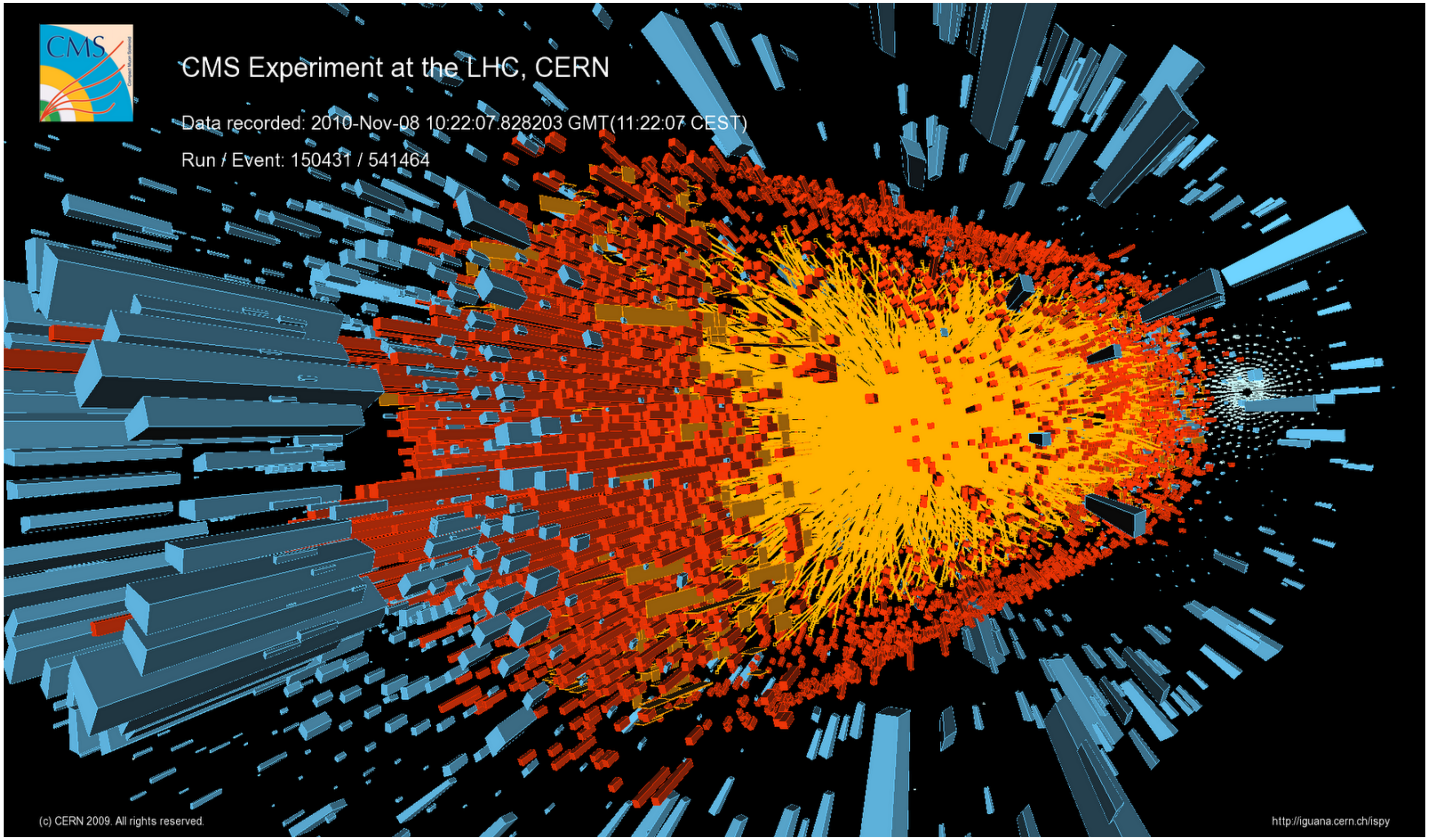
Future *pp* Colliders

Ashutosh Kotwal
Fermilab & Duke University



Mitchell Workshop on Collider and Dark Matter Physics
Texas A&M University
May 22, 2015

Setting the Stage – P5 Report (2014)

- Science Drivers
  - Use the Higgs boson as a new tool for discovery
  - Pursue the physics associated with neutrino mass
  - Identify the new physics of dark matter
  - Under stand cosmic acceleration: dark energy and inflation
  - Explore the unknown: new particles, interactions, and physical principles

History of Tools of Discovery

- After W/Z discovery at Sp$\bar{p}$S,
    - Precision Z and W boson measurements became the tool for discovery at electron-positron collider (LEP)
    - W bosons became the tool for discovery – discovered top quark at hadron collider (Tevatron)

- B-quark became a tool for discovery
    - Precision measurement of b-quark properties at ARGUS, CLEO, CUSB, CDF, D0, Babar, Belle, super-b factory
    - B-quark also played crucial role in top quark discovery at Tevatron

- The idea of a higher-energy electron-positron collider and a higher-energy hadron collider has physics synergy and appeal

Circular e^+e^- and *pp* Colliders

- Unlike the situation after W and Z discovery
  - Which created a “guaranteed” physics goal to discover the agent(s) of electroweak symmetry breaking
- And the situation after the discovery of *b*-quark
  - Which again created a “guaranteed” physics goal to discover the *SU*(2) partner top quark

- … the Higgs boson discovery does not easily generate the next guaranteed physics goal(s)

- Do we need guaranteed physics discoveries?
- Can we articulate a physics case based on exploration alone?

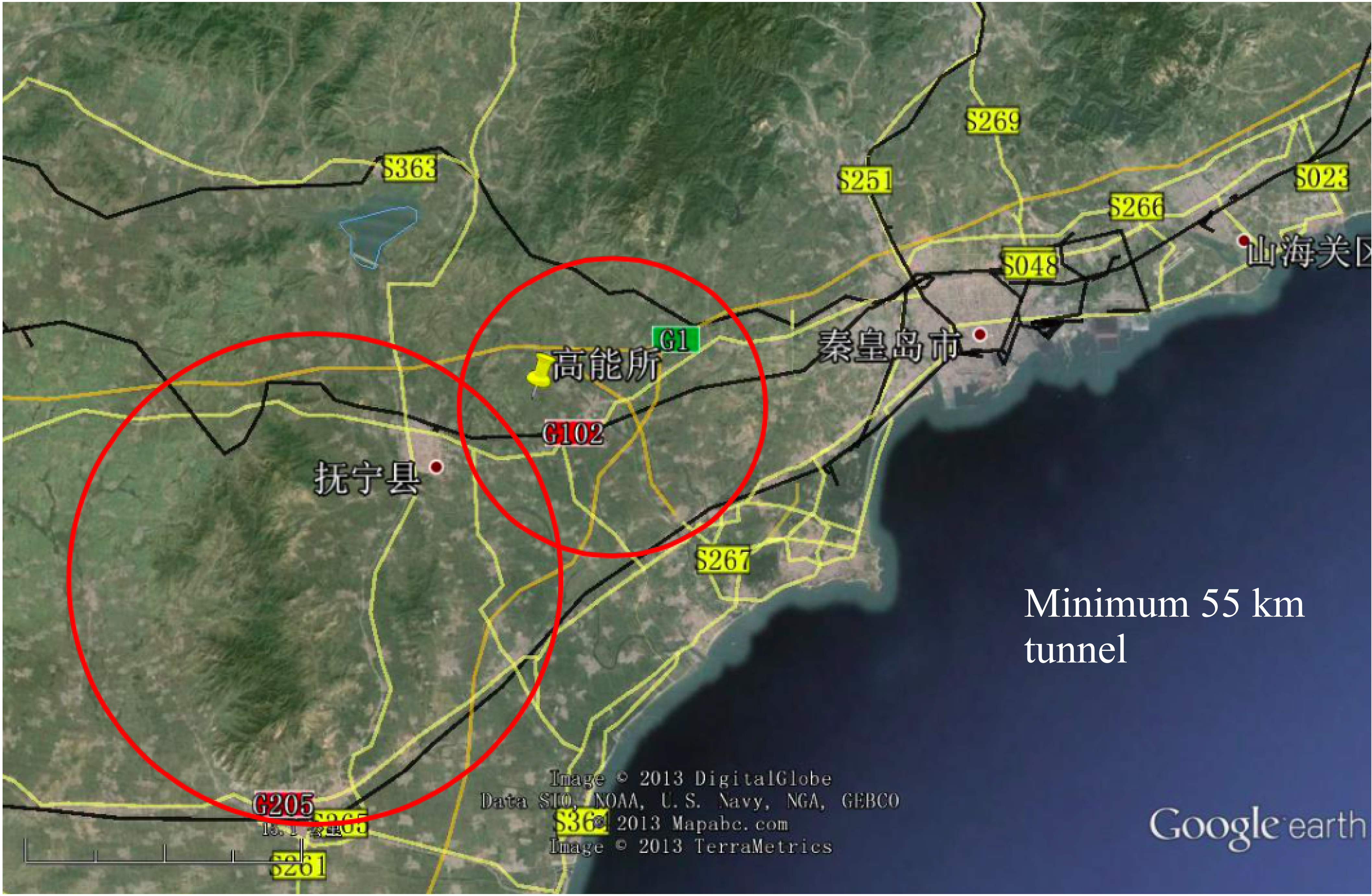
Circular e^+e^- and *pp* Colliders – two views

- First view:
  - e^+e^- circular collider already guarantees physics deliverables
    - High-precision measurements of most Higgs properties (but NOT the very-important triple Higgs coupling)
    - Very-high precision measurement of W boson mass (~1 MeV or less)
    - Ultra-high precision electroweak measurements on the Z boson pole
  - Circular *pp* collider goals become clear after future discoveries from
    - LHC or HL-LHC
    - direct and indirect dark-matter searches
    - Rare or forbidden processes at intensity frontier
    - Muon *g*-2, electric dipole moments, …

Circular e^+e^- and *pp* Colliders

- The other view:
  - A combined circular collider program with e^+e^- phase and *pp* phase is ultimately contingent on the physics case for the *pp* collider
  - Parameters of *pp* collider –
    - physics case for target energy and luminosity
    - technical feasibility
    - cost estimate
  - define one irreversible decision: the radius of the collider tunnel
  - Physics case, technological choices and cost are all driven by the ultimate *pp* machine

Chinese Site 300 km East of Beijing

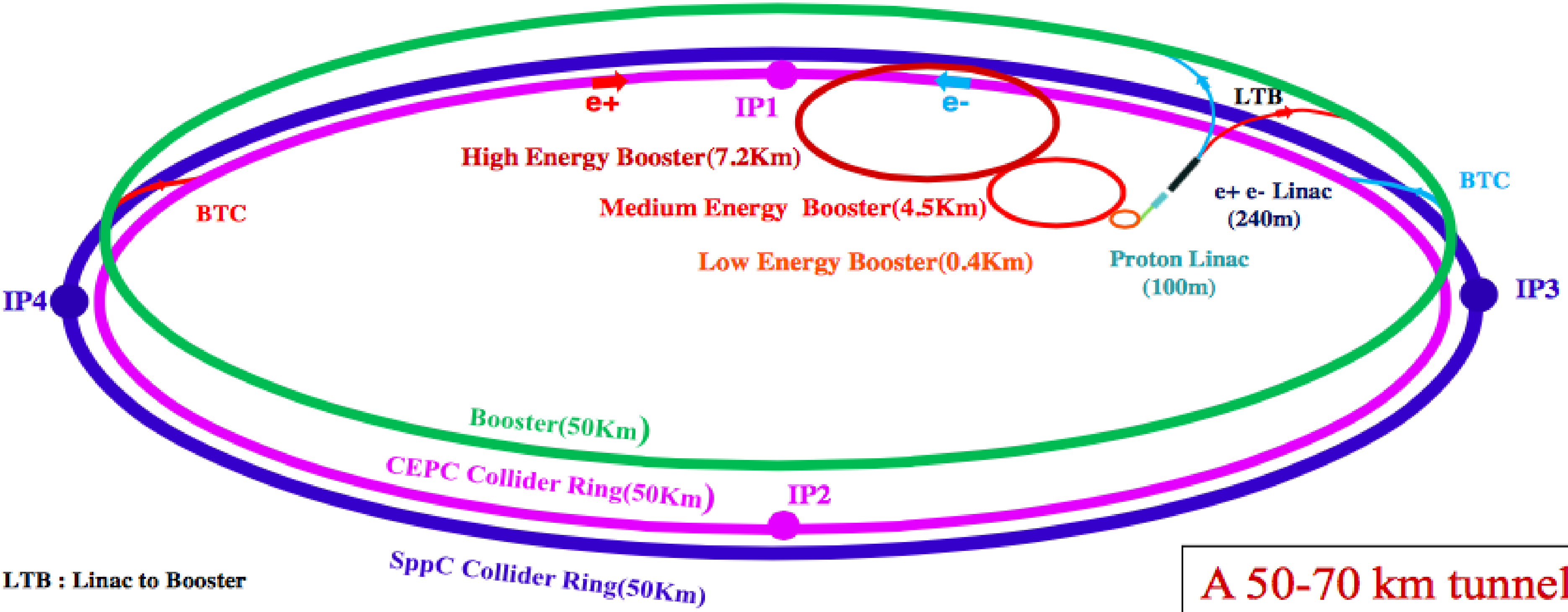


Minimum 55 km tunnel

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

From Yifang Wang lecture

Scientific Goals

- **CEPC (e+e-: 90-250 GeV)**
  - Higgs Factory: Precision study of Higgs(m_H, J^{PC}, couplings)
    - Same as SM prediction ? Other Higgs ? Composite ? New properties ? CP effect ?
  - Z & W factory: precision test of SM
    - New phenomena ? Rare decays ?
  - Flavor factory: b, c, τ and QCD studies
- **SppC (pp: 50-100 TeV)**
  - Directly search for new physics beyond SM
  - Precision test of SM
    - e.g., h^3 & h^4 couplings

Complementary with each other

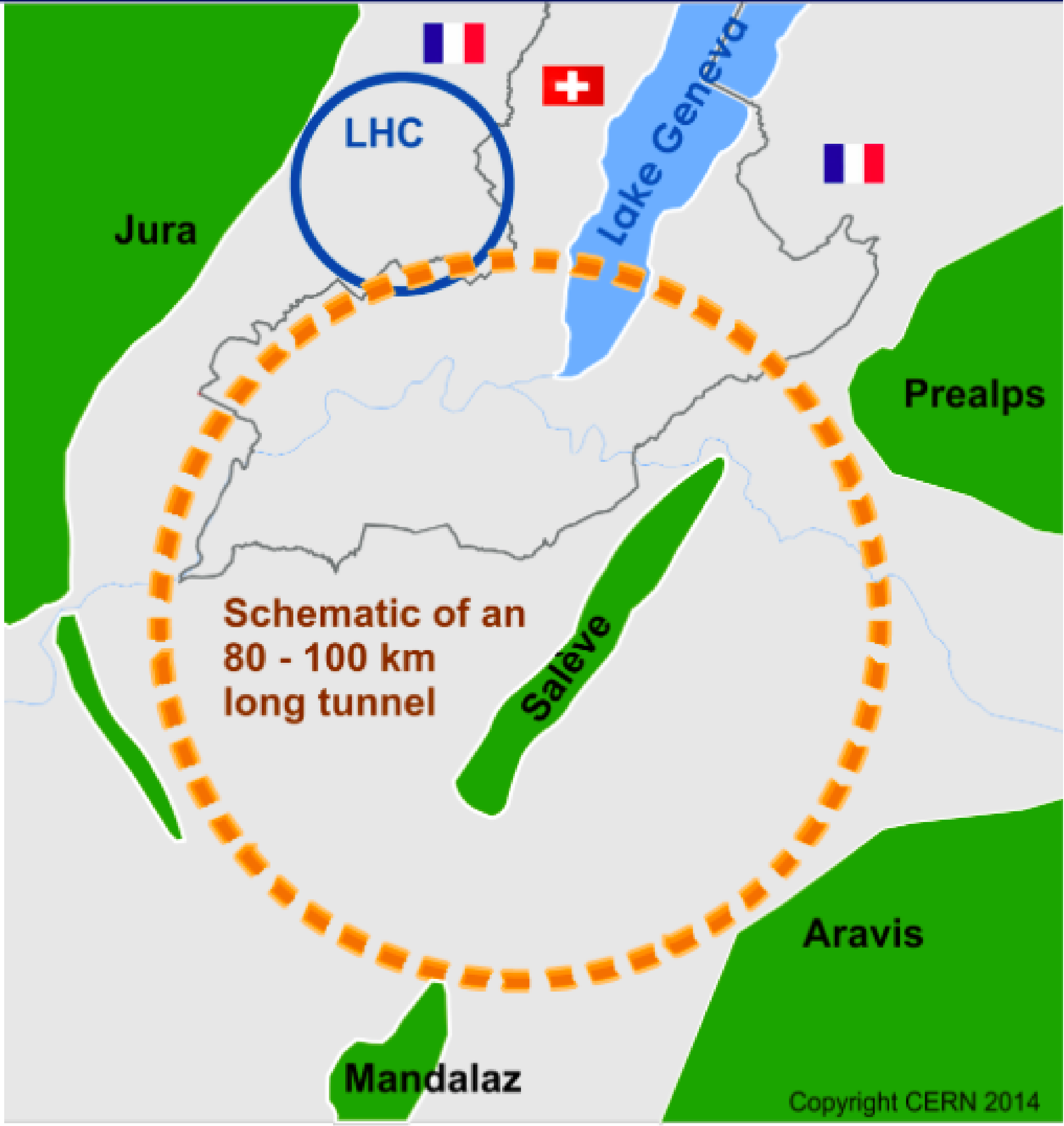
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

