Muon Collider Crash Course: Experiment

Kiley Kennedy, Princeton University

12 May 2025

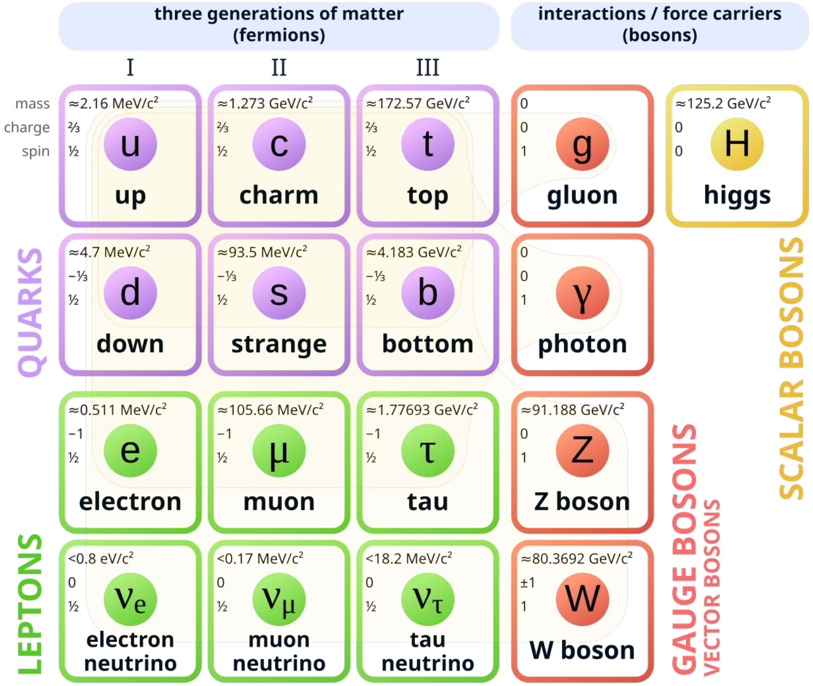
Title image: L. Lee, C Bell

Overview

- Introduction: How do we measure particles?
- Beam-induced background at a muon collider
- Detector design, technologies, and challenges
- Particle reconstruction and identification
- Overview of analysis building
- Open questions, ongoing work, and conclusions

How Do We Measure Particles?

Standard Model of Elementary Particles



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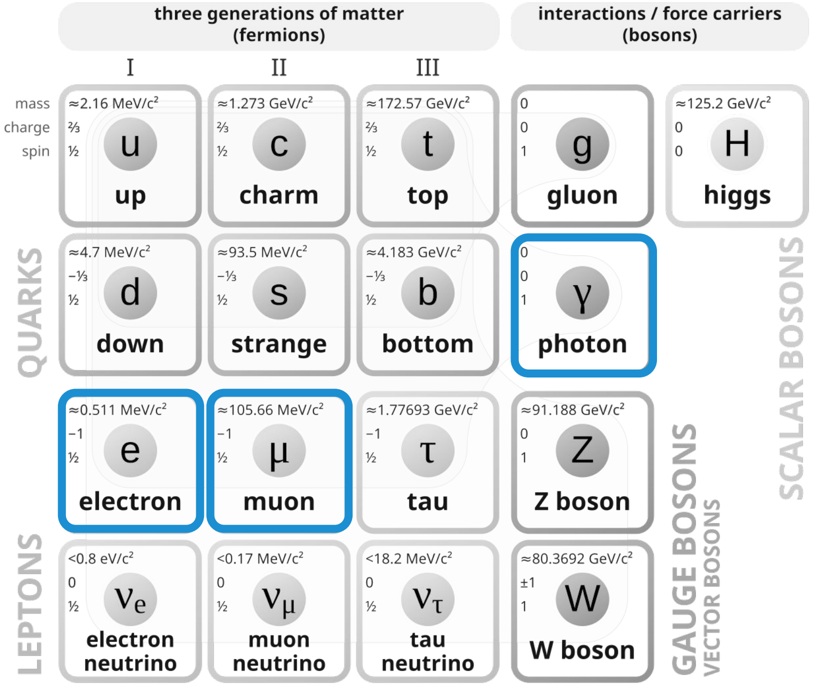
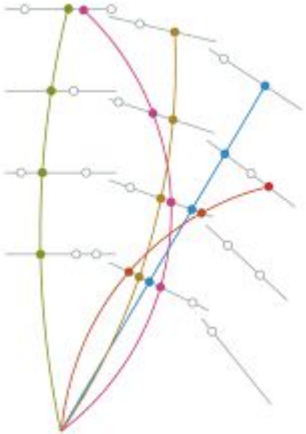


+ stable and metastable composite particles

Particles we detect directly

Tracking

Track paths of charged particles a B field → measure p, q



Calorimetry

Use dense materials stop particles → measure E

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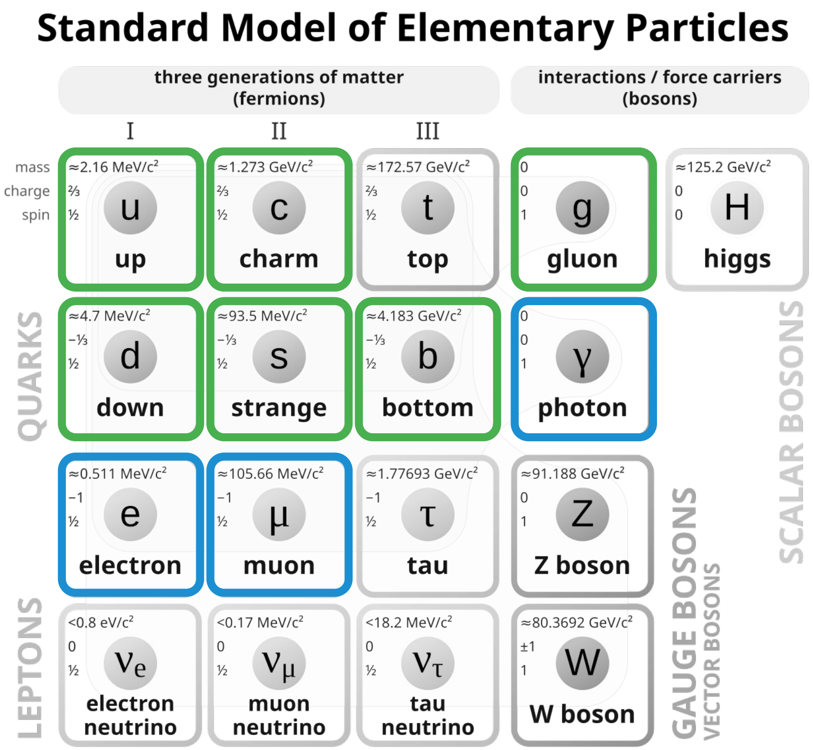
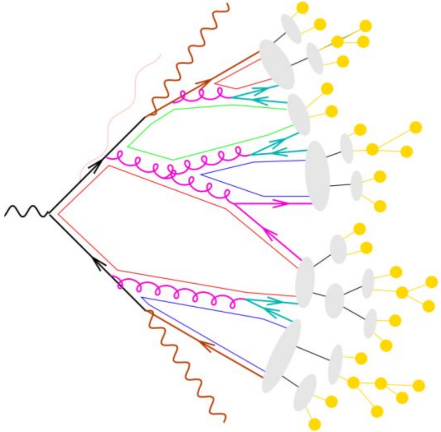


