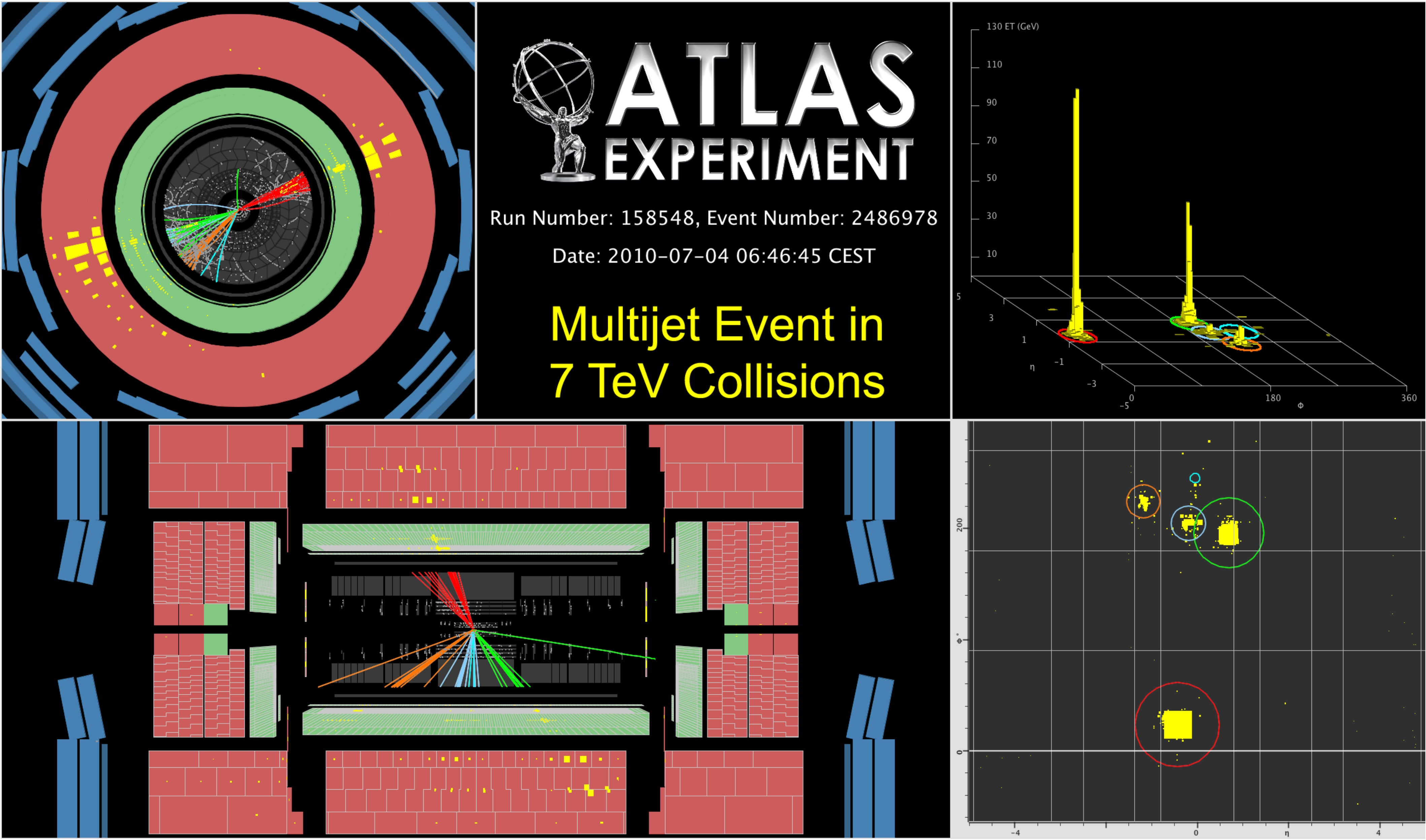
Muon chambers: detect penetrating particles behind shielding

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

Collider Detector at Fermilab (CDF)



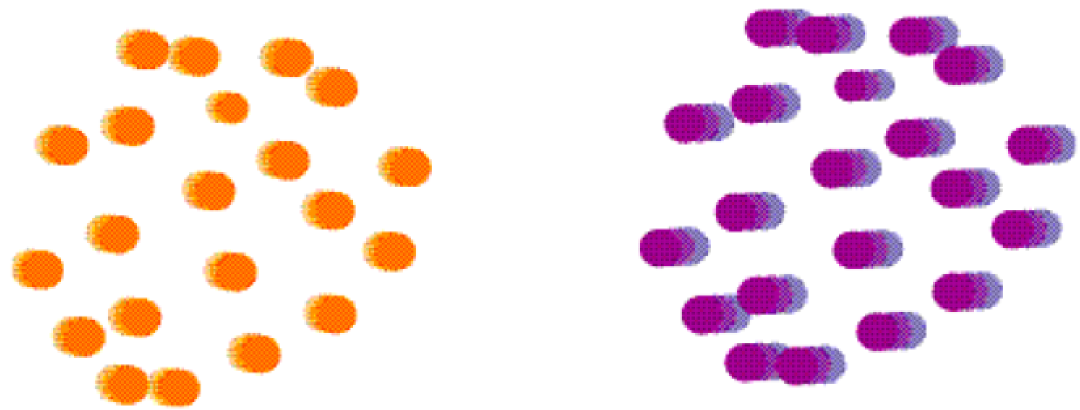
Particle Detection



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

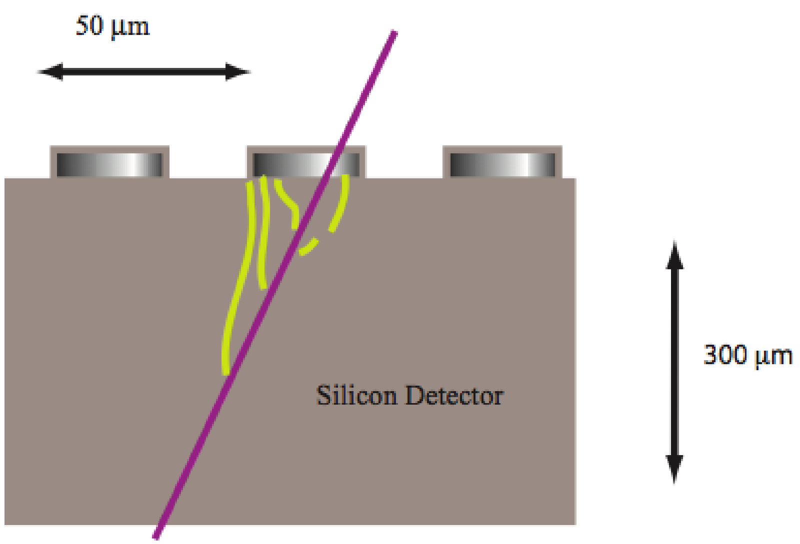
Reducing *s* is not easy for the accelerator; 5 ns option to be considered

Beam power increases in inverse proportion to crossing time

Thanks to H. Schellman

Magnetic Tracking

ATLAS Silicon Tracker

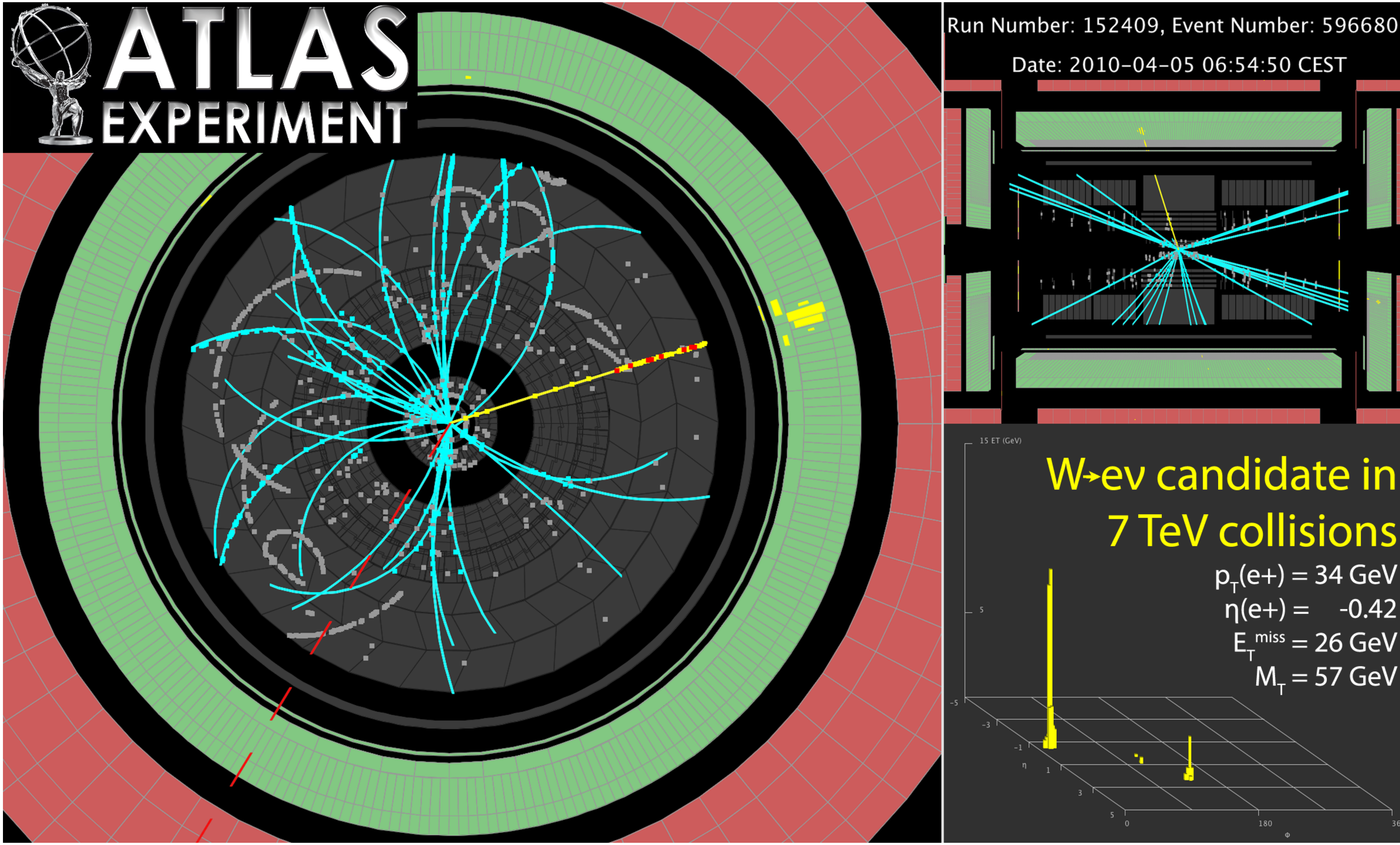


Detect ~2000 e in a 350 µm thick detector

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

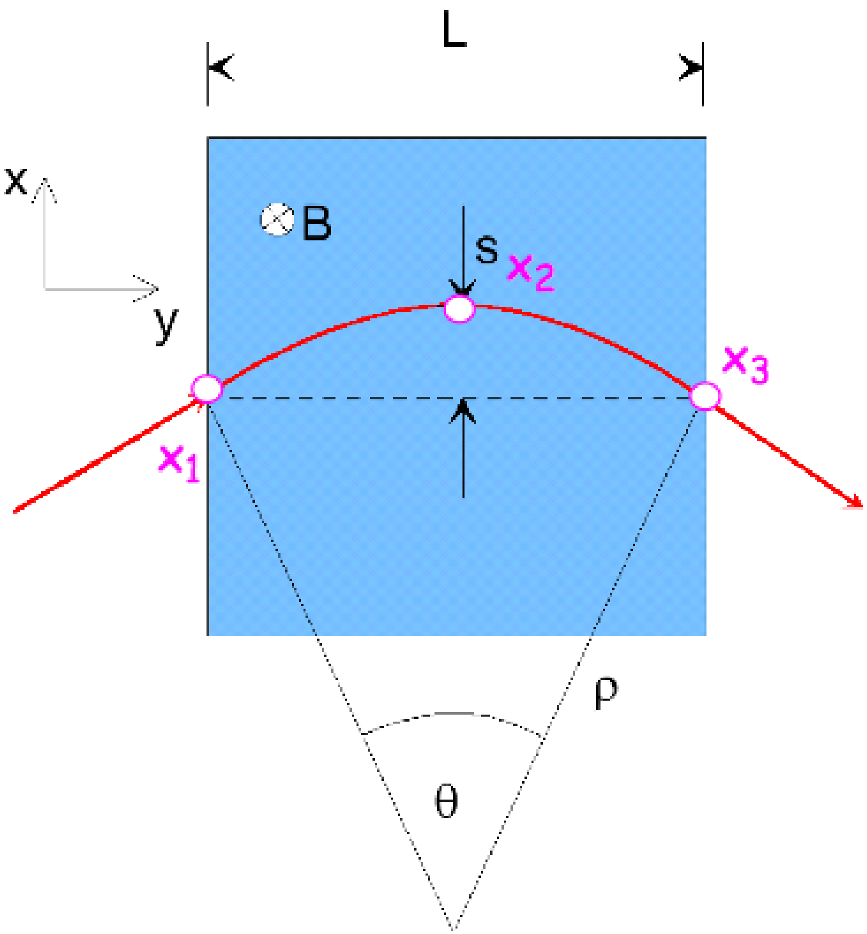
Tracker Design – the heart of the experiment

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



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

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

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

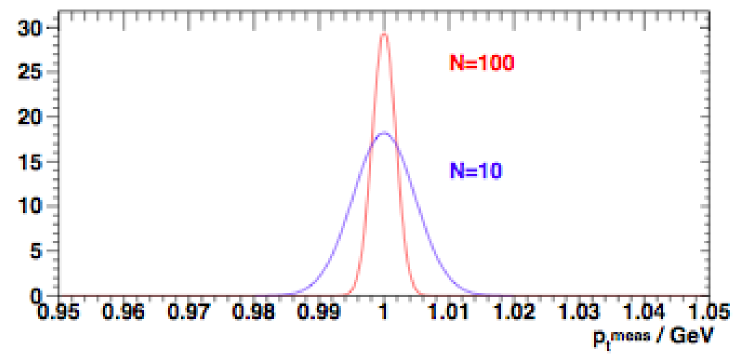
In the case of N equidistant measurements according to Gluckstern [NIM 24 (1963) 381]:

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

(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:

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



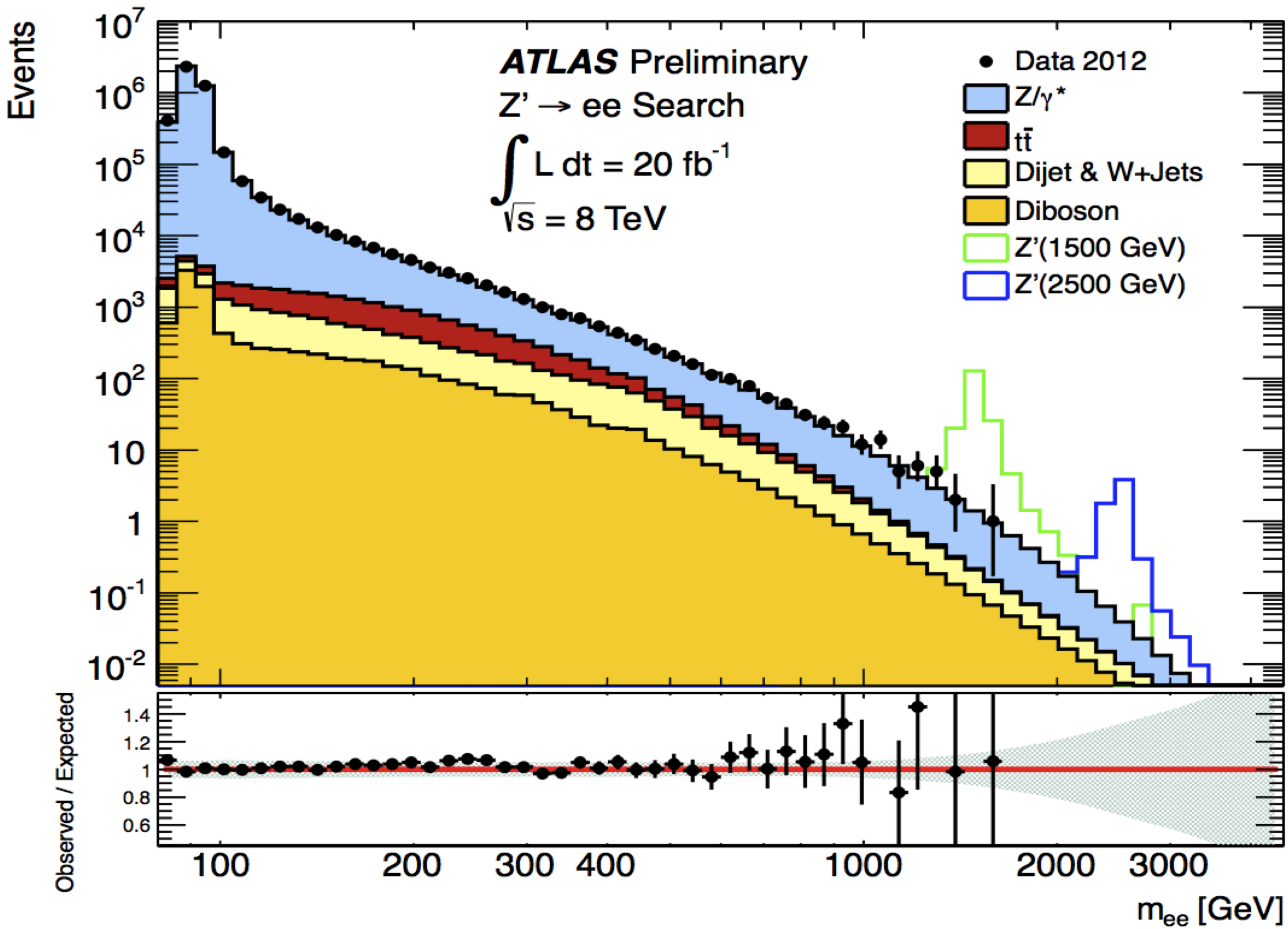
Important track detector parameter: $\frac{\sigma(p_T)}{p_T^2}$ (%/GeV)

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

Thanks to Carsten Niubuhr

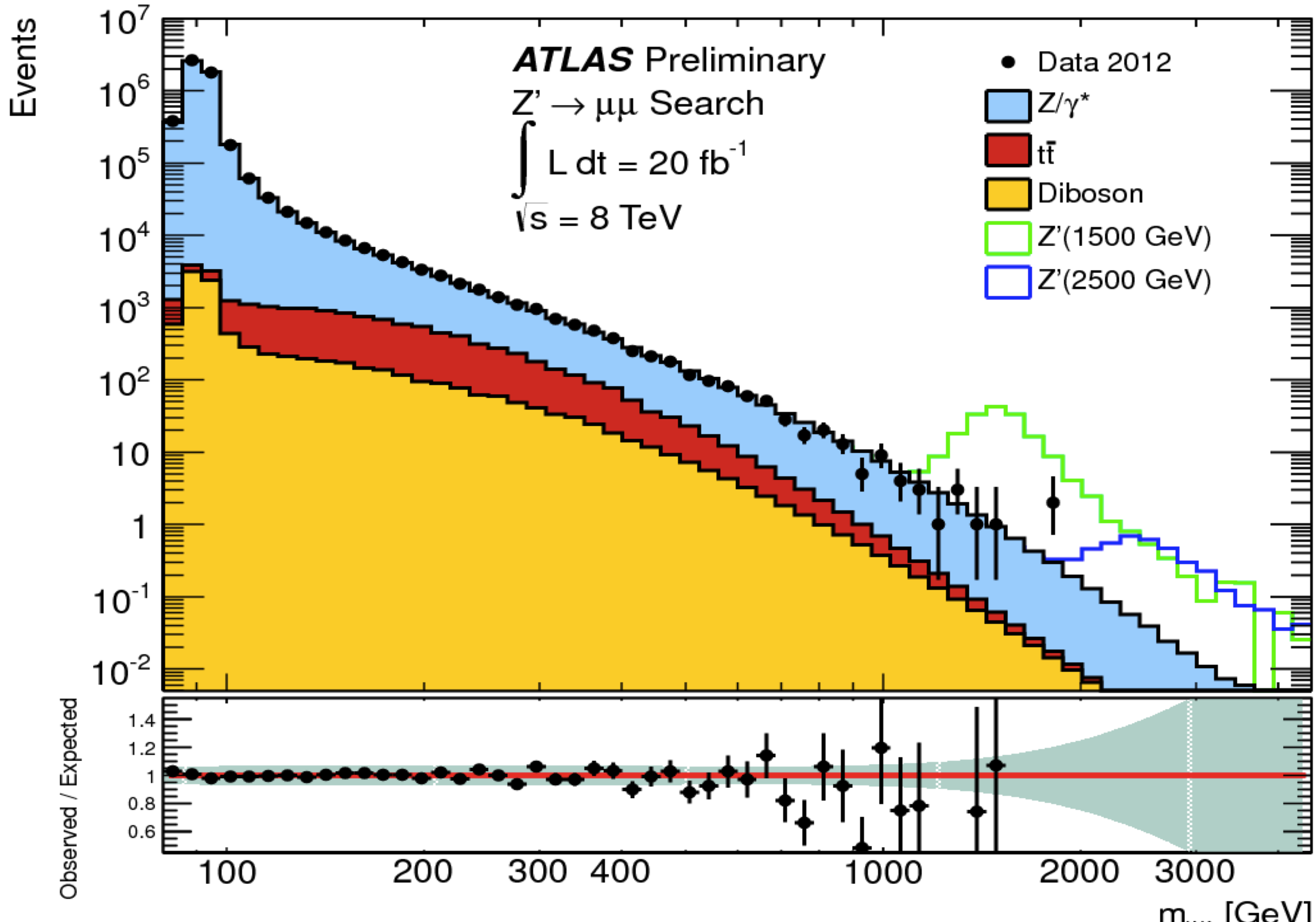
Dielectron Mass Spectrum

Multi-TeV masses probed at LHC



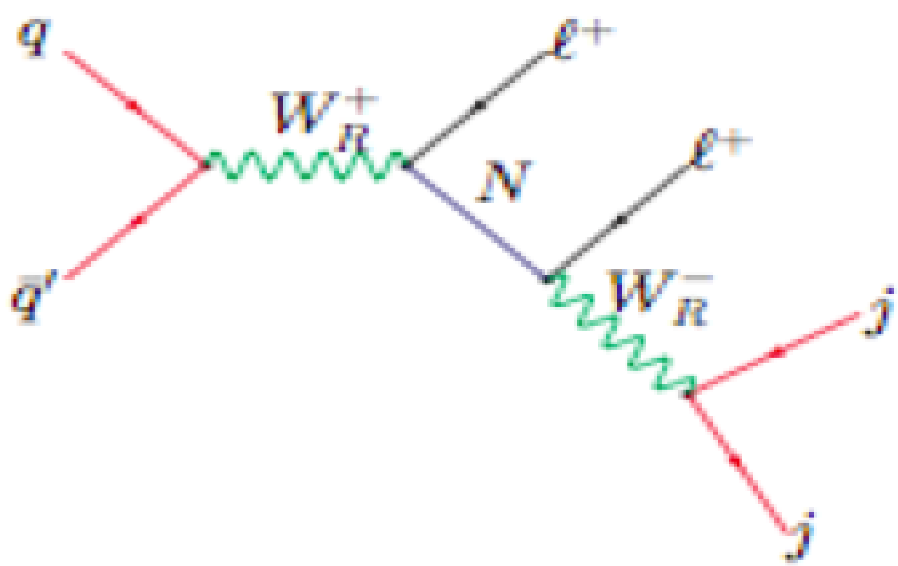
Dimuon Mass Spectrum

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 $H \to \mu\mu$
  - Left-right seesaw model of neutrino masses



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

(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

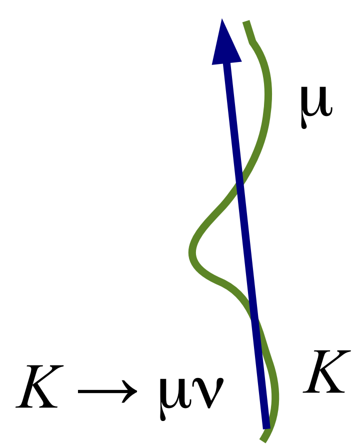
Three tracker/magnet geometries being considered:

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

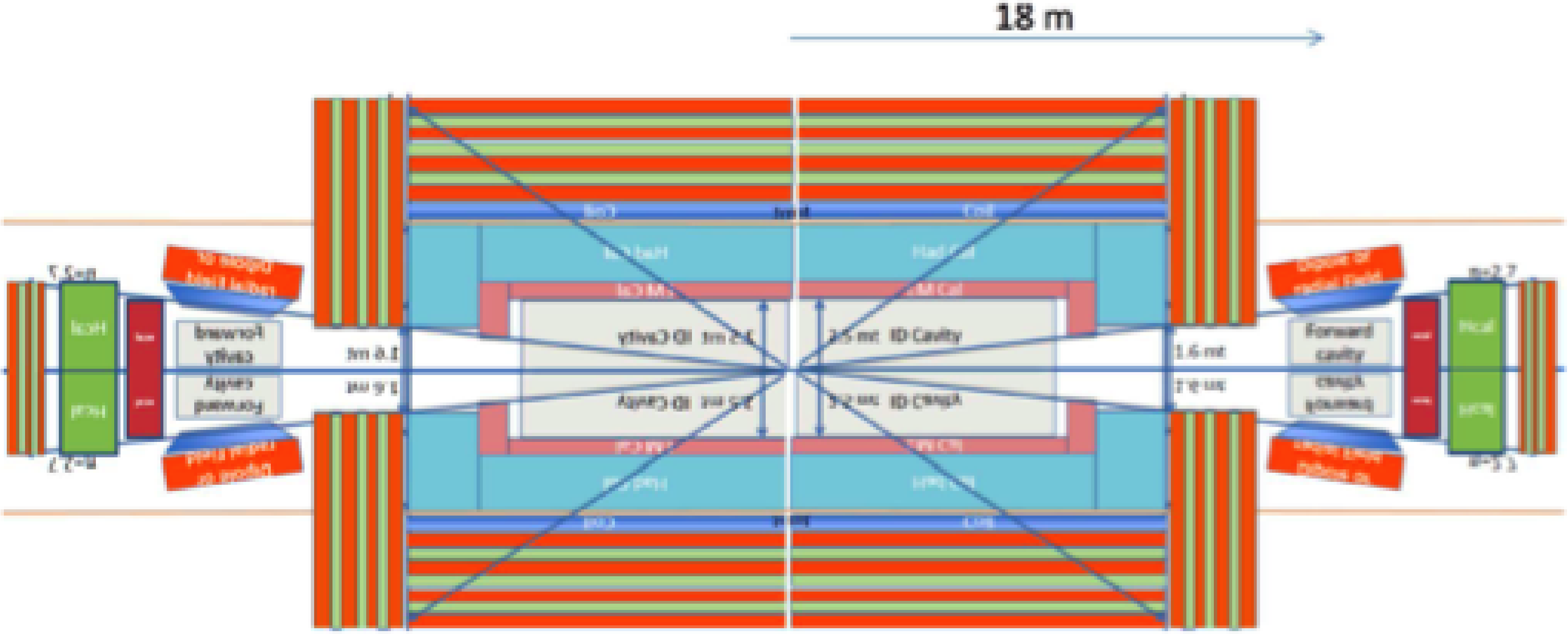
https://indico.fnal.gov/conferenceOtherViews.py?view=standard&confId=7864