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

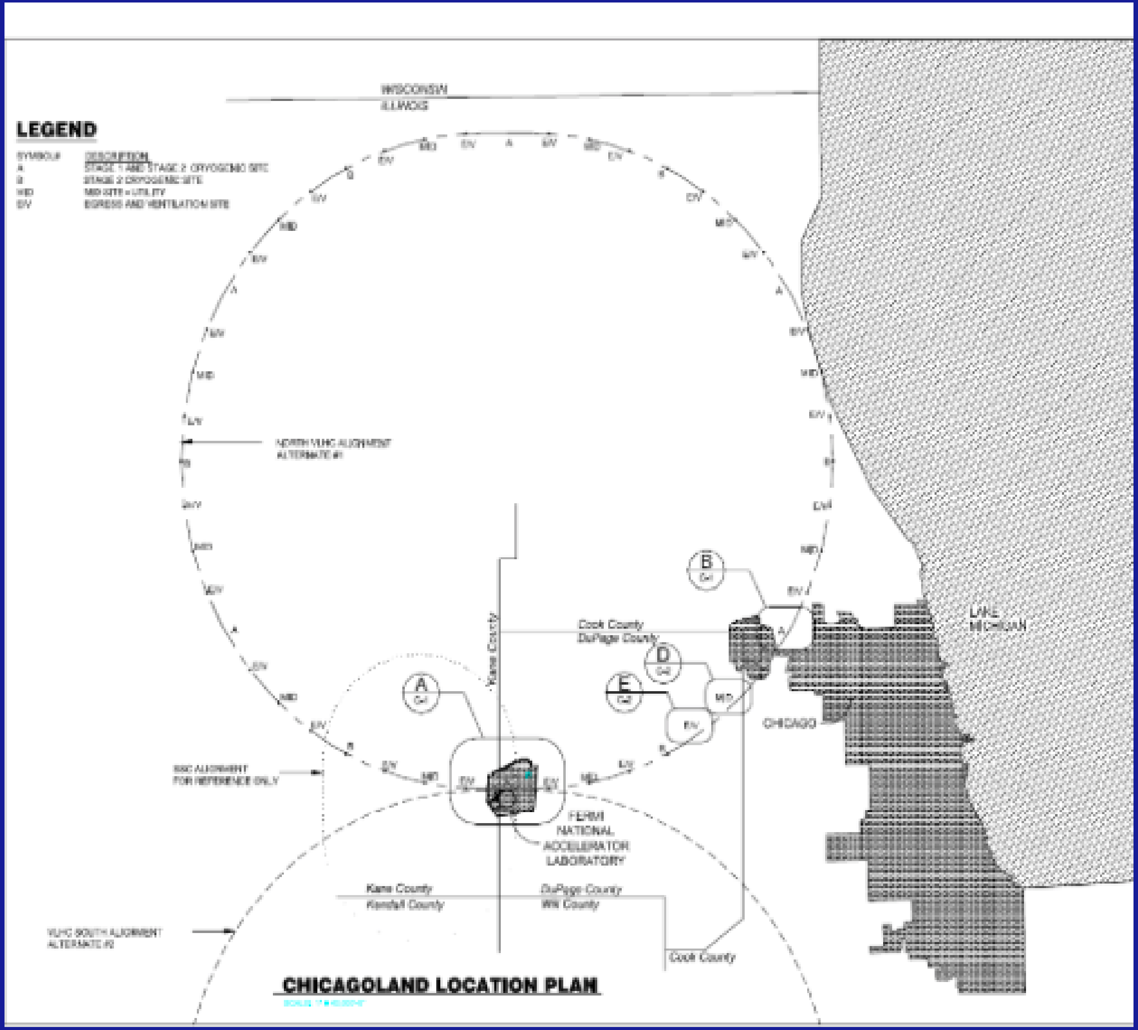
- ***e^+e^-* collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area

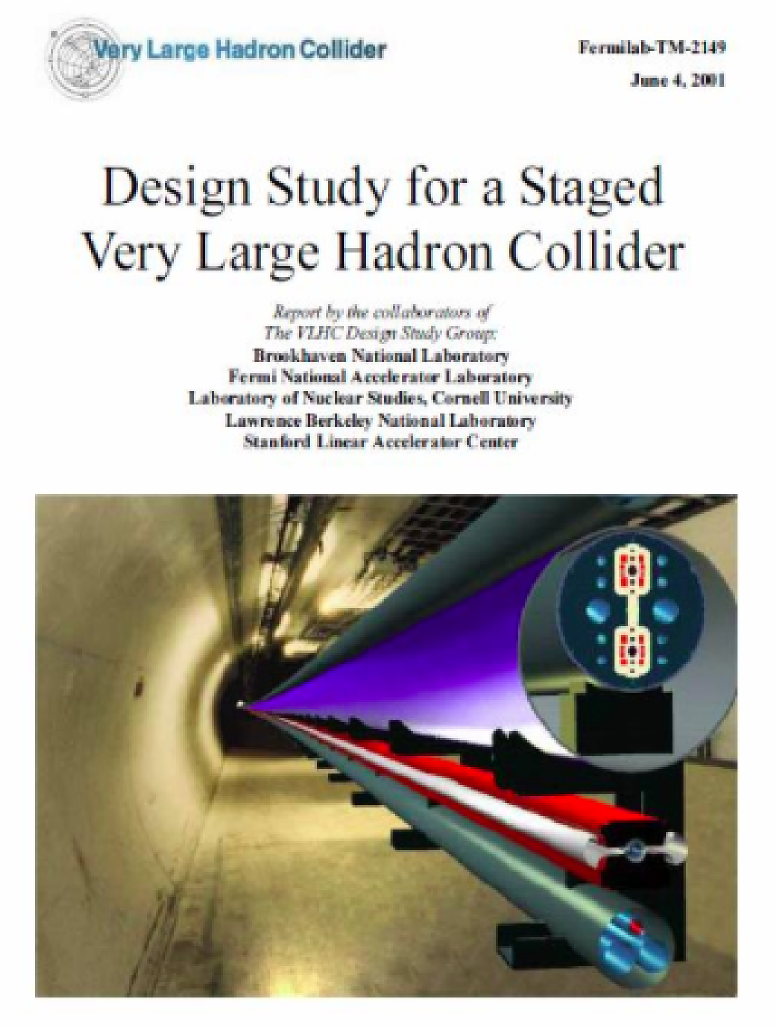


Schematic of an 80 - 100 km long tunnel

Copyright CERN 2014

273 Pages VLHC Technical Proposal





Very Large Hadron Collider

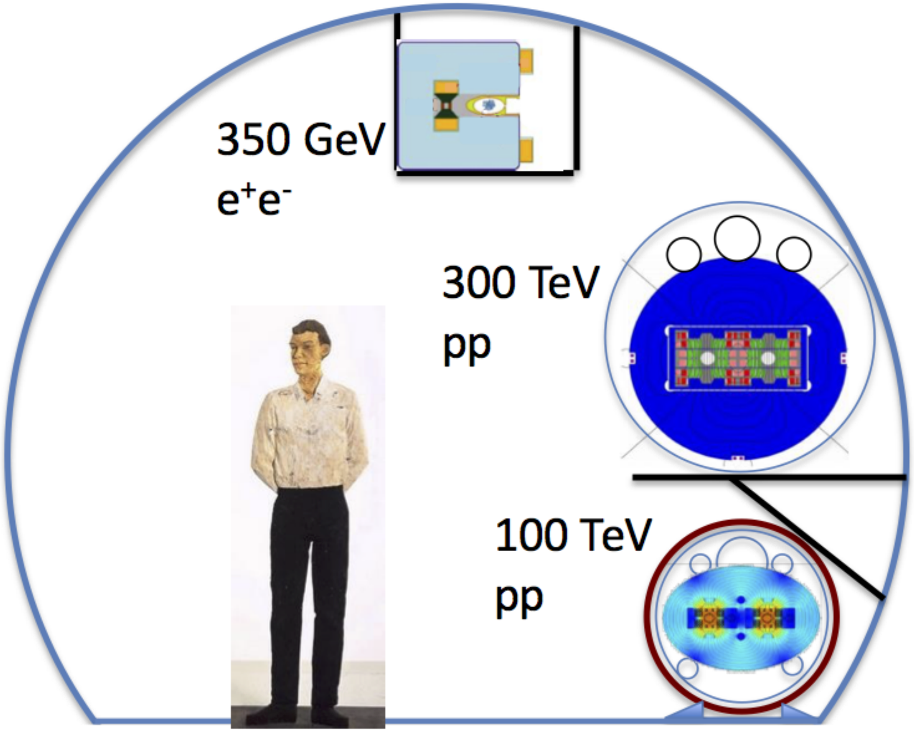
Fermilab-TM-2149
June 4, 2001

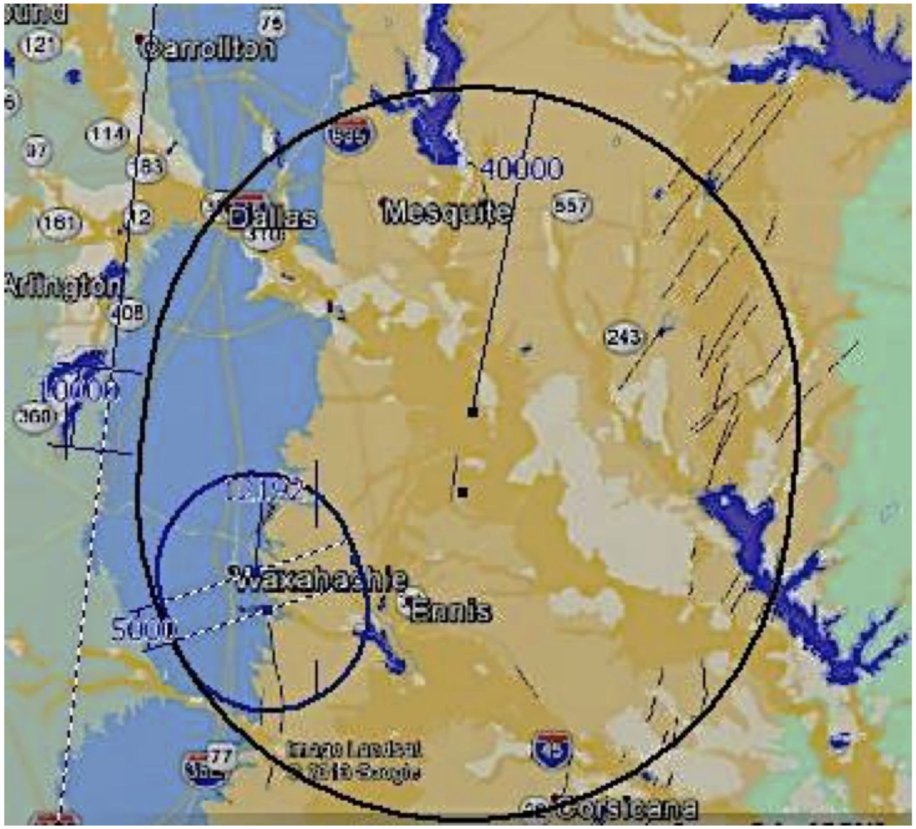
Design Study for a Staged
Very Large Hadron Collider

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**

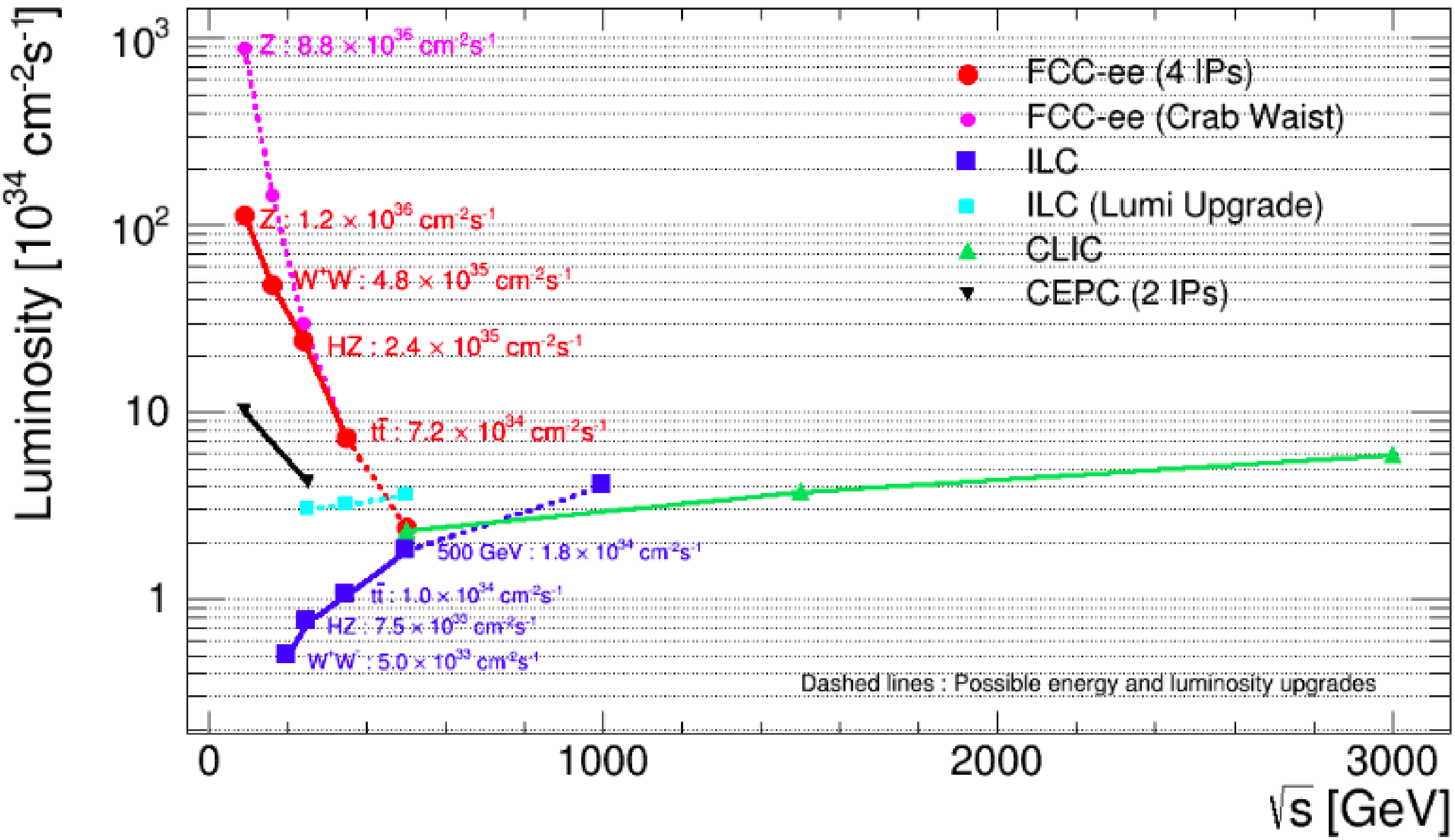
100 TeV hadron collider: 4.5 dipoles in a 270 km tunnel





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

Texas A&M University



(from A. Blondel's presentation at FCC Week)

Circular e^+e^- Collider Physics Goals

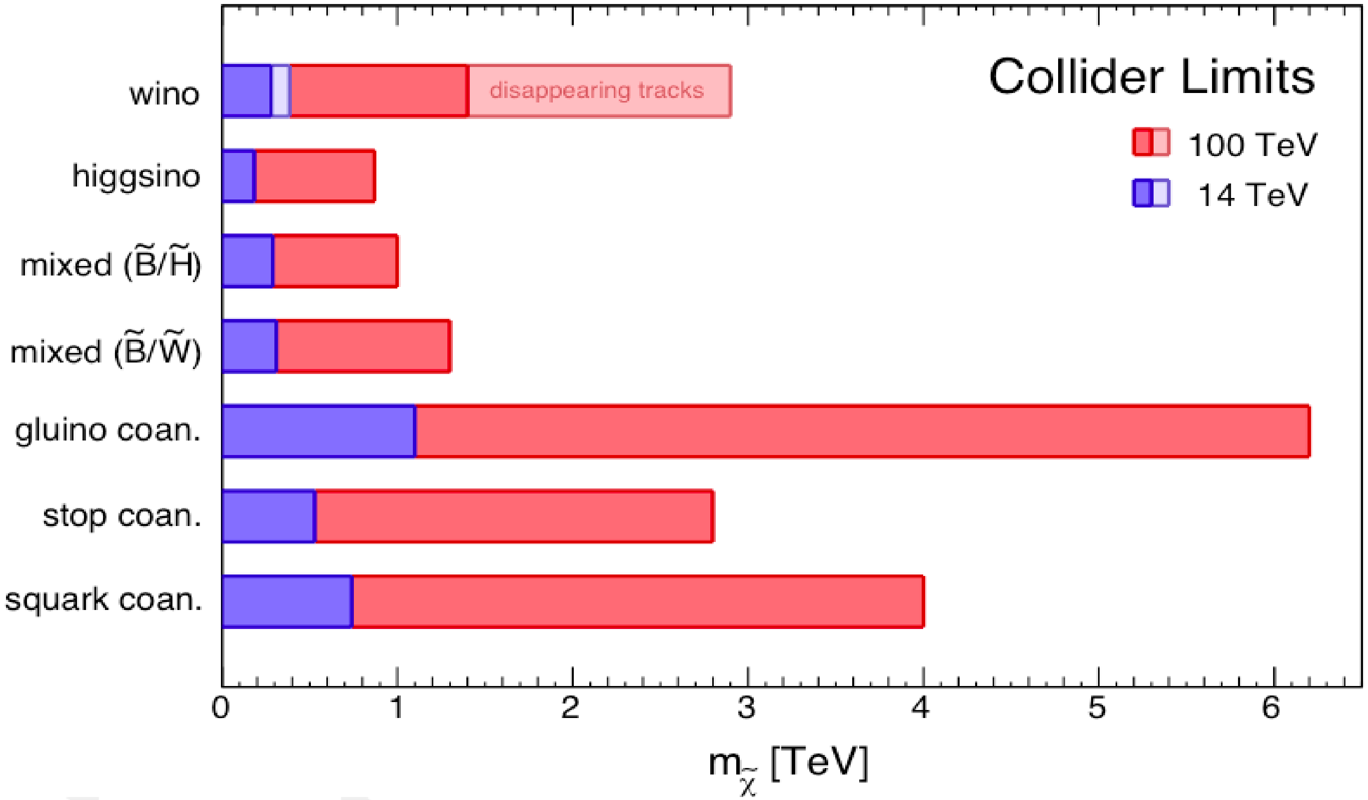
- 100 billion (CEPC) to 1 trillion Z bosons (FCC-ee)
  - 10K to 100K more statistics than LEP
  - 100 times smaller statistical errors
  - Potential for probing 10 times higher mass scales in loops
  - Current electroweak precision observables already probing new physics at the few TeV scale through dim-6 operators
- 0.1-0.5 MeV W mass measurement (systematics TBD) from WW threshold scan
- 1-2 million Higgs boson events
  - Percent to parts per thousand precision on many Higgs branching ratios
  - Model-independent extraction of Higgs couplings
  - Invisible Higgs branching ratio to 0.3% precision
- FCC-ee proposes $t\bar{t}$ threshold scan, top quark mass with <100 MeV precision (10 MeV statistical error)

Circular *pp* Collider Physics Goals

- Testable reasons why the Standard Model must be incomplete
    - Dark Matter could be
        - Weakly-interacting particles
        - Particles interacting through Higgs portal
        - Interacting with SM particles through gravity
    - Electroweak Baryogenesis
        - Can the electroweak phase transition (formation of Higgs VeV) provide the out-of-equilibrium condition needed for matter-antimatter asymmetry observed?
    - Can the parameter space of couplings and masses associated with the above be a bounded parameter space?
        - Can it be fully covered with an appropriately designed *pp* collider?
- Naturalness – the need to explain the lightness of the Higgs mass – is testing Naturalness at 10^{-4} good enough to conclude something valuable?