Particles we ~somewhat detect directly



1. Parton Shower

Quarks radiate gluons → cascade of particles

2. Hadronization:

Quarks form bound states with each other → stable and metastable hadrons

TLDR: quarks produce a shower of hadrons → messy but measurable objects called “jets”

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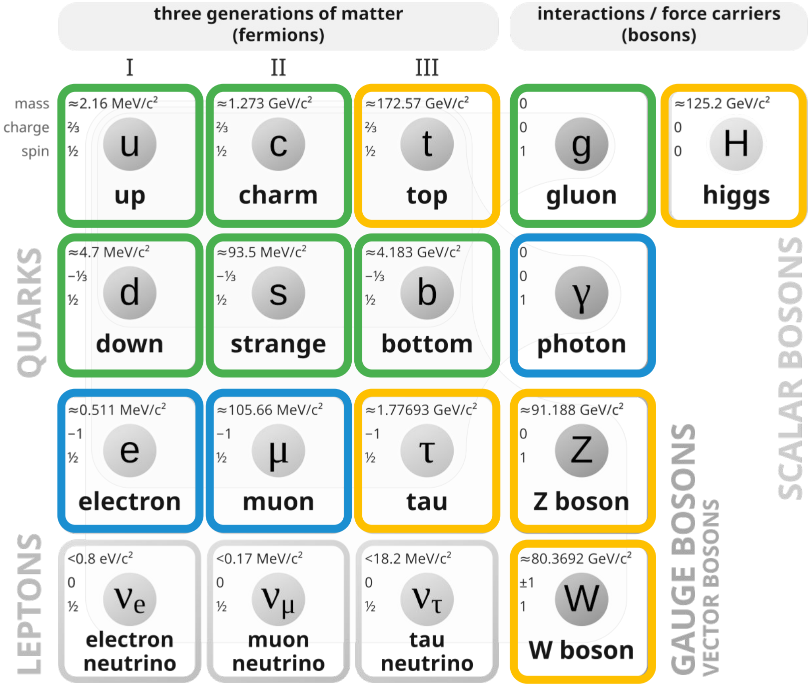
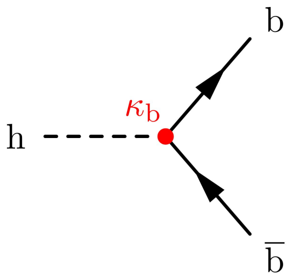


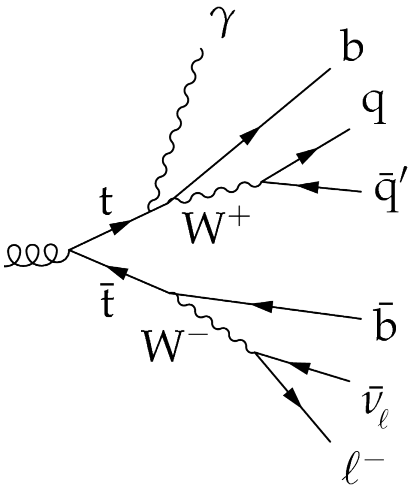
Particles we reconstruct via their decay products

Special relativity:

Reconstruct parent particle properties (m, p) from decay products



Combinatorics can quickly escalate…



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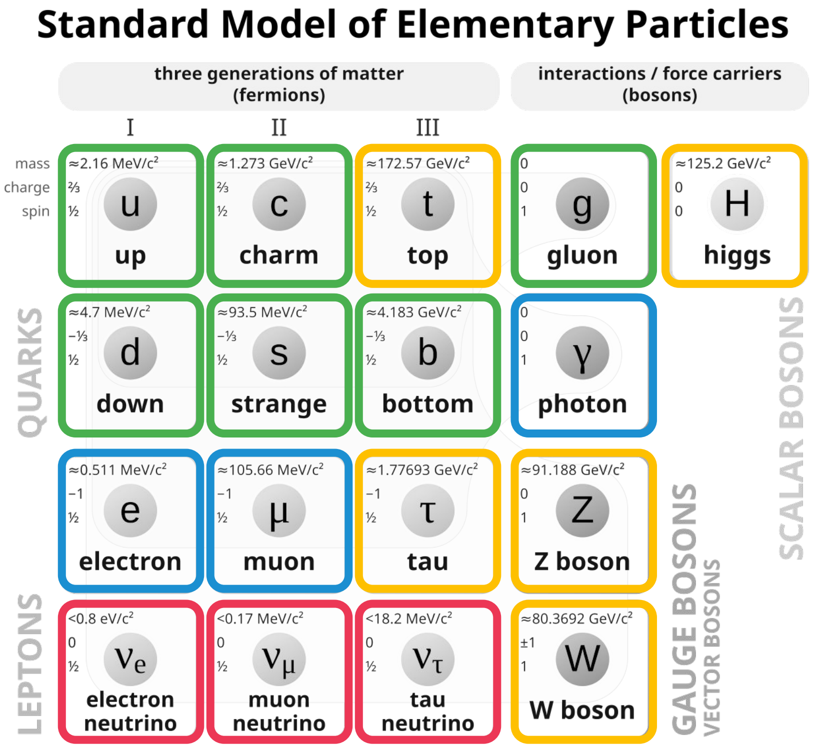
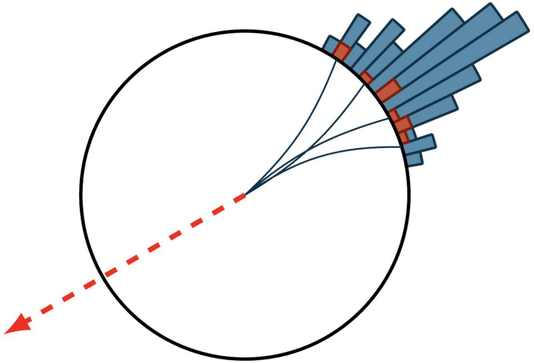


