Physics and Experiments at Future *pp* Colliders

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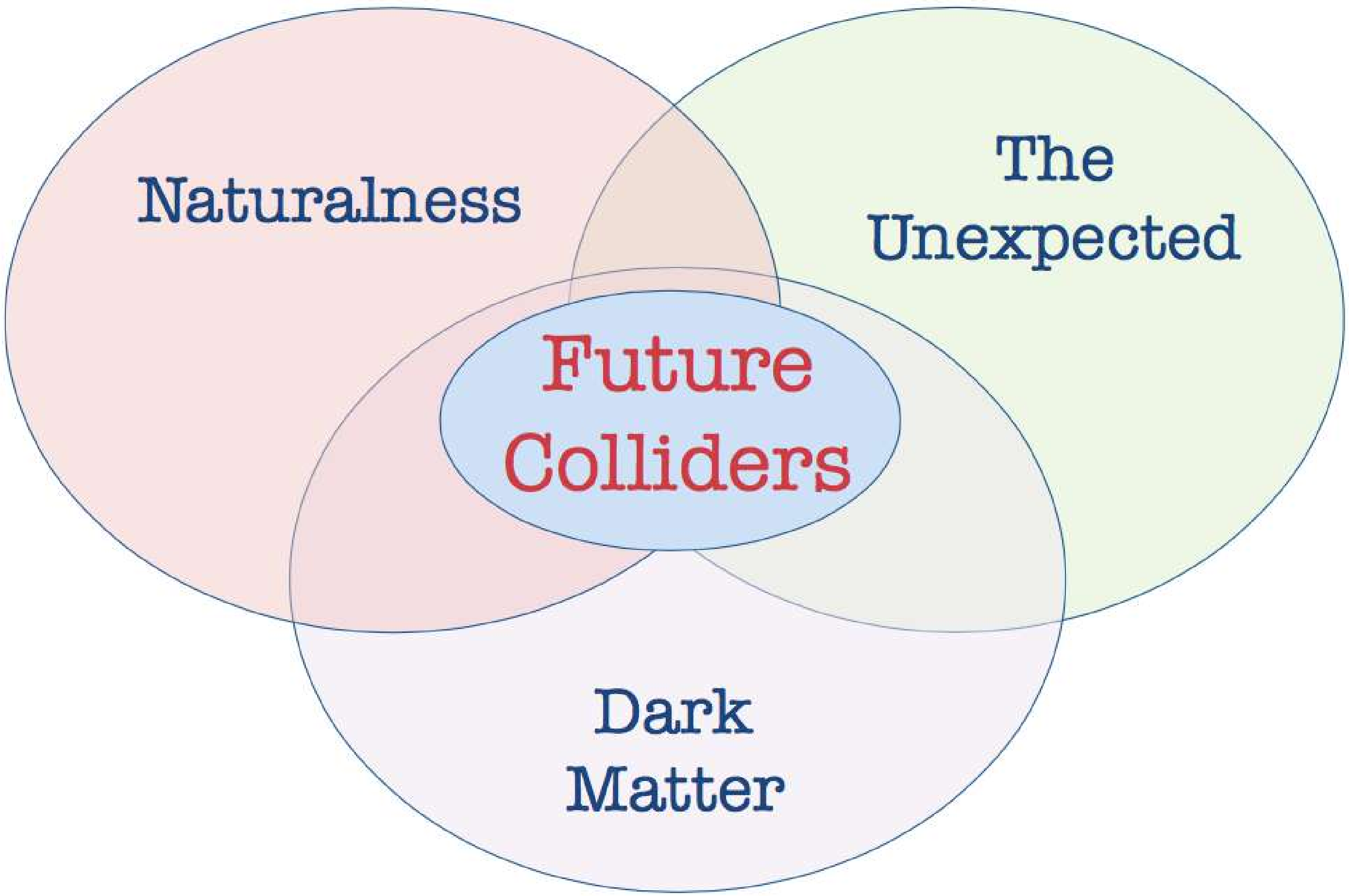

TIFR, Mumbai
28 September 2023

Experiments at Future *pp* Colliders

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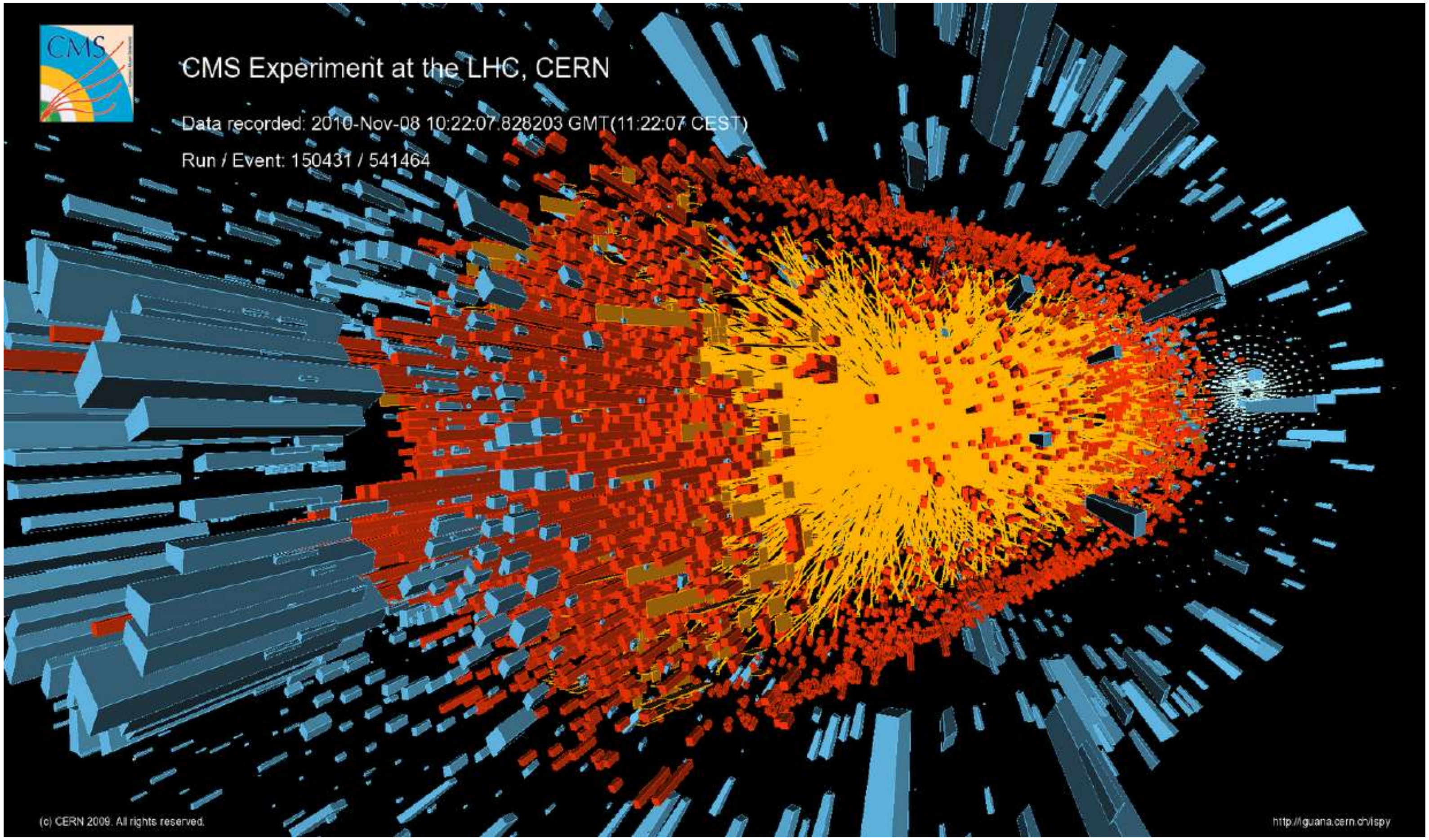

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Dawn of a New Age

- 2008 Nobel Prize in Physics

  "for the discovery of the mechanism of spontaneously broken symmetry in subatomic physics"

- 2013 Nobel Prize in Physics

  "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Old and New Questions

- How to think of the vacuum as an “electroweak condensed state” ?
- How are the mysteries associated with a single, fundamental scalar field solved?
- What is the origin and nature of Dark Matter?
- What is the origin of the Baryon Asymmetry in the Universe?
- Why is Dark Energy so small but non-zero?
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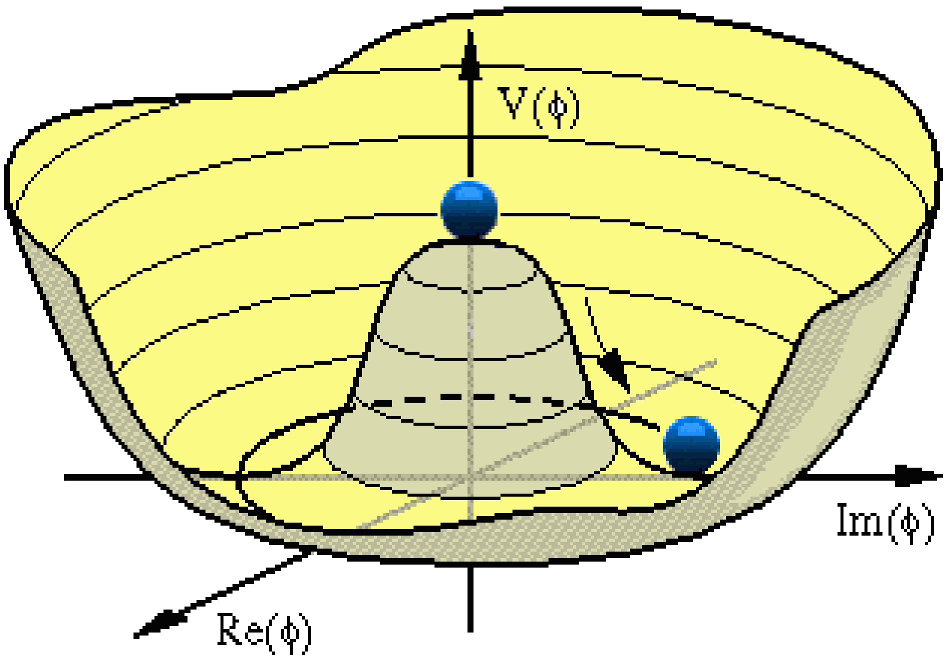
Spontaneous Symmetry Breaking of Gauge Symmetry

- scalar Higgs field develops a vacuum expectation value (VeV) via spontaneous symmetry breaking
  - Goldstone modes appear as the new longitudinal modes of gauge bosons



- Phase transition → vacuum state possesses non-trivial quantum numbers
  - Dynamical origin of this phase transition is not known
  - Implies vacuum is a condensed, superconductor-like state

Fundamental *vs* Parametric Physics

- Fundamental principles lead to
  - Chiral fermions from irreducible representations of Lorentz group
    - fermions as spin ½ representations of Lorentz group
    - Fermi-Dirac statistics → Pauli Exclusion Principle
    - why matter occupies volume
  - Massless force mediators (gauge bosons) from gauge invariance
  - Massive gauge bosons and fermions from spontaneous breaking of gauge symmetry

- In comparison, the breaking of gauge symmetry by the Higgs VeV is parametrically induced
  - No dynamic or underlying principle behind it in the Standard Model

Why is Higgs Puzzling

Gauge sector $L = i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - \frac{1}{2}F_{\mu\nu}F^{\mu\nu}$

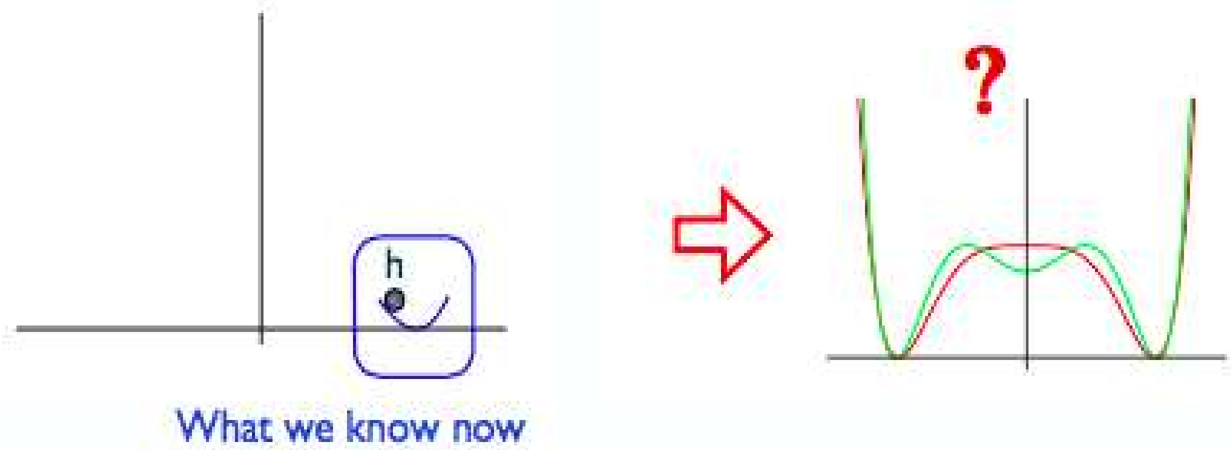
particle	spin
quark: u, d,...	1/2
lepton: e...	1/2
photon	1
W,Z	1
gluon	1
Higgs	0

h: a new kind of
elementary particle

Higgs sector

$$L = \left(h_{ij}\bar{\psi}_i\psi_j H + \text{h.c.}\right) - \lambda|H|^4 + \mu^2|H|^2 - \Lambda^4_{CC}$$