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

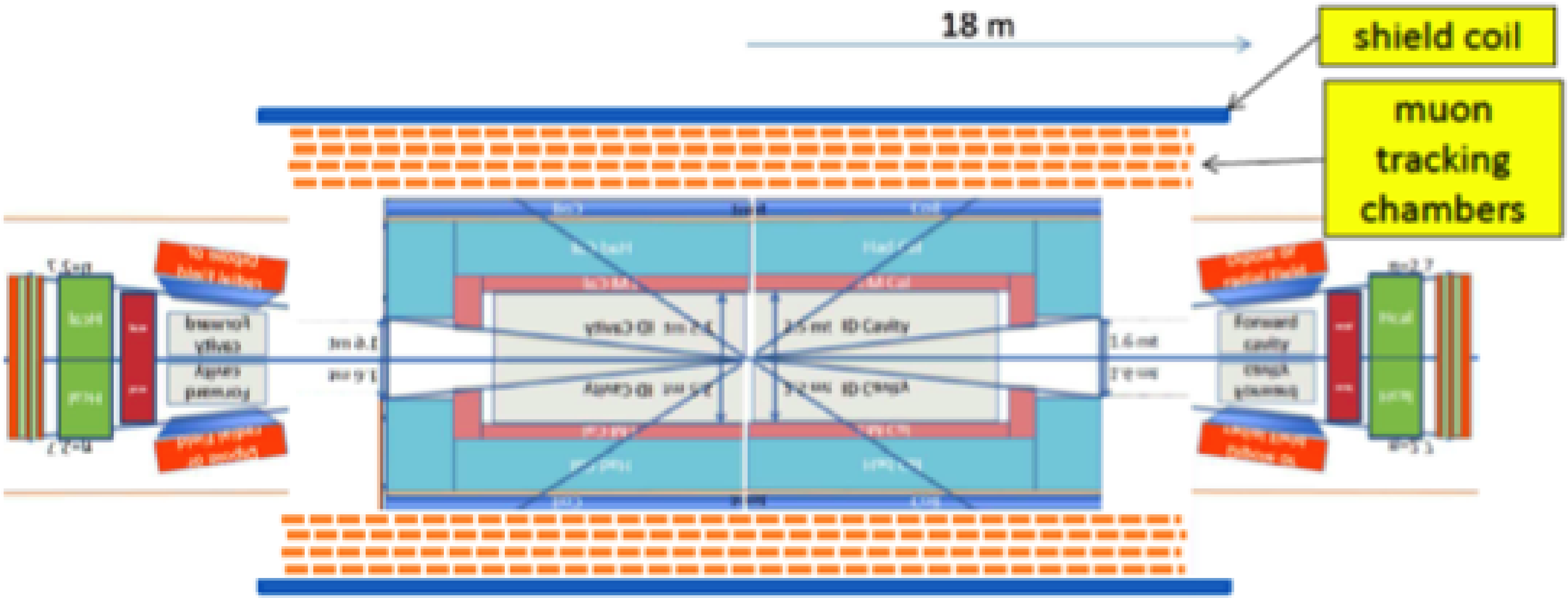


2. Option 1: Solenoid-Yoke + Dipoles (CMS inspired)



- **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

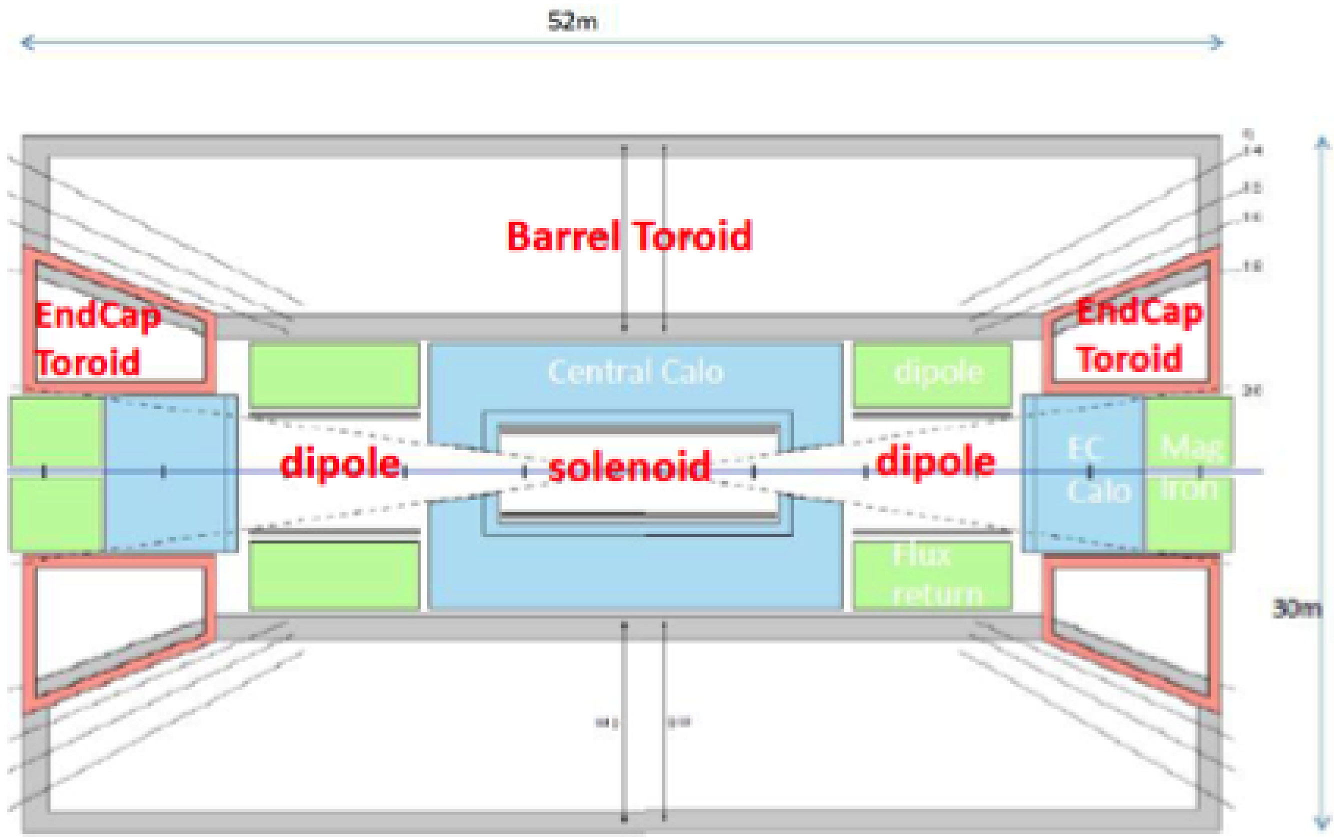


Twin Solenoid: a 6 T, 12 m dia x 23 m long main solenoid + an active shielding coil

Important advantages:

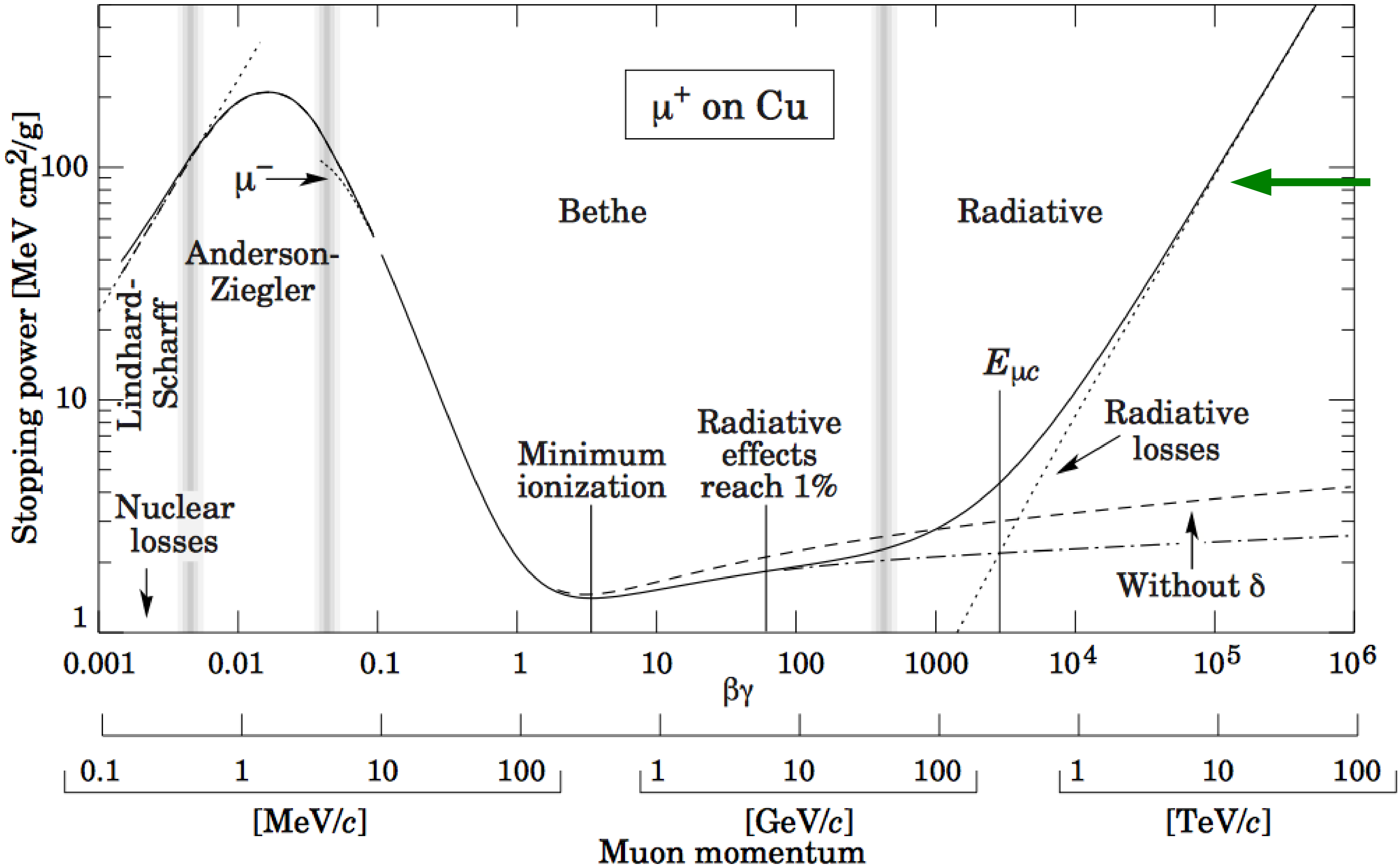
- ✓ **Nice Muon tracking space:** area with 2 to 3 T for muon tracking in 4 layers.
- ✓ **Very light:** 2 coils + structures, ≈ 5 kt, only ≈ 4% of the option with iron yoke!
- ✓ **Much smaller:** system outer diameter is significantly less than with iron .

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 m³).

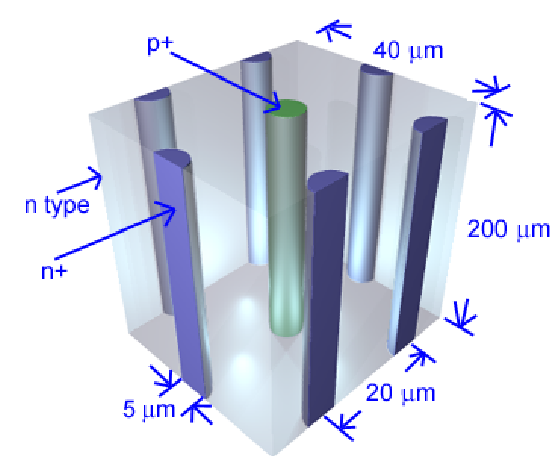
High Energy Muon Bremsstrahlung



- 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

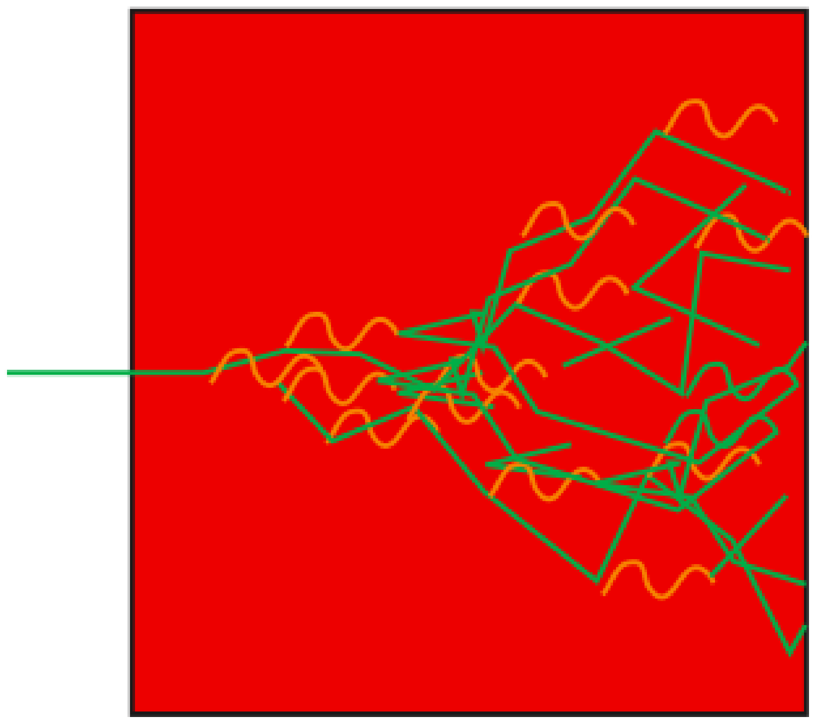
- Smaller pixels with silicon sensors have multiple advantages
  - Improved hit resolution linearly improves momentum resolution at high p_T
  - Higher granularity improves two-track resolving power
    - Helps resolve close-by tracks and maintain track reconstruction efficiency in
      - high-density 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