Particles that are completely invisible to the detector

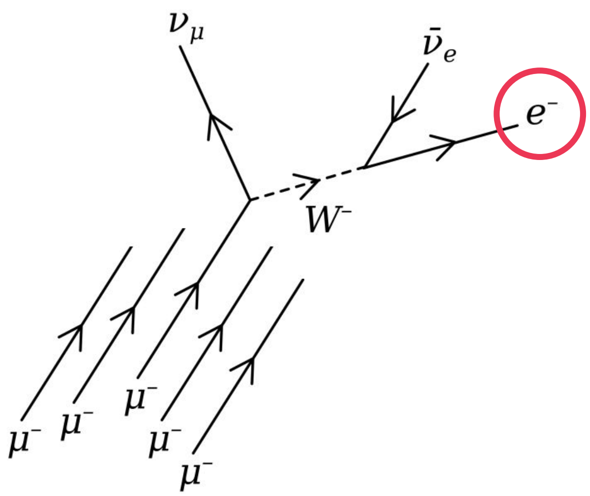
Conservation of Momentum:

Initial state transverse momentum of μμ beams is 0 →
Final state transverse momentum of collision products is 0



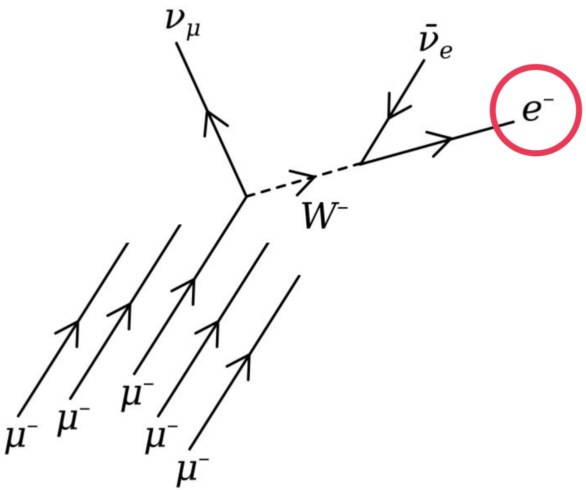
MET: Missing Transverse Energy

Central Challenge: Muon Beams Decay



Multi-TeV muon decays produce TeV-scale electrons

Central Challenge: Muon Beams Decay

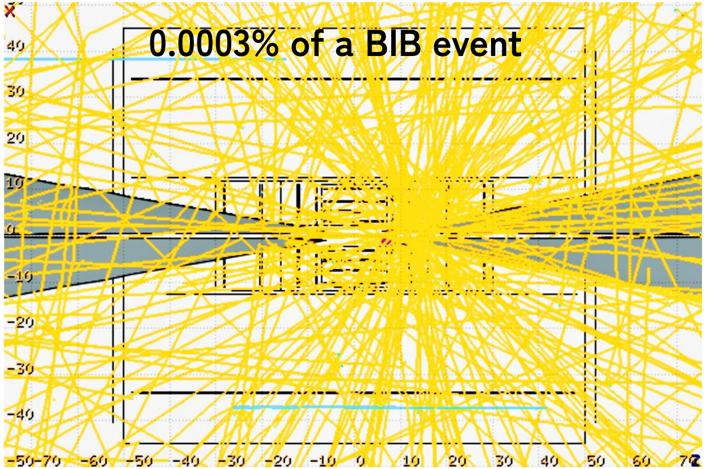


Multi-TeV muon decays produce TeV-scale electrons

Beam Induced Background (BIB)

Electrons shower and make an EeV-scale mess in the detector

(1 EeV = 1e6 TeV)

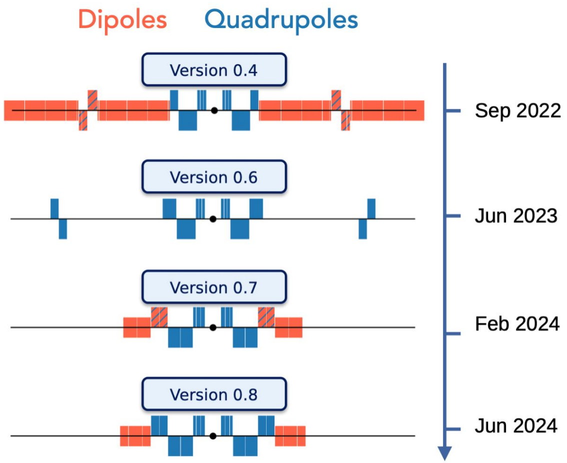


BIB Mitigation

L. Lee, D. Calzolari

1. Collider lattice design

- Configure lattice near the interaction region (IR) to minimize BIB
- E.g. short straight section



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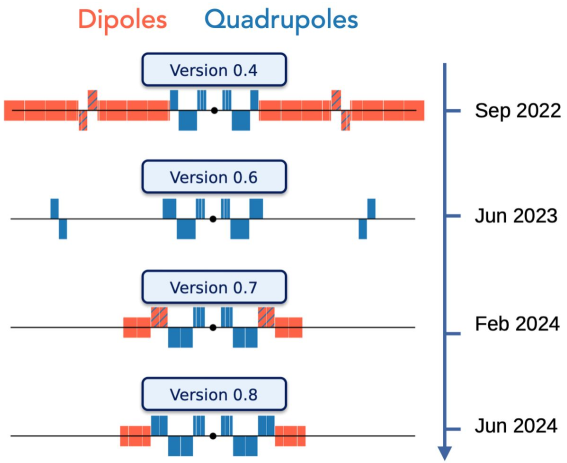
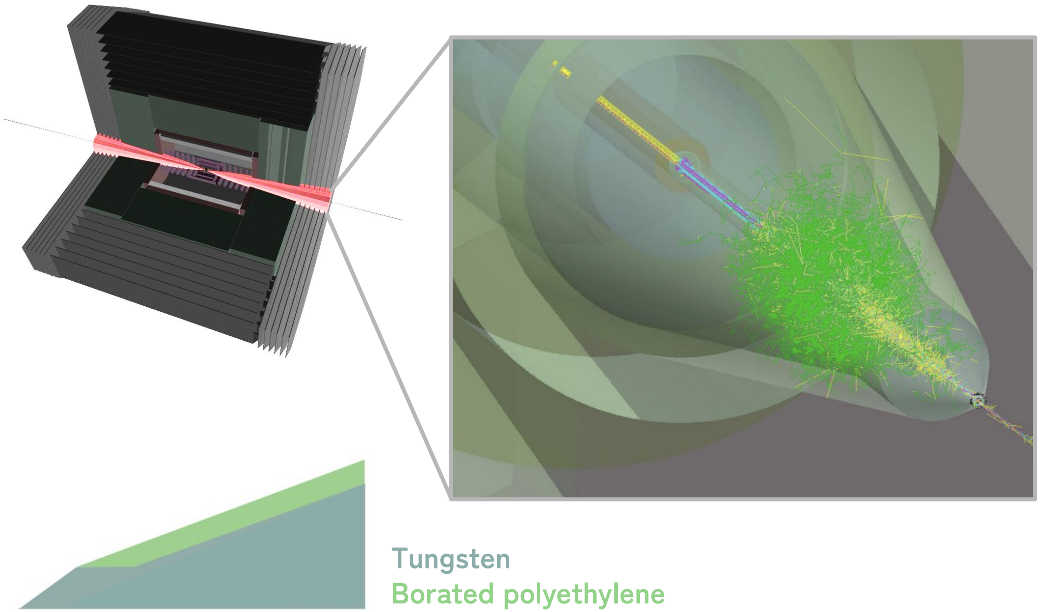