Dark Matter

- $M_{\text{Dark Matter}} < 1.8$ TeV ($g_{\text{DM}}^2/0.3$) based on WIMP thermal relic hypothesis



M. Low, Lian-Tao Wang,
ArXiv:1404.0682
(mono-jet channel)

Can we prove exhaustive coverage of WIMP dark matter scenarios ?

Can we prove exhaustive coverage of Higgs portal DM ?

How does DM model coverage compare between *pp* collider, ILC and CLIC ?

Plan to address these questions in physics case studies

What is the Origin of the Baryon Asymmetry?

POSSIBLE EXPLANATIONS...

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-9}$$ (from BBN)

- ⇨ **Baryogenesis at EW Scale** → **TESTABLE!**
- ⇨ ...

SAKHAROV CONDITIONS (for dynamical generation of baryon asymmetry)

B Violation ✓ *Sphalerons*

*V. A. Kuzmin, V. A. Rubakov, M. Shaposhnikov, Phys. Lett. B**155** (1985) 36*

C/CP Violation ✗ *not enough*

Departure from Thermal Equilibrium ✗ *not enough*

SM

(from Jose Miguel No)

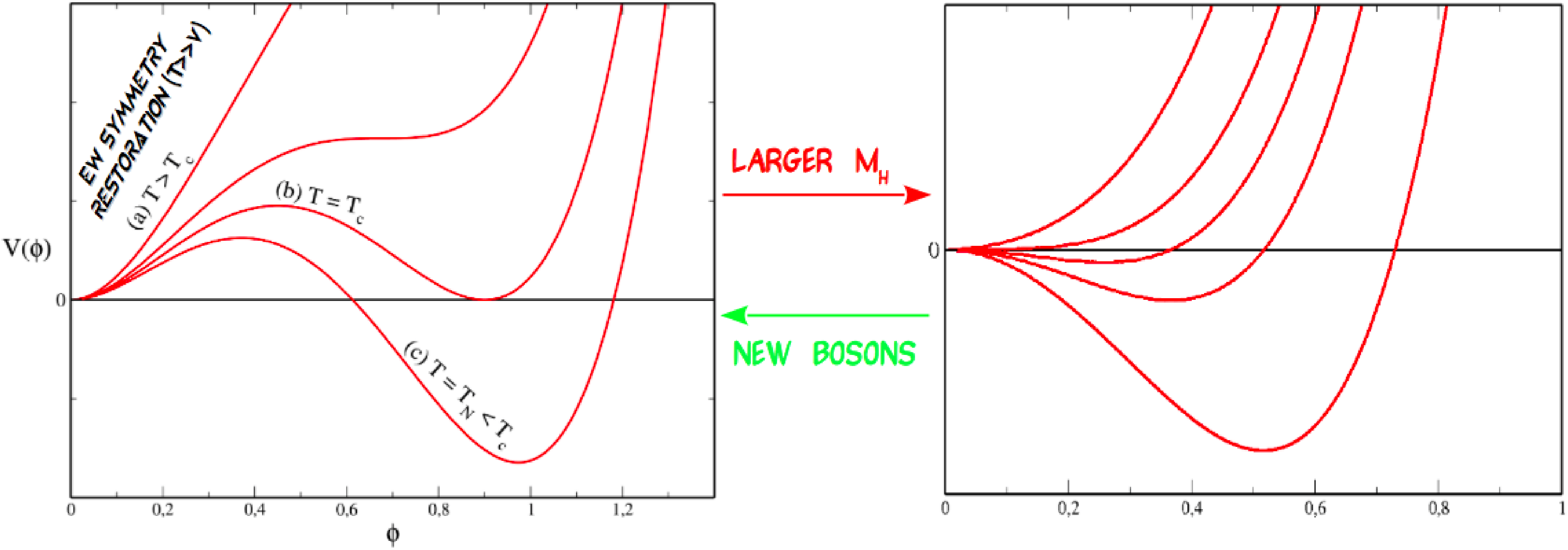
Baryon Asymmetry and Electroweak Phase Transition

1^{st} Order:

$\langle\phi\rangle = 0 \rightarrow \langle\phi\rangle = \phi(T)$ Discontinuous

2^{nd} Order:

$\langle\phi\rangle = 0 \rightarrow \langle\phi\rangle = \phi(T)$ Continuous



In the SM (m_h = 125 GeV) EW Phase Transition Smooth CrossOver

K. Kajantie, M. Laine, K. Rummukainen, M. Shaposhnikov, Phys. Rev. Lett. ***77*** *(1996) 2887*

(from Jose Miguel No)

Baryon Asymmetry and Electroweak Phase Transition

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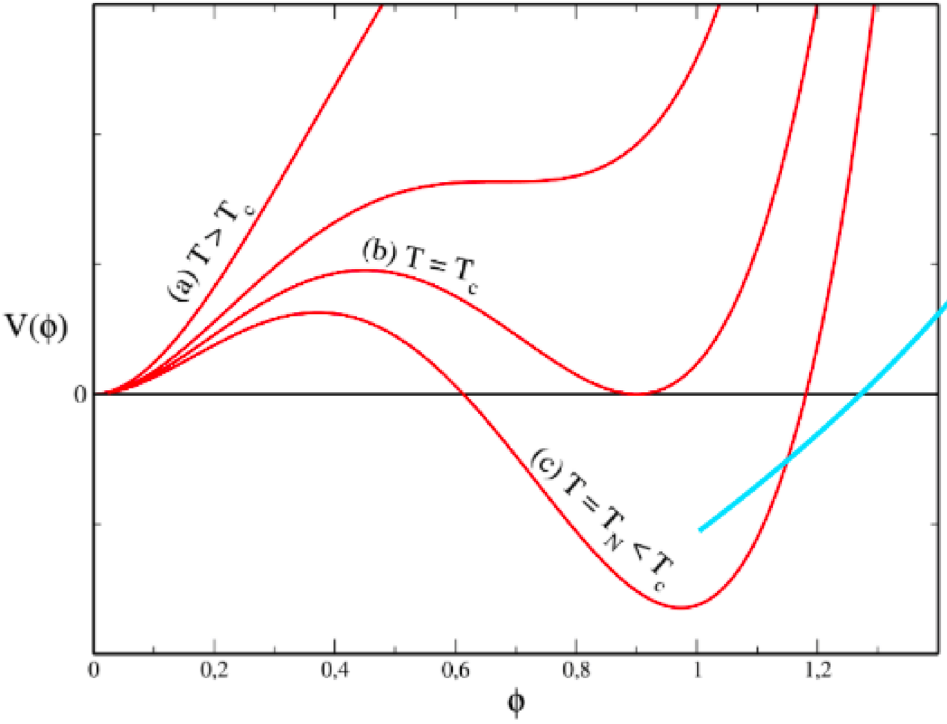
$\langle\phi\rangle = 0 \rightarrow \langle\phi\rangle = \phi(T)$ Discontinuous

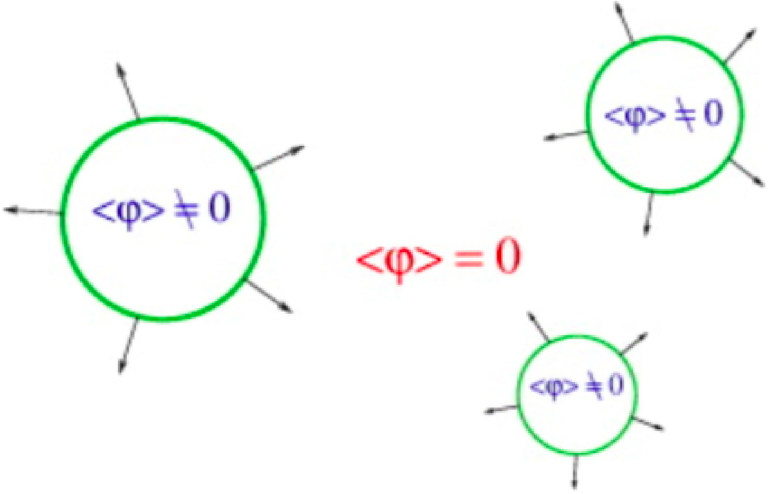


Nucleation of True Vacuum Bubbles (in False Vacuum Sea)

J. S. Langer, Ann. Phys. ***54*** *(1969) 258*

S. R. Coleman, Phys. Rev. D ***15*** *(1977) 2929*

A. D. Linde, Nucl. Phys. B ***216*** *(1983) 421*

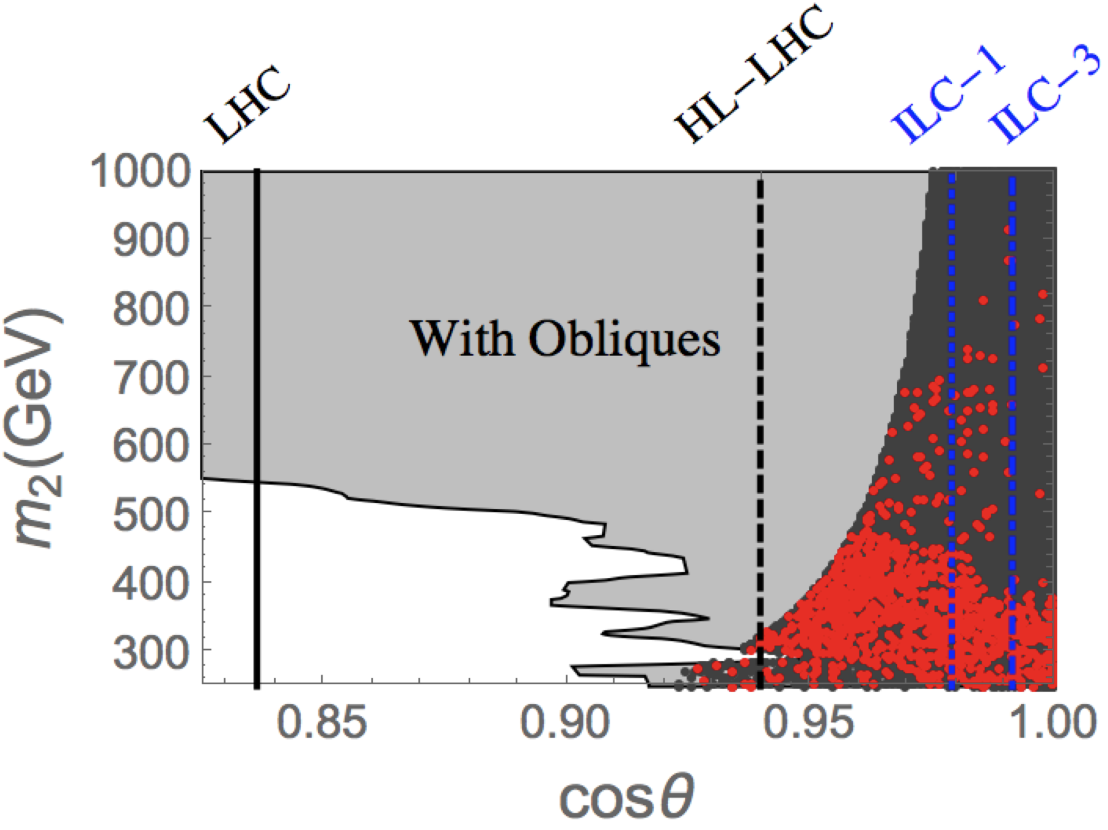


SUDDEN CHANGE IN HIGGS VEV

(from Jose Miguel No)

First Order Phase Transition

$$V(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4$$



(from P. Winslow)

S. Profumo, M. J. Ramsey-Musolf, C. L. Wainwright and P. Winslow, arXiv:1407.5342 [hep-ph]

Can TeV-scale new physics associated with Electroweak Baryogenesis be completely covered by a *pp* collider?

What's the complementarity with ILC, CLIC?

Plan to address these questions in building the physics case.

Collider Luminosity and Energy

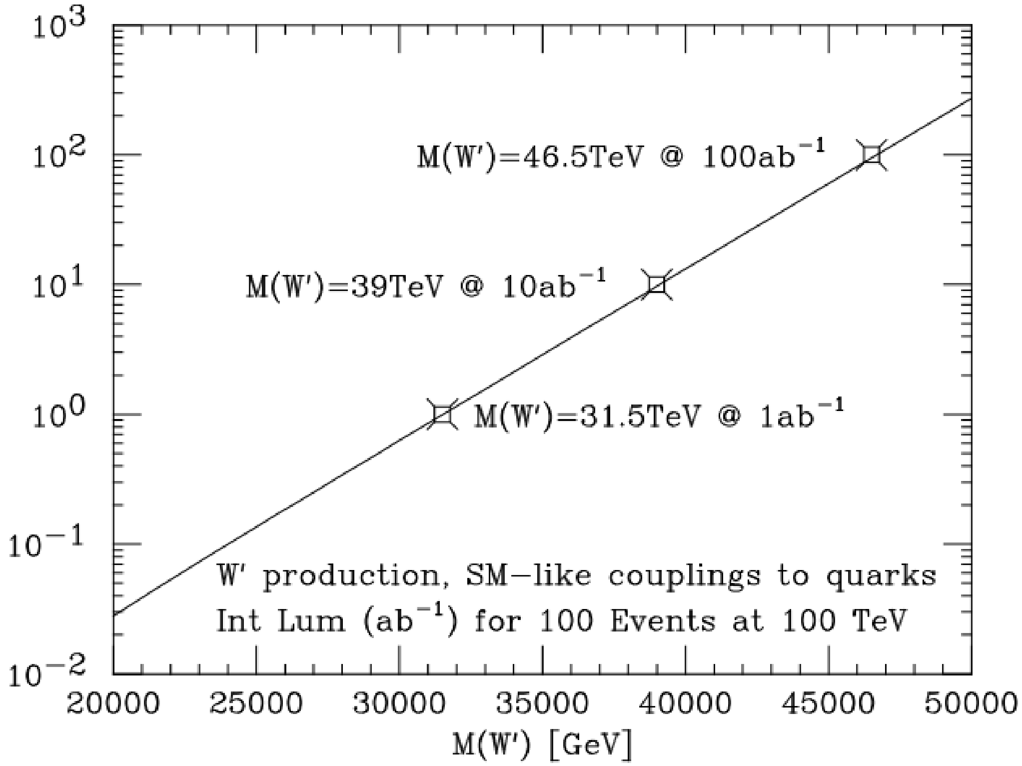
- As long as Standard Model continues to work, “higher energy is better”
- What is the cost *vs* benefit for
  - Higher energy
  - Higher luminosity
  - Energy *vs* Luminosity tradeoff?
- Physics case studies must generate information needed to answer these questions

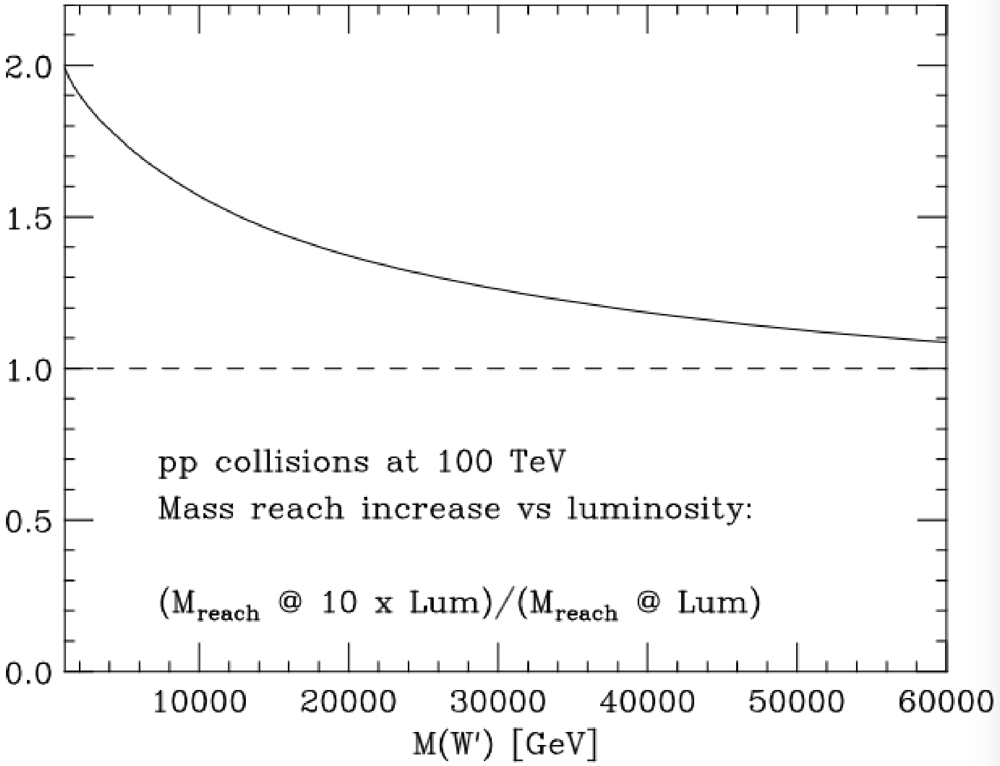
- Naturalness arguments push towards higher masses => higher energy

- Dark Matter, Electroweak Baryogenesis *may* relate to physics at lower masses and smaller couplings
  - Different optimizations of energy and luminosity

Collider Luminosity and Energy

- With 100 TeV collider, 7 TeV increase in mass reach for ten-fold increase in luminosity