Why is Higgs Puzzling



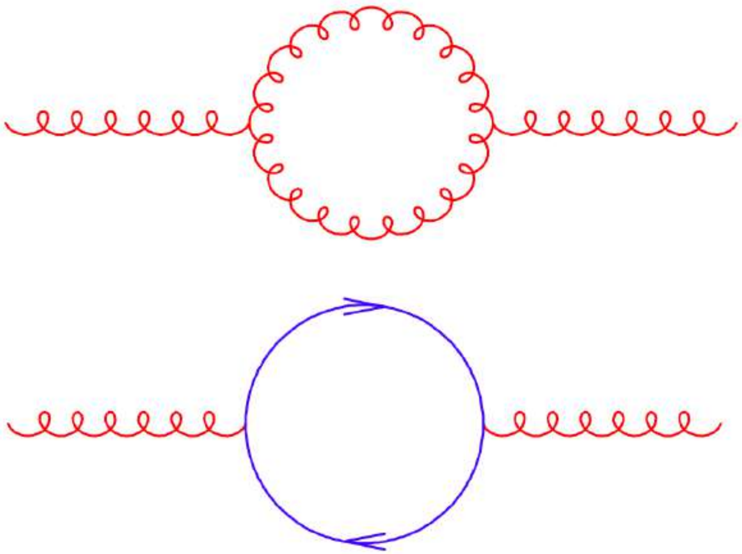
$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4 \quad \text{or} \quad V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4 + \frac{1}{\Lambda^2} h^6$$

Ad-hoc potential, similar to and motivated by Landau-Ginzburg theory of superconductivity

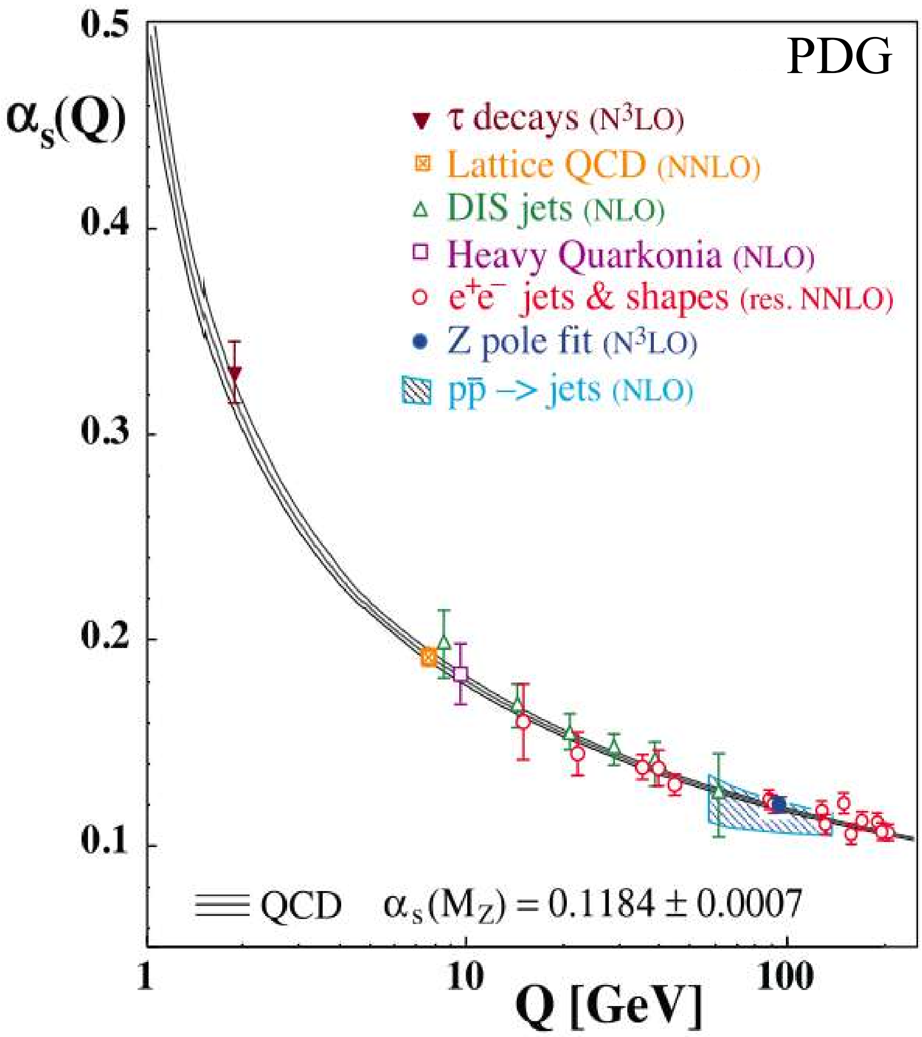
Higgs potential in SM can be extrapolated to Planck scale without additional parameters; but no a-priori reason for a parameterization to respect this condition

Radiative Stability of Higgs potential parameters

Example I - Test of QCD Quantum Loops at High Energy

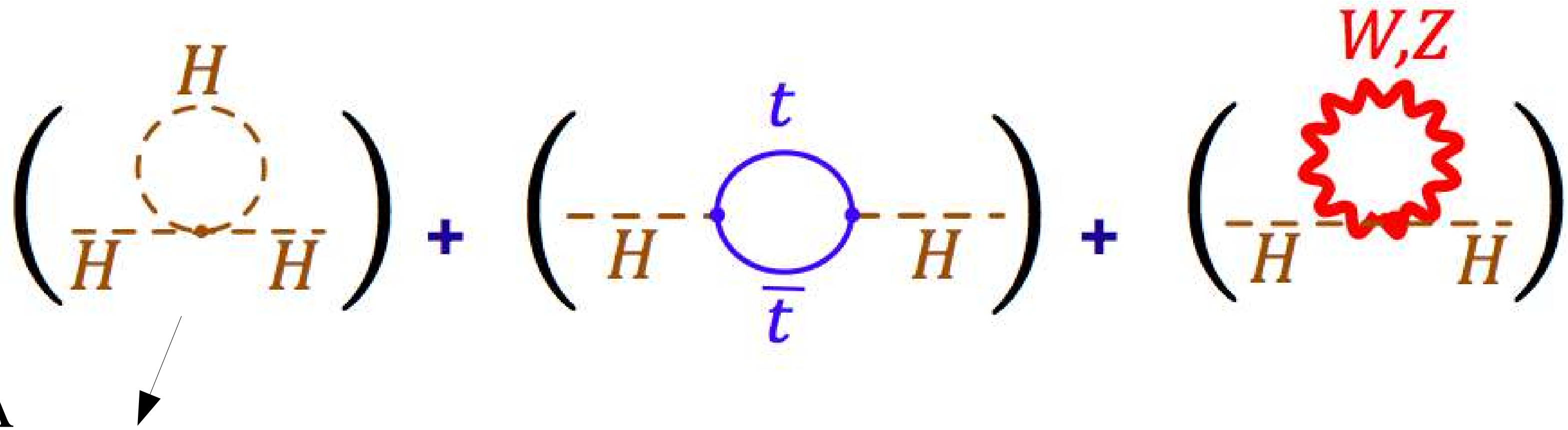


Running of strong coupling
has been confirmed experimentally



Why is the Higgs Boson so Light?

$$m_H^2 - m_{\text{bare}}^2 =$$



$$\lambda \int^{\Lambda} d^4k \, (k^2 - m_H^{\ 2})^{-1} \sim \Lambda^2 \lambda$$

For the first time, we have additive corrections to parameters which are quadratically divergent

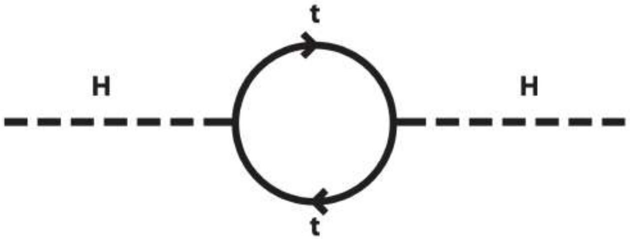
The Higgs boson ought to be a very heavy particle, naturally

However, observed $m_H << \Lambda$

Fine-tuning Problem of Higgs Boson Mass

- The divergent integral in this quantum loop must be regulated by a high-momentum cutoff, Λ, which could be the gravitational Planck energy scale $M_{planck} \sim 10^{19}$ GeV
  - Loop calculation gives Higgs boson mass correction $\sim M^2_{planck}$

Top quark loop

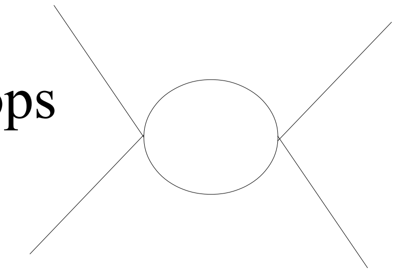


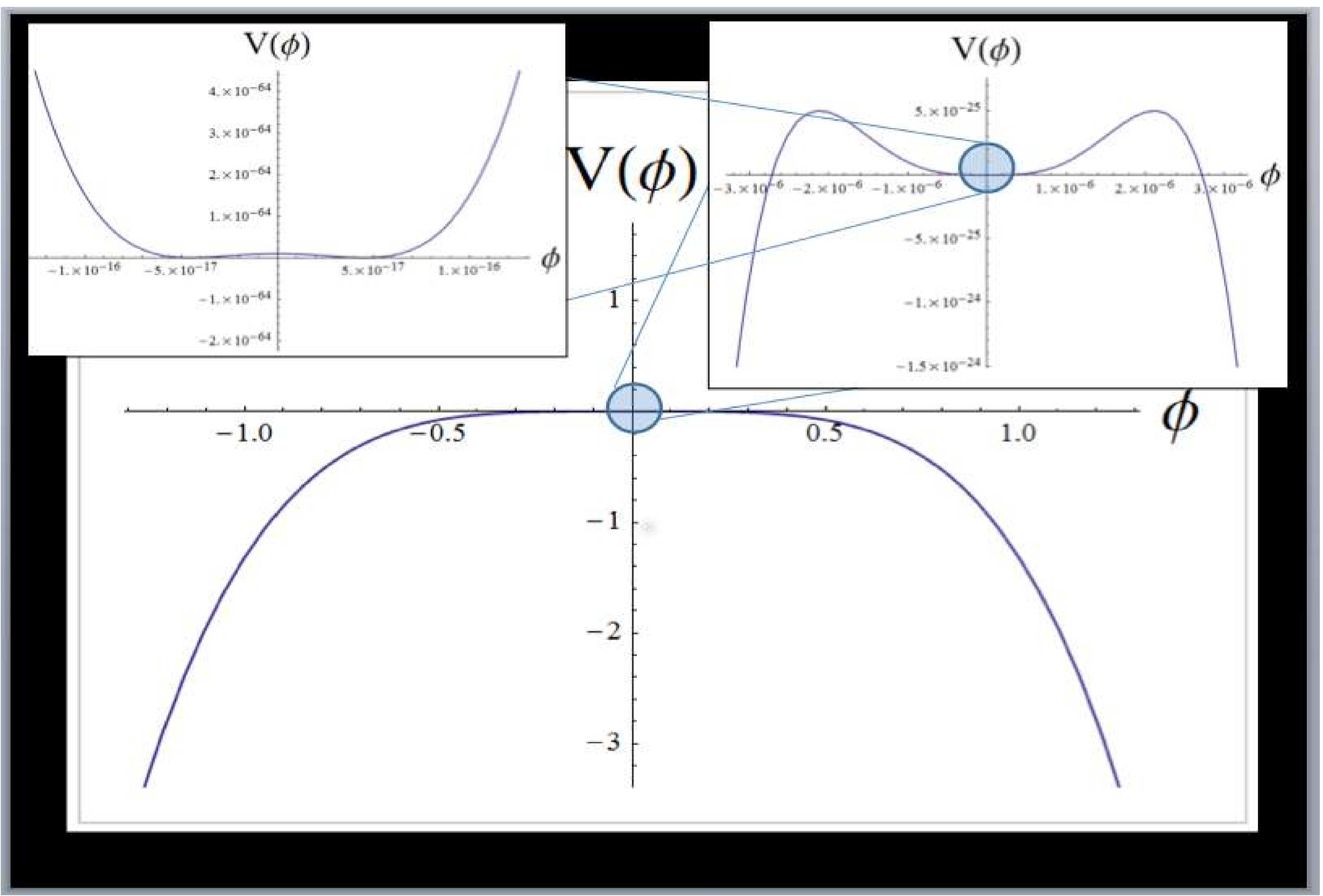
- physical Higgs boson mass ~ 125 GeV

- Therefore need extreme "fine-tuning" of bare lagrangian parameters at high energy