2. Shielding via "nozzles"

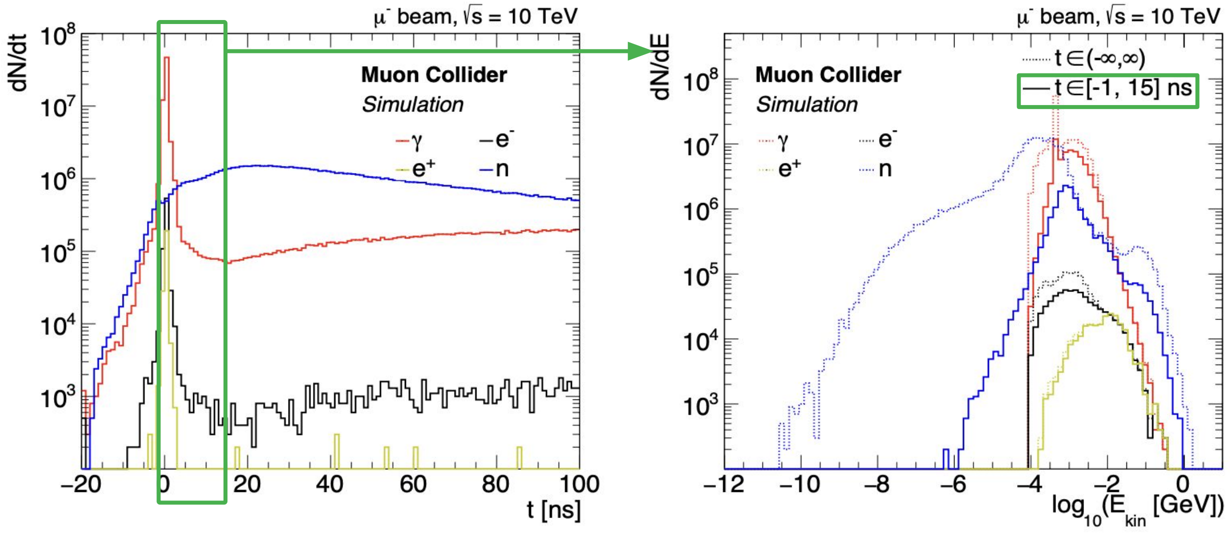
- Reduces BIB by several orders of magnitude
- Changes BIB composition (highly energetic particles → diffuse)



BIB Mitigation

3. Apply timing selection

- Can reduce BIB by ~orders of magnitude, especially low-energy contributions
- Precision timing O(10-100) ps critical to perform meaningful physics analyses



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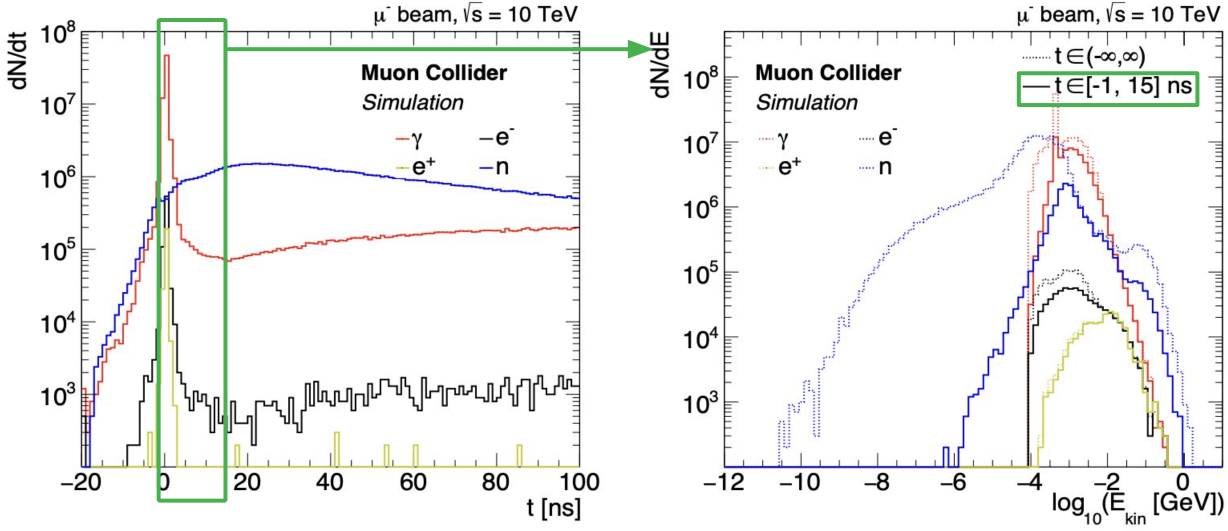
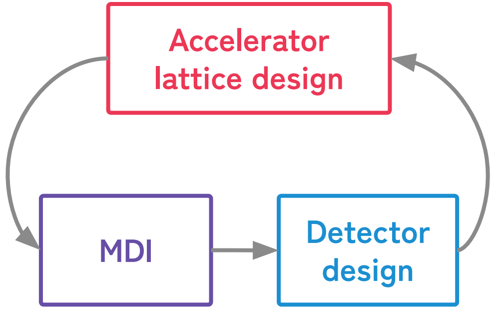


Machine-Detector Interface (MDI)

- Interplay between collider lattice design, detector design, and physics capabilities



For more, checkout the IMCC MDI Session!

Detector Design: Challenges + Goals

1. Robust against BIB
   - Dominated by MeV-scale γ/n, generally out-of-time + non-projective

2. Sensitive to physics signatures of interest
   - Multi-TeV objects from $\mu^+\mu^-$ annihilation processes
   - Both known physics (e.g. Higgs decays) and exotic BSM physics signatures

Key Themes:

- High spatial granularity and precision
- Excellent timing resolution

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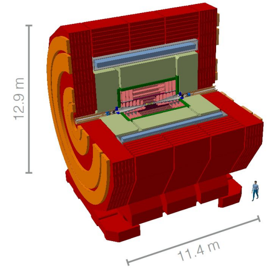
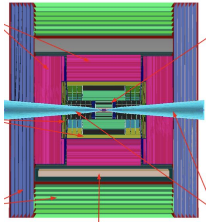
Evolution of Muon Collider Detector Concepts

Starting Point: CLIC



3 TeV: Add Nozzles



10 TeV: MUSIC

10 TeV: MAIA

MAIA

For more, checkout MUSIC and MAIA talks on Wednesday!