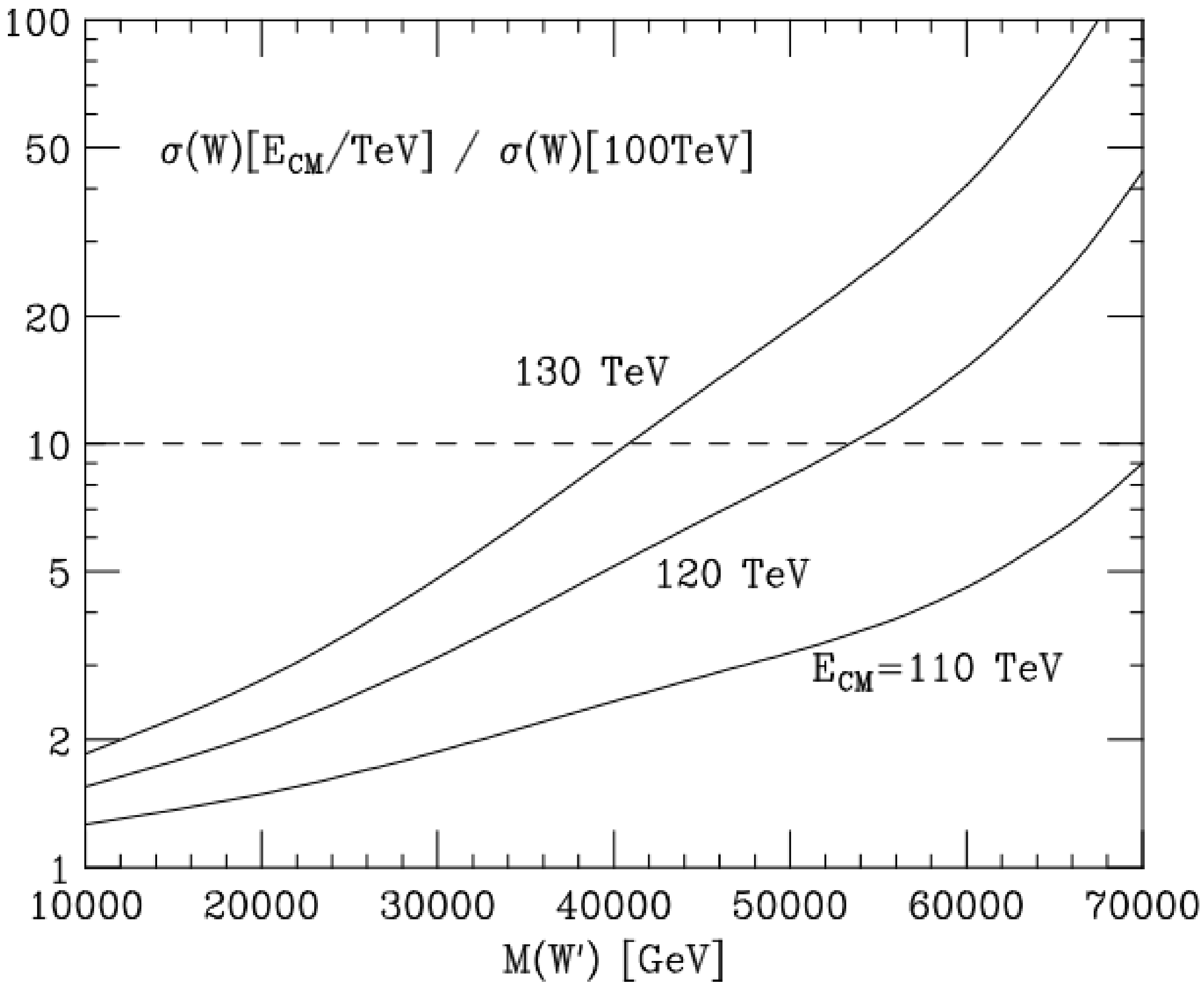




(from M. Mangano)

Collider Luminosity and Energy

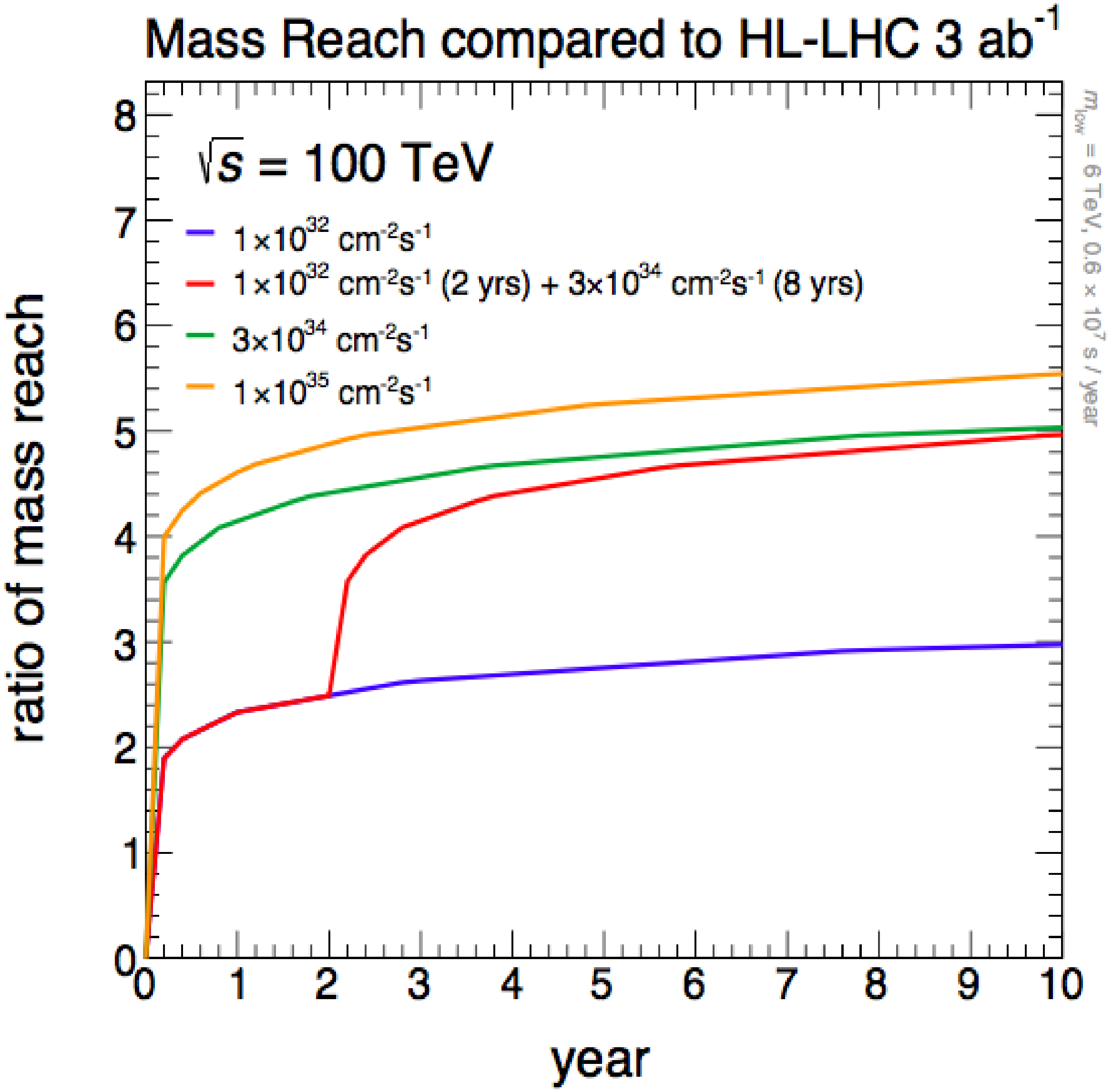
- Collider energy wins rapidly at higher masses



(from M. Mangano)

Collider Luminosity and Energy

- Collider luminosity evolution for high-mass reach



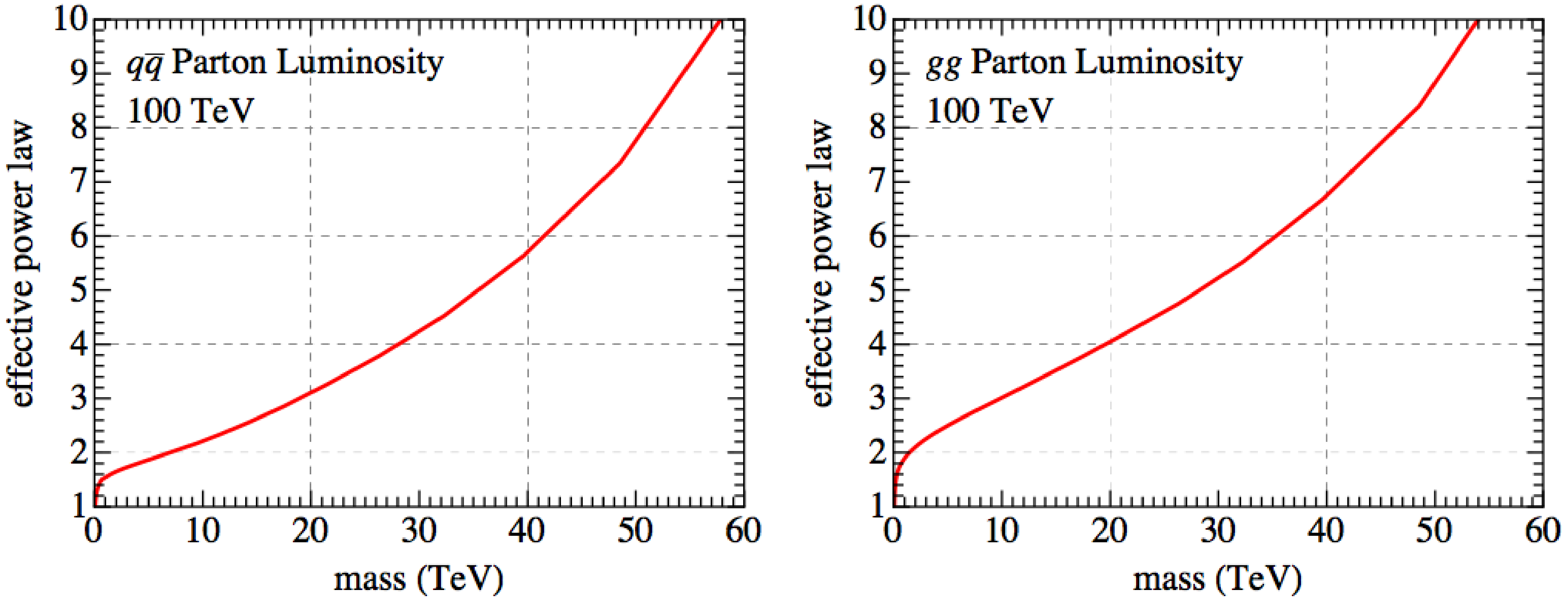
(from L. Wang)

Collider Luminosity and Energy

- Collider luminosity more important for low-mass, low cross-section physics

(from Liantao Wang)

$$\begin{aligned} \sigma &\sim L_{\mathrm{p}} \cdot \hat{\sigma} \\ &\sim \frac{1}{\tau^{a}} \hat{\sigma}, \end{aligned}$$



The dependence of power a on mass scale $M = \sqrt{\hat{s}} = \sqrt{s\tau}$

Detector Goals in a Nutshell

- Maximize A x ε: all detectable particles
  - should be detected 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
- high performance of τ-lepton reconstruction and jet rejection for H → ττ

- 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

Magnetic Tracking

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]:

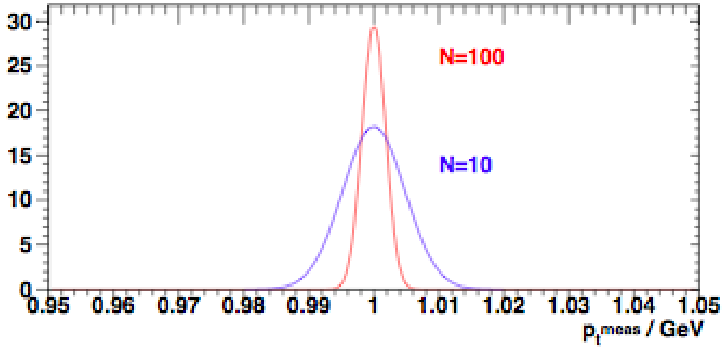
$$\boxed{\frac{\sigma(p_T)}{p_T} = \frac{\sigma(\kappa)}{\kappa} = \frac{\sigma_x \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{(N+4)}}}$$

(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: $\frac{\sigma(p_T)}{p_T^2}$ (%/GeV)

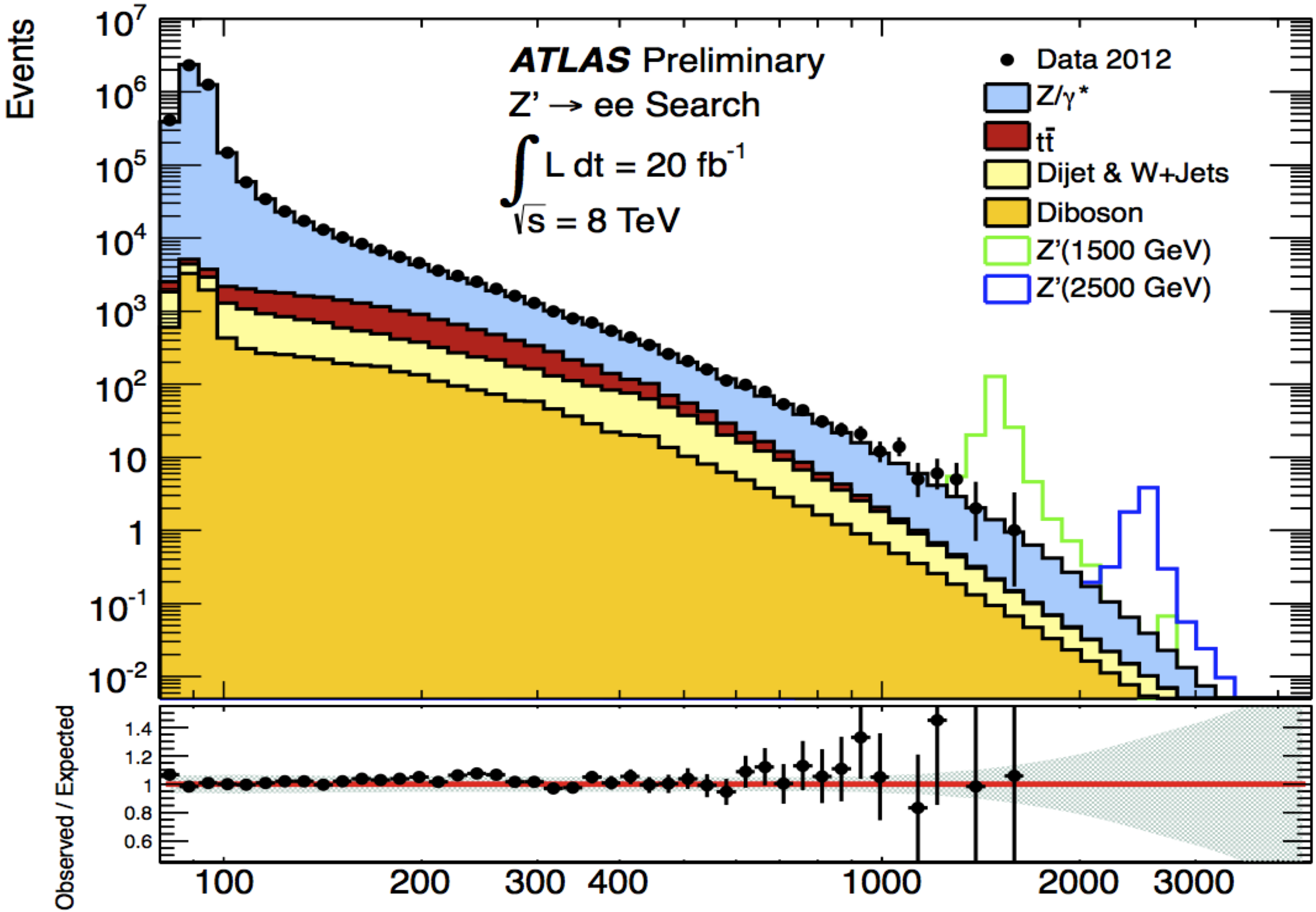


CDF achieved 0.015% with ~90 drift chamber hits, consistent with this example

Thanks to Carsten Niubuhr

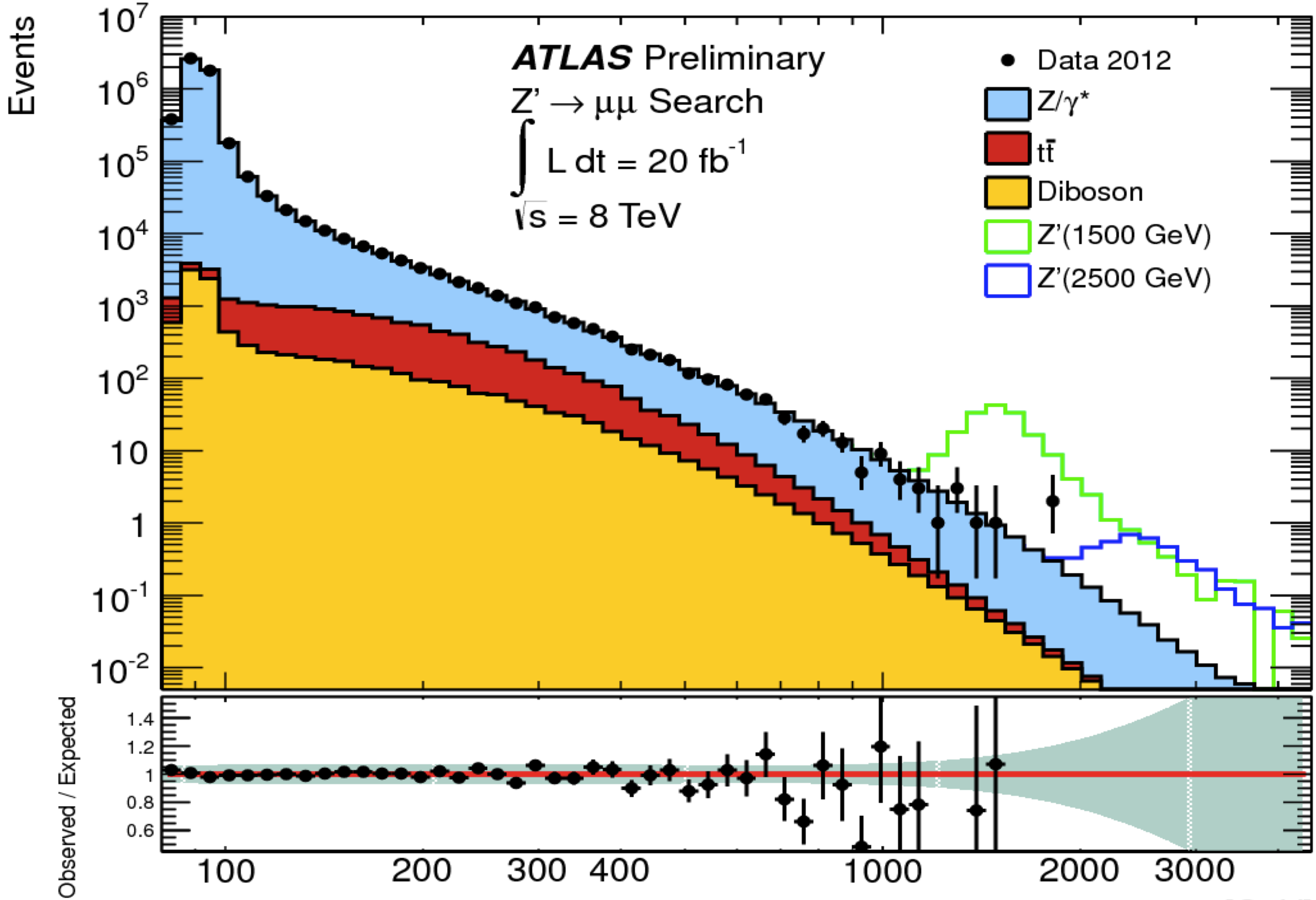
Dielectron Mass Spectrum

Multi-TeV masses probed at LHC



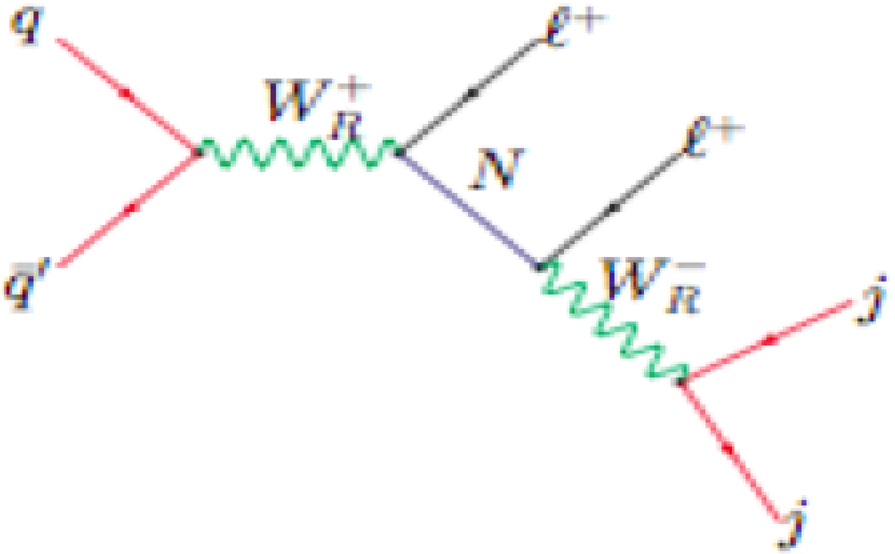
Dimuon Mass Spectrum

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

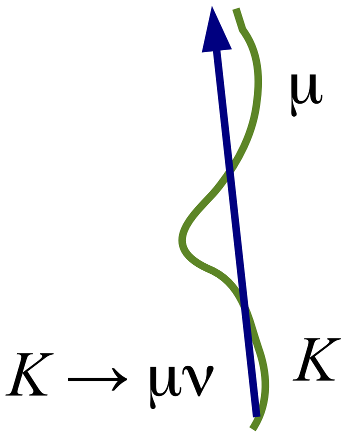
Three tracker/magnet geometries being considered:

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

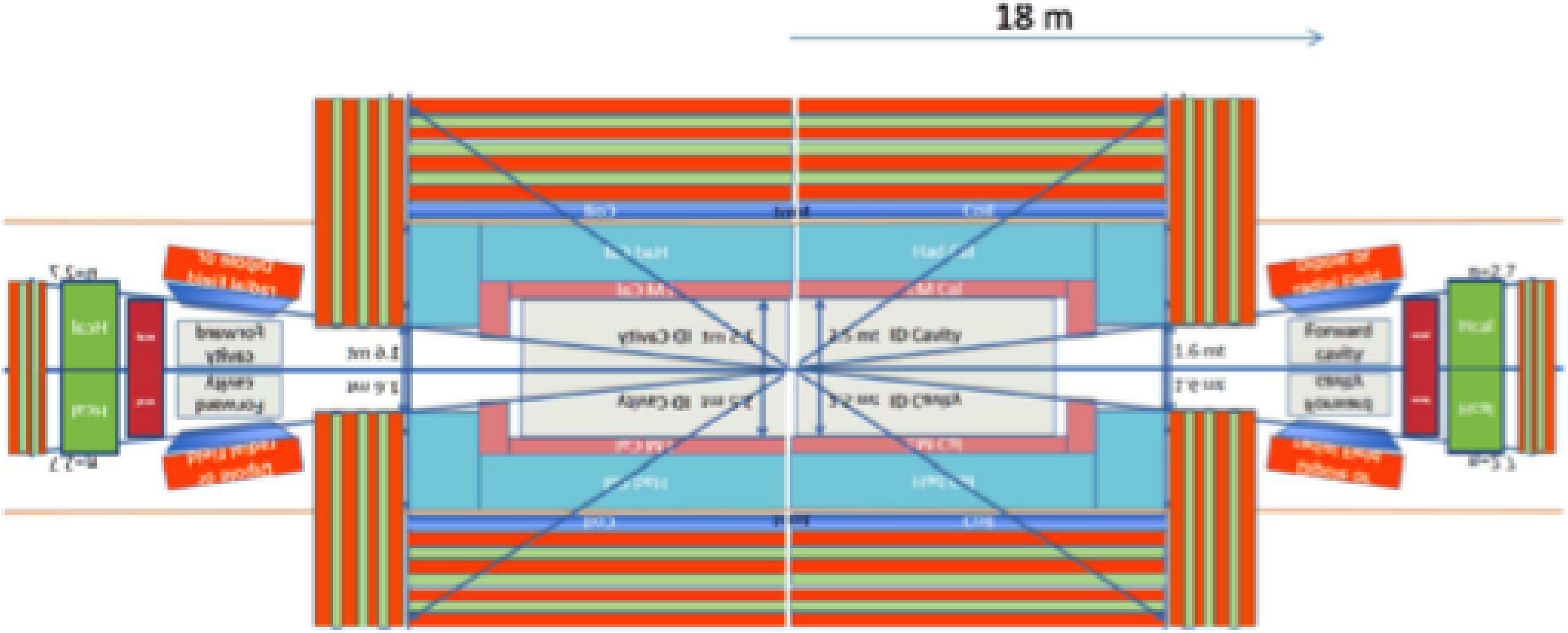
https://indico.fnal.gov/conferenceOtherViews.py?view=standard&confId=7864

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

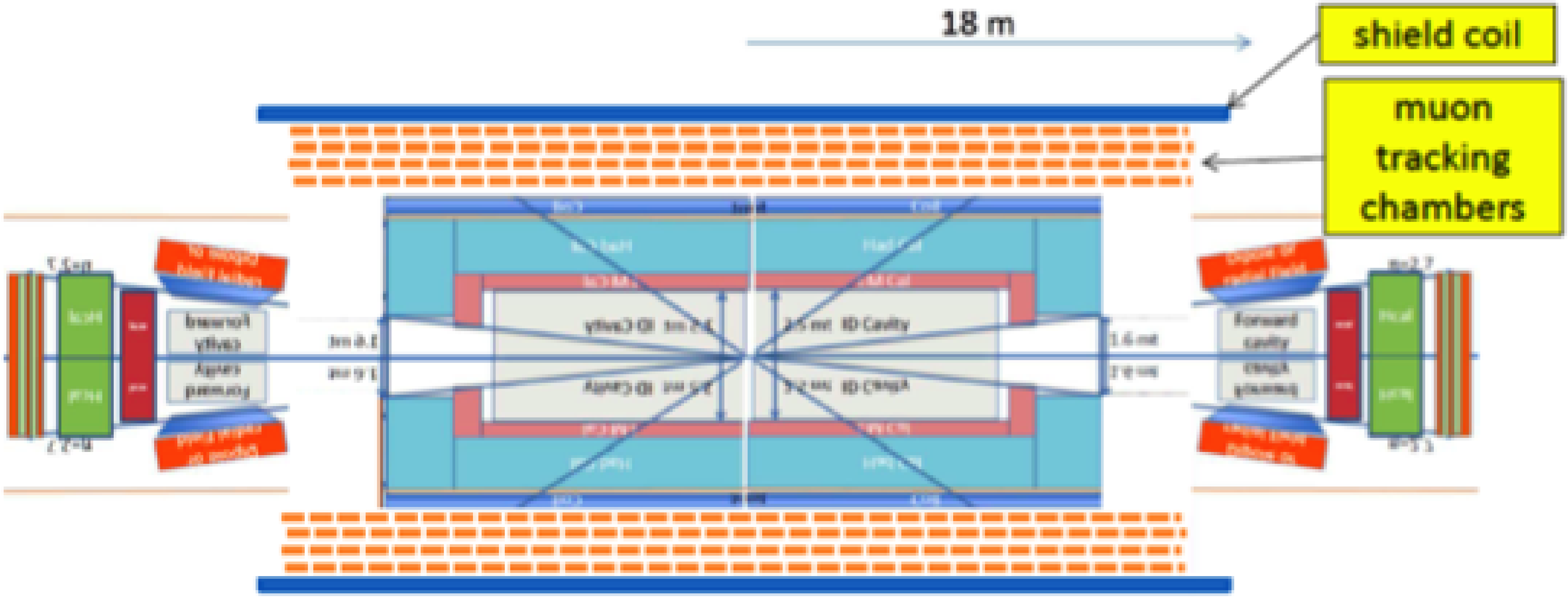


2. Option 1: Solenoid-Yoke + Dipoles (CMS inspired)



- **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

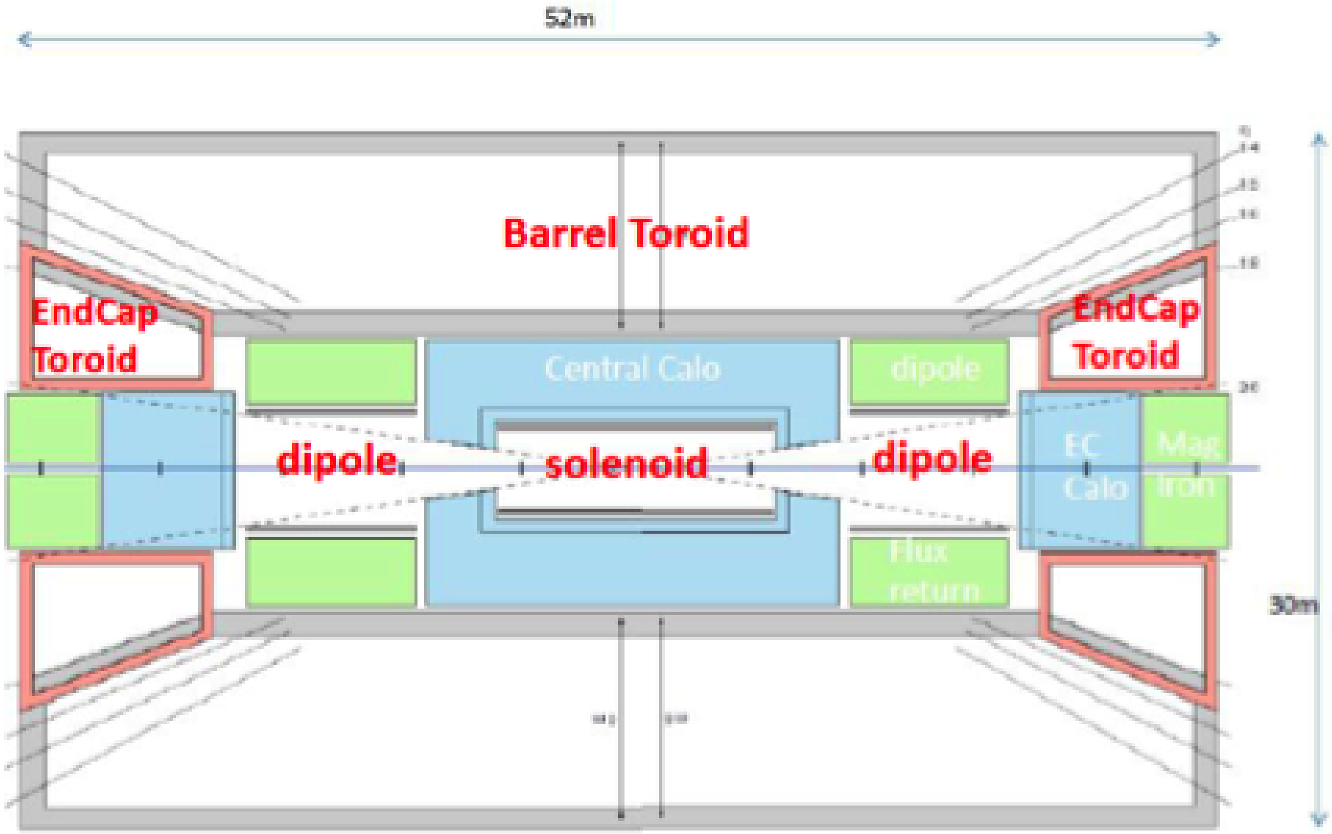


Twin Solenoid: a 6 T, 12 m dia x 23 m long main solenoid + an active shielding coil

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 .

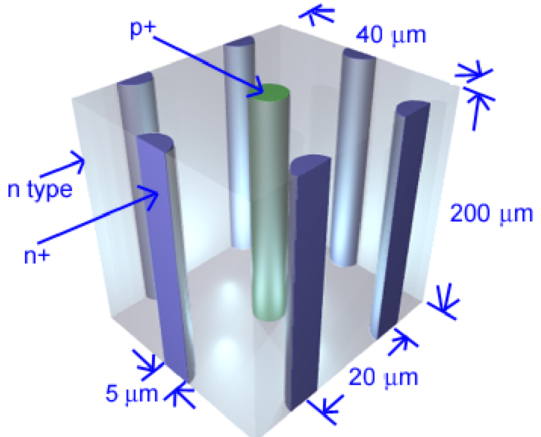
2. Option 3: Toroids + Solenoid + Dipoles (ATLAS +)



- 1 Air core Barrel Toroid with 7 x muon bending power B_zL^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).

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

Calorimeter Geometry Issues

- Conveniences for going to higher energy:
  - Shower depth for full containment grows as log(E)
  - Energy resolution improves as √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
      - τ2ΘϳMΠΛKO 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

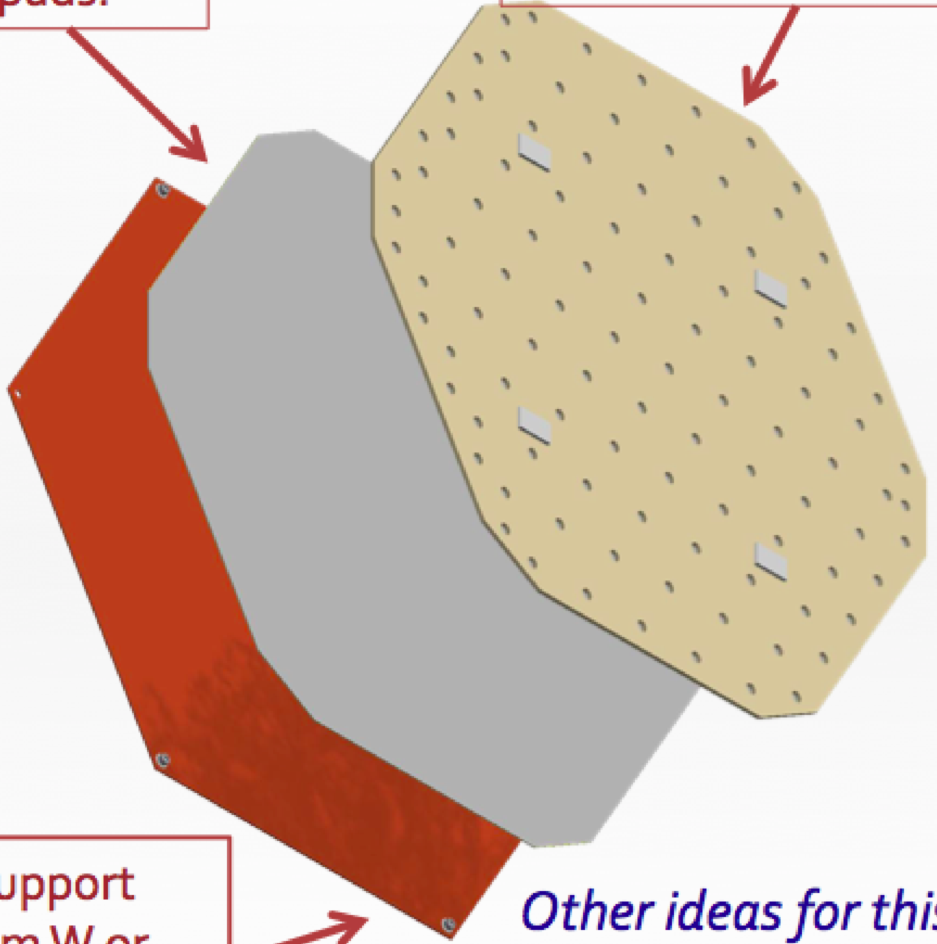
Proposal – Silicon High Granularity Calorimeter

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



Silicon sensor with hexagonal pads.

PCB with through-holes for wirebonds.

Baseplate for mechanical support during handling – made from W or W/Cu matching CTE of silicon.

Other ideas for this are under study.