Radiative Corrections to Higgs Self-Coupling

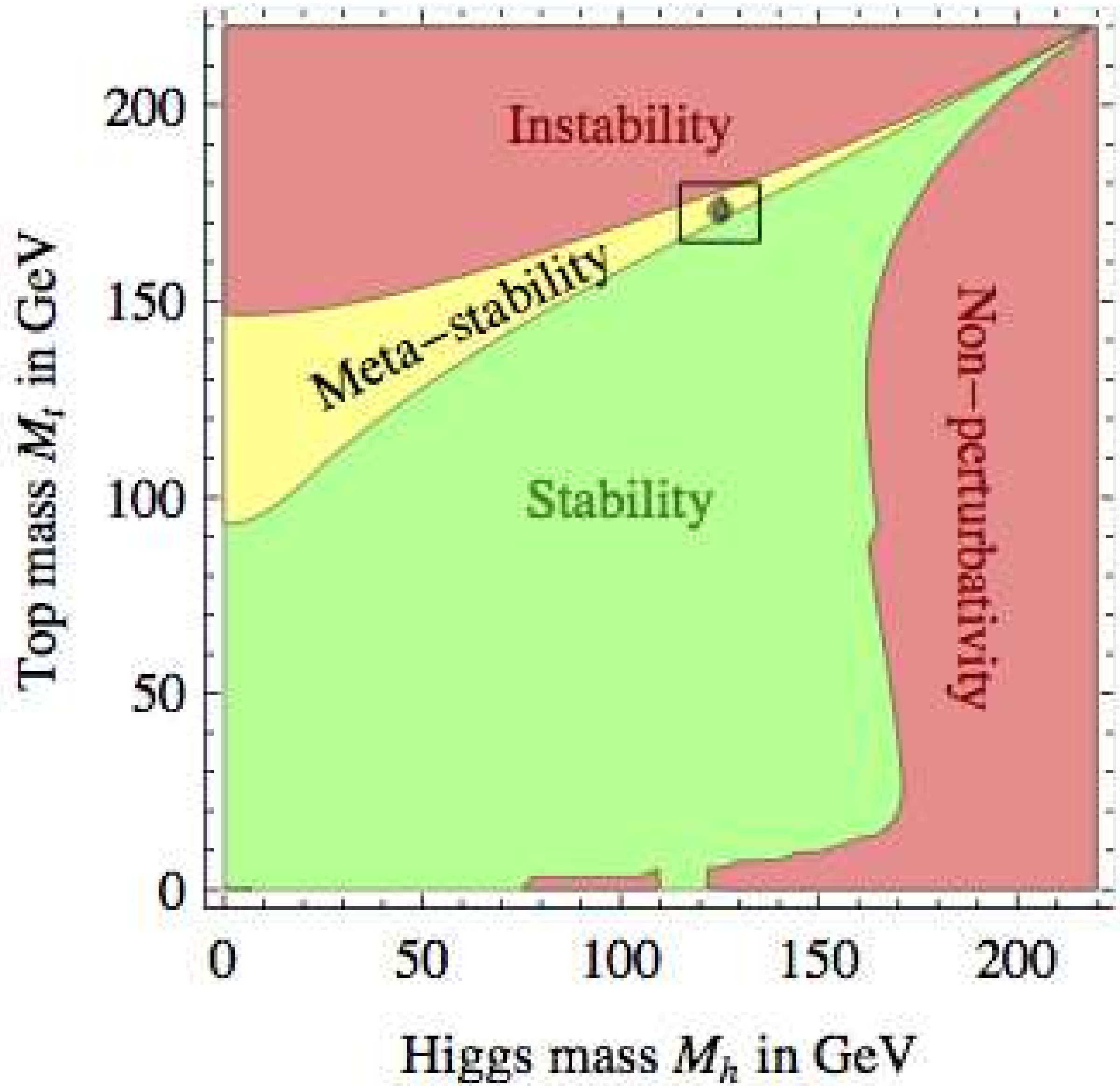
- $\lambda|\phi|^4$ receives radiative corrections from Higgs and top-quark loops





(from Paul Steinhardt)

Stability of Electroweak Vacuum



Higgs boson puzzles

- First fundamental (?) scalar field to be discovered
- Spontaneous symmetry breaking by development of a VeV
  - But VeV is induced parametrically by ad-hoc Higgs potential, no dynamics
- Parameters of Higgs potential are not stable under radiative corrections
  - First time that the radiative correction to a particle mass is additive and quadratically divergent
  - Gauge boson masses are protected by gauge invariance
  - Fermion masses are protected by chiral symmetry of massless fermions
- Single scalar Higgs field is a strange beast, compared to fermions and gauge bosons
- Additional symmetries and/or dynamics strongly motivated by Higgs discovery

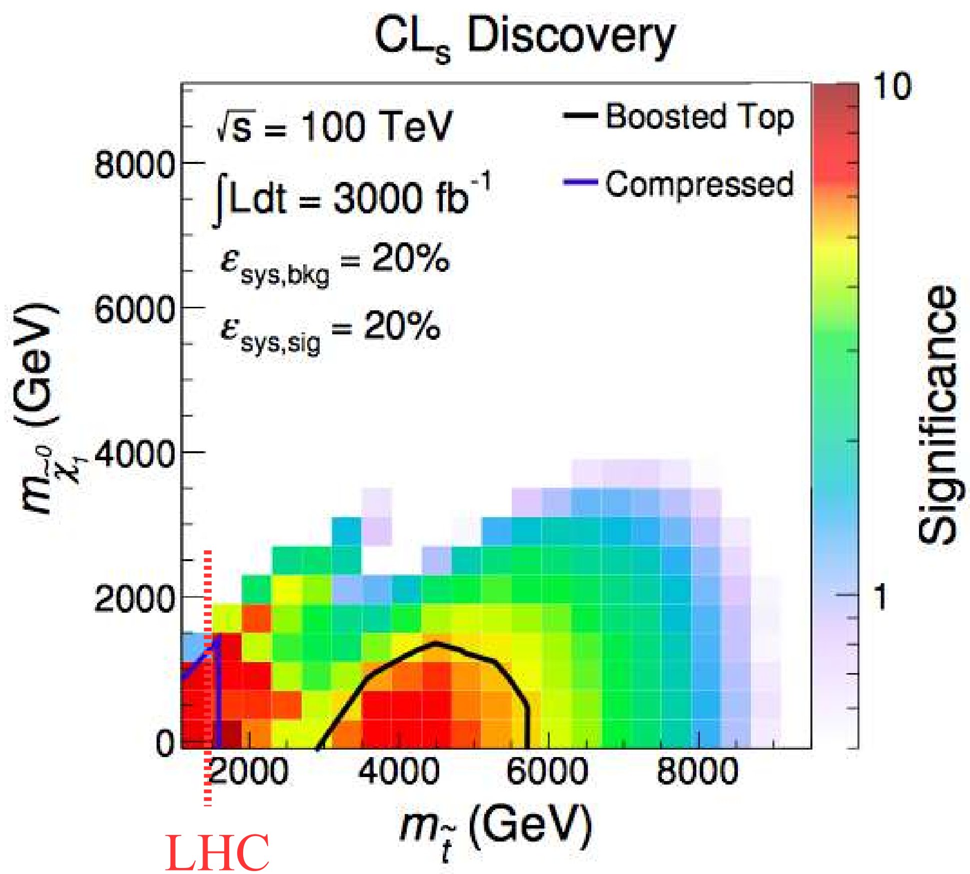
Circular *pp* Collider

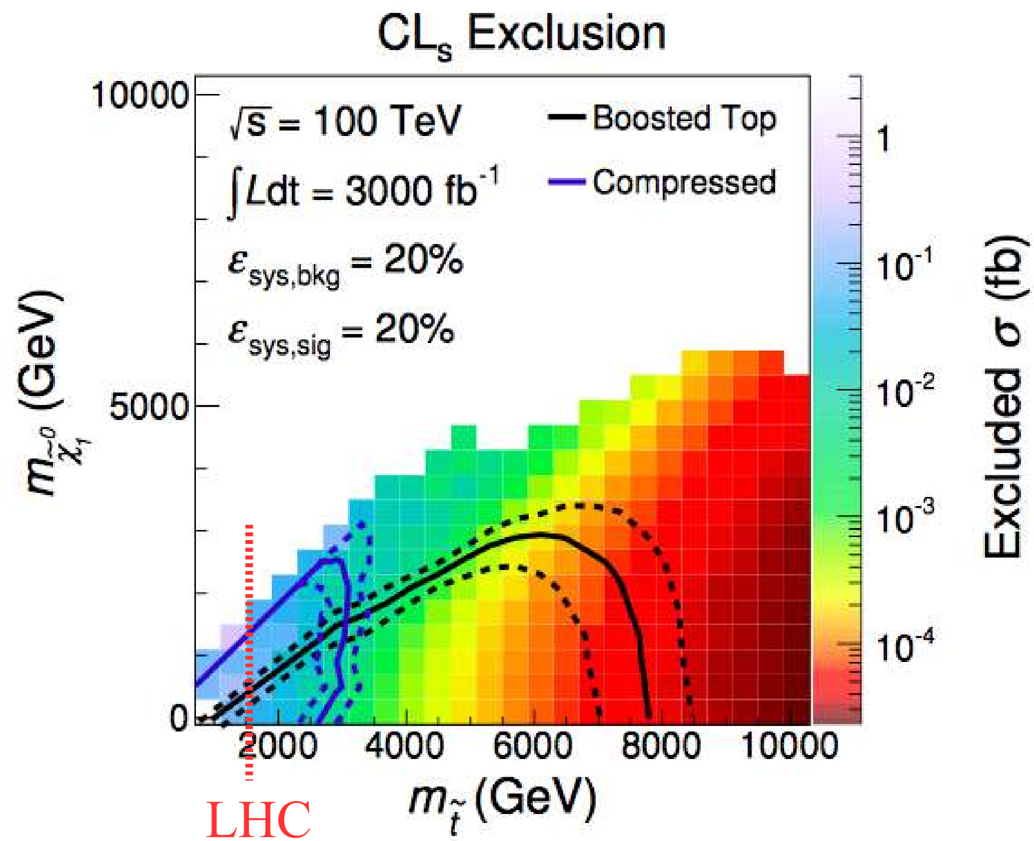
Circular *pp* Collider Physics Goals

- 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 new physics be a bounded parameter space?
    - Can it be fully covered with a 100-TeV scale *pp* collider?
- Naturalness – the need to explain the lightness of the Higgs mass – testing Naturalness at 10^{-4}

Supersymmetric Colored Top Partner Sensitivity

(Cohen *et al*, 2014)





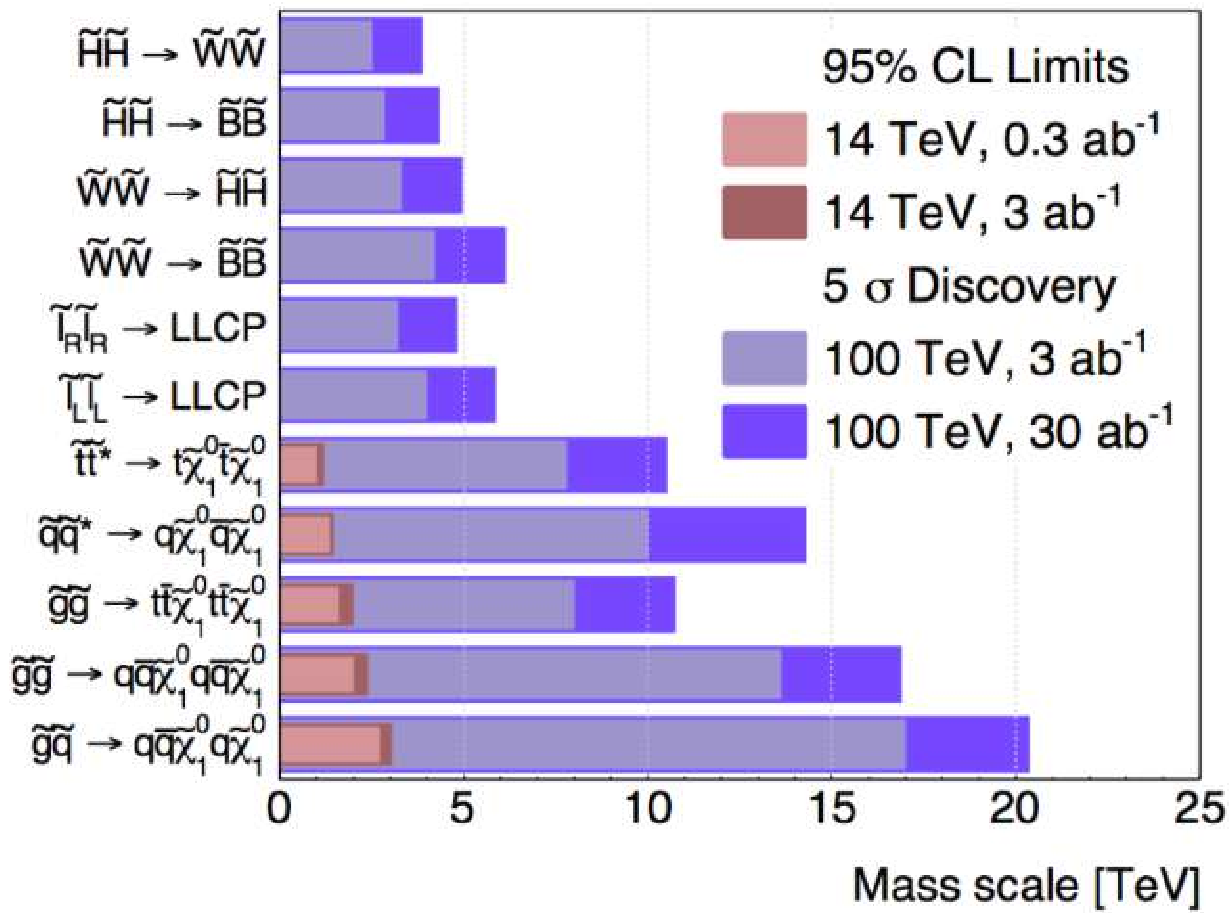
Fine-tuning ~ $m_{stop}^{2} \sim 10^{-4}$