Let’s Build a Particle Detector

Beamline ⊗⊙

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Let’s Build a Particle Detector

Tracker

Observables: Tracks & vertices

Driving Challenge: Occupancy

- Also consider timing, material budget, cost, etc

Technology: Silicon sensors

- Pixels, strips, macropixels
- LGADs (excellent timing)
- & more!

Let’s Build a Particle Detector

Tracker

Three Si Tracking Sub-Detectors

1. Vertex Detector (VXD) – Barrel, Endcap
2. Inner Tracker (IT) – Barrel, Endcap
3. Outer Tracker (OT) – Barrel, Endcap

Track reconstruction performance:

- MAIA 10 TeV efficiency with BIB > 95% in barrel, ~50% in endcaps

Observables: Tracks & vertices

Driving Challenge: Occupancy

- Also consider timing, material budget, cost, etc

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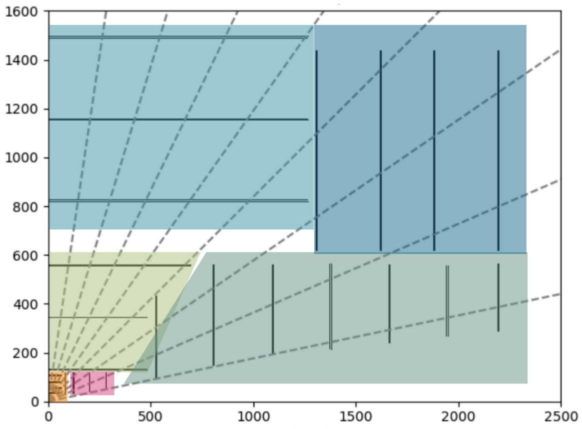
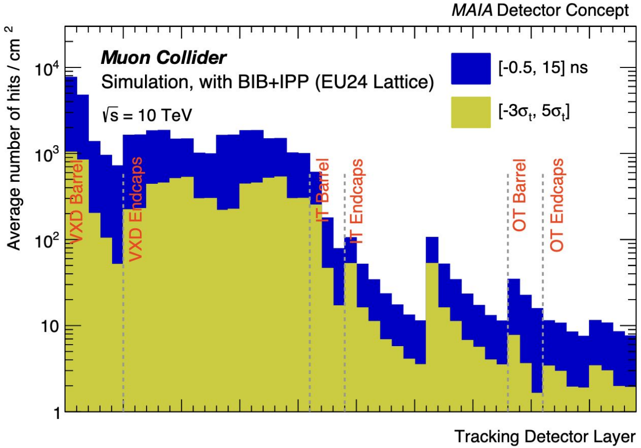




Let’s Build a Particle Detector

Calorimeters

ECAL *HCAL*

Observable: energy deposits

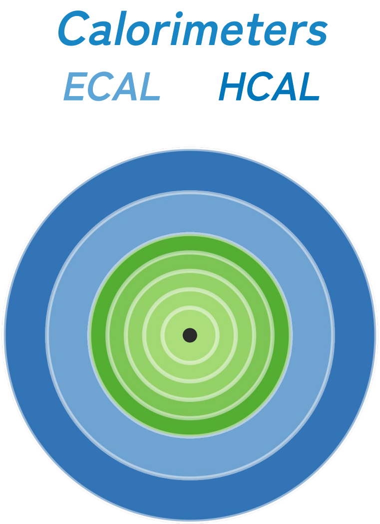
Driving Challenge: large cell sizes and integration times

- “5D Calorimetry”

Technology: several options explored

- W-Si: Tungsten-silicon
- Crilin: Lead fluoride crystal
- Fe/Steel+Scintillator

Let’s Build a Particle Detector



- Separate systems for electromagnetic (e/γ) and hadronic calorimetry
- Excellent calorimeter performance without BIB, but the addition of BIB significantly degrades resolutions – ongoing work!

Observable: energy deposits

Driving Challenge: large cell sizes and integration times

- “5D Calorimetry”

Technology: several options explored

- W-Si: Tungsten-silicon
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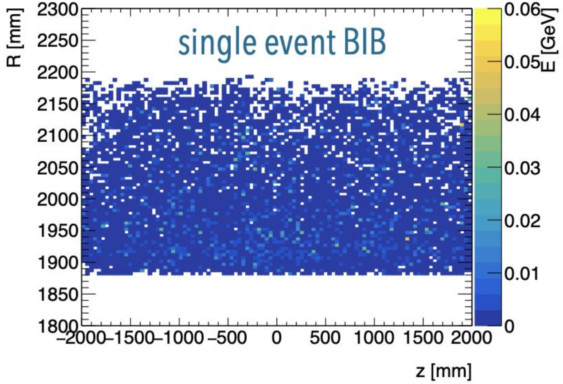
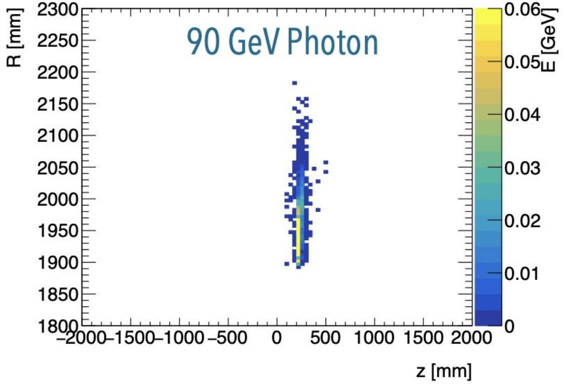
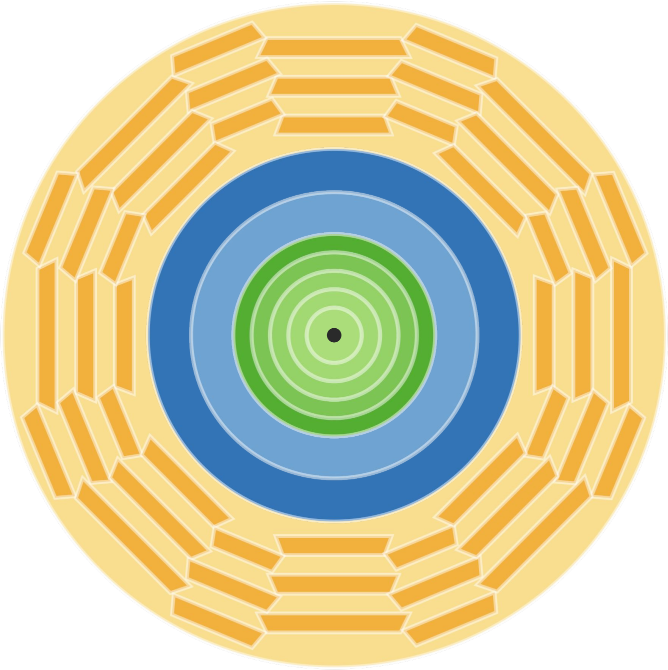