Thanks to R. Rusack, ECFA 2014

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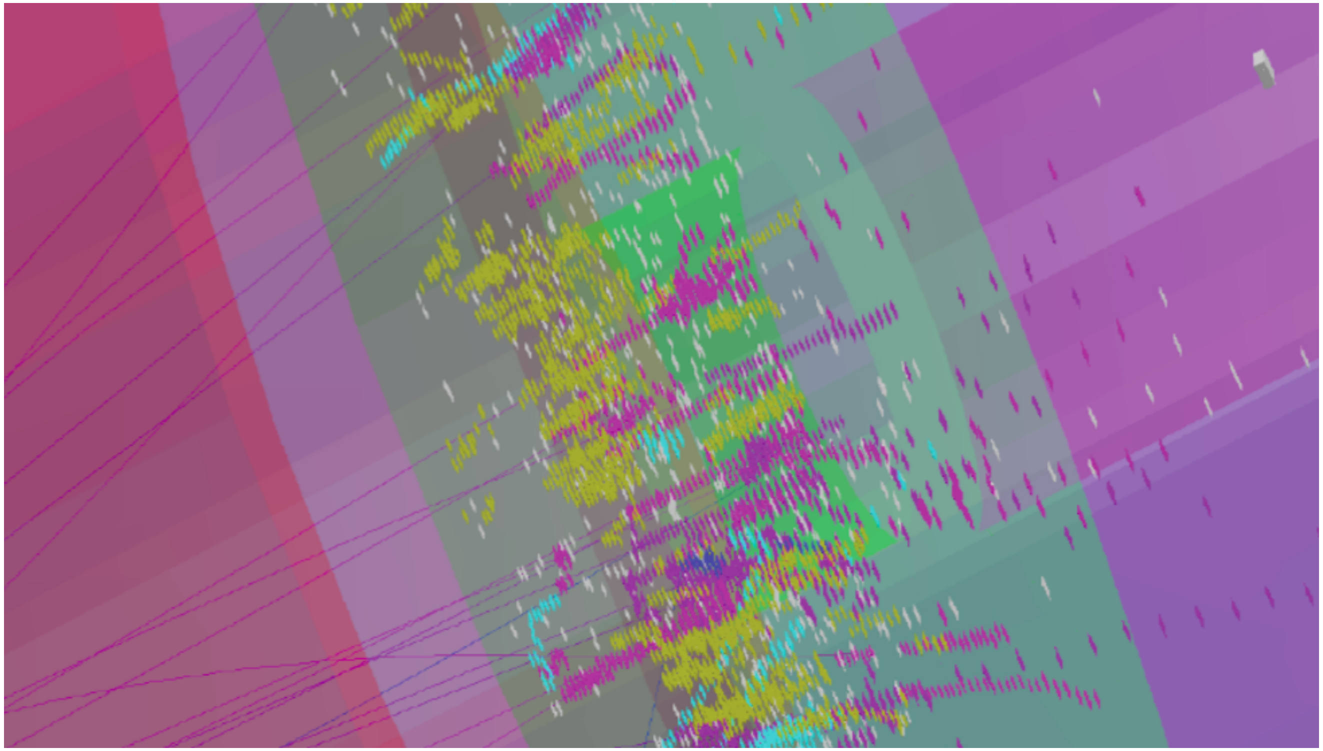
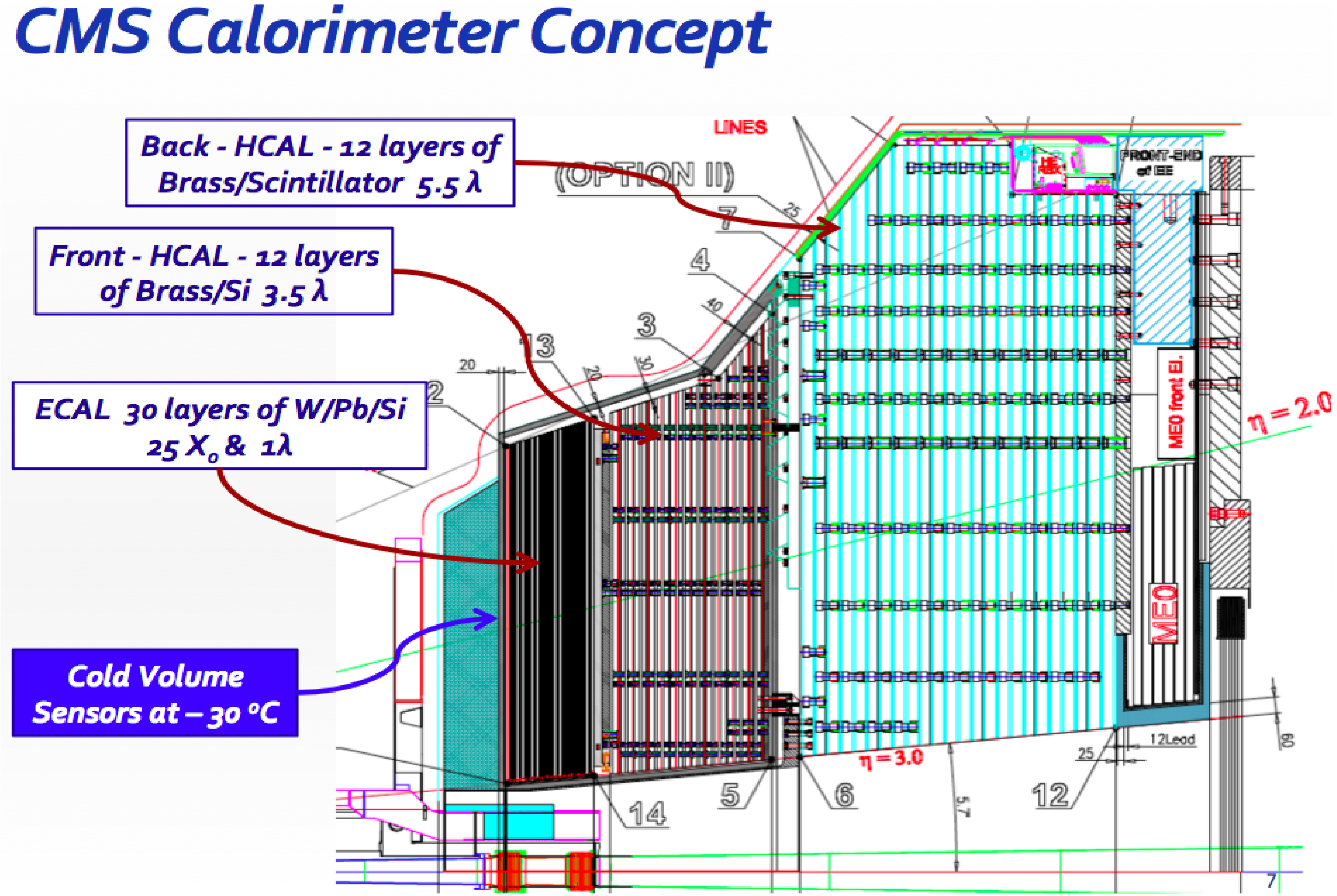


Thanks to R. Rusack, ECFA 2014

Proposal – Si-HGC for CMS Endcap



CMS Calorimeter Concept

Back - HCAL - 12 layers of Brass/Scintillator 5.5 λ

Front - HCAL - 12 layers of Brass/Si 3.5 λ

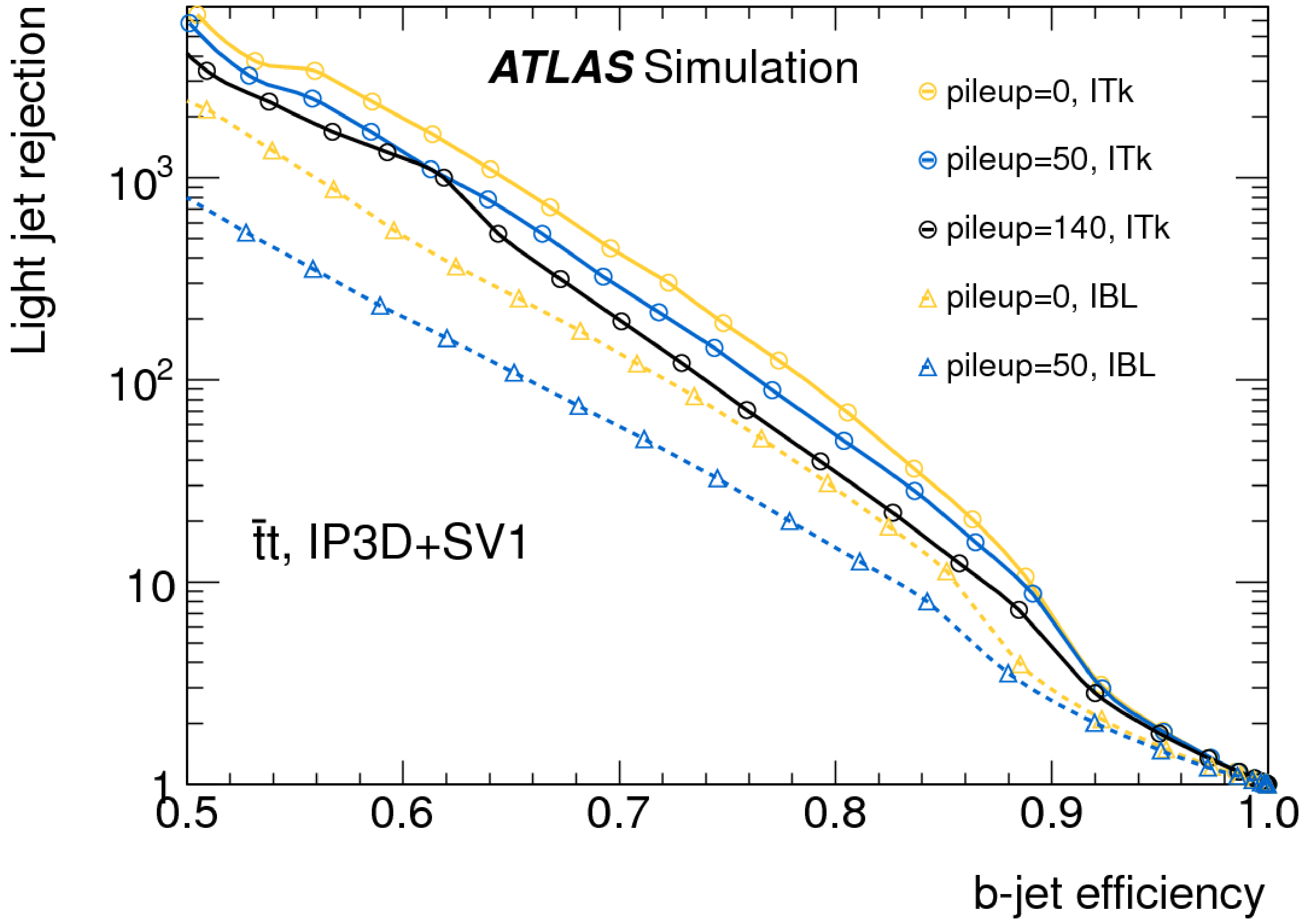
ECAL 30 layers of W/Pb/Si 25 X_0 & 1λ

Cold Volume Sensors at – 30 °C

Thanks to R. Rusack, ECFA 2014

b-tagging

Design Performance for HL-LHC



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

Forward rapidity coverage

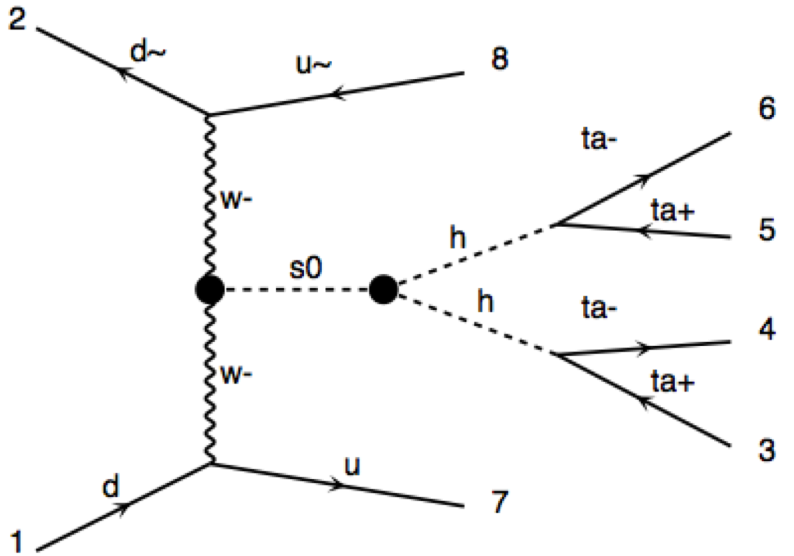
Why is the Higgs Boson So Light?

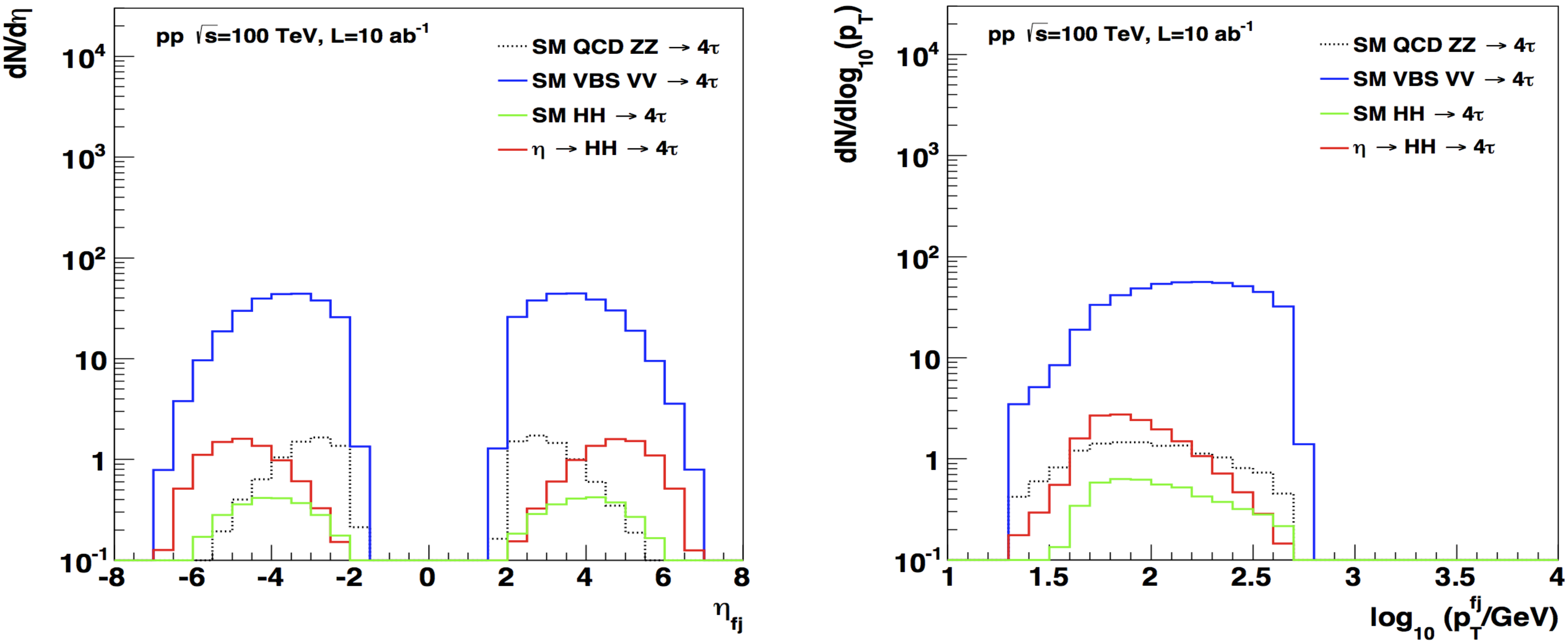
- Old idea: Higgs doublet (4 fields) is a Goldstone mode generated from the spontaneous breaking of a larger global symmetry
  - Higgs boson and W_L, Z_L are all Goldstone bosons from, eg. Spontaneously breaking global $SO(5) \rightarrow SO(4)$
  - Examples: Holographic Higgs, Little Higgs models...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

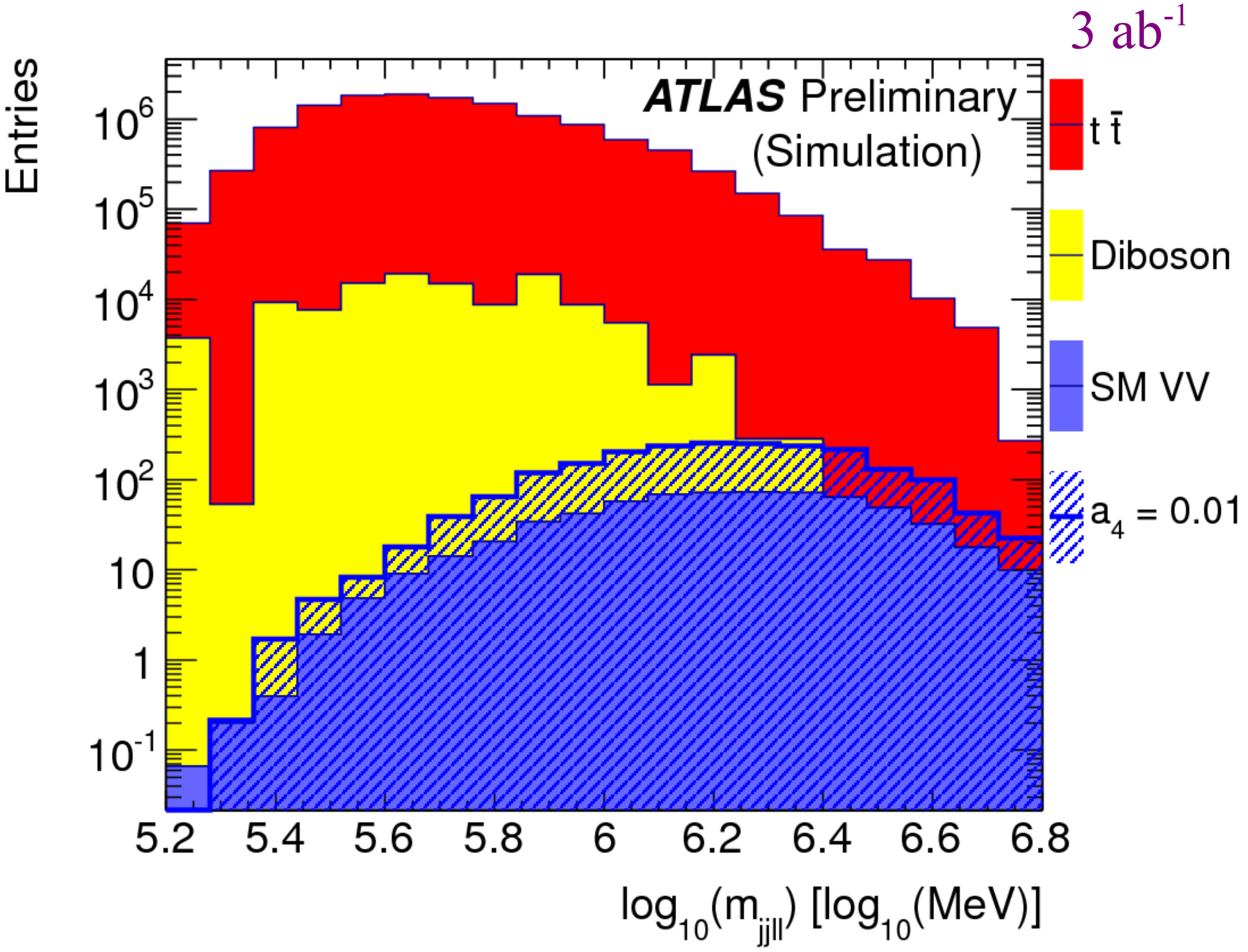
Vector Boson Scattering

(AK, Chekanov & Low, arXiv:1504.08042)





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

Summary of Fermilab/USA Study Group Activities

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) – accepted in PRD

- Biweekly Seminar + Brainstorming Session Friday 2 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)