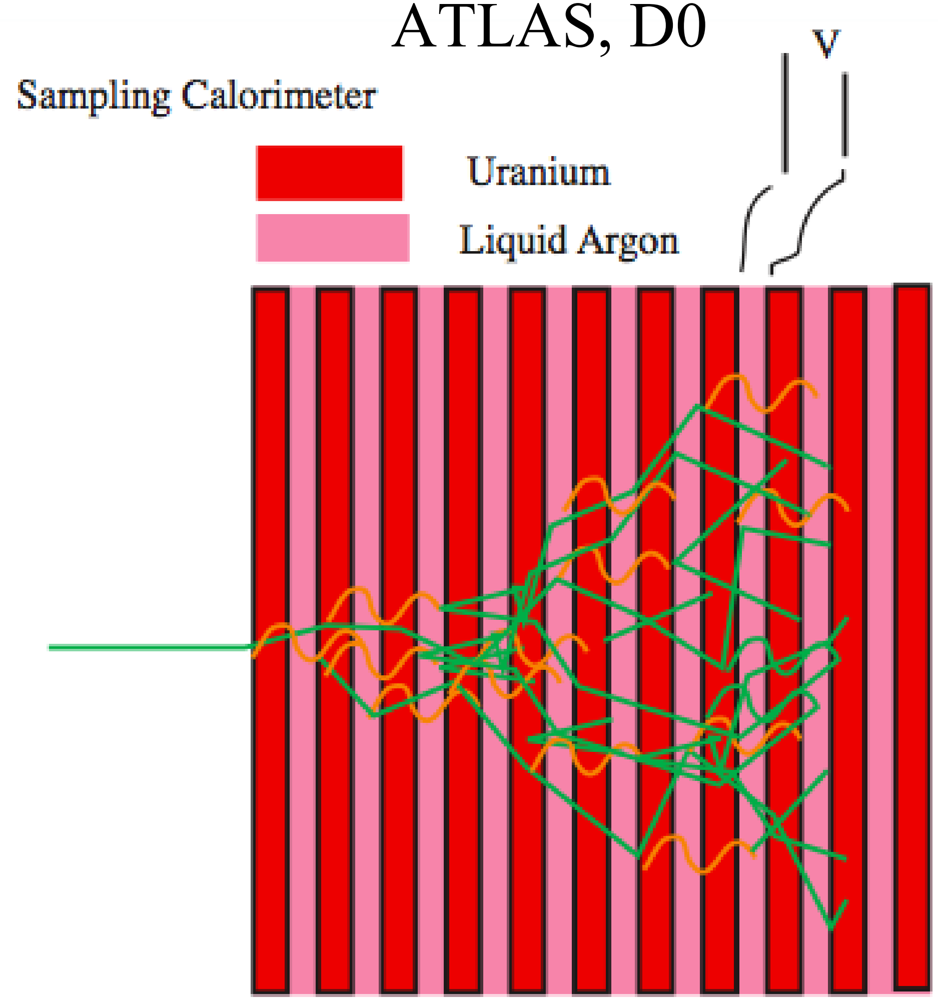
Calorimetry

Photon and Electron Detection

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



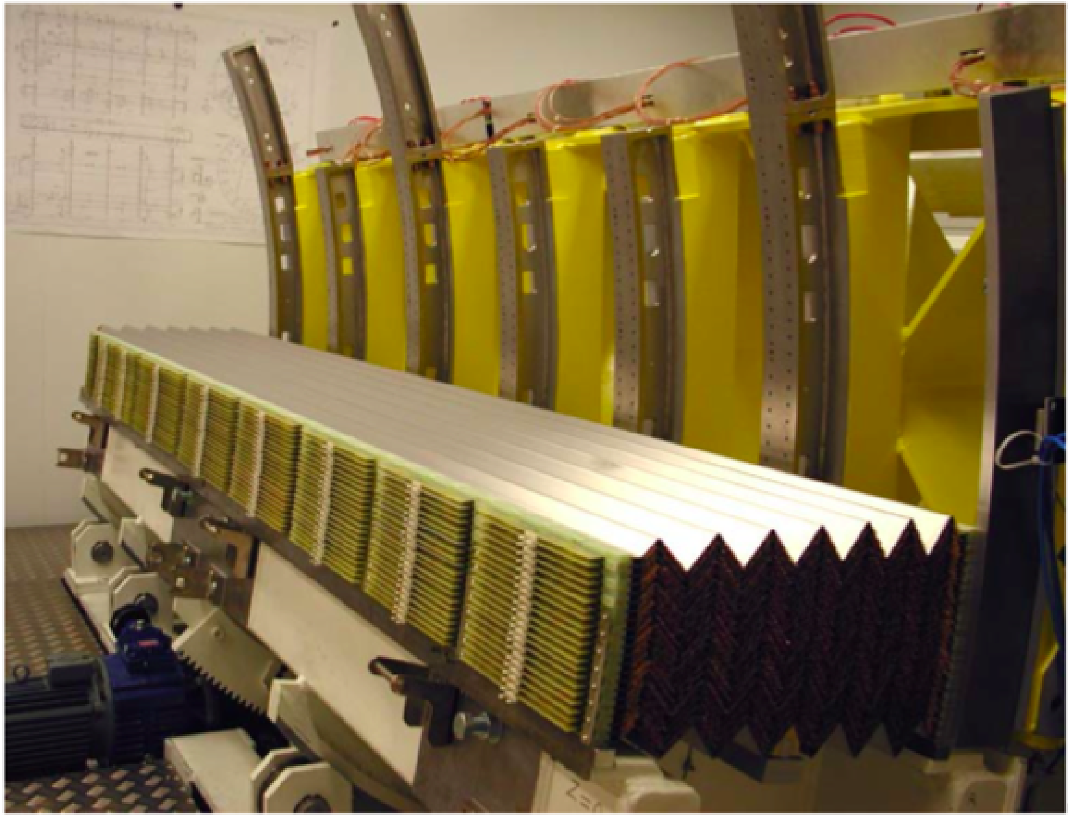
ATLAS, D0

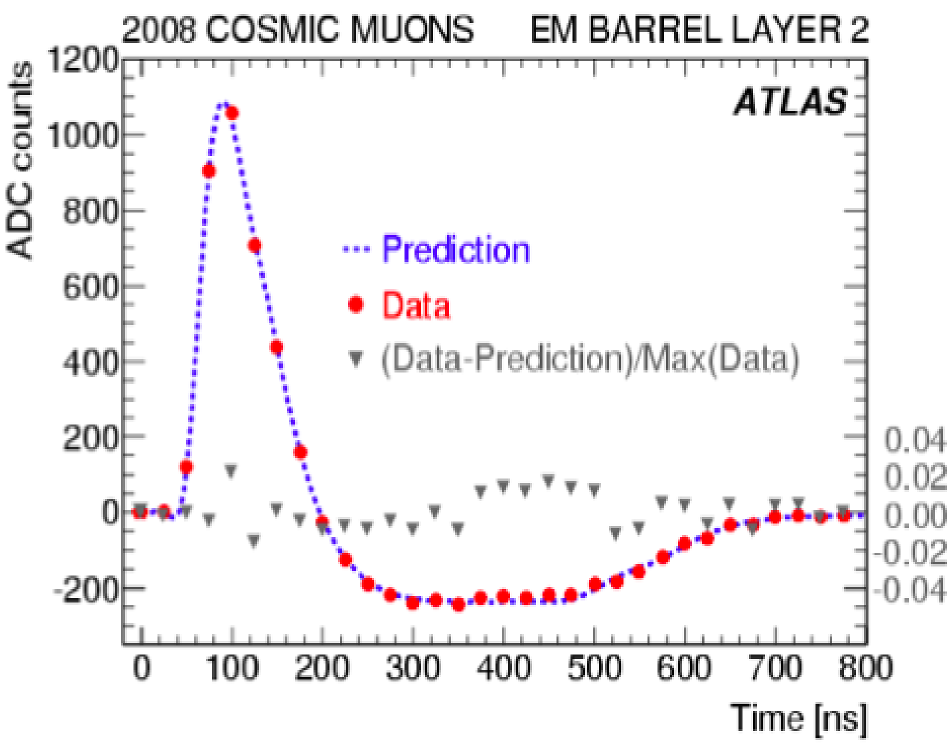


Cascade of electrons and photons due to repeated pair-production and bremsstrahlung

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

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 η=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 → HH → 4 τ produces 1 TeV τ2lepton
      - Photons within τ-jet are separated by ~1 mm
      - τ2ΘϑΜΠΛΚΟ from Higgs separated by ~5 mm
    - 30 TeV resonance → *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

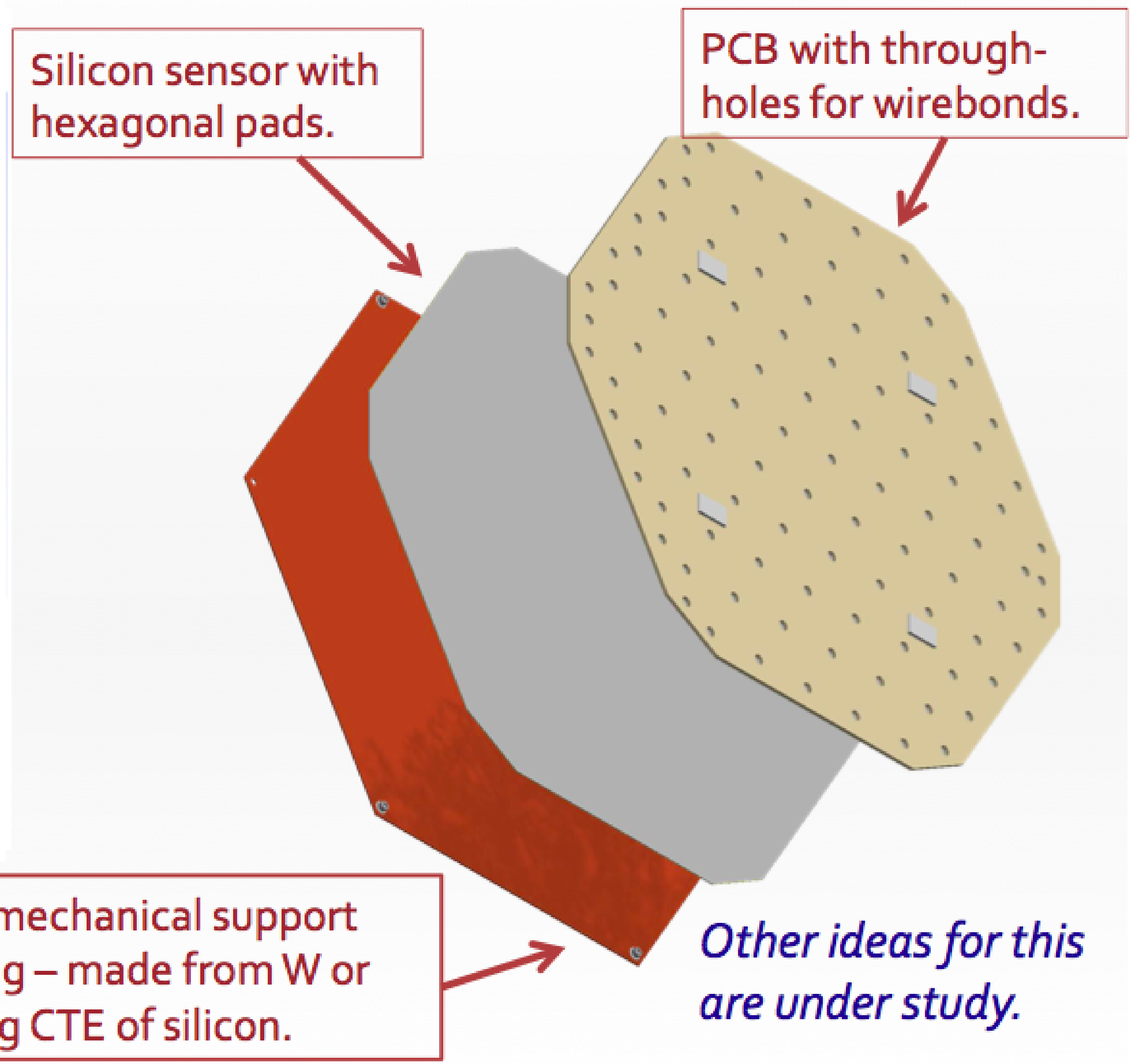
Proposal – Silicon High Granularity Calorimeter

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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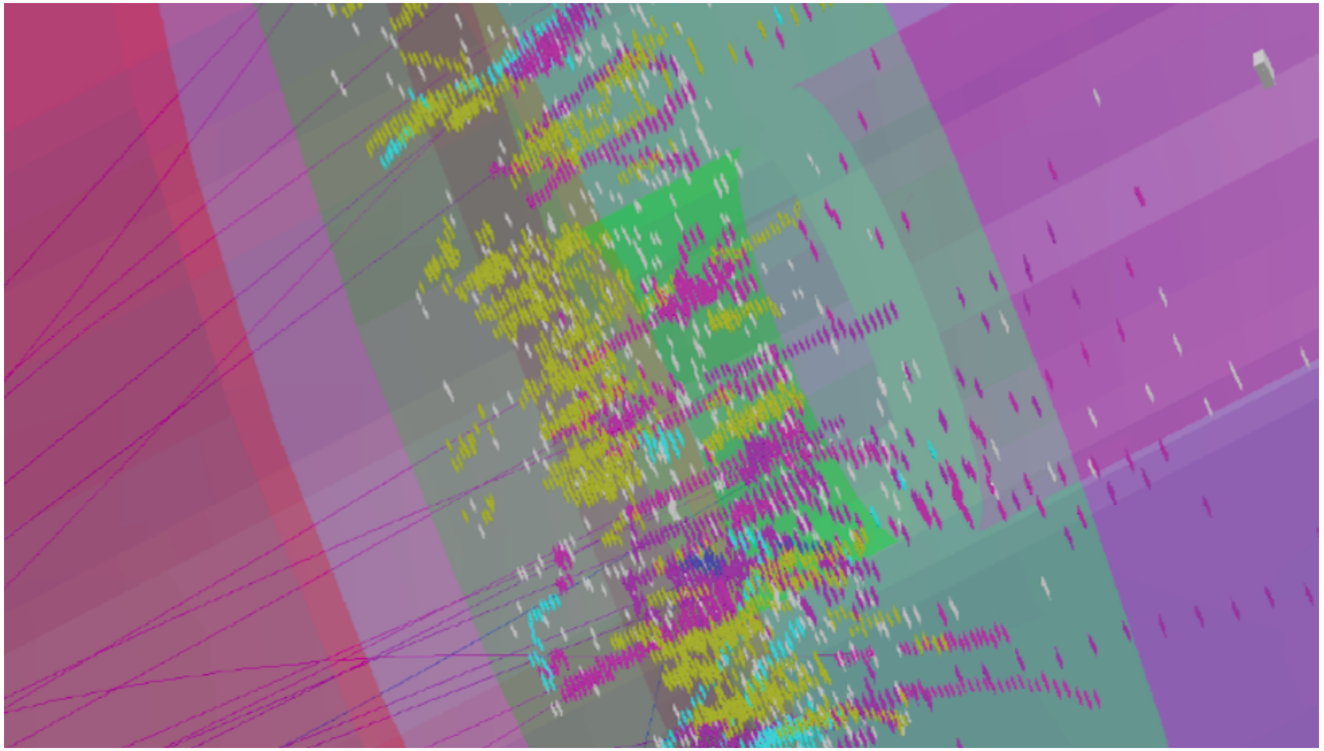
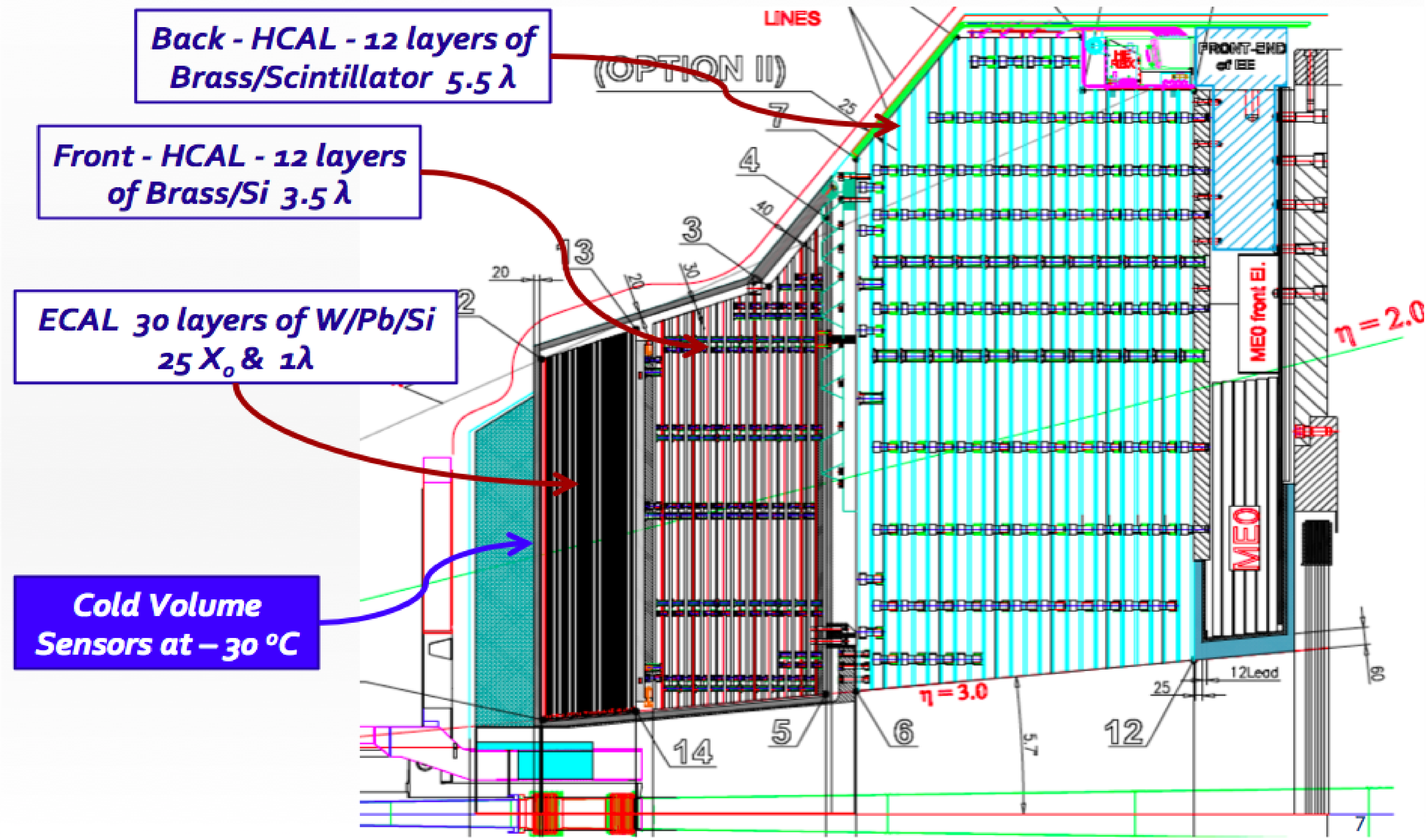