Let’s Build a Particle Detector

Muon Spectrometer



Observable: muon tracks

Driving Challenge: “forward” region close to the beamline

Technologies:
- RPC, LGADs, & more

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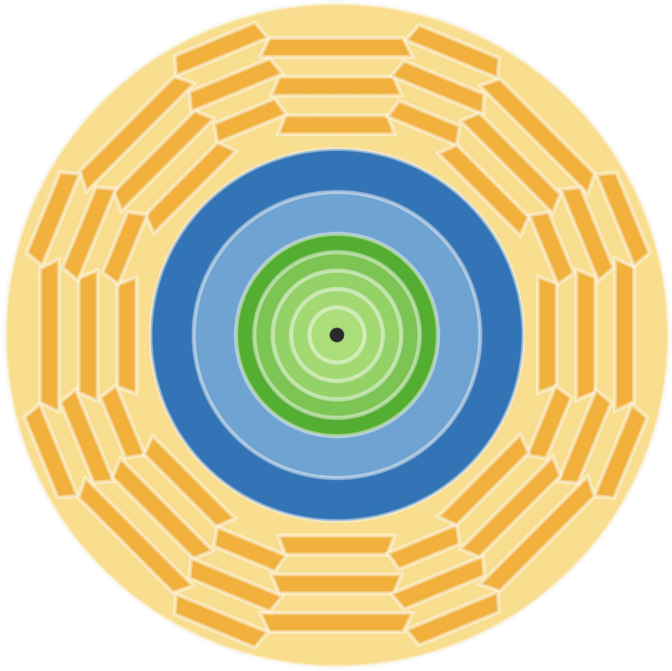


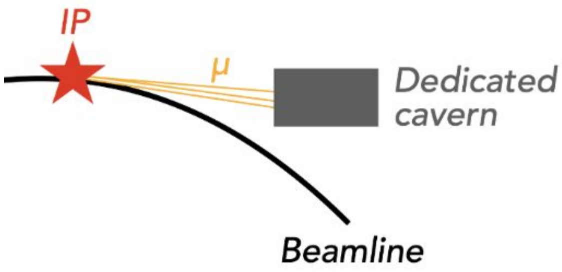
- Muons typically pass through calorimeters with minimal interactions
- Generally the least impacted by BIB, since it's shielded by calorimeters
- Forward region along the beamline more challenging
  - Really important for physics goals!
  - A few different options being considered:

Silicon Layers in the Nozzle

Small detector, high background

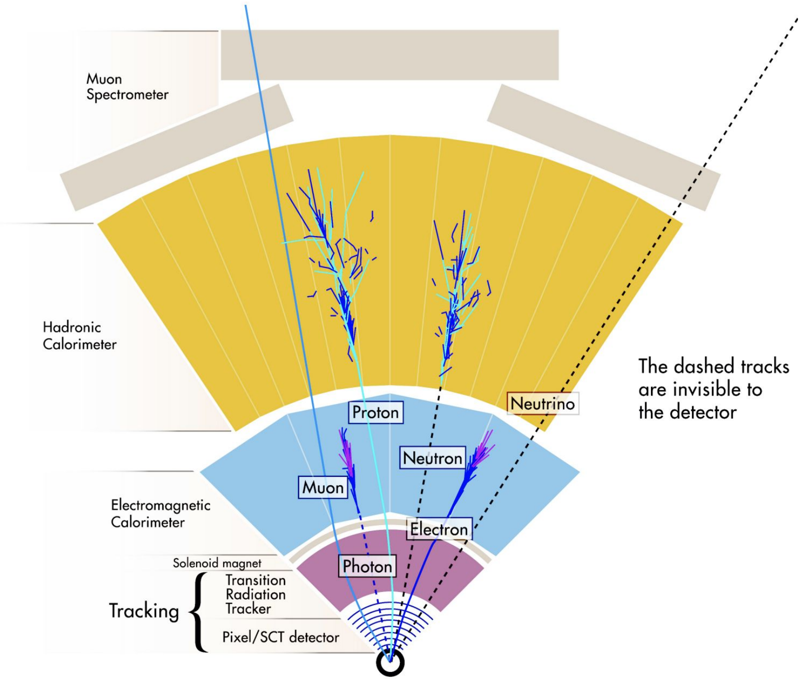
Separate Forward Cavern

Large detector, low background



Particle Reconstruction + Identification

Use combination of detector subsystems to reconstruct and identify different particles



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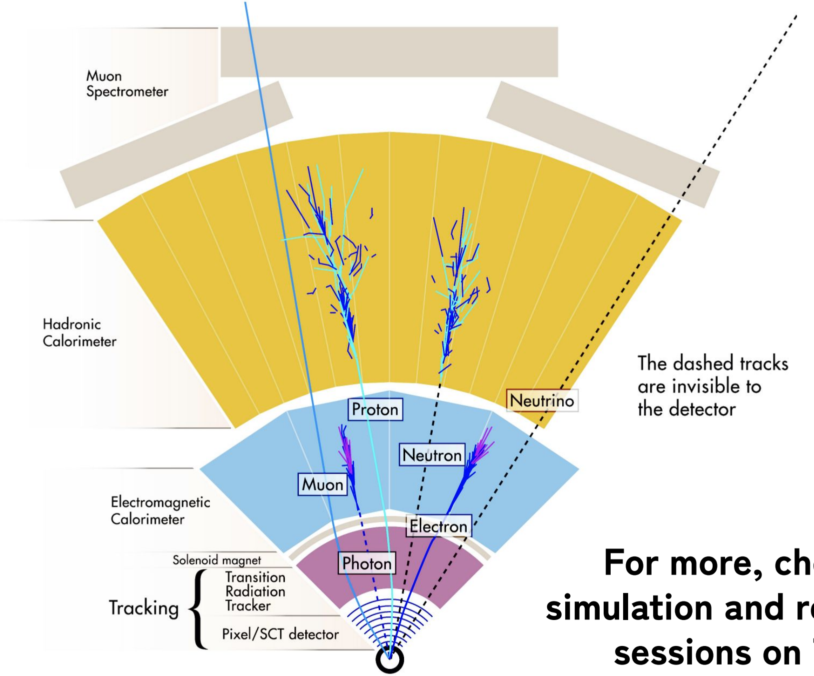
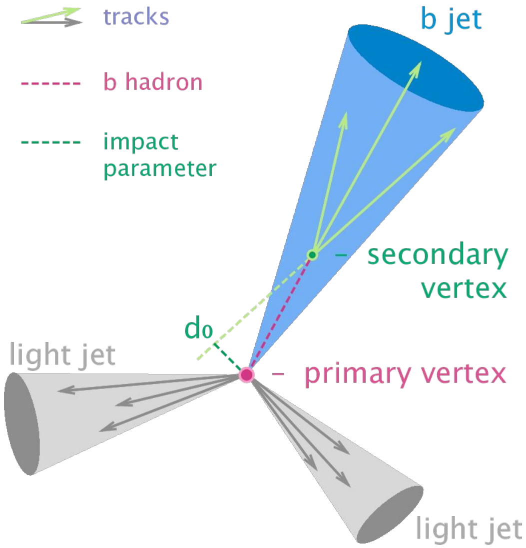