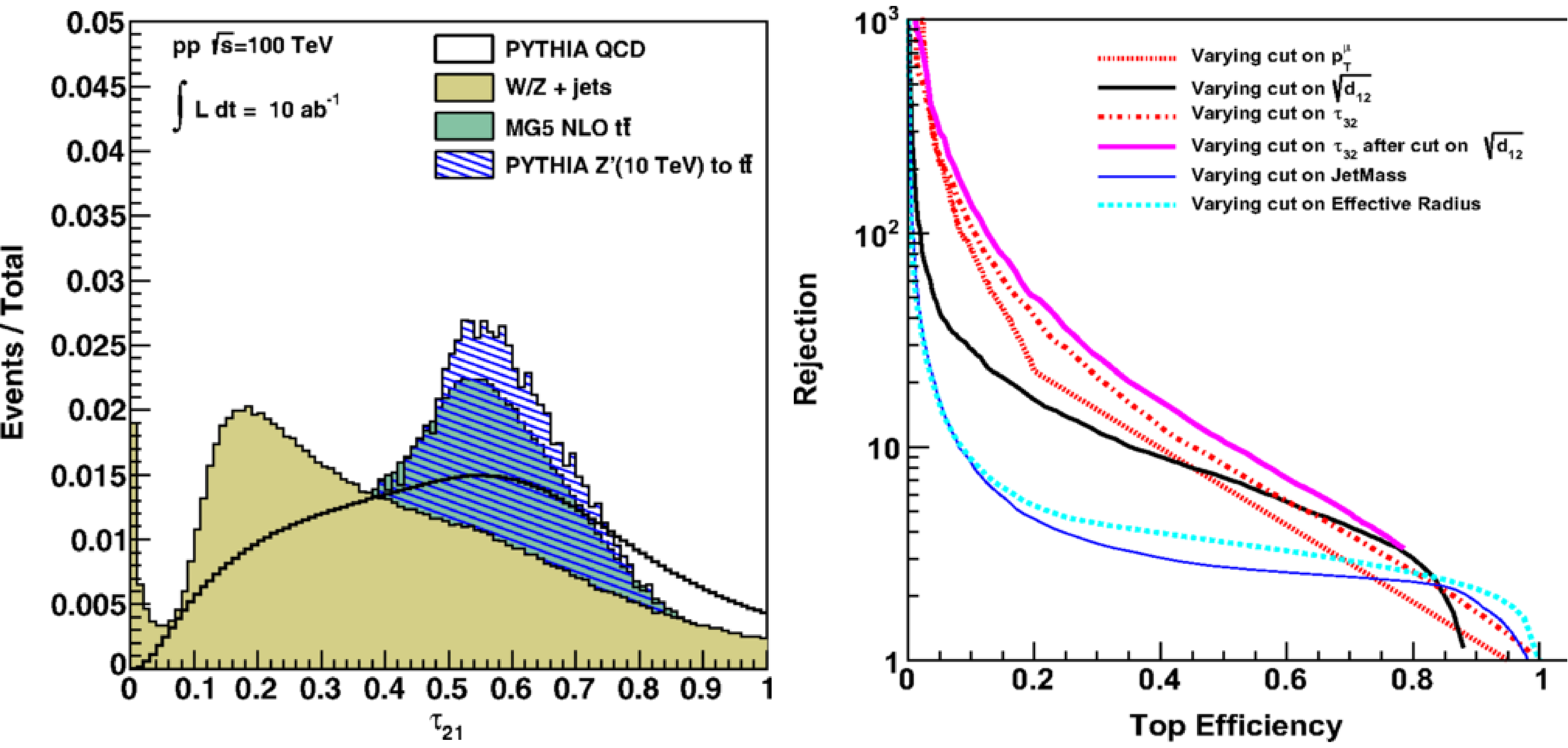
Physics Case and Detector Goals

- 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, 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
    - "how to convert ATLAS / CMS analysis into VHEPP study over the weekend"
    - Additional paper and visibility with only 10% more work !

Granularity Requirements for Boosted Top Quarks

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

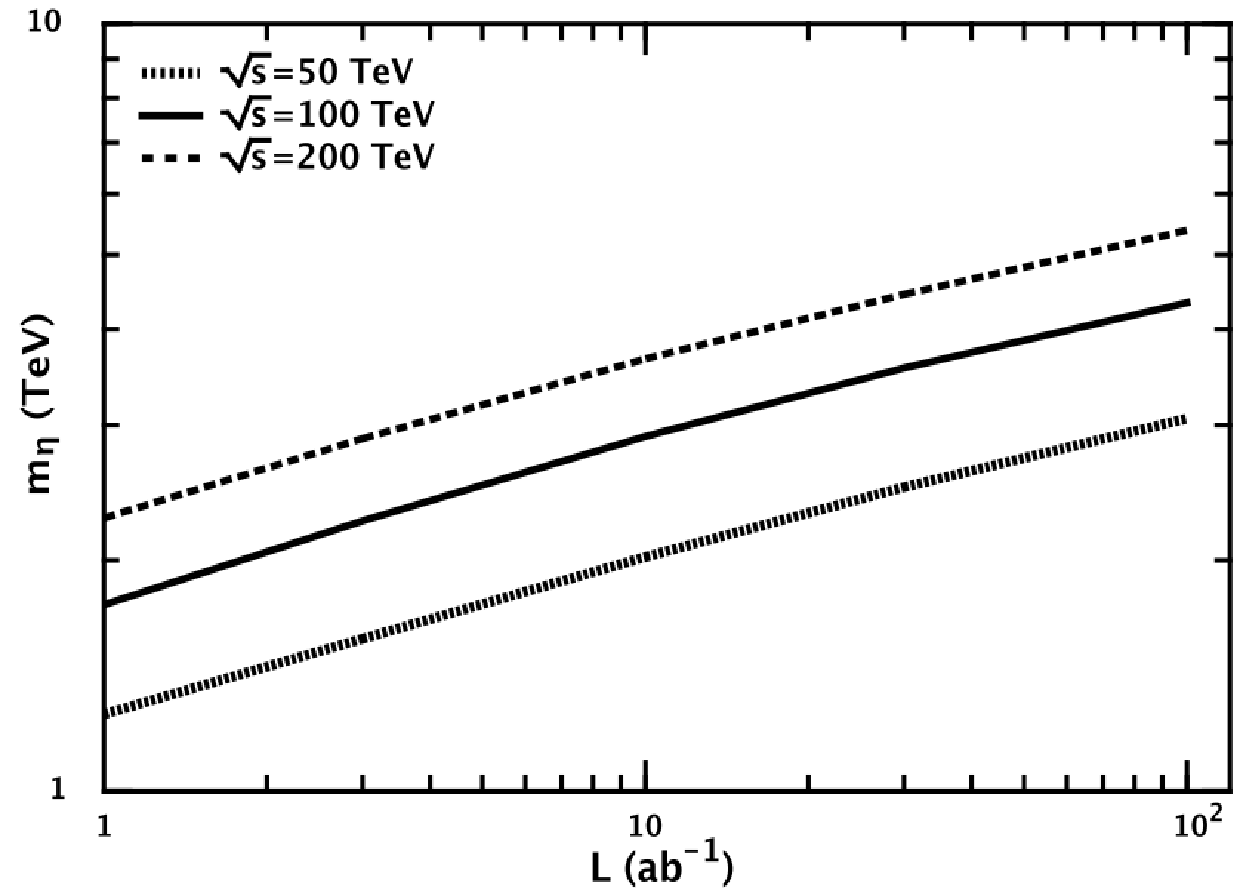
B. Auerbach, S. Chekanov, J. Love, J. Proudfoot, and A. V. Kotwal
Phys. Rev. D **91**, 034014 – Published 17 February 2015



Forward Jet Coverage for Longitudinal VBS

$V_L V_L \rightarrow$ eta $\rightarrow$ HH

M. Low,
S. Chekanov,
AVK



5sigma discovery mass reach

Forward Jet Coverage for Longitudinal VBS

$V_L V_L$ →eta→ HH

M. Low, S. Chekanov, AVK

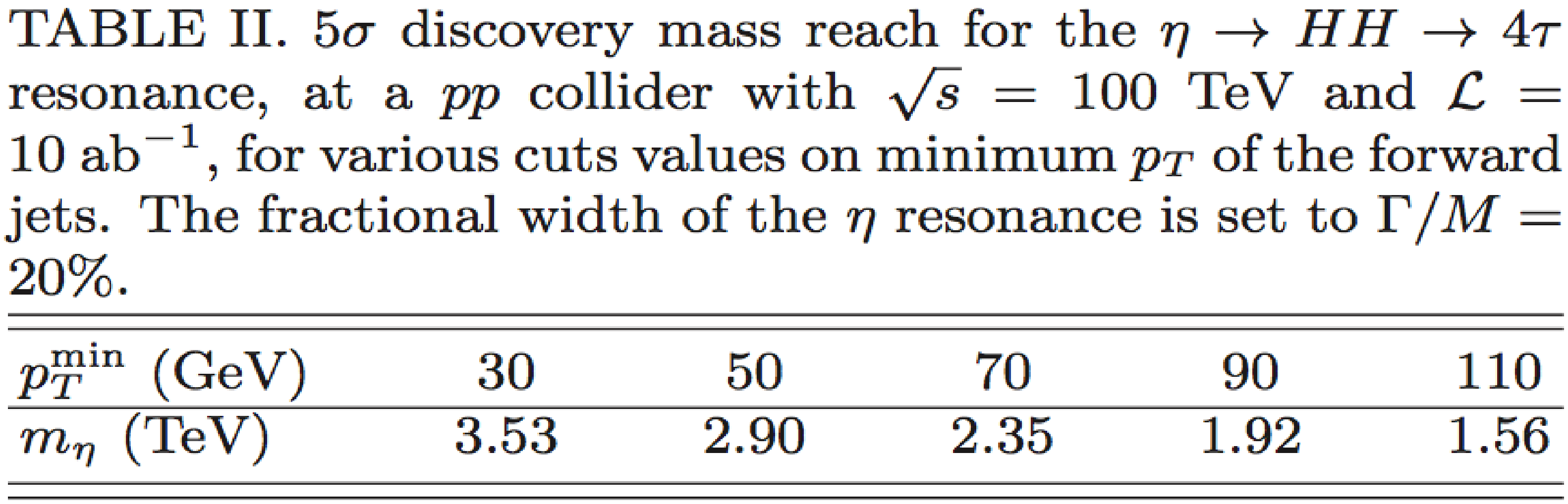


TABLE II. 5σ discovery mass reach for the $\eta \to HH \to 4\tau$ resonance, at a pp collider with $\sqrt{s} = 100$ TeV and $\mathcal{L} = 10\ \text{ab}^{-1}$, for various cuts values on minimum p_T of the forward jets. The fractional width of the η resonance is set to $\Gamma/M = 20\%$.

$p_T^{\min}$ (GeV)	30	50	70	90	110
m_η (TeV)	3.53	2.90	2.35	1.92	1.56

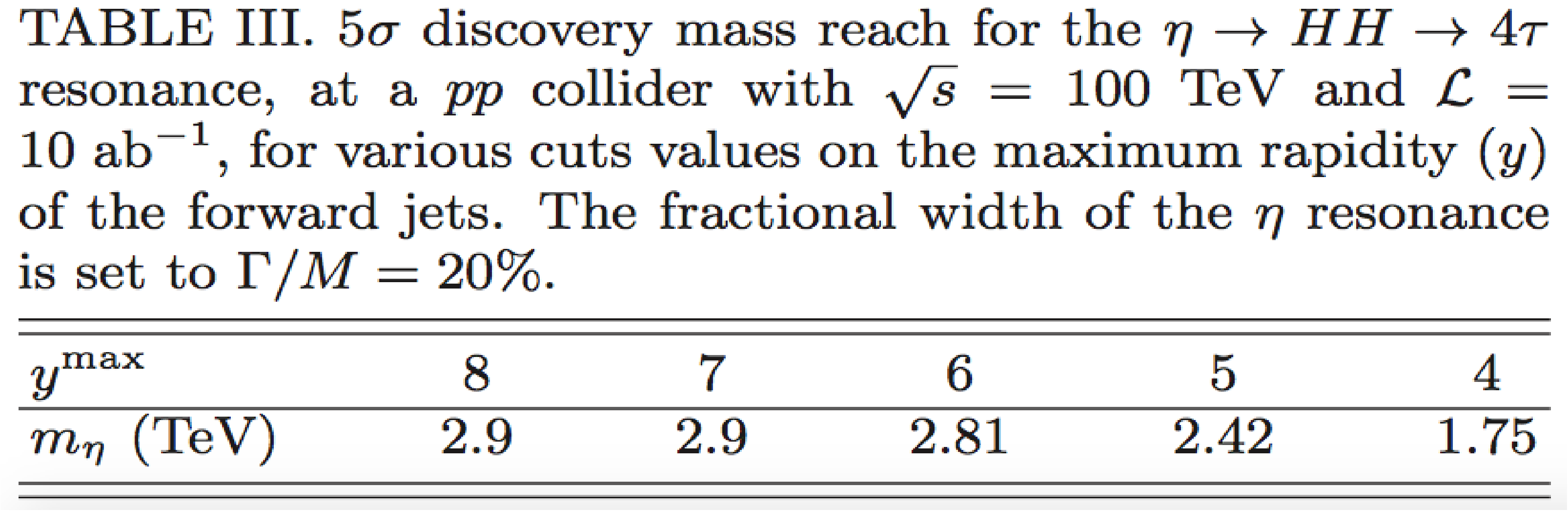


TABLE III. 5σ discovery mass reach for the $\eta \to HH \to 4\tau$ resonance, at a pp collider with $\sqrt{s} = 100$ TeV and $\mathcal{L} = 10\ \text{ab}^{-1}$, for various cuts values on the maximum rapidity (y) of the forward jets. The fractional width of the η resonance is set to $\Gamma/M = 20\%$.

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

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:
  - Fermilab work with GEANT simulations
    - 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

Magnet Technology

- US contributions to superconducting magnets have been world-leading
  - Tevatron, SSC → LHC

- Niobium-Titanium going to Niobium-Tin for higher field

- Fermilab has 11 Tesla accelerator-quality magnet 1m long

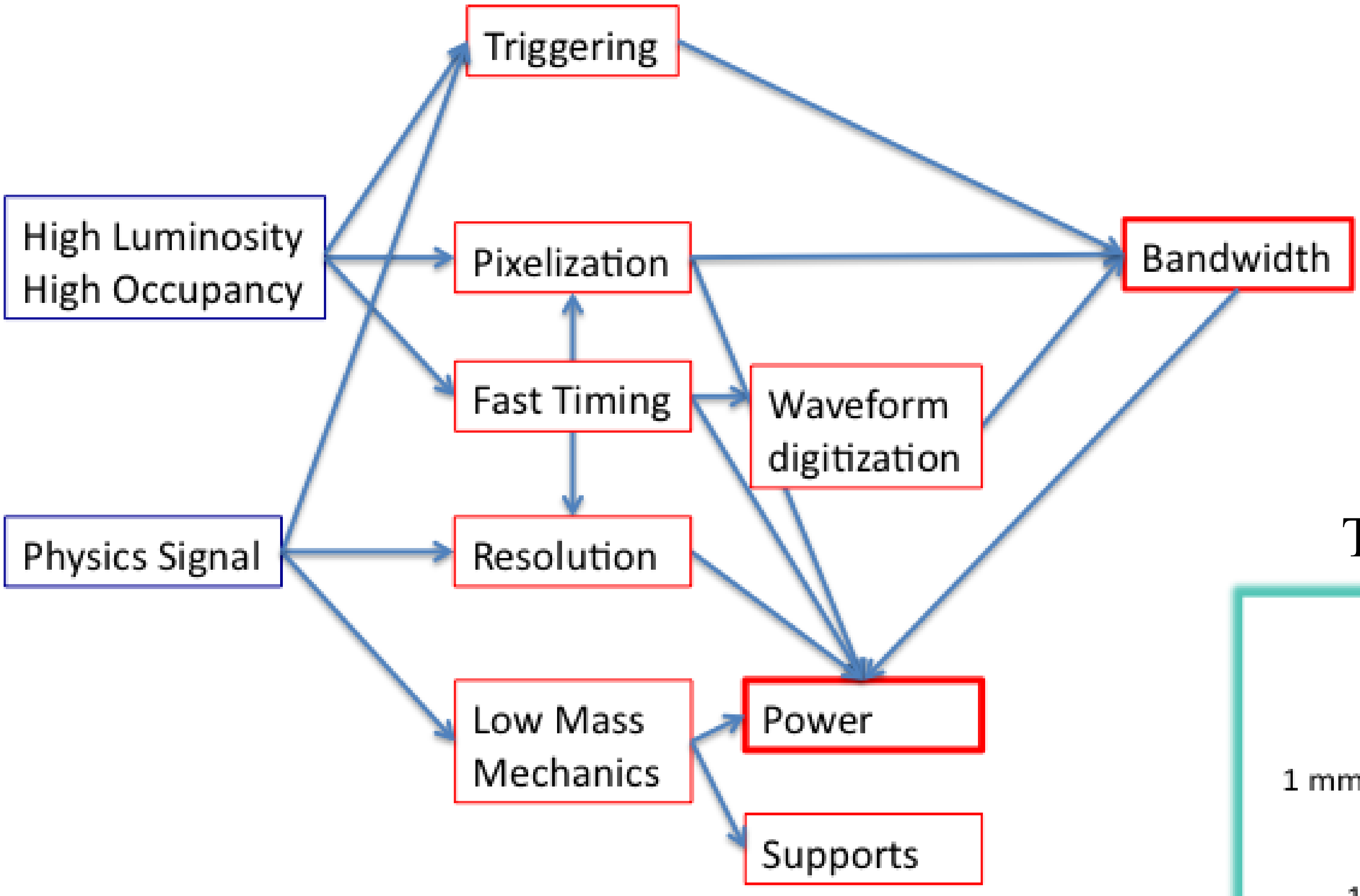
- LARP program going to provide Niobium-Titanium based quadrupoles for HL-LHC

- General Accelerator R&D (GARD) Panel of DOE recommends
  - Superconducting RF advances
  - High-field magnet advances
  - ...