Thanks to R. Rusack, ECFA 2014

Proposal – Si-HGC for CMS Endcap

CMS Calorimeter Concept

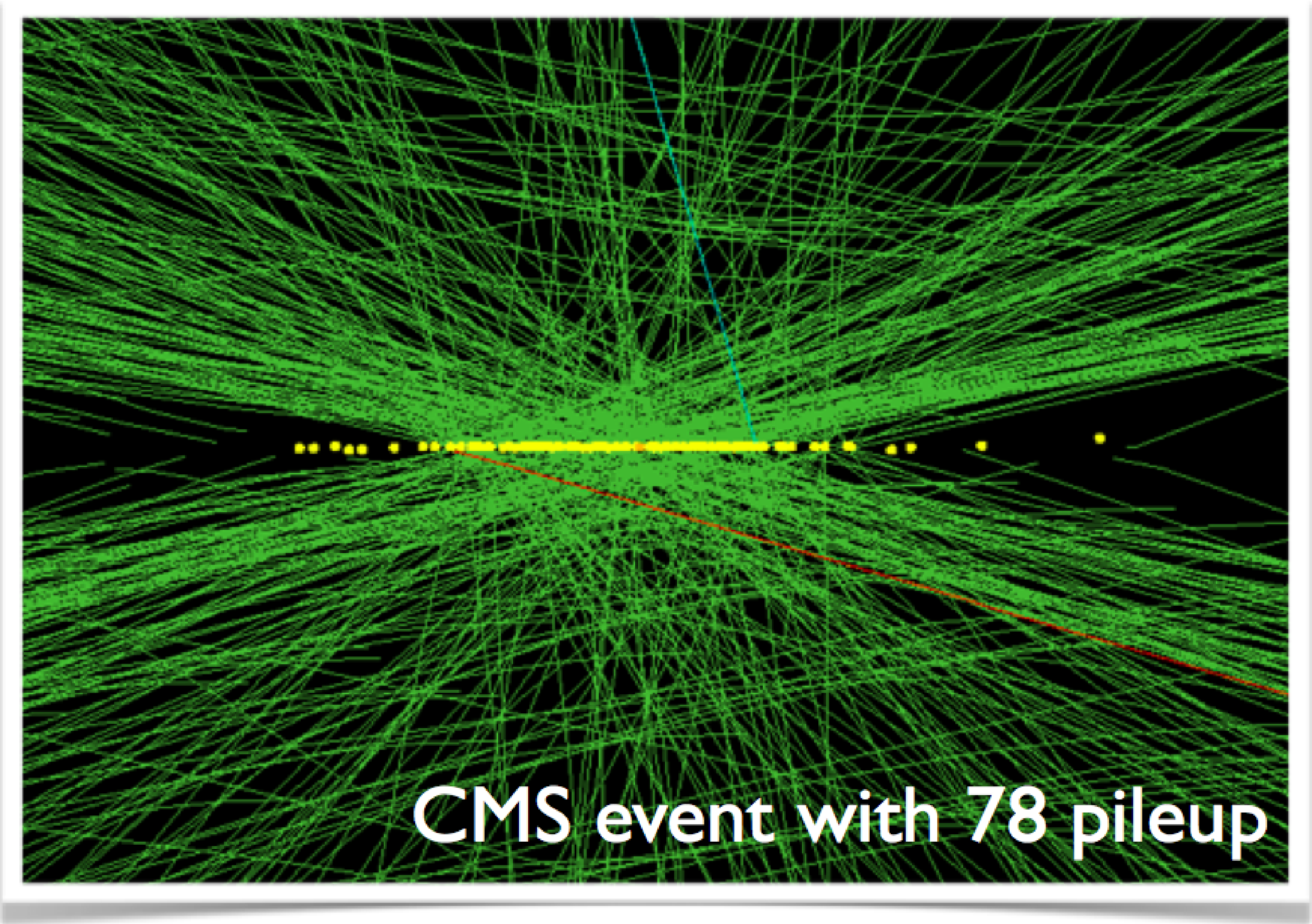


Thanks to R. Rusack, ECFA 2014

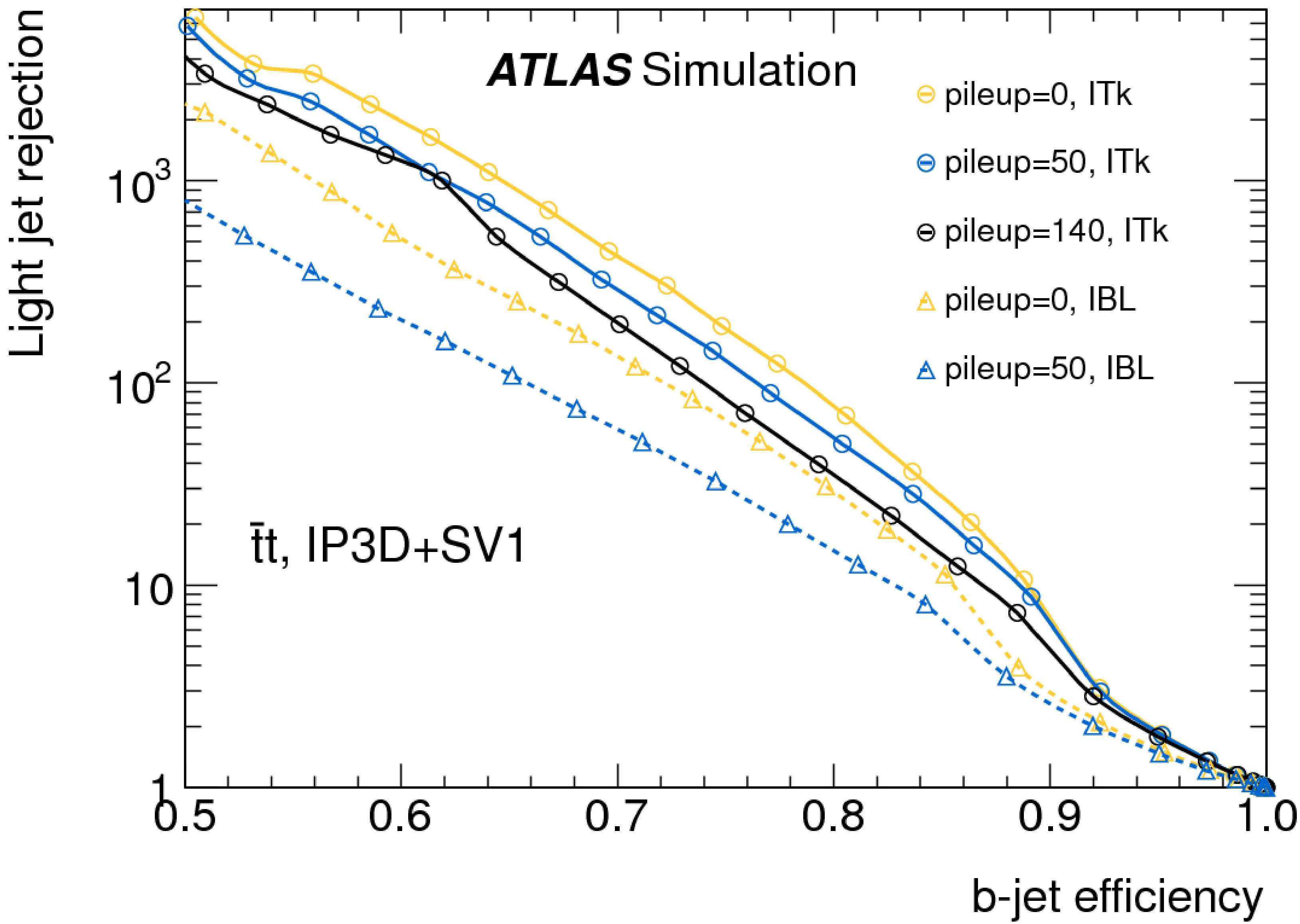
b-tagging

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?

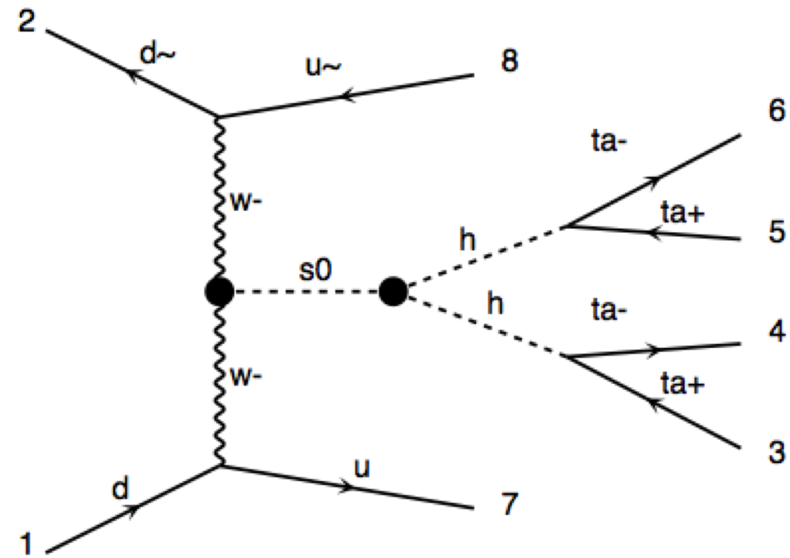
- Old idea: Higgs doublet (4 fields) is a Goldstone mode generated from the spontaneous breaking of a larger global symmetry
  - Higgs boson and W_L, Z_L are all Goldstone bosons from, eg. Spontaneously breaking global SO(5) $\rightarrow$ SO(4)
  - Examples: Holographic Higgs, Little Higgs models...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

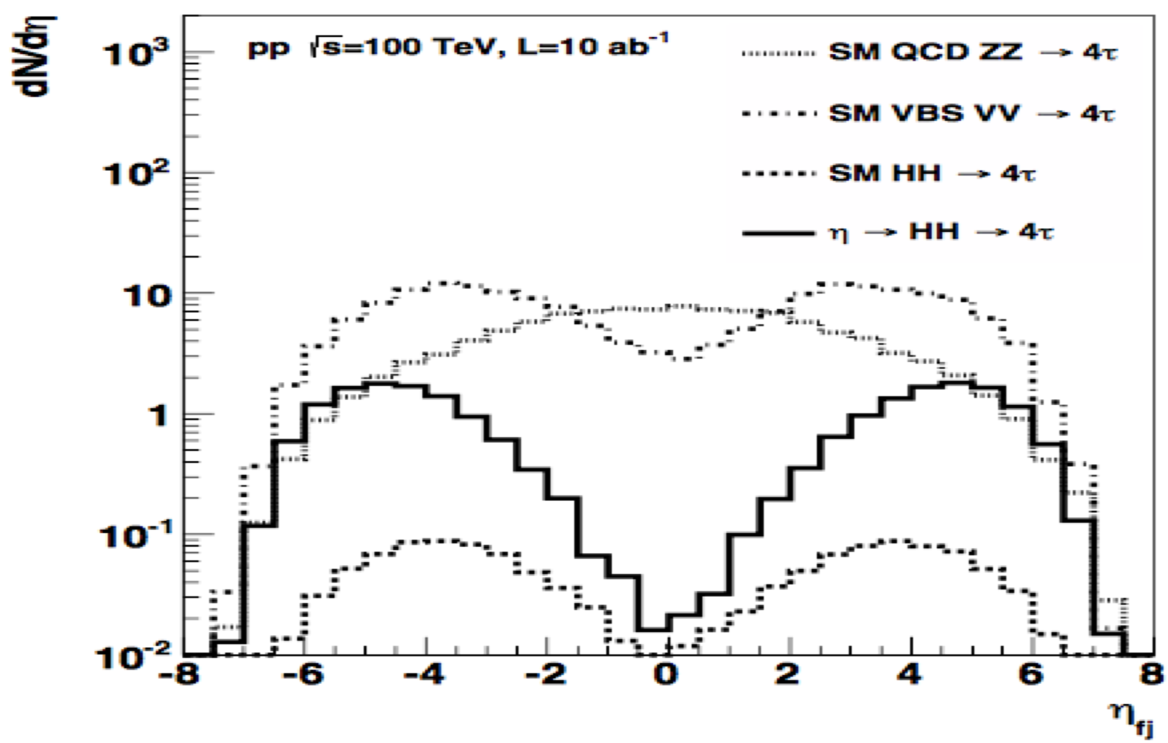
- Vector boson scattering topology
  - Quarks emit longitudinal vector bosons which interact with new (presumably strong) dynamics
  - Quarks scatter by small angle in the forward direction

Vector Boson Scattering

Double Higgs Boson Production in the 4τChannel from Resonances in Longitudinal Vector Boson Scattering at a 100 TeV Collider

AVK, S. Chekanov, M. Low
Phys.Rev. D91 (2015) 114018





(a)The pseudo-rapidity distributions of the forward jets.

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TABLE I. 5σ discovery mass reach for the $\eta \to HH \to 4\tau$ resonance, at a pp collider with $\sqrt{s} = 100$ TeV, as a function of integrated luminosity $\mathcal{L}$.

$\mathcal{L}$	m_η (TeV)		
(ab^{-1})	$\Gamma/M = 5\%$	$\Gamma/M = 20\%$	$\Gamma/M = 70\%$
1	0.85[a]	1.75	2.81
3	1.33	2.25	3.42
10	1.78	2.90	4.18
30	2.30	3.56	4.94
100	2.90	4.33	5.83

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TABLE III. 5σ discovery mass reach for the $\eta \to HH \to 4\tau$ resonance, at a pp collider with $\sqrt{s} = 100$ TeV and $\mathcal{L} = 10$ ab^{-1}, for various cuts values on the maximum rapidity (y) of the forward jets. The fractional width of the η resonance is set to $\Gamma/M = 20\%$.

$y^{\max}$	8	7	6	5	4
m_η (TeV)	2.9	2.9	2.81	2.42	1.75

Want jet rapidity coverage up to 6 at least

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TABLE V. 5σ discovery mass reach for the $\eta \to HH \to 4\tau$ resonance, as a function of the $\sqrt{s}$ of a pp collider. The fractional resonance width Γ_η/m_η is fixed at 70%. These results are illustrated in Fig. 14.

$\mathcal{L}$		m_η (TeV)	
(ab^{-1})	$\sqrt{s} = 50$ TeV	$\sqrt{s} = 100$ TeV	$\sqrt{s} = 200$ TeV
1	1.89	2.81	3.85
3	2.31	3.42	4.65
10	2.83	4.18	5.63
30	3.36	4.94	6.60
100	3.97	5.83	7.74

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Scaling behavior of sensitivity with integrated luminosity and collider energy

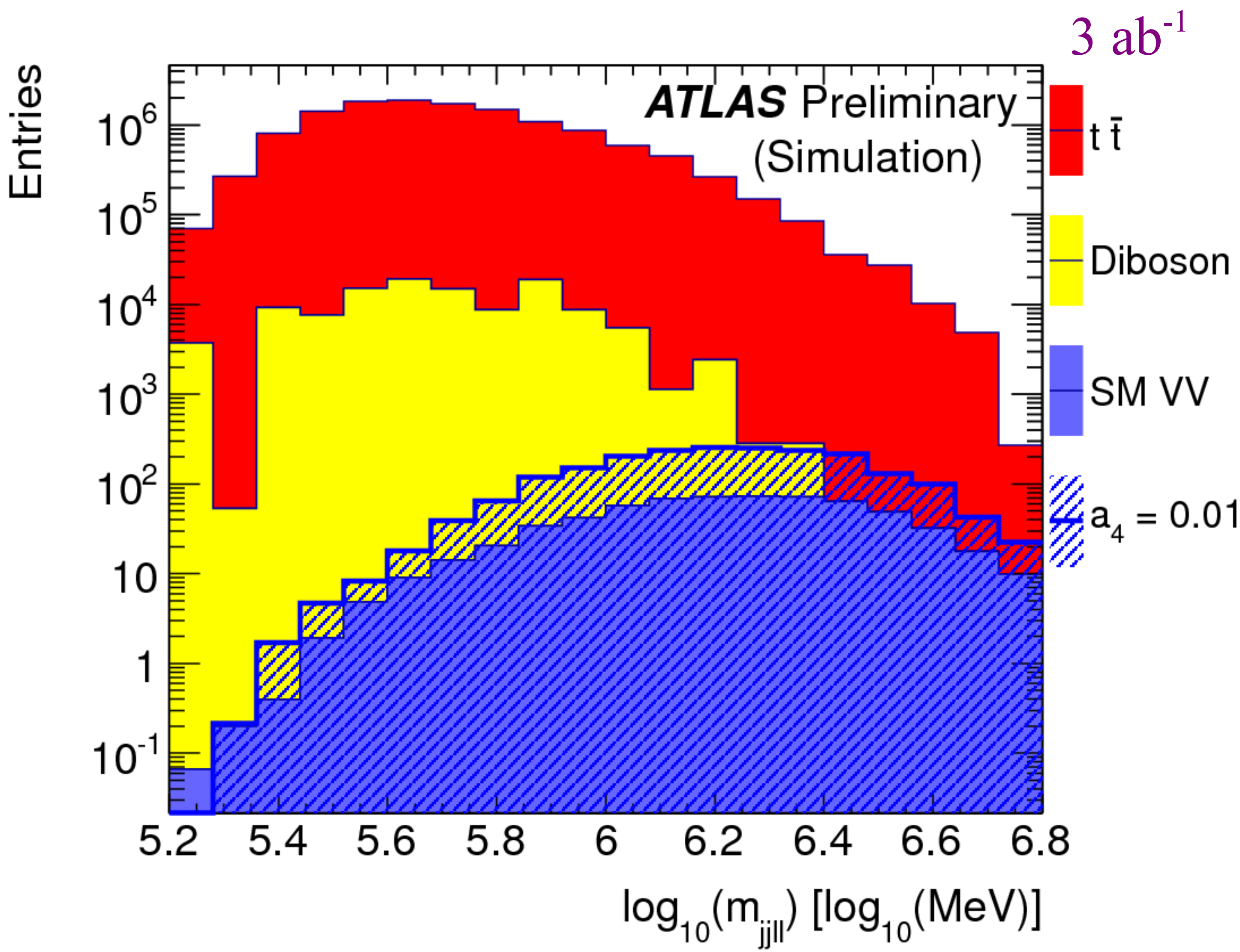
$$m_\eta^{5\sigma} \propto \mathcal{L}^\alpha \qquad\qquad m_\eta^{5\sigma} \propto (\sqrt{s})^\beta$$