Particle ID can actually be very challenging, e.g. distinguishing jets from different types of quarks

Example: b-tagging

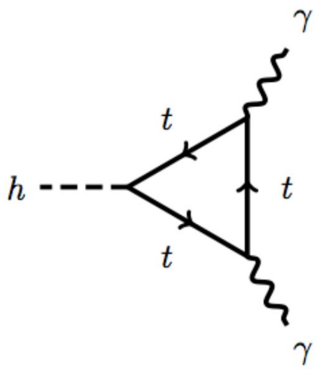


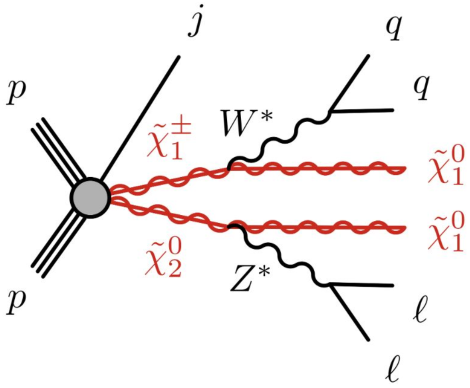
For more, checkout the simulation and reconstruction sessions on Thursday!

Building an Analysis*

**Highly simplified!*

1. Signal hypothesis: what process are you trying to measure or search for?
    - Multiple signal points varying parameters of interest, e.g. mass, coupling strength, generation or simulation parameters, etc





Building an Analysis*

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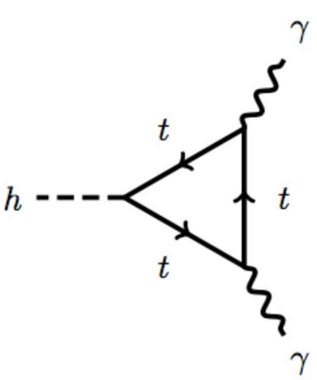
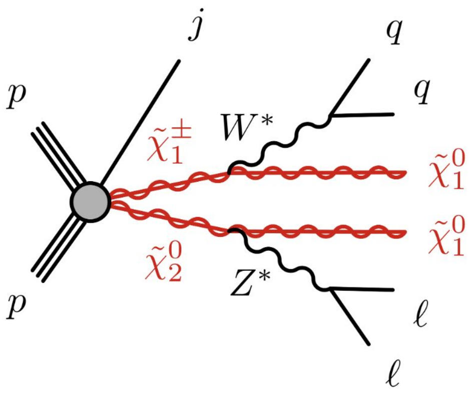
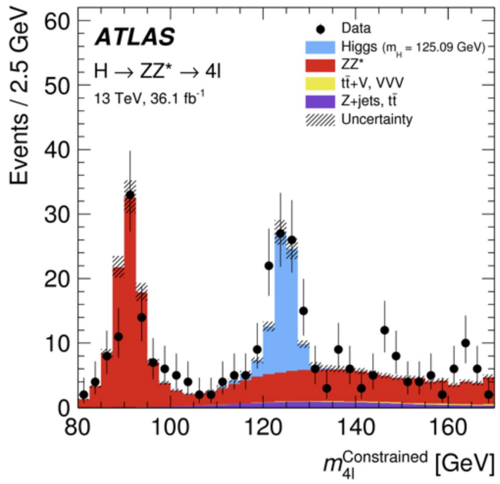
2. What background processes mimic your signal? Study, characterize, and reject them
    - Genuine physics processes
    - Fakes / mismeasurements / artifacts of your detector or reconstruction algorithm





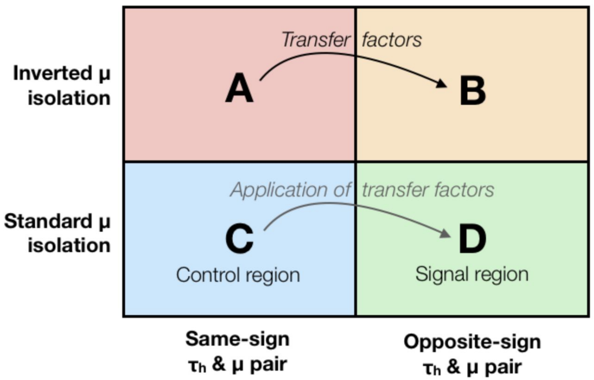


Building an Analysis*

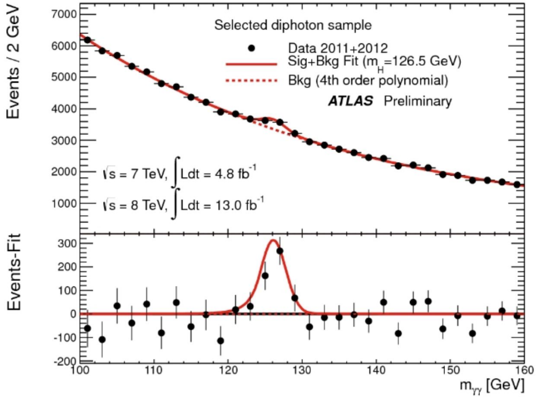
***Highly simplified!**

3. Analysis Strategy: how will you measure your quantities-of-interest?
    - Goal: define "Signal Region" and predict background using combination of simulation and data from other regions
    - Blinded analysis: don't look in signal region data during development – use additional regions to validate background prediction

ABCD Method



Bump Hunt



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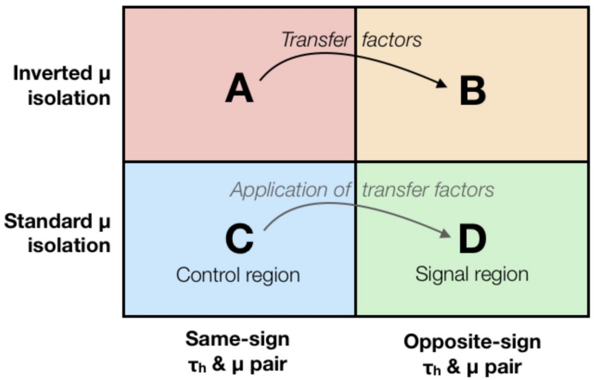
4. Statistical analysis
   - Integrate background estimation prediction, signal expectation/hypothesis, signal region measurement, and systematic uncertainties