A big jump beyond LHC

Discovering or eliminating “natural” low-energy SUSY

Exploring New Territory – Squarks and Gluinos

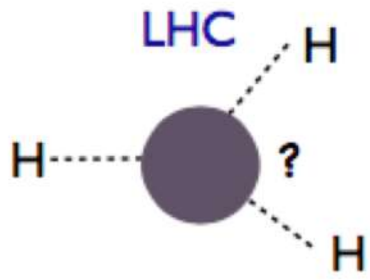
Summary from FCC Report:



Squark & gluino discovery potential up to 10-20 TeV

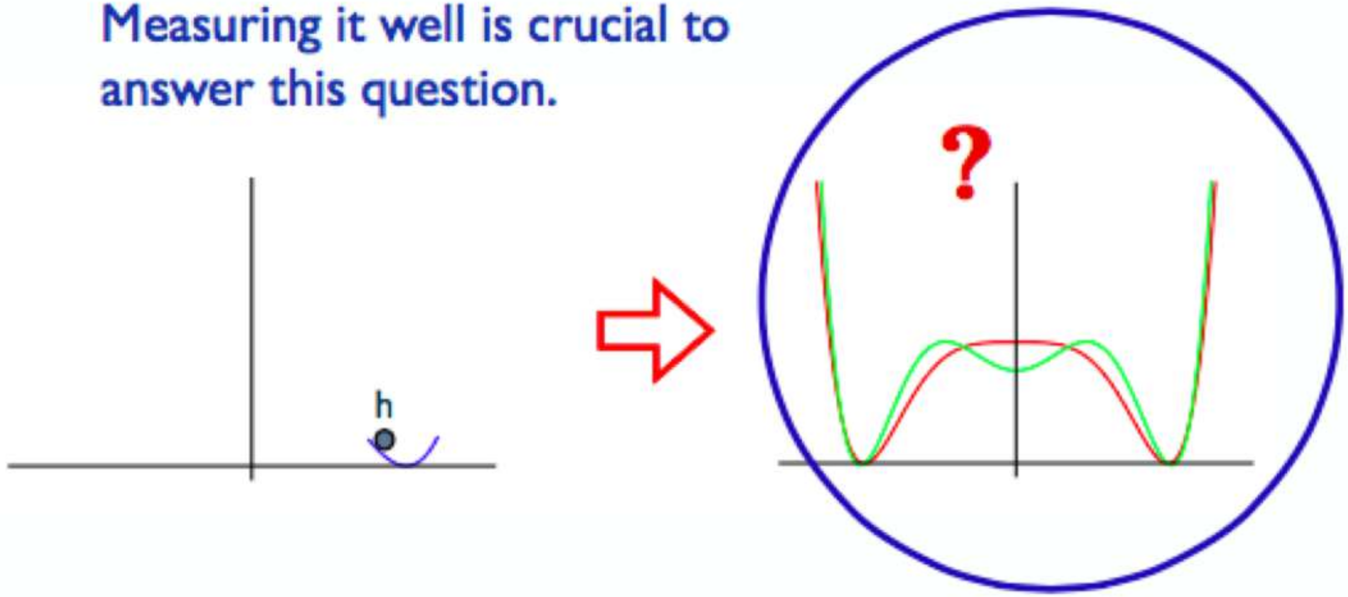
Full exploration of "low-scale" SUSY

Higgs Self-Coupling



Unique type of coupling for spin-0 scalars
Not seen before in nature!

Measuring it well is crucial to answer this question.



Expect $O(1)$ deviations from SM in self-coupling coefficient

Measuring the Higgs Self-Coupling

- gg→HH (most promising?) , qq→HHqq (via VBF)
- Reference benchmark process: HH→bb γγ
- Goal: 5% (or better) precision for SM selfcoupling

$HH \to b\bar{b}\gamma\gamma$	Barr,Dolan,Englert,Lima, Spannowsky JHEP 1502 (2015) 016	Contino, Azatov, Panico, Son arXiv:1502.00539	He, Ren Yao arXiv:1506.03302
FCC$_{@100TeV}$ 3/ab	30~40%	30%	15%
FCC$_{@100TeV}$ 30/ab	10%	10%	5%
$S/\sqrt{B}$	8.4	15.2	16.5
Details	✓ λ_{HHH} modification only ✓ $c \to b$ & $j \to \gamma$ included ✓ Background systematics ○ $b\bar{b}\gamma\gamma$ not matched ✓ $m_{\gamma\gamma} = 125 \pm 1$ GeV	✓ Full EFT approach ○ No $c \to b$ & $j \to \gamma$ ✓ Marginalized ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 5$ GeV ✓ Jet /W_{had} veto	✓ λ_{HHH} modification only ✓ $c \to b$ & $j \to \gamma$ included ○ No marginalization ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 3$ GeV

Work in progress to compare studies, harmonize performance assumptions, optimize, etc ⇒ ideal benchmarking framework

Origin of Matter-Antimatter Asymmetry

Origin of Baryon Asymmetry

POSSIBLE EXPLANATIONS...

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

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

⇨ ...

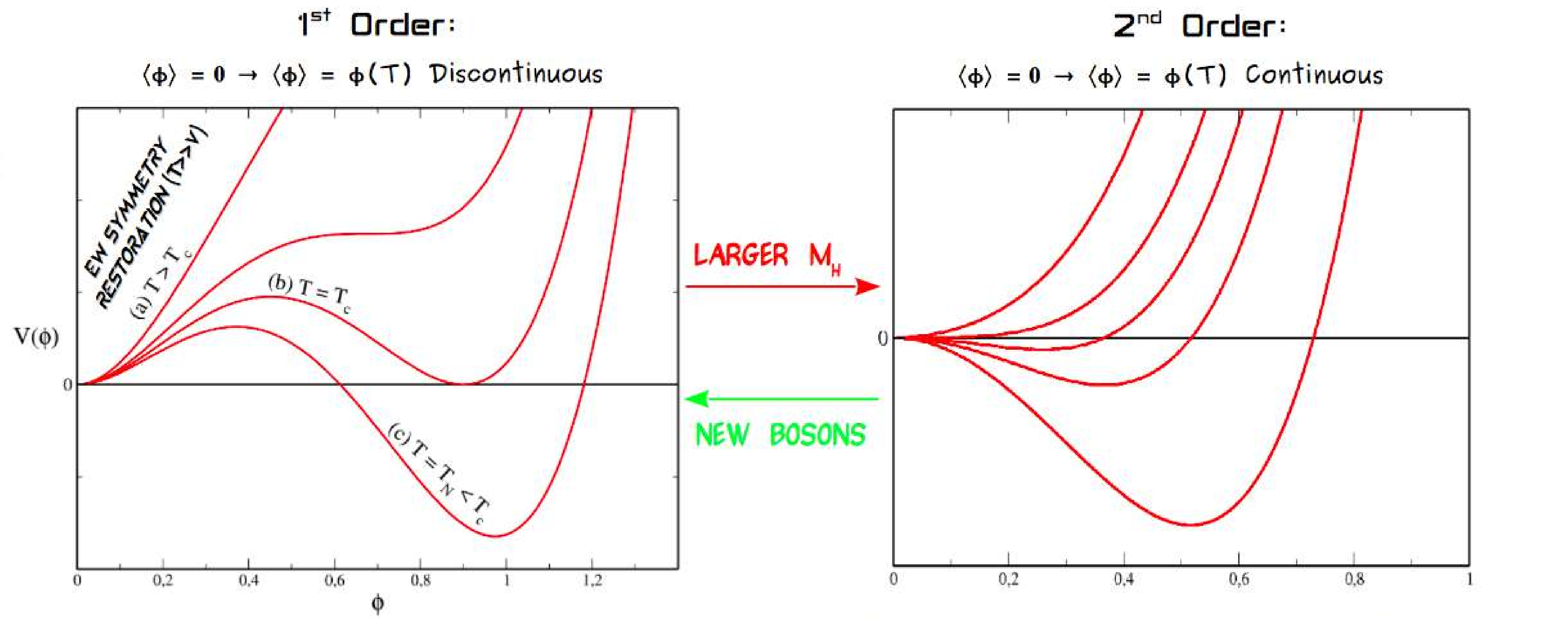
SAKHAROV CONDITIONS (for dynamical generation of baryon asymmetry)

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*

Baryon Asymmetry and Electroweak Phase Transition



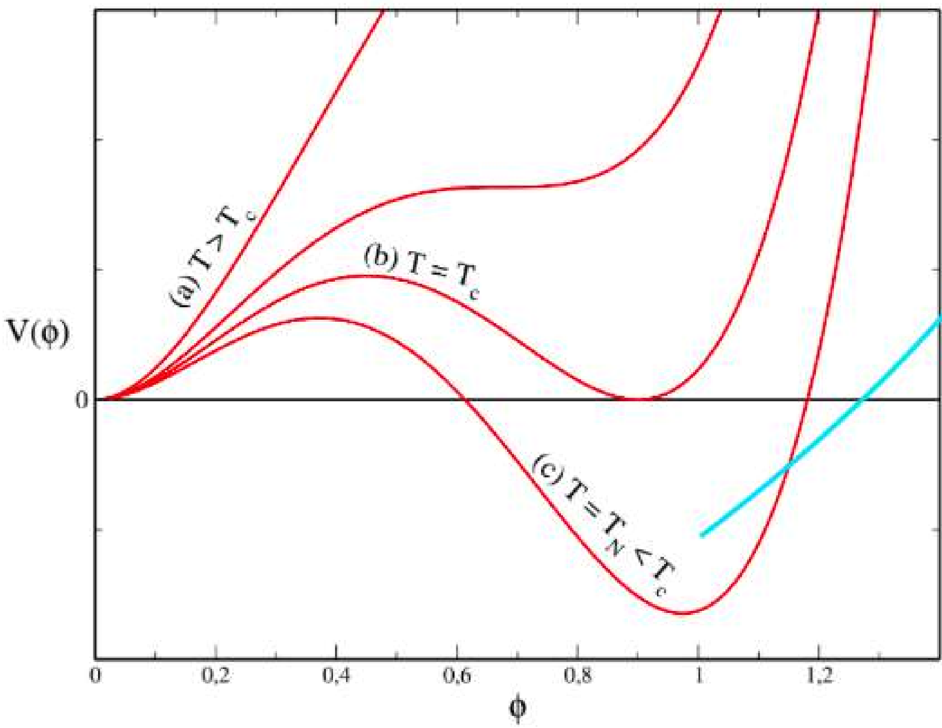
In the SM (m_h = 125 GeV) EW Phase Transition Smooth CrossOver

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

Baryon Asymmetry and Electroweak Phase Transition

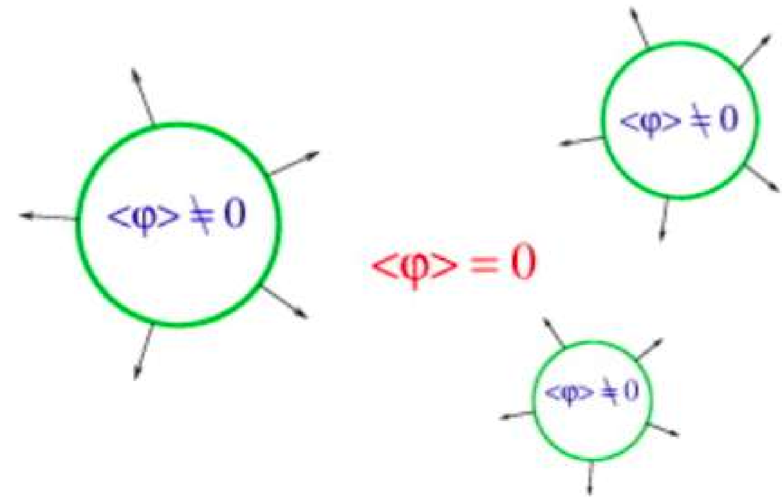
1^{st} Order:

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



Nucleation of True Vacuum Bubbles
(in False Vacuum Sea)

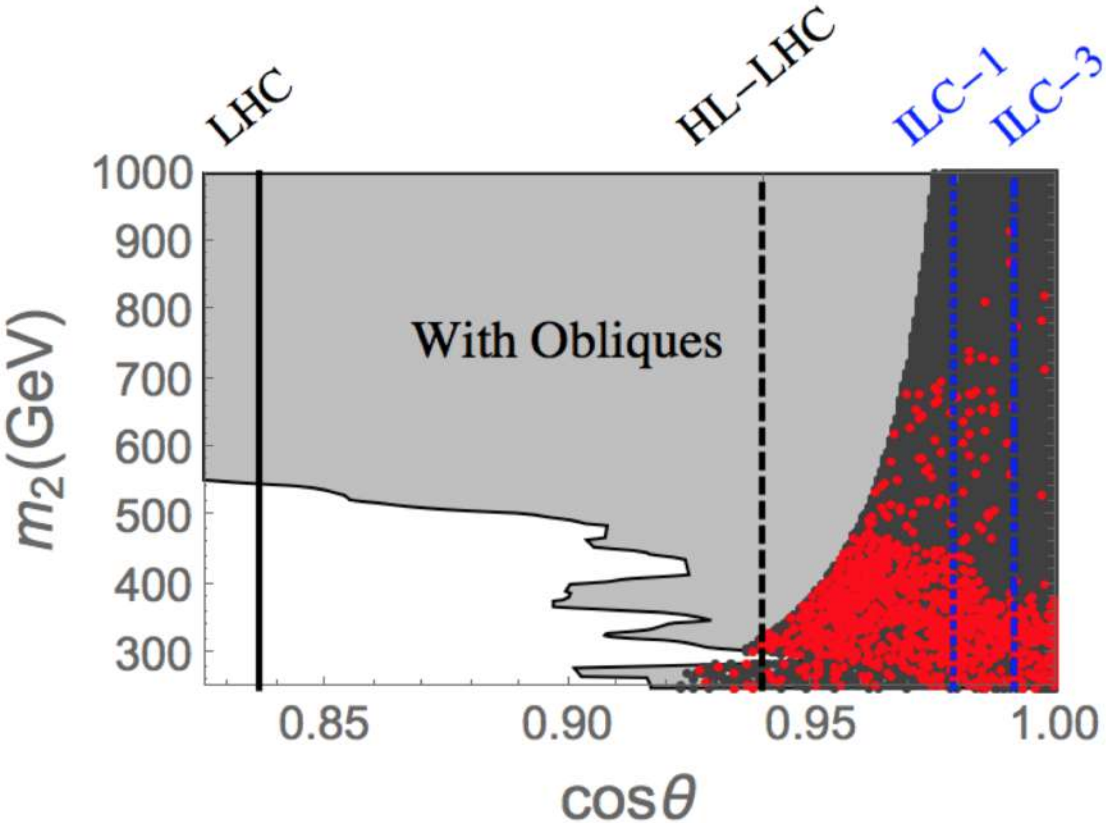
J. S. Langer, Ann. Phys. ***54*** *(1969) 258*
S. R. Coleman, Phys. Rev. D ***15*** *(1977) 2929*
A. D. Linde, Nucl. Phys. B ***216*** *(1983) 421*



SUDDEN CHANGE IN HIGGS VEV

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)

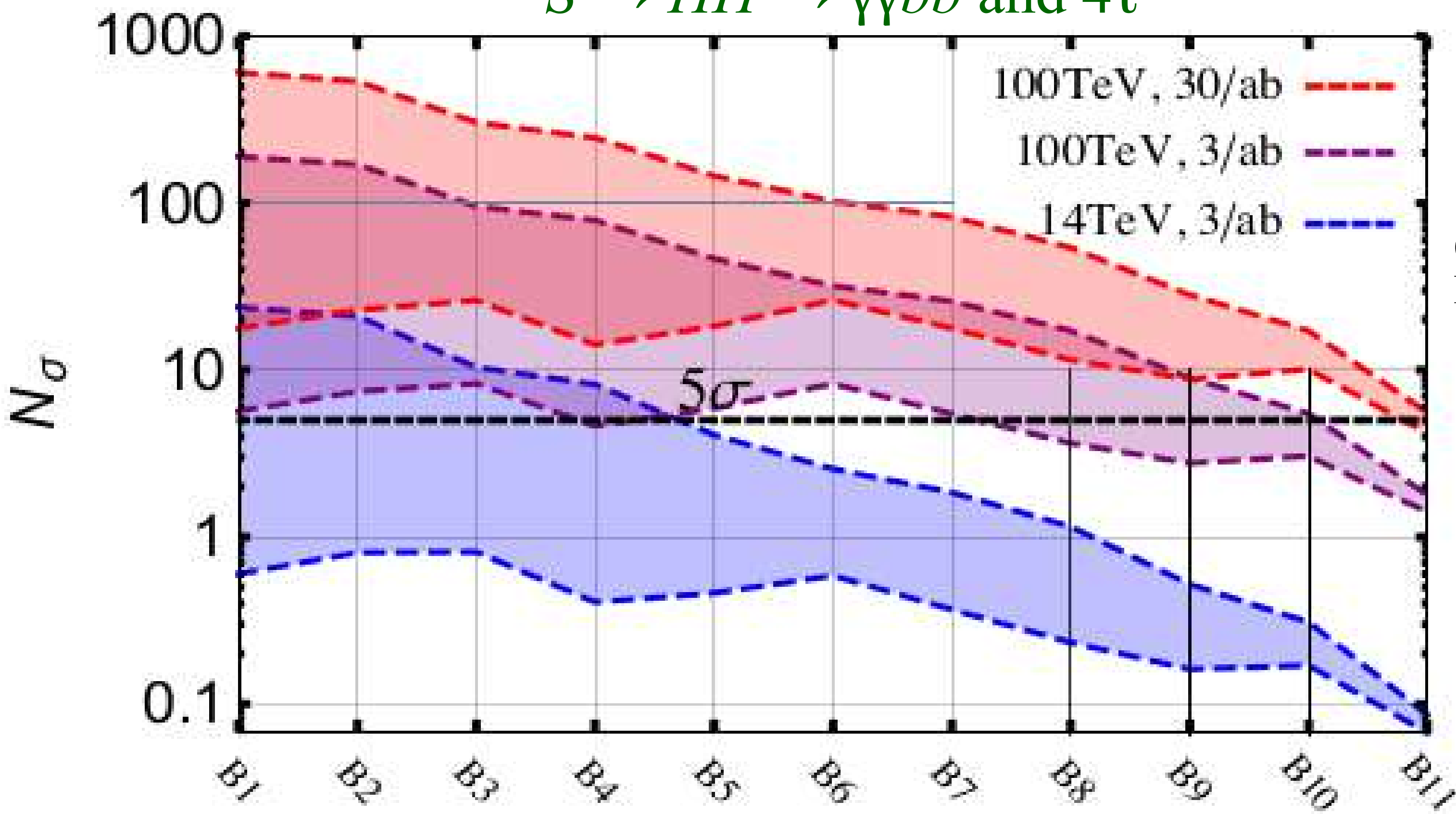
S. Profumo, M. J. Ramsey-Musolf, C. L. Wainwright and P. Winslow, arXiv:1407.5342

Can TeV-scale new physics associated with 1st order phase transition be completely covered by a *pp* collider?

Inducing First-Order Electroweak Phase Transition

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

$S \rightarrow HH \rightarrow \gamma\gamma bb$ and 4τ



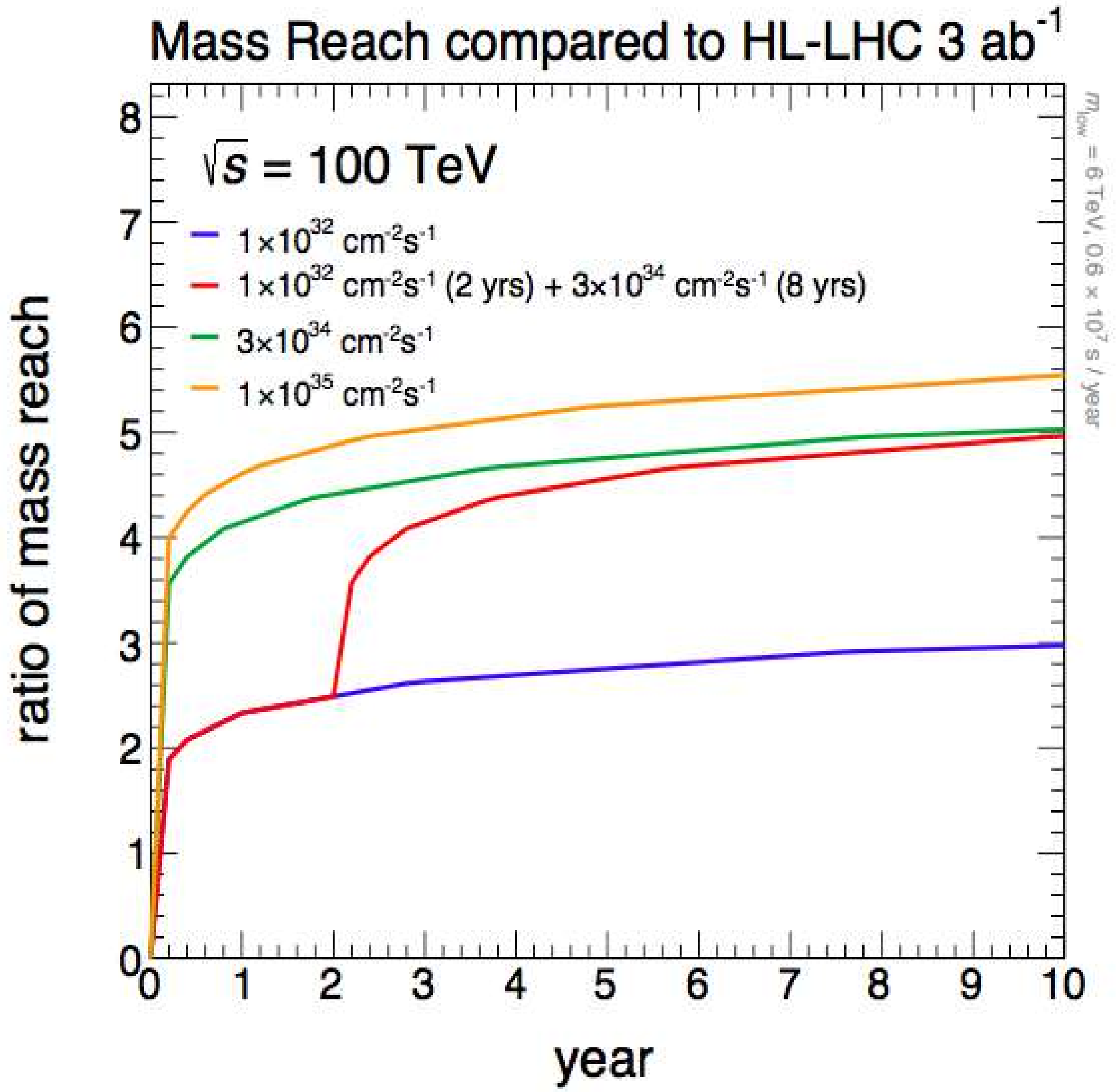
(P.Winslow, J.M. No, M.J.Ramsey-Musolf, AVK)

300 GeV ← benchmark m_s → 900 GeV

Discovery potential across entire parameter space

Collider Luminosity and Energy

- Collider luminosity evolution for high-mass reach

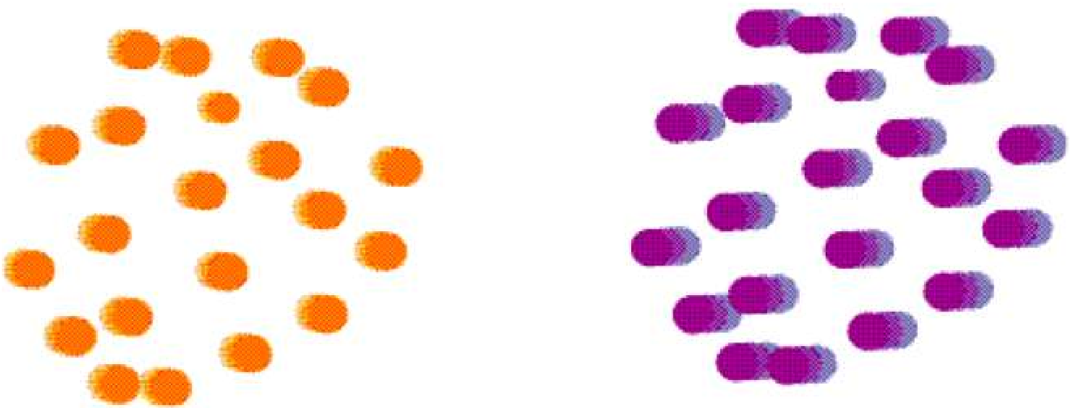


(from L-T. Wang)