Find approximate scaling coefficients (with some dependence on resonance width)

Factor of 10 more luminosity: 50% higher mass reach

Doubling of collider energy: 40% higher mass reach

VV → WW Scattering



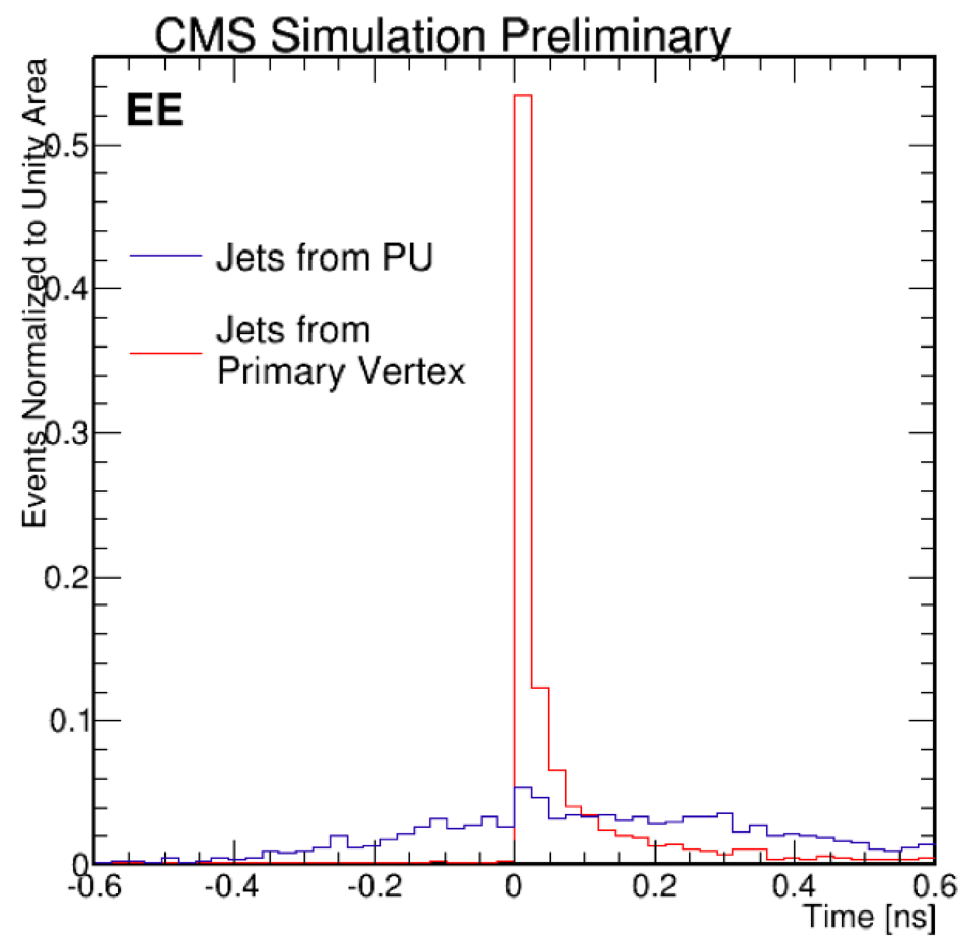
For W^+W^- final state in VBS, *tt* background is problematic

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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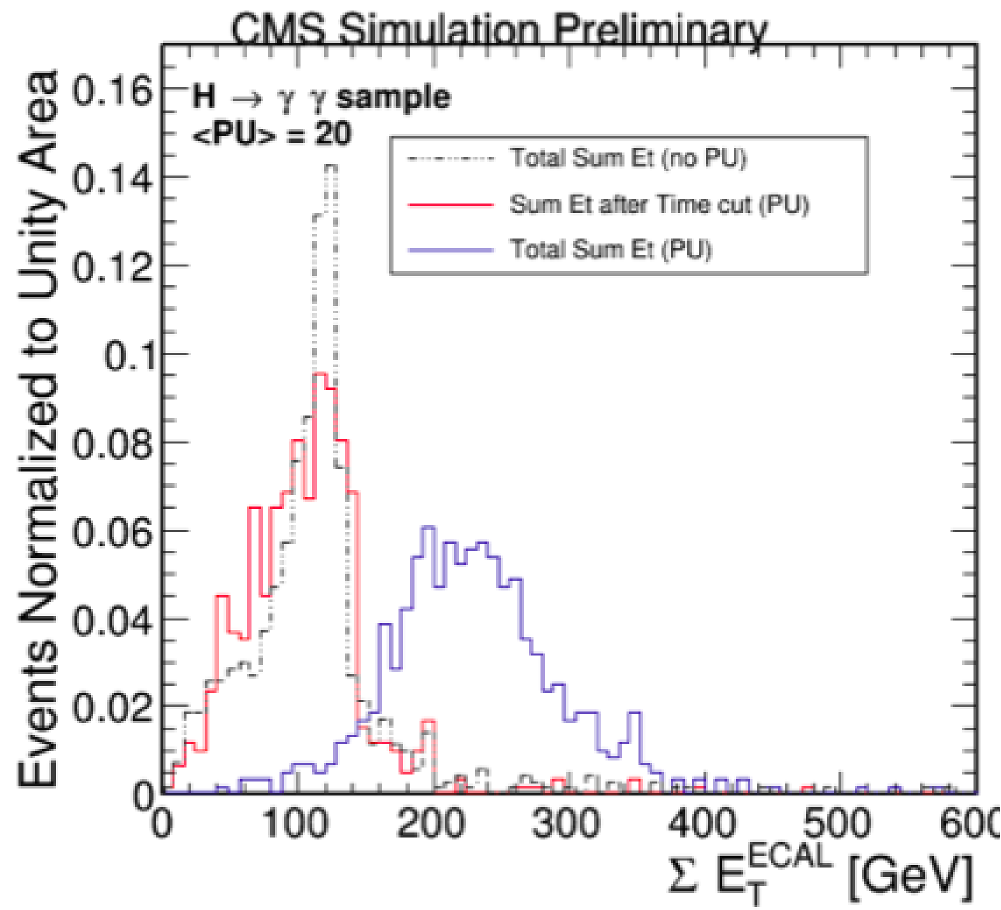
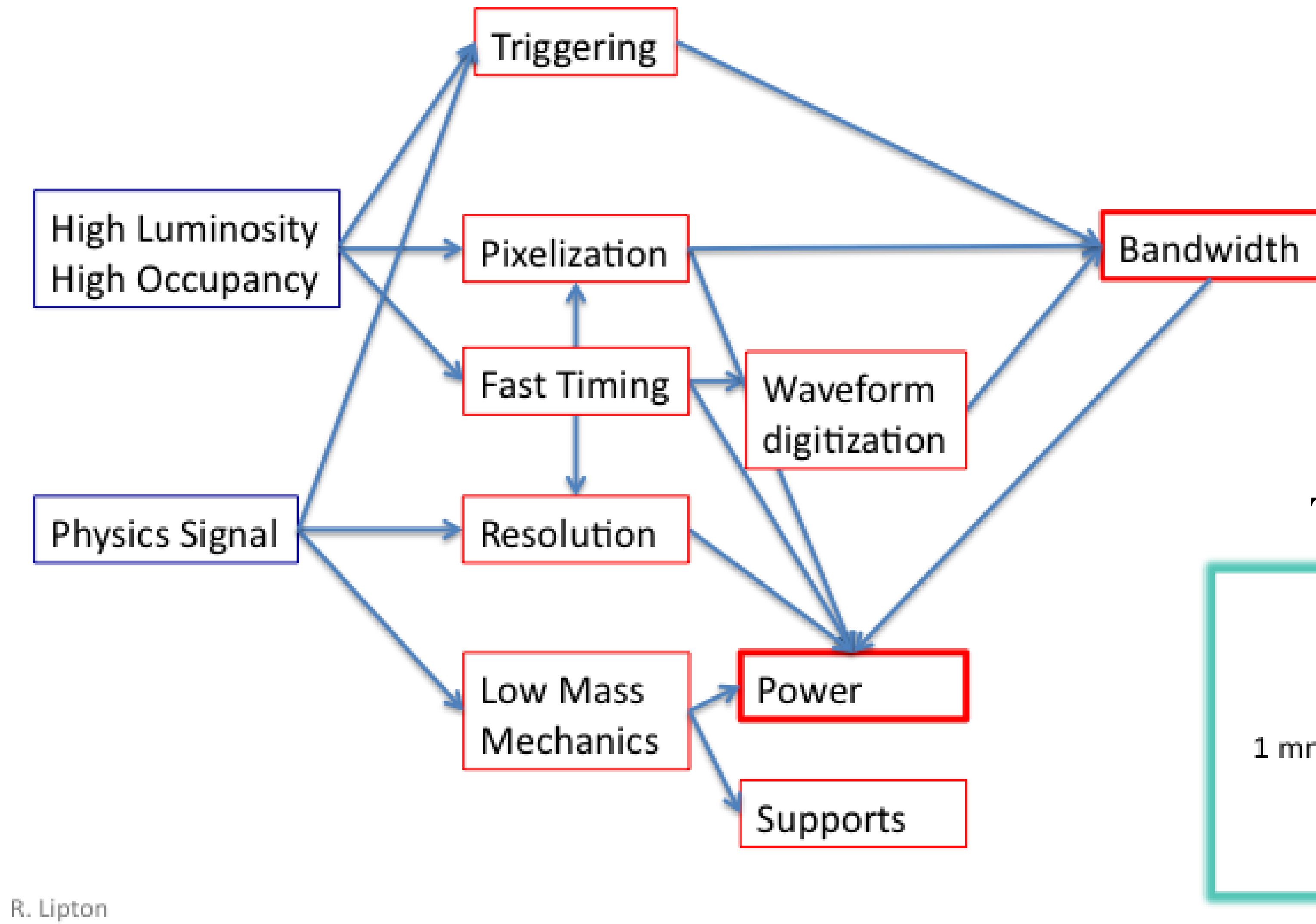
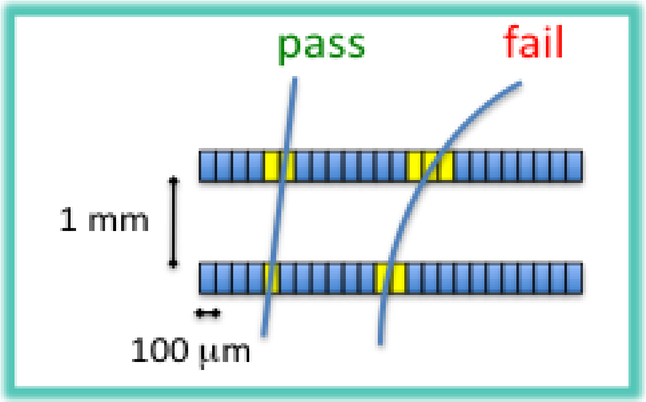


Summary

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
    - ∫ P∪Γ ΓΕΒΓ ⌡ΞΞ⌡ΟΛΘΡΙΕΛΚ
    - ∫ P∪Γ ΓΕΒΓ ⌡ΞΒΞ⊂ΚΡΘΞΞΙΦ
    - Much more forward-detection capability
    - Much higher bandwidth, smarter triggers
- Substantial knowledge & experience on detector design will be gained from HL-LHC upgrade

Summary

- Experimental guidelines:
  - Be ambitious (we have >25 years to do R&D)
  - What experimental capabilities does the physics require?

- Accelerator capabilities:
  - 100 TeV *pp* center-of-mass energy is a baseline "round number"
  - Is 50 TeV enough? Will the physics reach be substantially higher with 200 TeV?
  - CERN FCC proposal is 100 TeV, initial Chinese proposal is 55 TeV with 16 Tesla magnets
  - LHC uses 8.4 Tesla magnets, Fermilab has demonstrated an 11 Tesla magnet

- Integrated luminosity
  - 10 ab^{-1} is a good starting point
  - CERN-FCC has proposed 17 ab^{-1} target
  - Useful to compare 3 ab^{-1}, 10 ab^{-1} and 30 ab^{-1} sensitivities
  - Motivate higher luminosity if needed to produce definitive answer

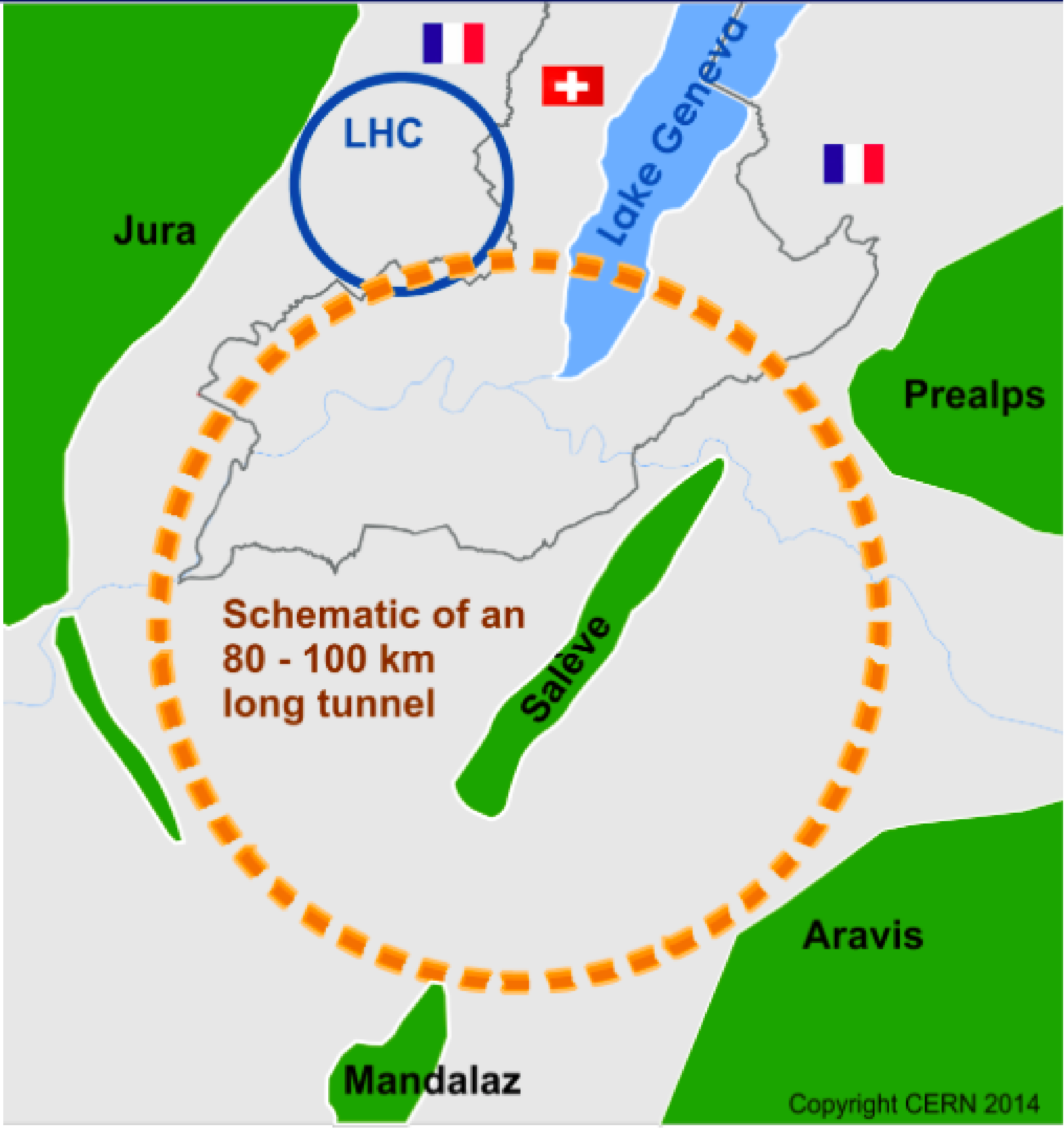
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