ABCD Method



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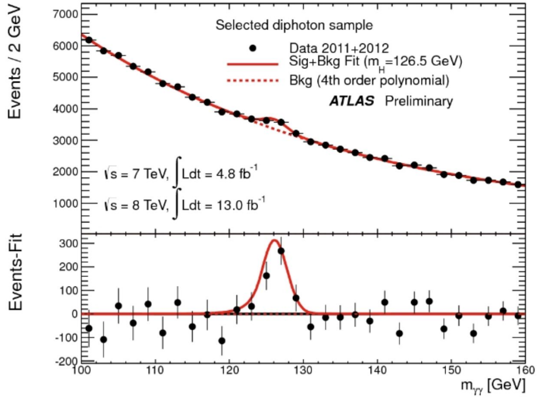
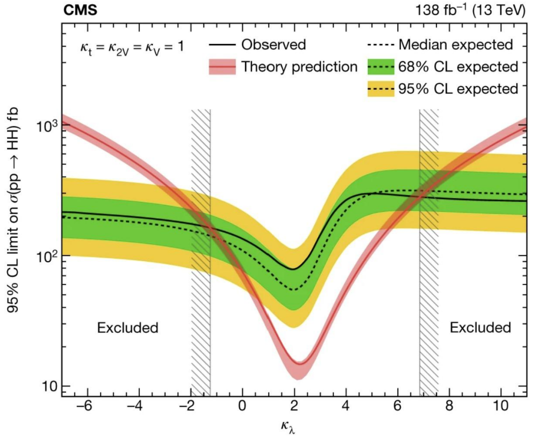


Limits

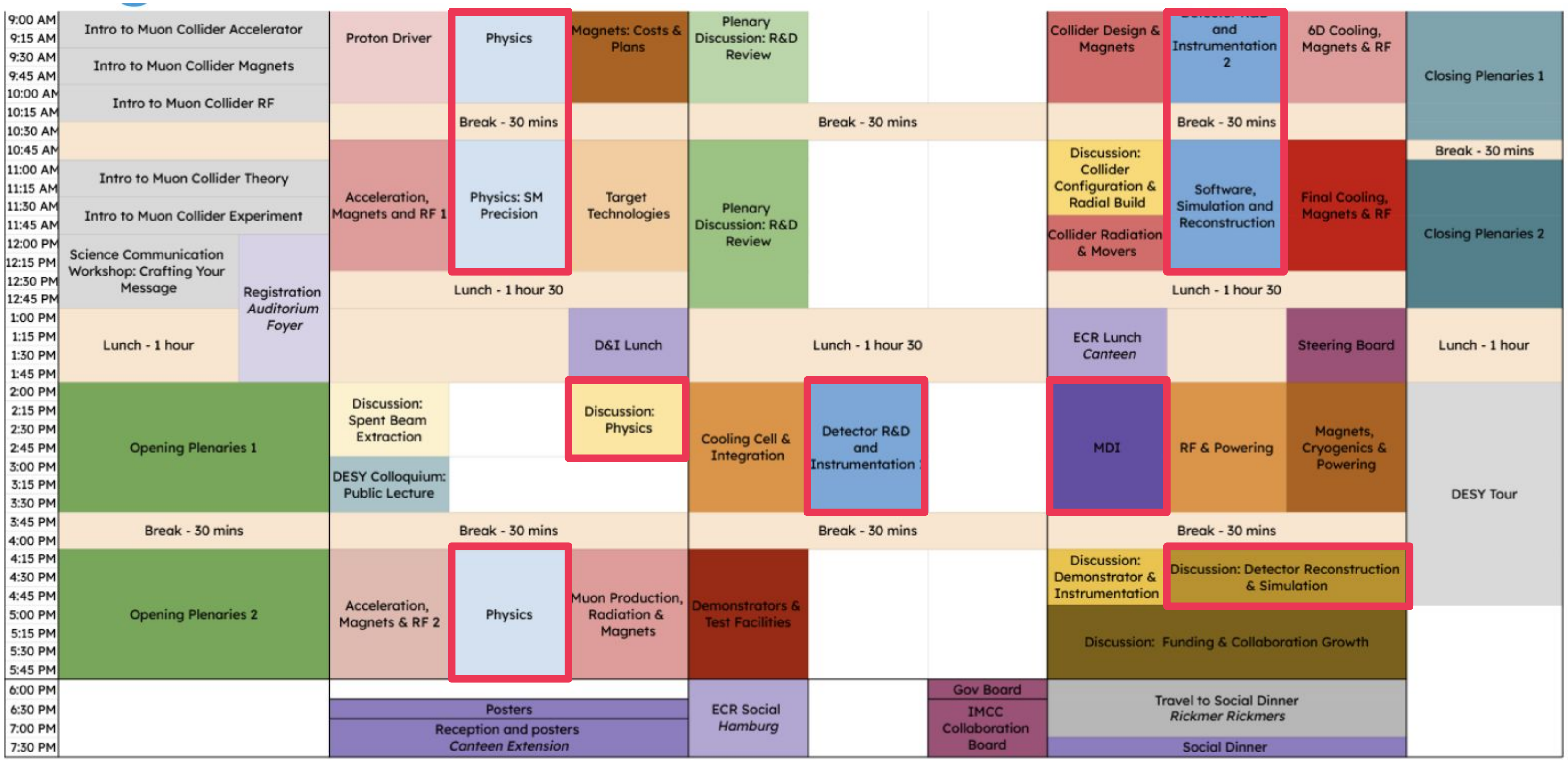


Many Open Questions + Ongoing Work!*

***A non-exhaustive list**

- Detector optimization
  - E.g. multiplicity and positions of various detector layers, magnet field strength(s) (at least for 10 TeV)
  - Must be done in conjunction with collider lattice design + nozzle optimization (MDI)
- Mechanical Requirements
  - Room for services, cooling, and support infrastructure
  - Physical support for the nozzle
- Software and Simulation
  - BIB simulation extremely computationally intensive!
  - Need dedicated and improved reconstruction algorithms
  - Latest SW release built on key4hep stack
- Physics in the forward region
  - Forward muon tagging very important for VBF processes – how to detect these muons?
- DAQ system
  - Not much development done here yet...

Exciting Physics, Detector + MDI Program this Week!



Outlook + Conclusions

- Experimental physics at a muon collider integrates theoretical frameworks, instrumentation R&D, collider lattice design considerations, and advancements in software & computing
    - A lot of talented people making great progress in each of these areas
    - Check out the dedicated parallel sessions this week focusing on these topics!

- There are many different ways to become involved – please reach out if you are interested in learning more about or joining any of these efforts!

- Looking forward to an exciting IMCC annual meeting and learning about further opportunities to collaborate with and identify synergies across the accelerator and physics/detector fields

Thank You!

L. Lee, C Bell