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
  - Prepare studies with “definitive” physics deliverables – discoverable or excludable scenarios of Dark Matter, Electroweak Baryogenesis, others?
- Detectors will need to be more capable on all fronts
  - Faster
  - Much higher granularity
  - Much higher resolution
  - Much more forward-detection capability
  - Much higher bandwidth, smarter triggers
- Substantial knowledge & experience on detector design will be gained from HL-LHC upgrade

Whole Picture – The Drivers



High Luminosity
High Occupancy

Physics Signal

Triggering

Pixelization

Fast Timing

Resolution

Low Mass
Mechanics

Waveform
digitization

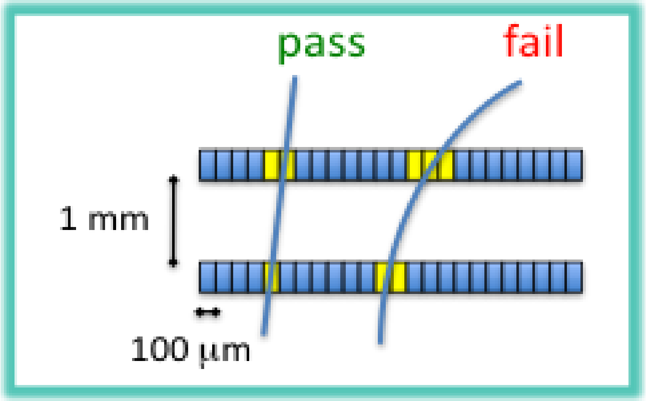
Bandwidth

Power

Supports

R. Lipton

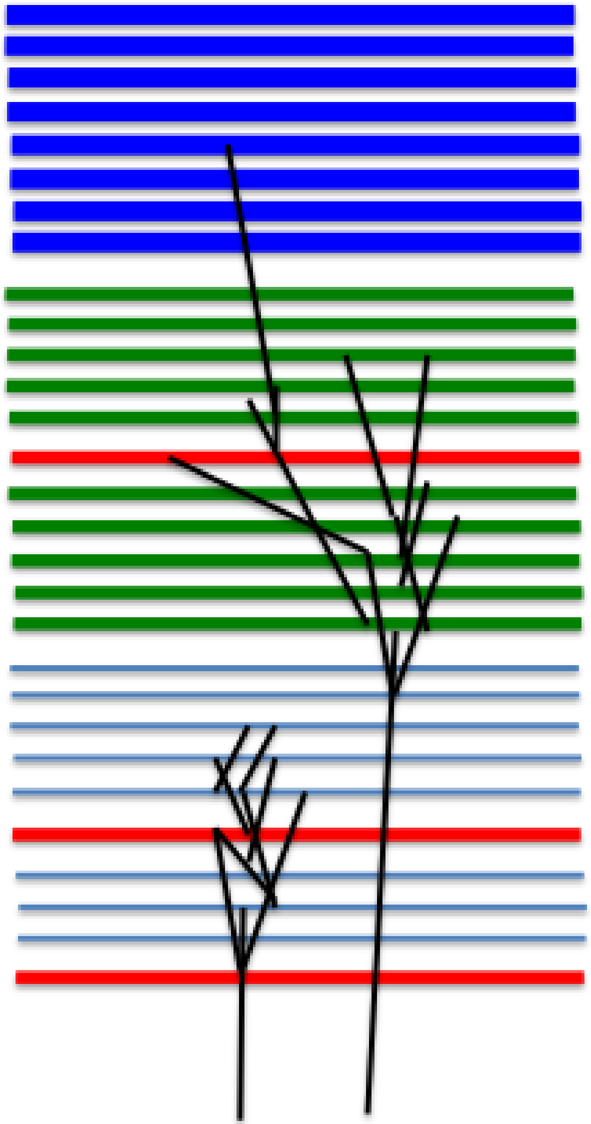
Track triggering



Radiation damage:

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

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



Muon+ Tail Catcher

Hadron Calorimeter

Hadron Shower Max Timing

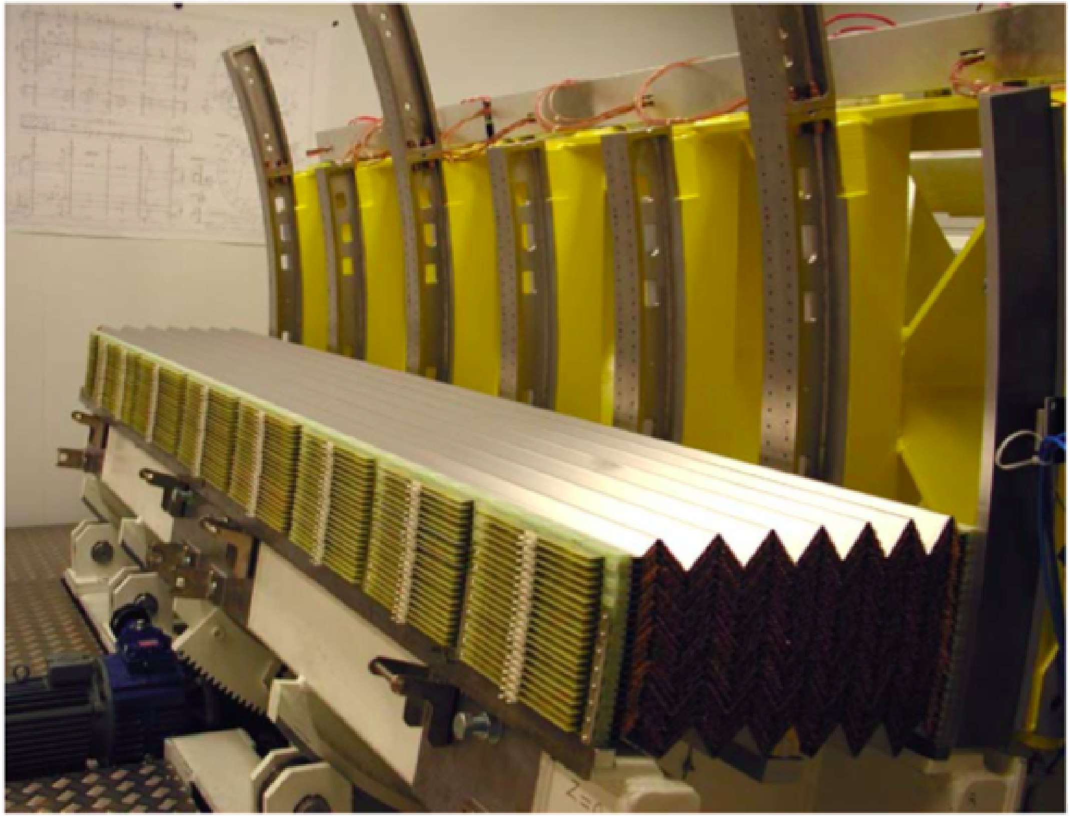
EM Calorimeter

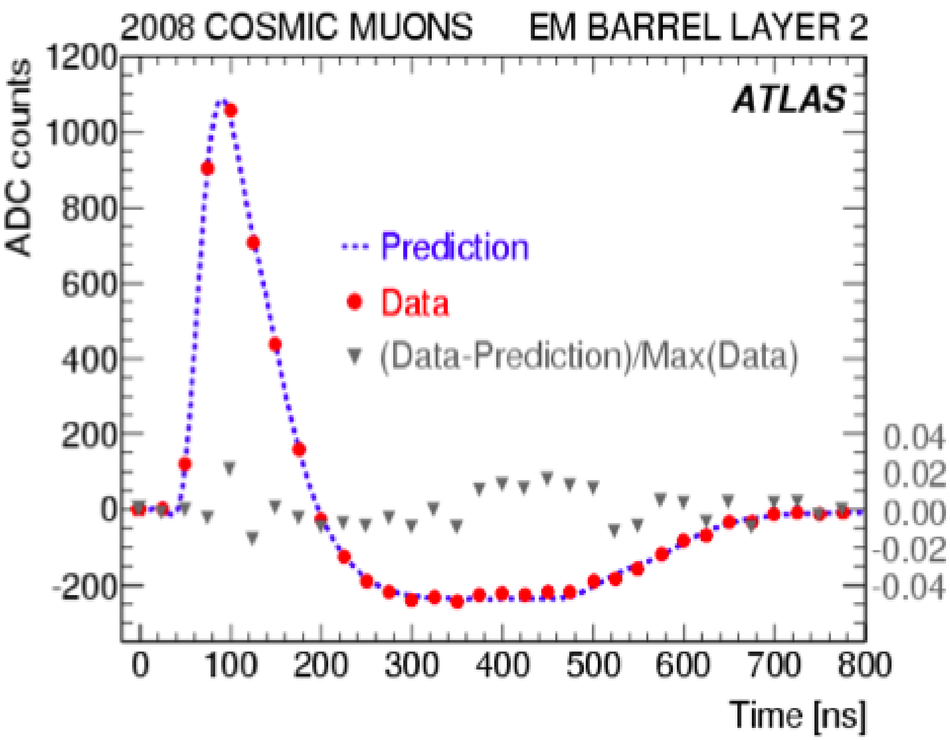
EM Shower Max Timing

Pre-shower / TOF

Eric Ramberg, Fermilab Workshop talk

Accordion Sampling Calorimeter



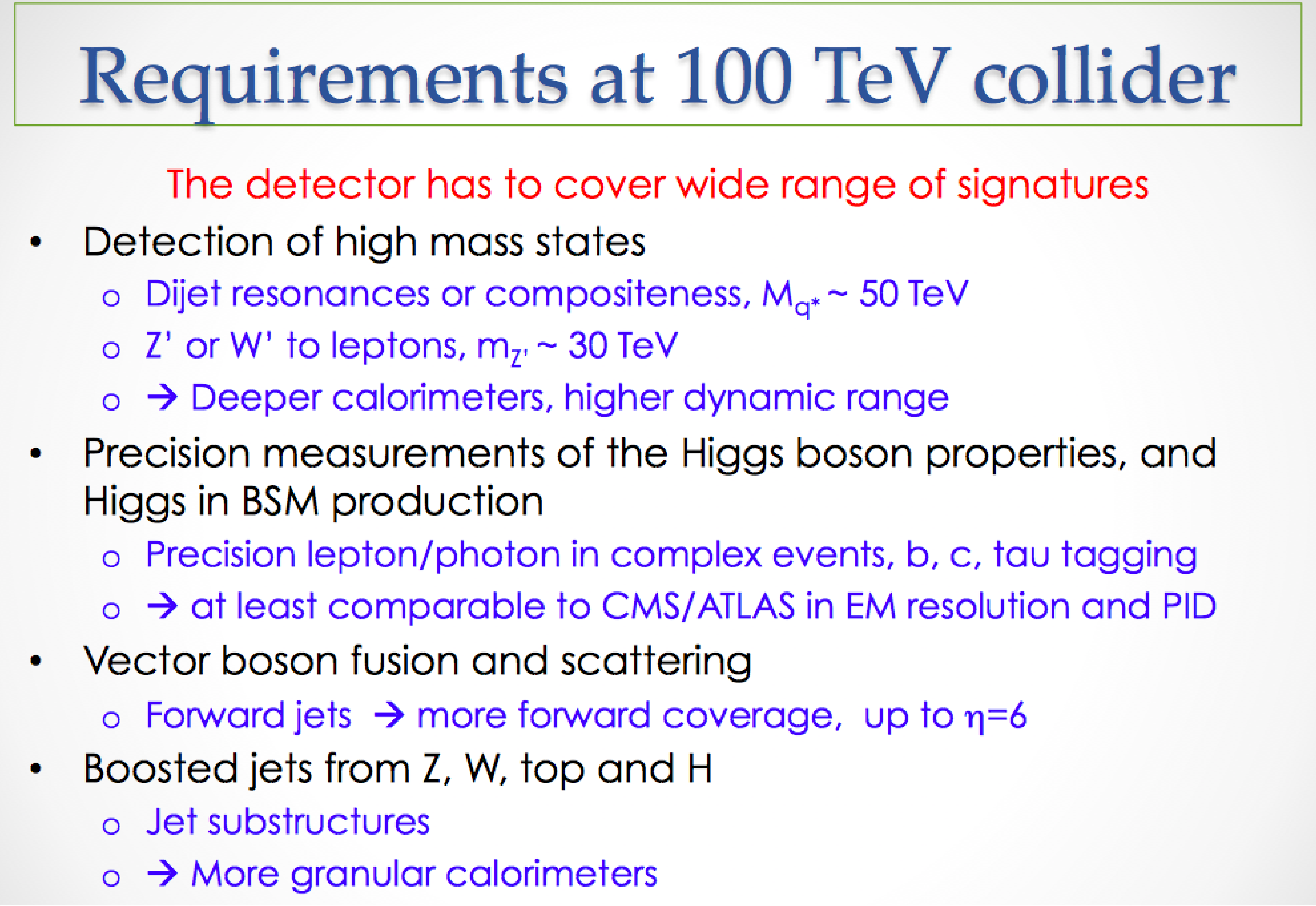


ATLAS L-Ar accordion calorimeter allows fast pulse-shaping

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



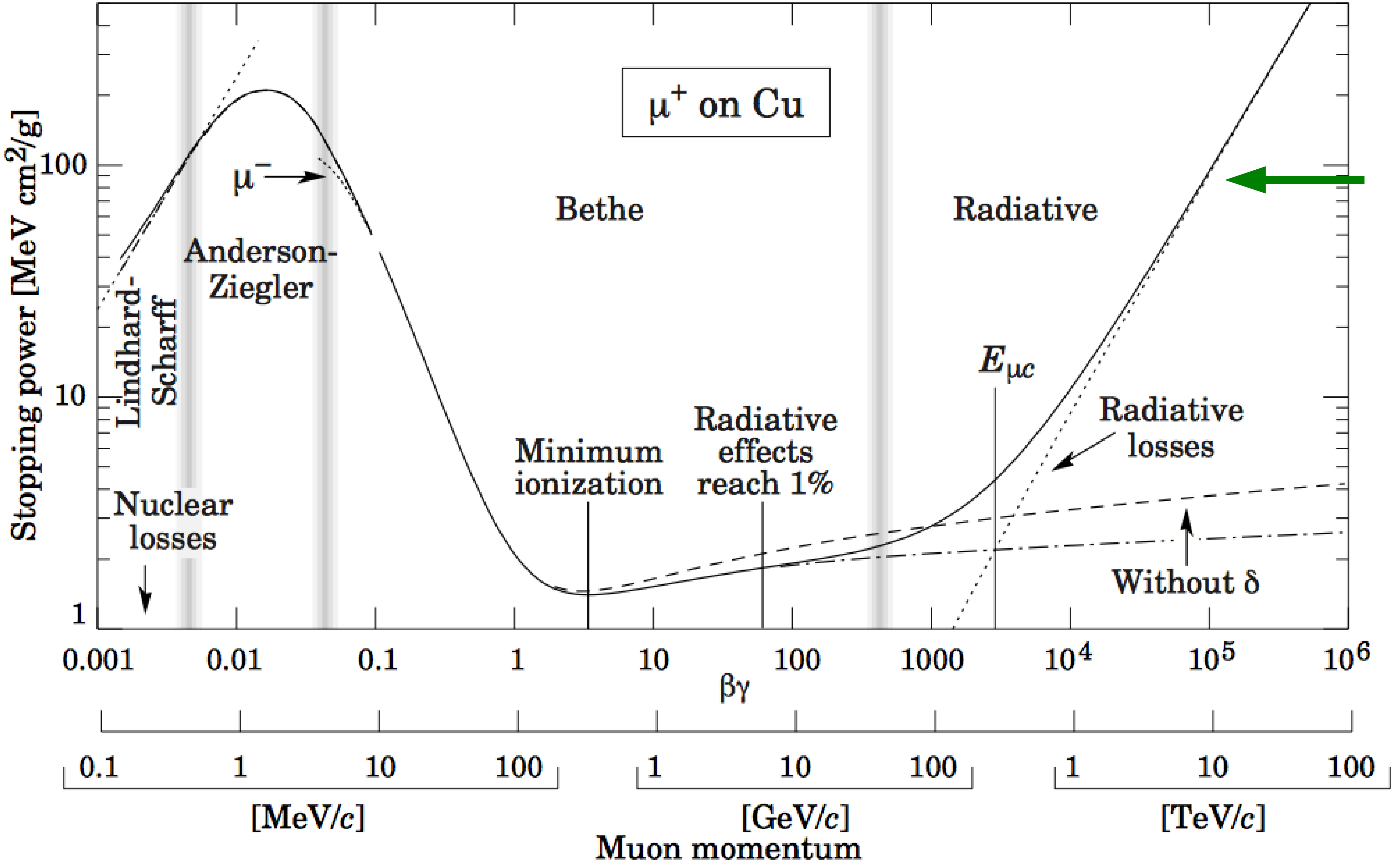
Requirements at 100 TeV collider

The detector has to cover wide range of signatures

- Detection of high mass states
  - Dijet resonances or compositeness, M_{q^*} ~ 50 TeV
  - Z' or W' to leptons, $m_{Z'}$ ~ 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

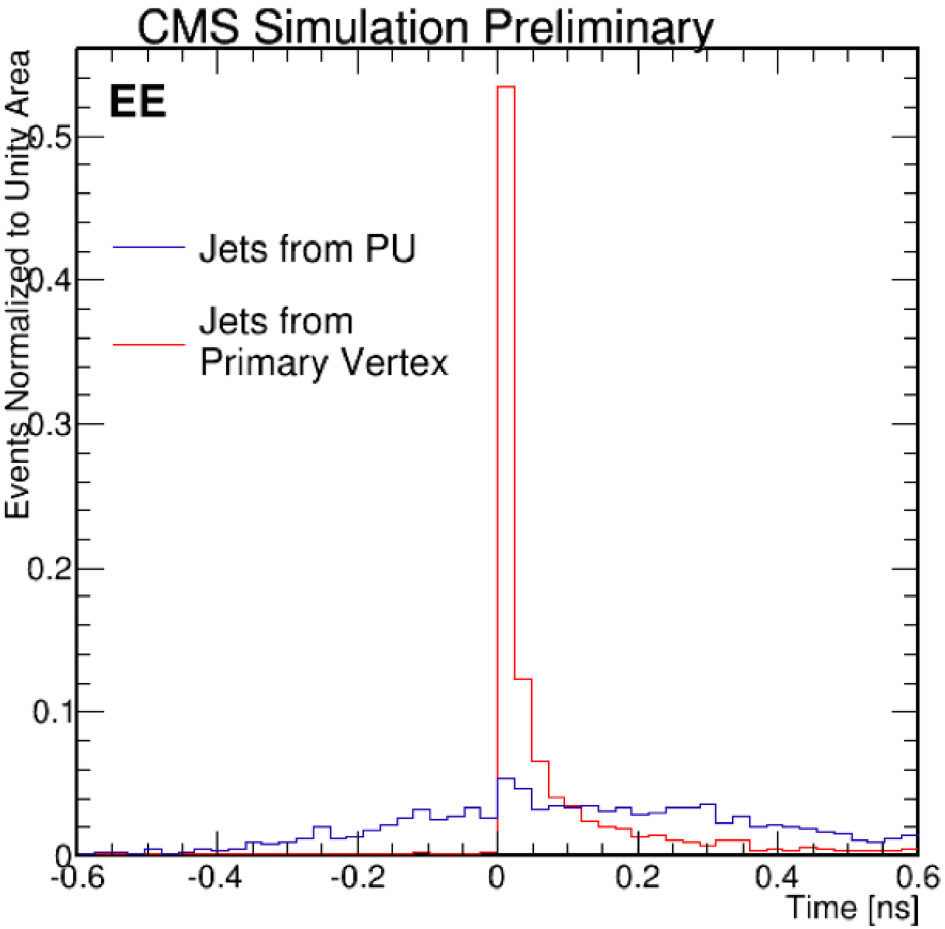
High Energy Muon Bremsstrahlung



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

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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