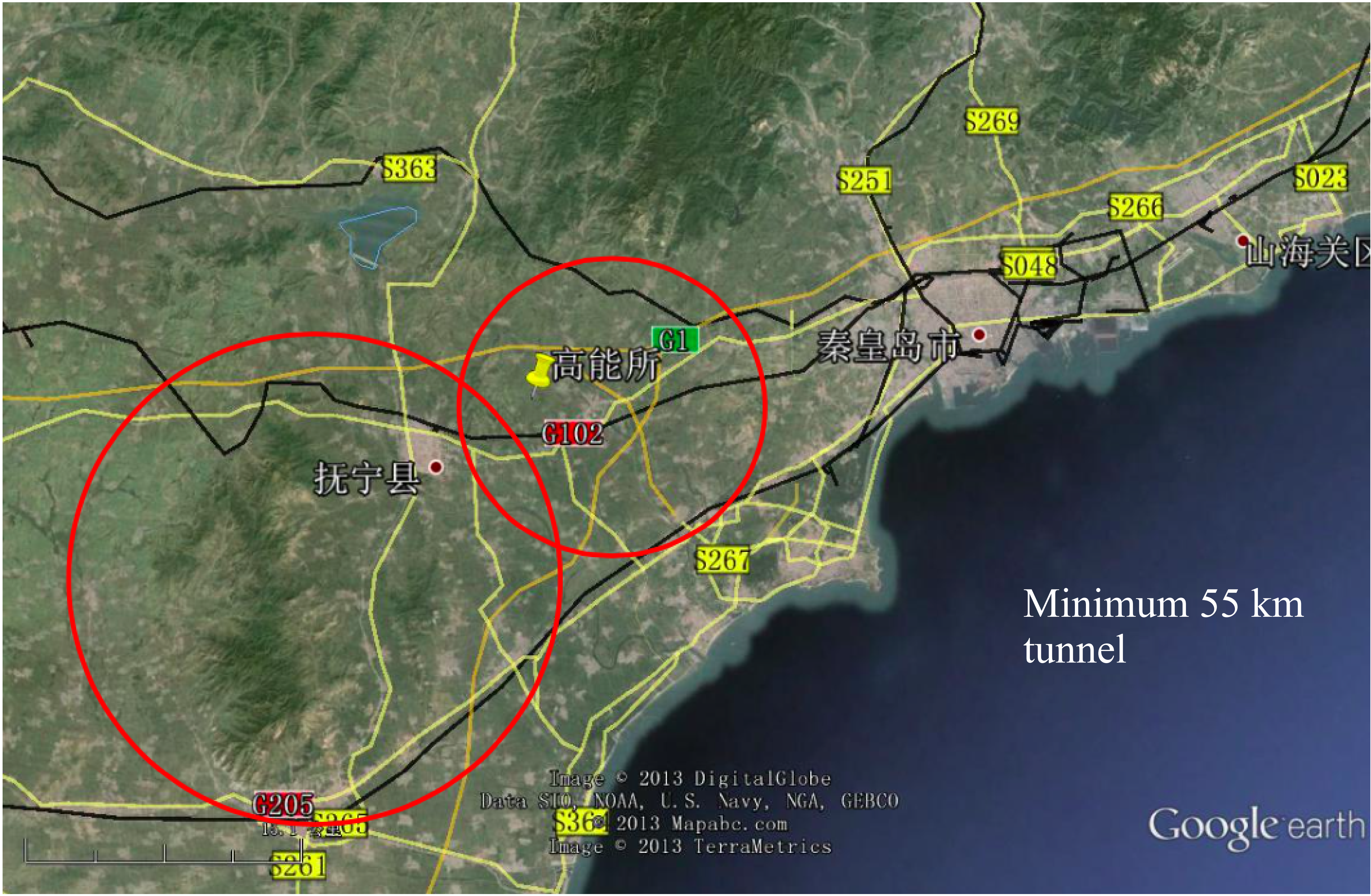
- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km ~20 T ⇒ 100 TeV *pp* in 80 km

- ***e^+e^-* collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area



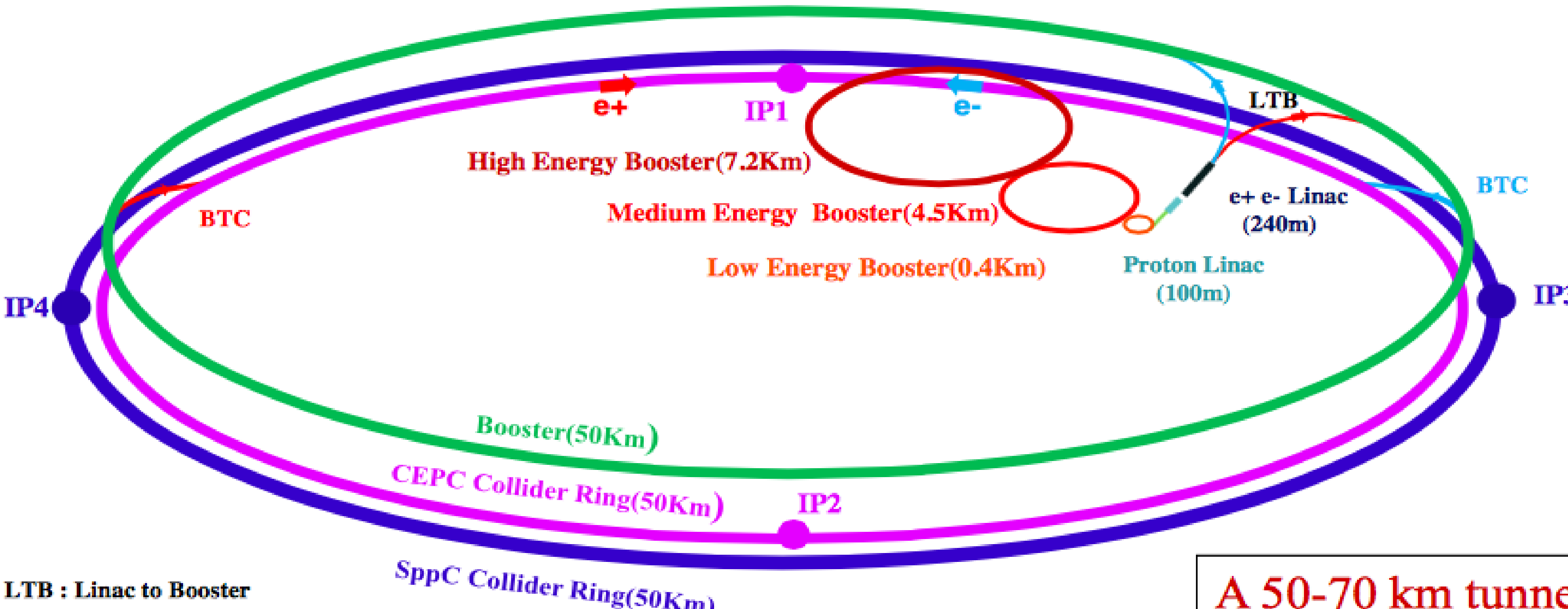
Chinese Site 300 km East of Beijing



From Yifang Wang lecture

The Future: CEPC+SppC

- For about 8 years, we have been talking about "What can be done after BEPCII in China"
- Thanks to the discovery of the low mass Higgs boson, and stimulated by ideas of Circular Higgs Factories in the world, CEPC+SppC configuration was proposed in Sep. 2012

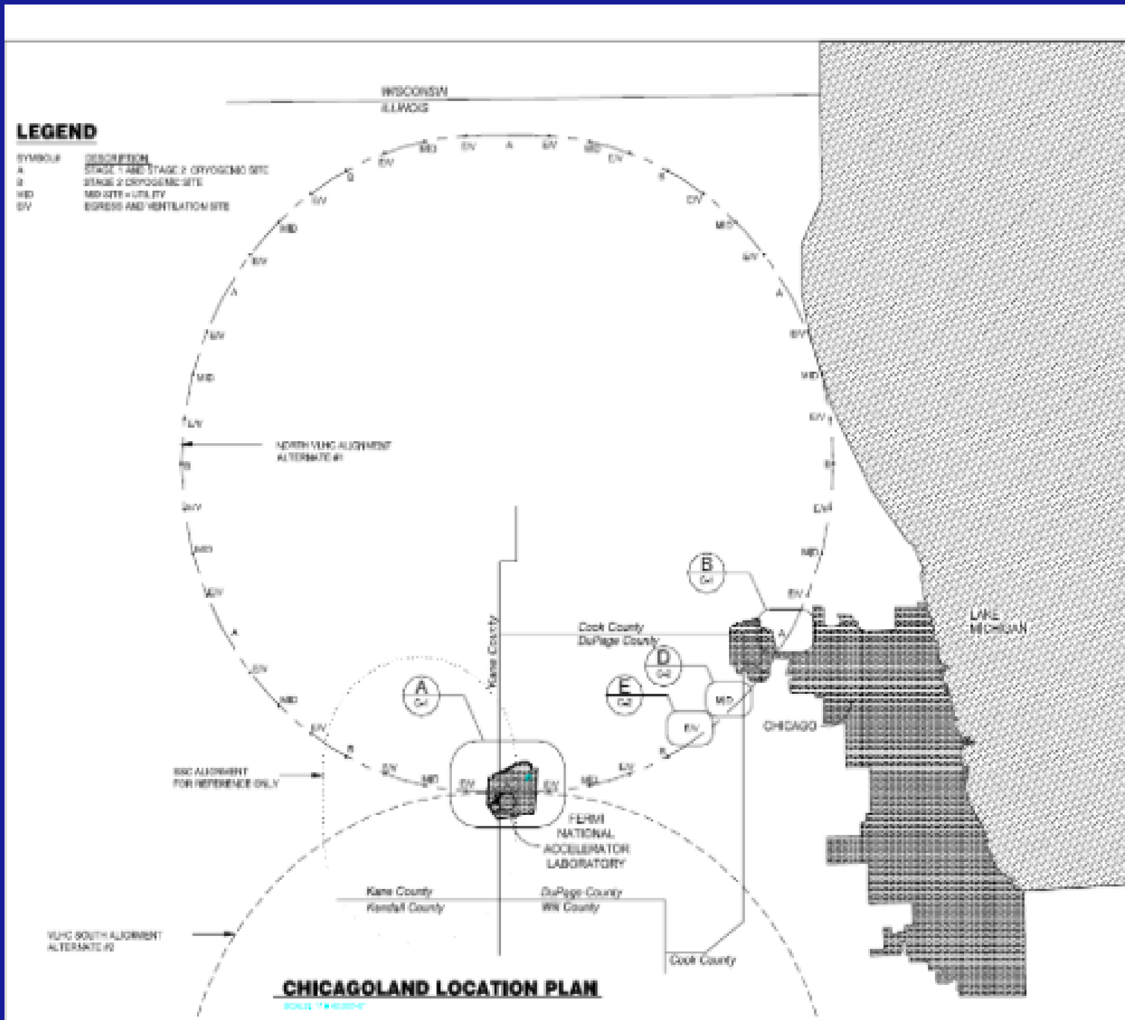


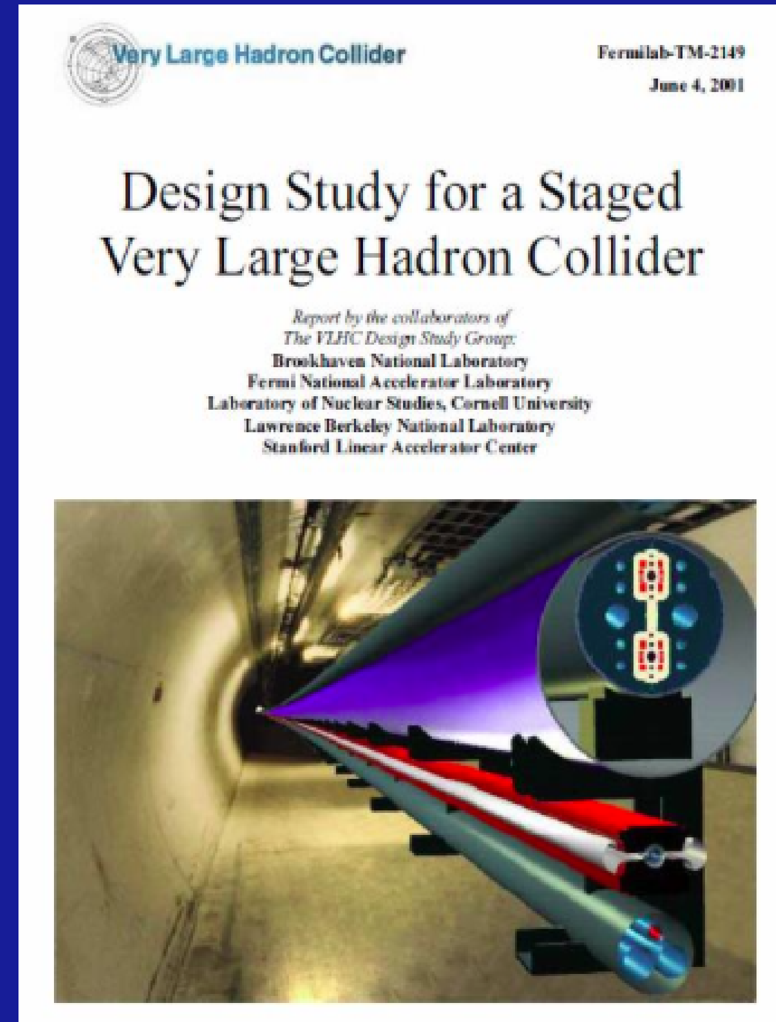
LTB : Linac to Booster

BTC : Booster to Collider Ring

A 50-70 km tunnel is relatively easier NOW in China

273 Pages VLHC Technical Proposal




Very Large Hadron Collider

Fermilab-TM-2149

June 4, 2001

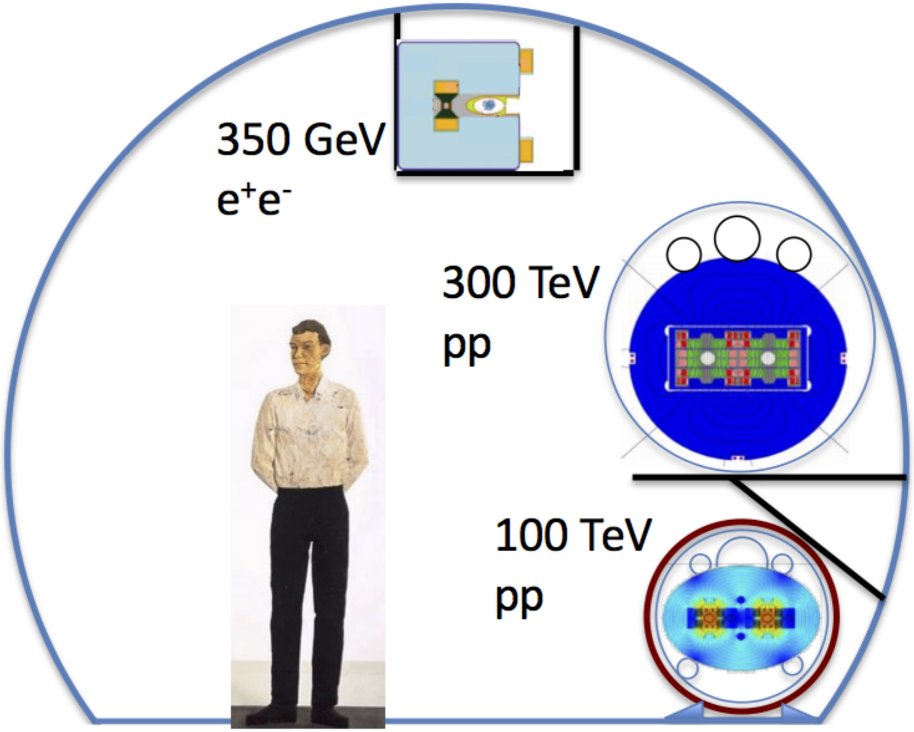
Design Study for a Staged Very Large Hadron Collider

Report by the collaborators of The VLHC Design Study Group:

Brookhaven National Laboratory
Fermi National Accelerator Laboratory
Laboratory of Nuclear Studies, Cornell University
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center

- The VLHC proposal was well developed with all major technical solutions documented, including many details on the tunneling
- Very important outcome was that there are no technical "show stoppers" in building 175 TeV pp collider

100 TeV hadron collider:
4.5 dipoles in a 270 km tunnel



Peter McIntyre, Saeed Assadi, James Gerity, Joshua Kellams, Tom Mann, Chris Mathewson, Al McInturff, Nate Pogue, Akhdiyor Sattarov, Klaus Smit

Texas A&M University

Summary of Fermilab/USA Study Group Activities

Physics Case and Detector Goals

- Strategy:
  - Physics case studies should be published in refereed journals
  - Arguments should be "interesting" not just for particle physicists but also other fields of physics, other fields of science
  - We will need broad support from all scientists for (at least) the science case
  - Planning a series of "theme" workshops focussing on Dark Matter (December 4-6 @ Fermilab), Electroweak Baryogenesis, High-Granularity Calorimetry...
- Resources:
  - Full analysis chain available for MADGRAPH + PYTHIA showering → Ntuples → repository → C++ analysis code
  - Argonne HEP analysis cluster for CPU and Ntuple storage
  - Quick ramp-up for anyone to pursue any model and channel of interest
  - Need experimentalists with analysis experience collaborating with theorists
    - "how to convert ATLAS / CMS analysis into VHEPP study over the weekend"
    - Additional paper and visibility with only 10% more work !

Physics Case and Detector Goals

- Generate interest in the US HEP Community for physics case studies for a VHEPP (very high energy *pp*) collider

- Form collaborations between theorists and experimentalists to publish fairly detailed truth-level studies of "key" channels
  - Electroweakino dark matter (Ismail Ahmed, AVK)
  - 1st order phase transition via additional scalar (P. Winslow, J. M. No, M. Ramsey-Musolf, AVK) – PRD in progress
  - Ttbar resonances and highly boosted tops with substructure (S. Chekanov, J. Love, J. Proudfoot, AVK) – PRD published
  - Vector boson scattering (AVK, S. Chekanov, M. Low) – PRD published

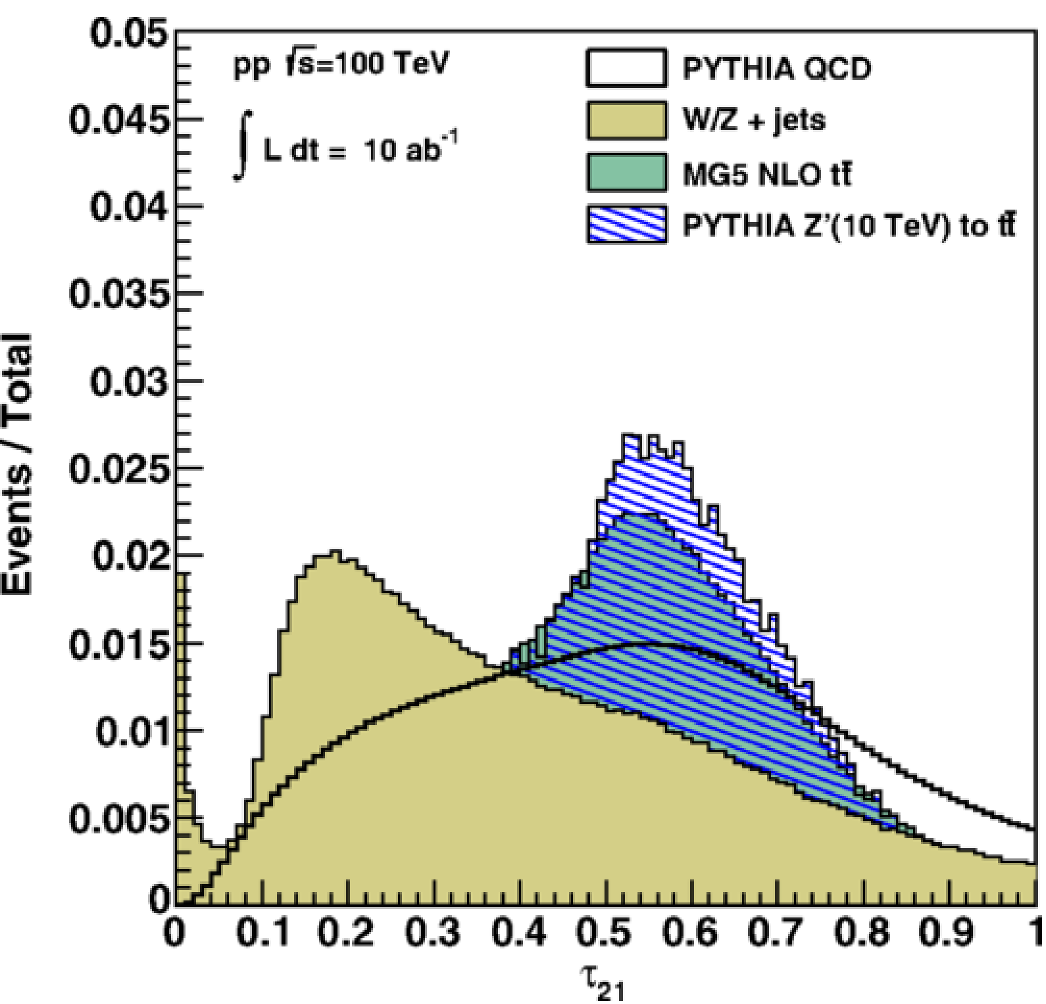
- Biweekly Seminar + Brainstorming Session Thursday 1 PM CST via ReadyTalk/Indico on some "hot topic" relevant for VHEPP
  - Announcement on Fermilab Today / Labwide Calendar & VHEPP Mailing list
  - VLHCPHYSICS@fnal.gov (or email me at kotwal@fnal.gov)

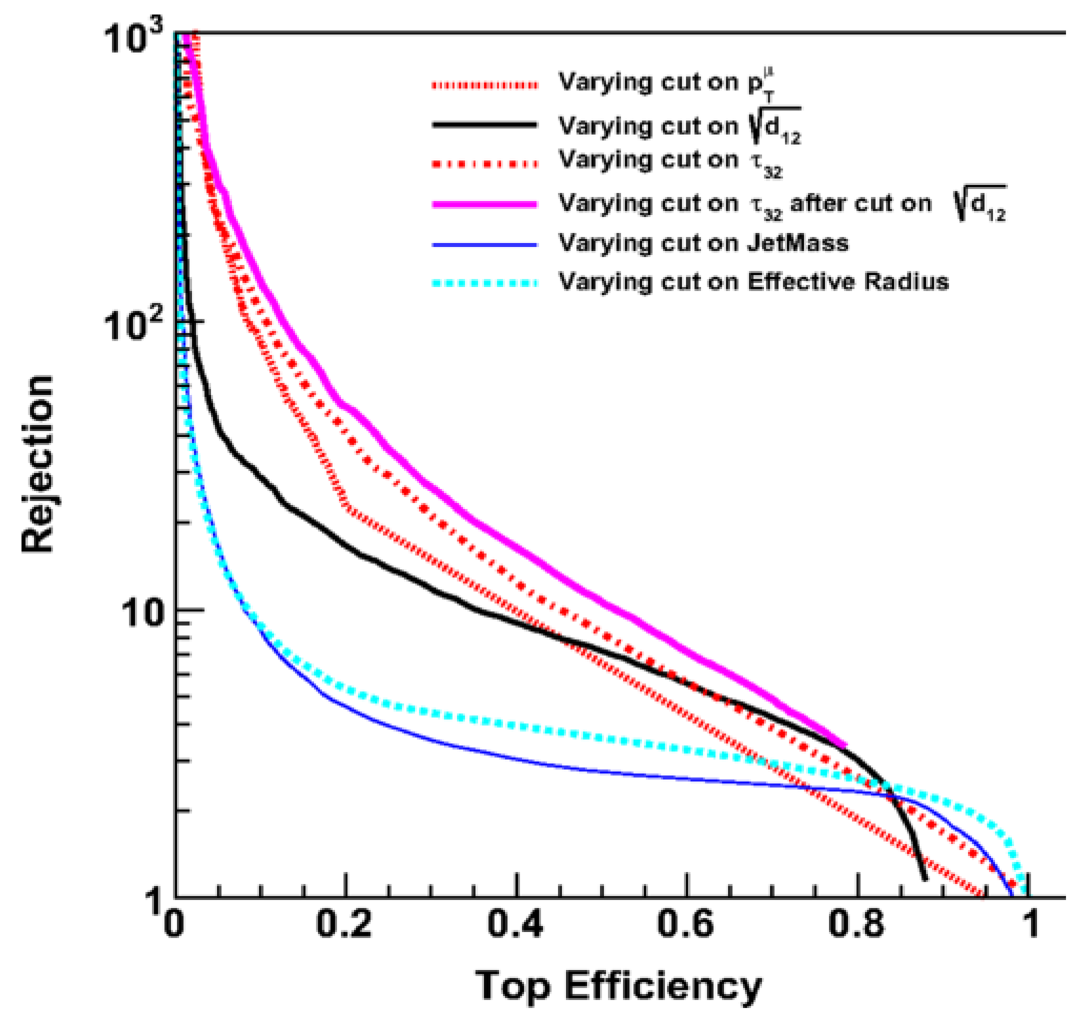
Granularity Requirements for Boosted Top Quarks

Sensitivity to new high-mass states decaying to $t\bar{t}$ at a 100 TeV collider

B. Auerbach, S. Chekanov, J. Love, J. Proudfoot, and A. V. Kotwal

Phys. Rev. D **91**, 034014 – Published 17 February 2015

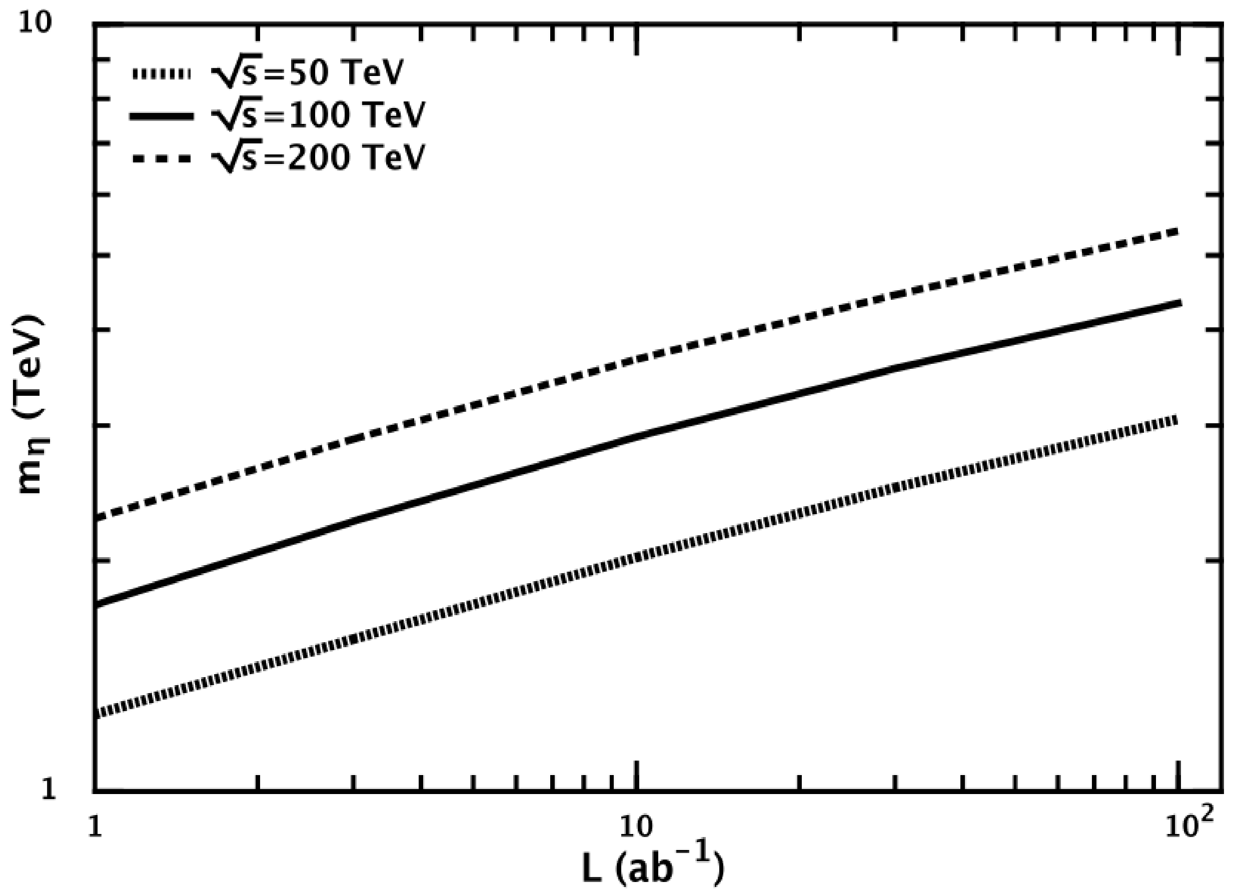




Forward Jet Coverage for Longitudinal VBS

$V_L V_L \rightarrow \eta \rightarrow HH$

M. Low,
S. Chekanov,
AVK



5σ discovery mass reach

Detector Concept Focus

- Strategy:
  - Focus on high-granularity calorimeters
  - Resolve highly-boosted vector bosons and Higgs bosons, top quarks
  - Tau-lepton requirements (say boosted to 1 TeV) present an interesting challenge
    - Can tau-decay products (photons from pi0) be resolved at ~1mm separation?
- Resources:
  - work with GEANT simulations using ILC-SOFT on OSG
    - tungten-silicon high-granularity calorimeter
    - HL-LHC plug upgrade
- Planning a series of "theme workshops" on this topic and others
- GOAL: White Paper on key physics case topics and detector requirements in a few years