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 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

Rate comparisons at 8, 14, 100 TeV

	N_{100}	N_{100}/N_8	N_{100}/N_{14}
gg→H	16 G	4.2×10^4	110
VBF	1.6 G	5.1×10^4	120
WH	320 M	2.3×10^4	66
ZH	220 M	2.8×10^4	84
ttH	760 M	29×10^4	420
gg→HH	28 M		280

$N_{100} = \sigma_{100\,TeV} \times 20\ ab^{-1}$

$N_8 = \sigma_{8\,TeV} \times 20\ fb^{-1}$

$N_{14} = \sigma_{14\,TeV} \times 3\ ab^{-1}$

Statistical precision:

- O(100 - 500) better w.r.t Run 1
- O(10 - 20) better w.r.t HL-LHC

Guidance for Detector Design

- As long as Standard Model continues to work, "higher energy is better"
- Covering the "Naturalness-motivated" models push towards higher masses
- Dark Matter, Electroweak Baryogenesis *may* relate to physics at lower masses and smaller couplings
- Other reasons that new physics may hide at low mass with weak couplings
  - "Neutral Naturalness" (partners without QCD color charge)
  - e.g. twin Higgs, Hidden Sector
  - Higgs portal to new sector (SM interactions via Higgs only)

- Implications for detector design: larger dynamic range of p_T of objects
  - Starting at ~20 GeV leptons, photons and *b*-quarks (same as LHC, e.g. $gg \to HH$)
  - Going up to ~7 times the highest p_T probed at LHC
- Also large rapidity range for all objects due to higher longitudinal boost

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

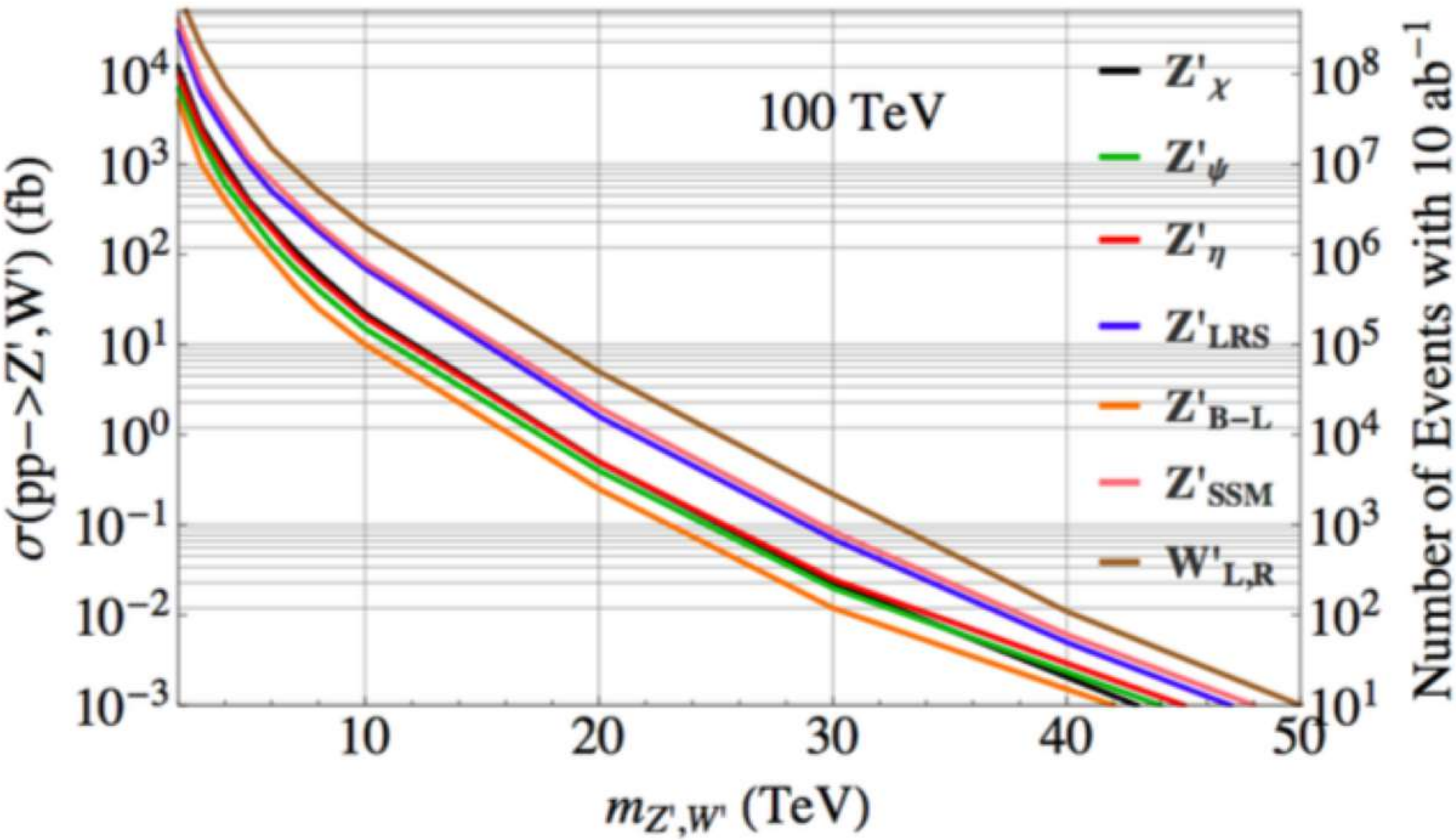
Detector Goals in a Nutshell (2)

- 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

Magnetic Tracking

Exploring New Territory - New Weak Gauge Interactions



Discovery reach

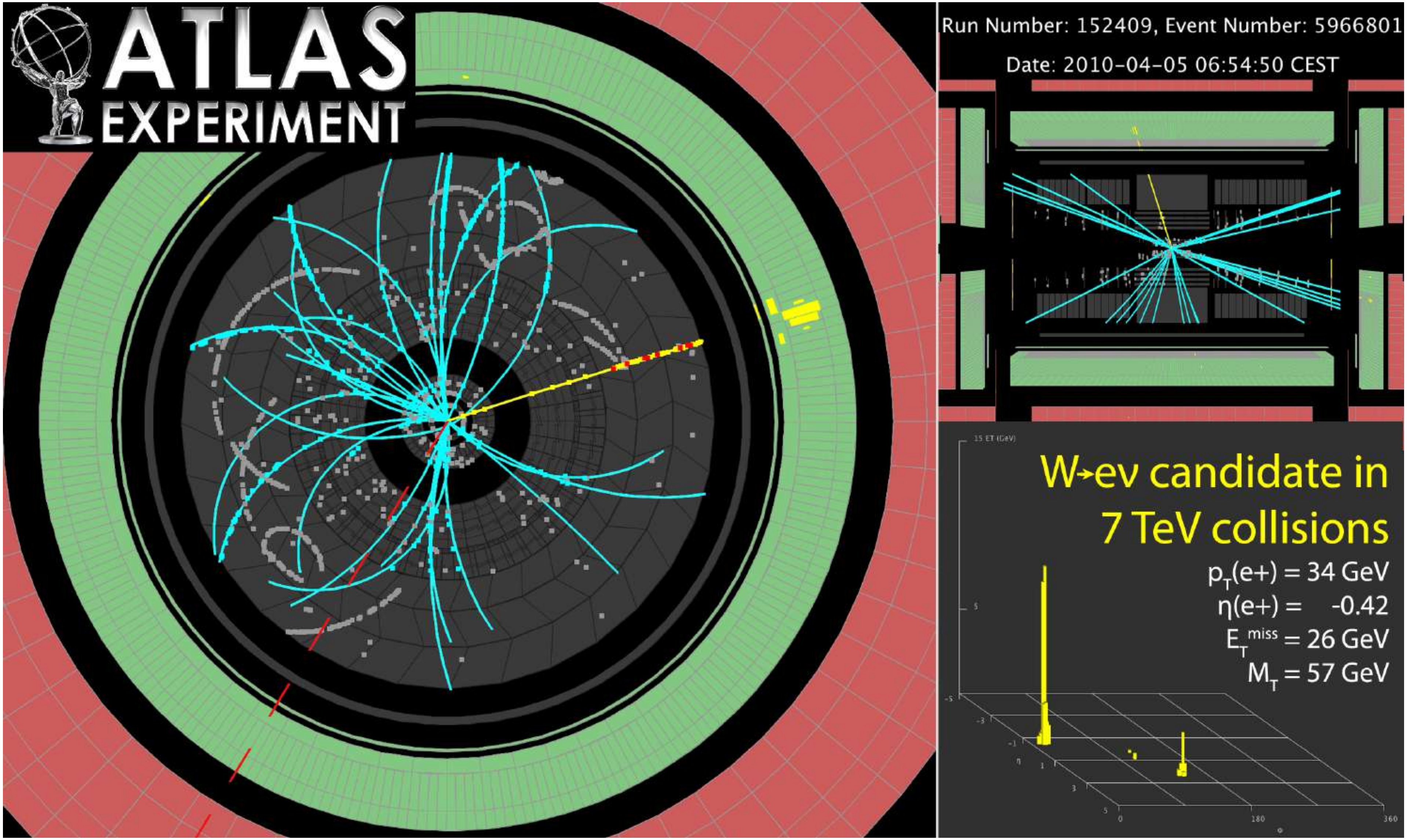
T.Rizzo, arXiv:1403.5465

Model	1 ab^{-1}	10 ab^{-1}	100 ab^{-1}
SSM	23.8	33.3	41.3
LRM	22.6	31.5	39.5
ψ	20.1	29.1	37.2
χ	22.7	30.6	38.2
η	20.3	29.8	38.0
I	22.4	29.2	36.2

10-fold increase in luminosity
→ ~7 TeV increase in mass reach

Magnetic Tracking

B field →



Fit the helical trajectory in the longitudinal magnetic field

=> Extract position, direction and momentum of charged particles

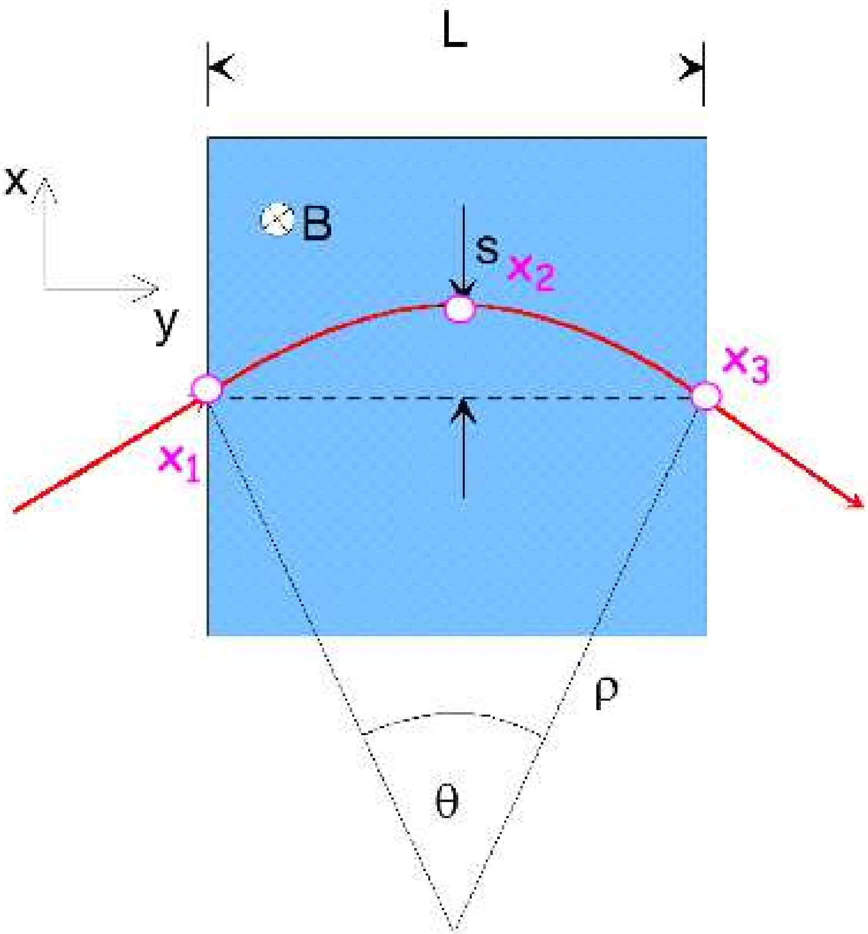
Tracker Design – the heart of the experiment

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]:

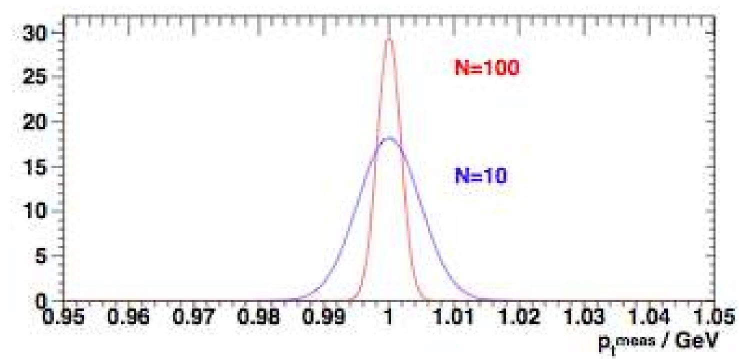
$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma(\kappa)}{\kappa} = \frac{\sigma_x \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{(N+4)}}$$

(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)

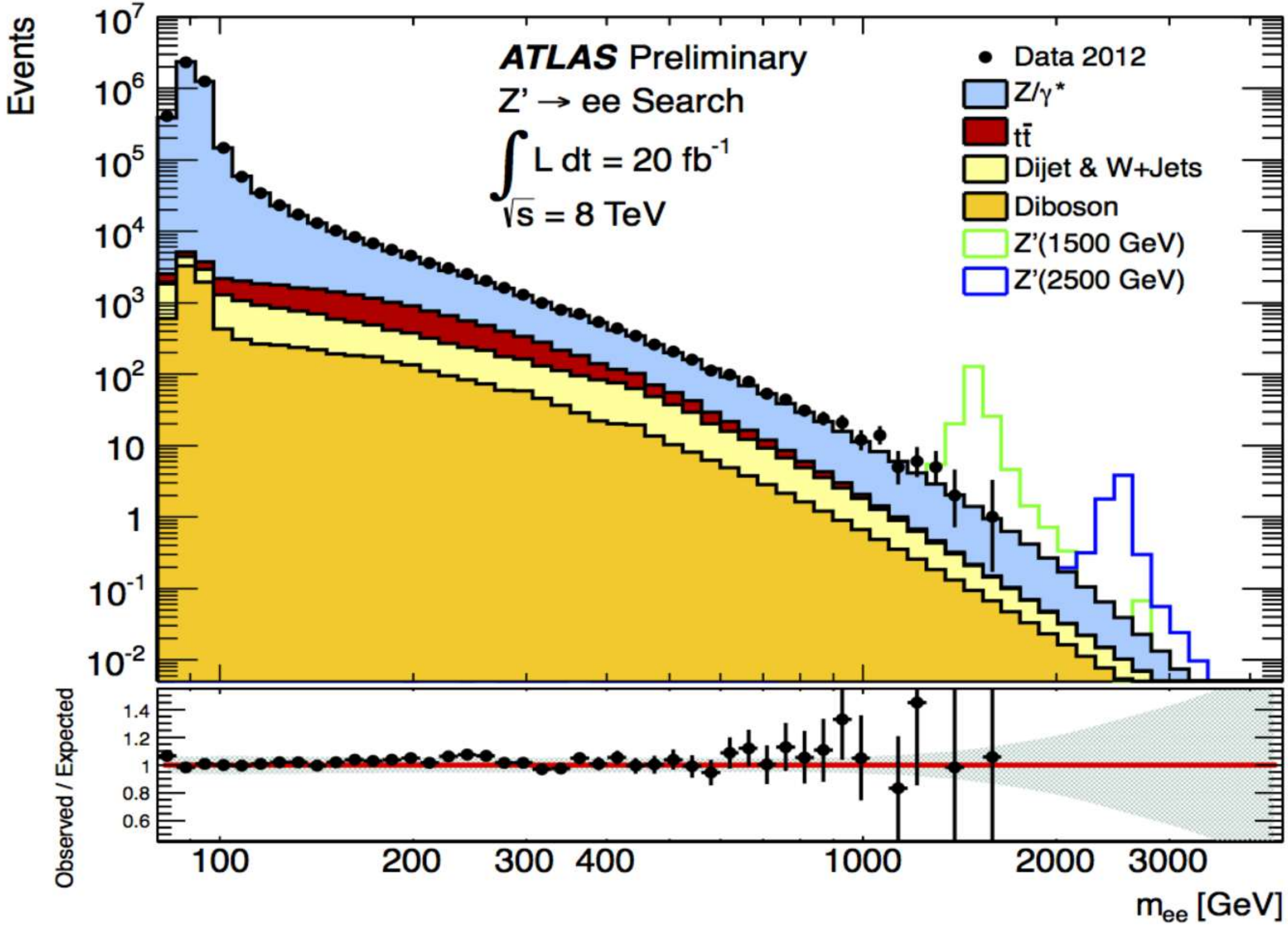


CDF achieved 0.015% with ~90 drift chamber hits, consistent with this example

Thanks to Carsten Niubuhr

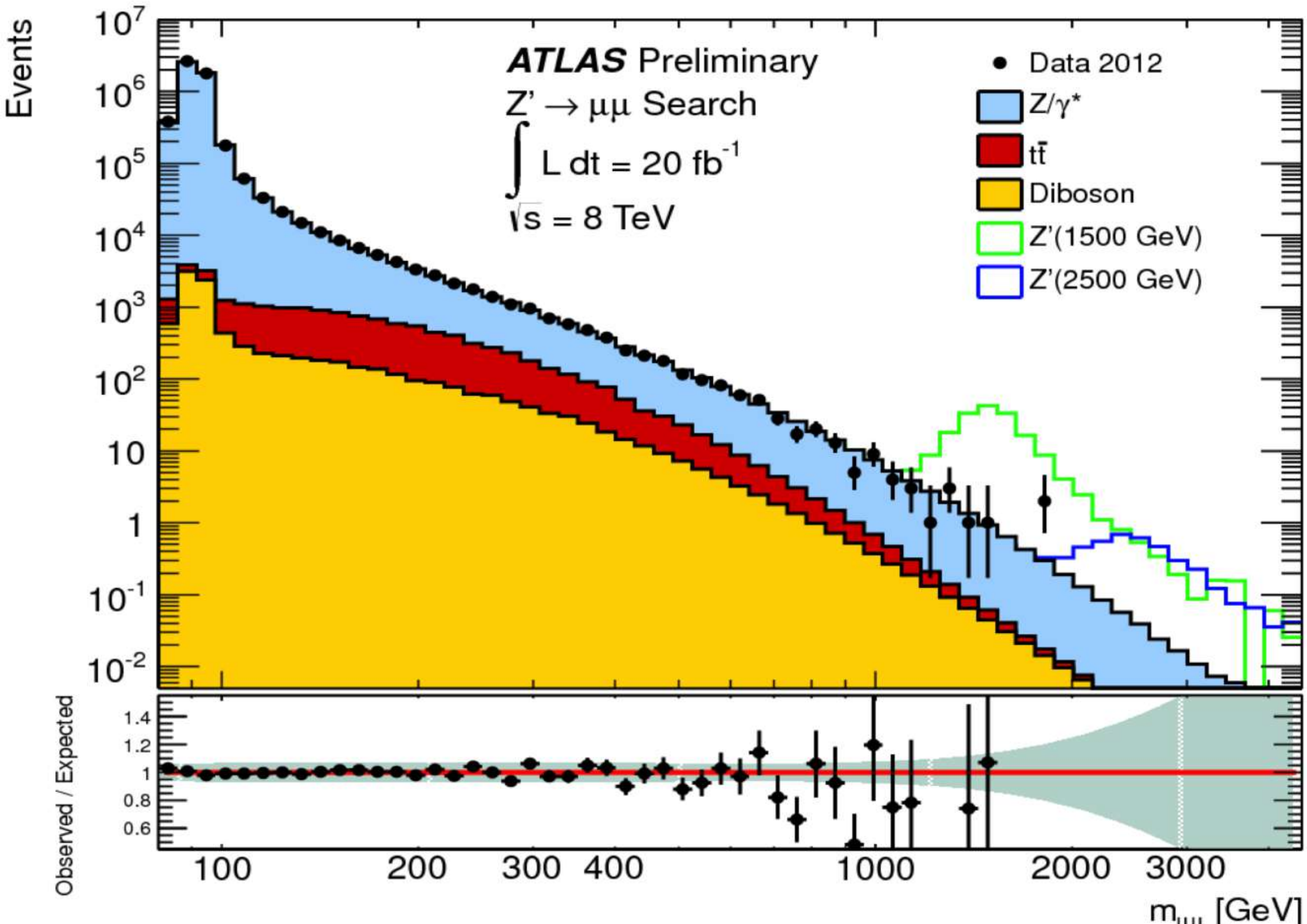
Dielectron Mass Spectrum

Multi-TeV masses probed at LHC



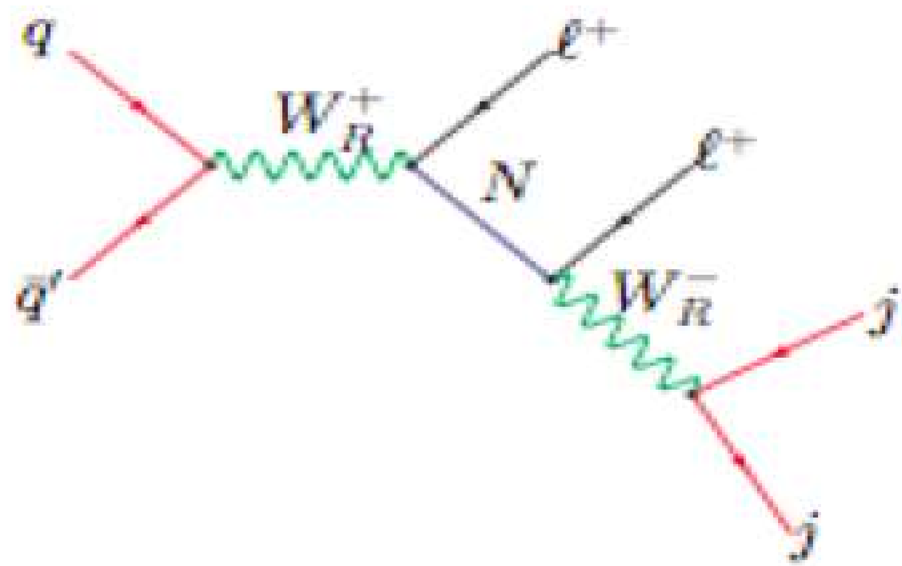
Dimuon Mass Spectrum

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



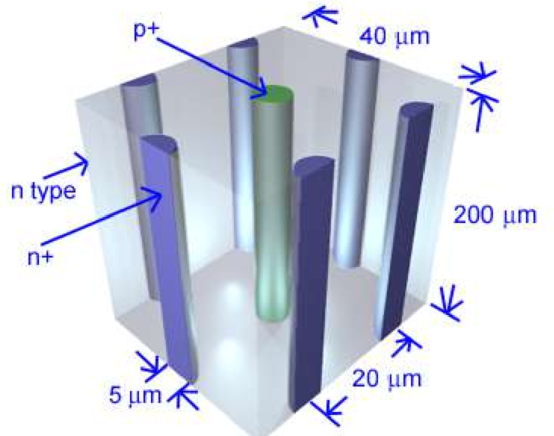
$$N \to l^{\pm} jj$$

(Keung, Senjanovic'83)

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

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



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

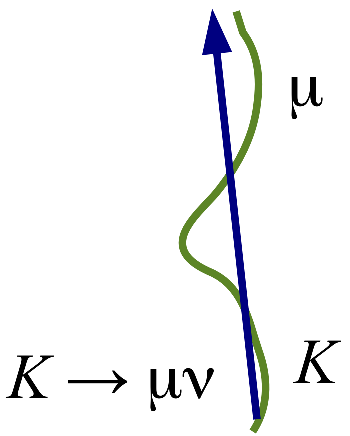
Three tracker/magnet geometries being considered:

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

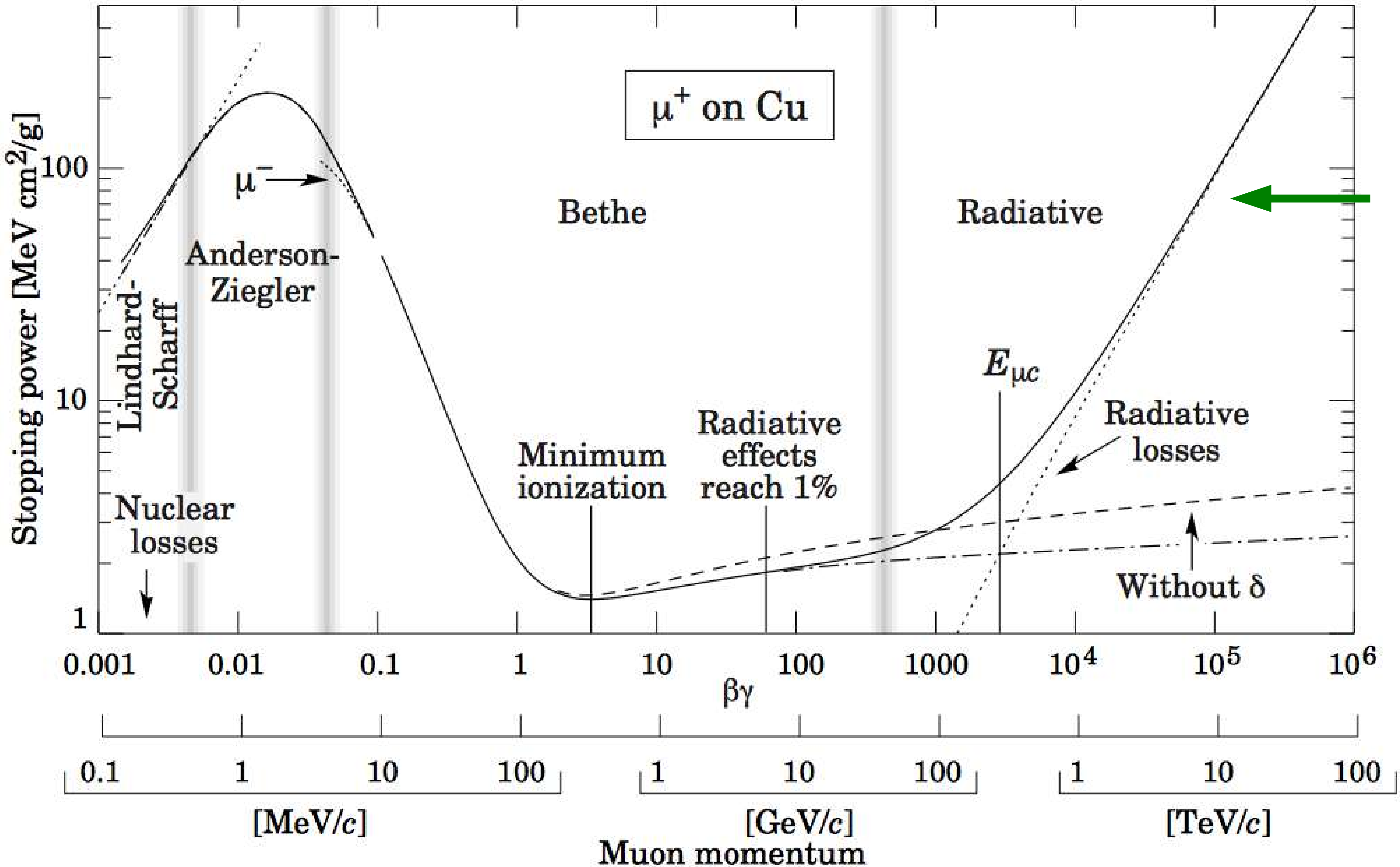
https://indico.fnal.gov/conferenceOtherViews.py?view=standard&confId=7864

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



High Energy Muon Bremsstrahlung

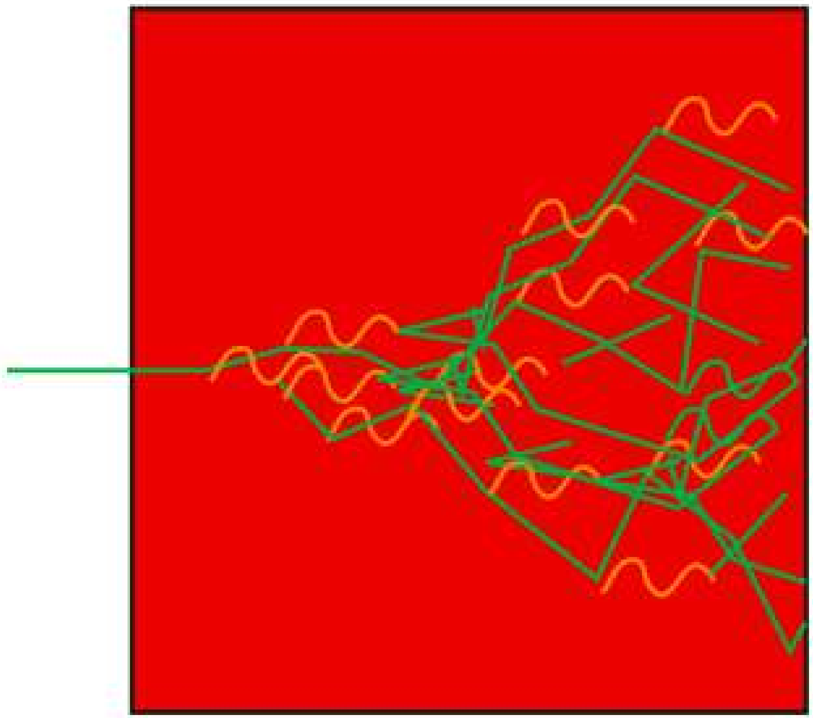


- For a ~10 TeV muon, average energy loss ~ 1 GeV / cm ~ 16 GeV / interaction length ~ 200 GeV in hadronic calorimeter, with long tailed distribution

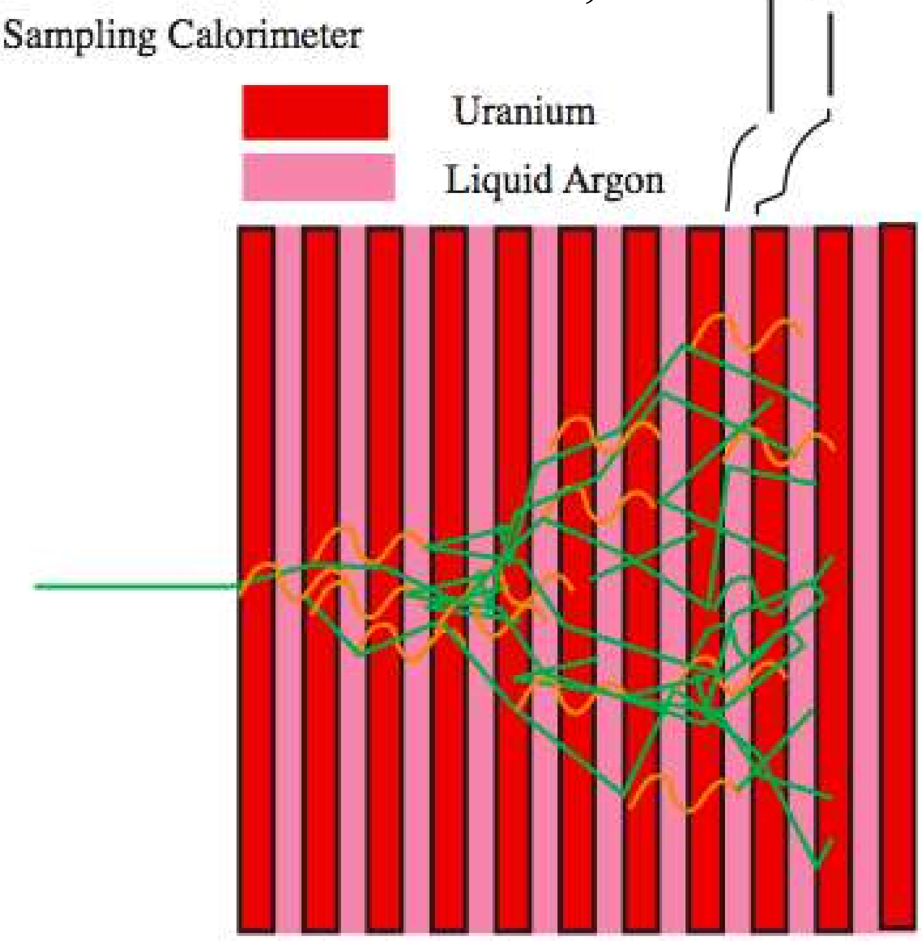
Calorimetry

Photon and Electron Detection

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



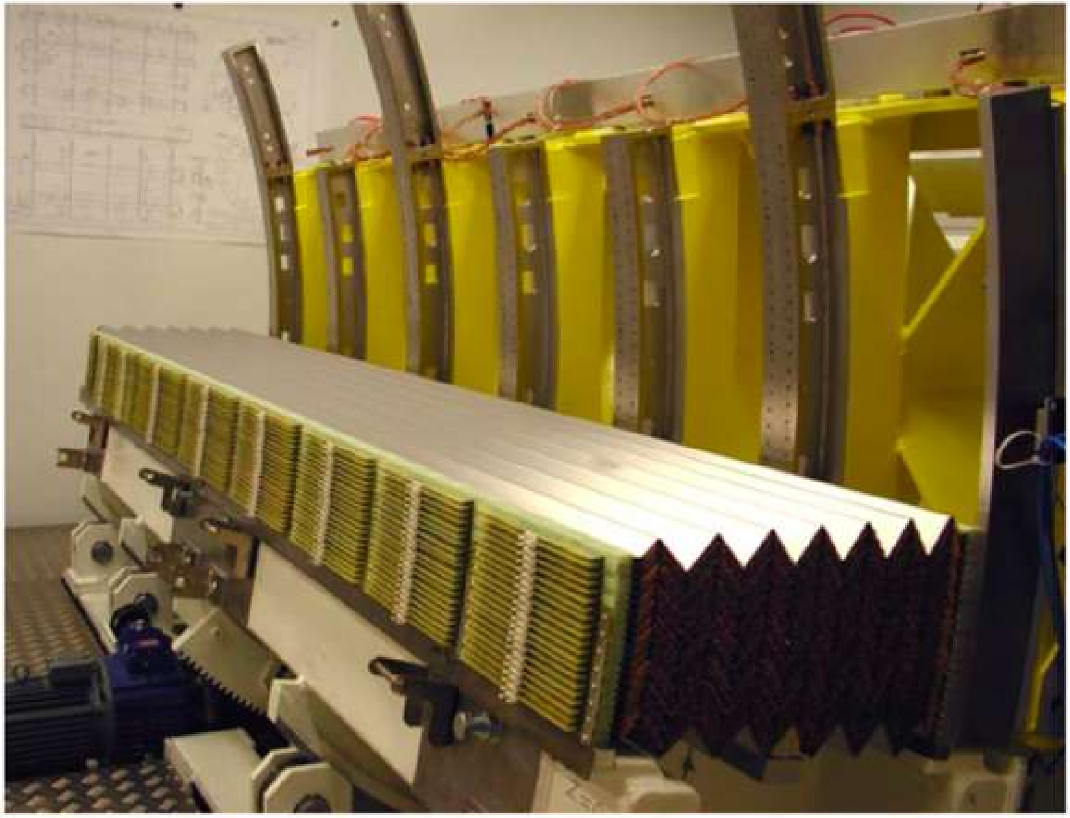
ATLAS, D0

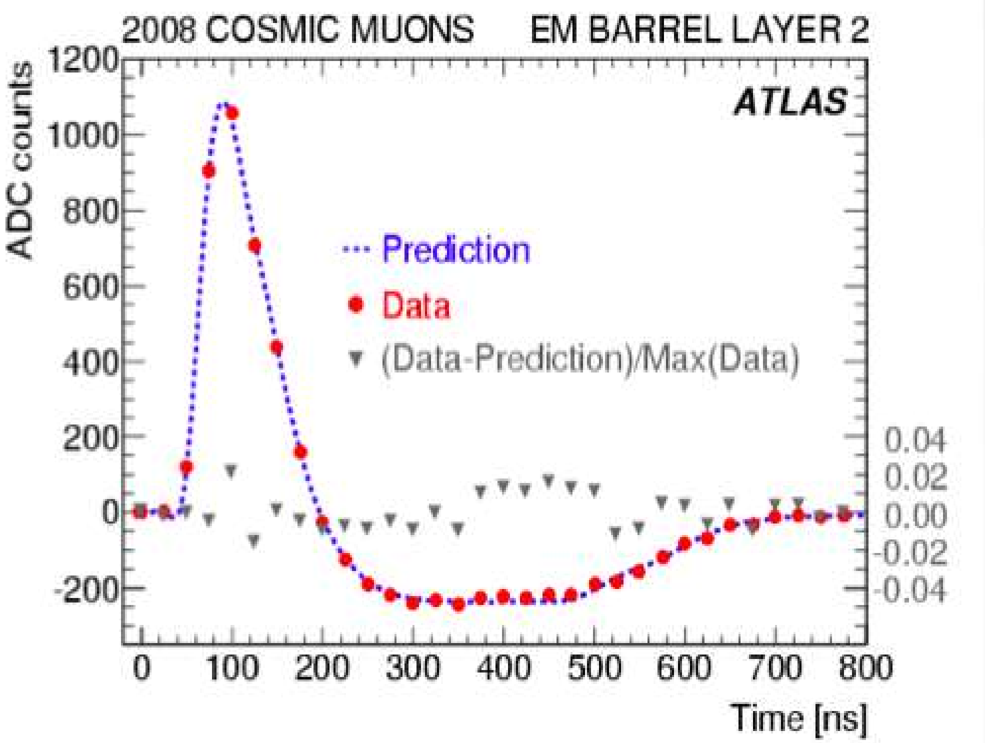


Cascade of electrons and photons due to repeated pair-production and bremsstrahlung

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

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
      - τ2ΘjMΛKO 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

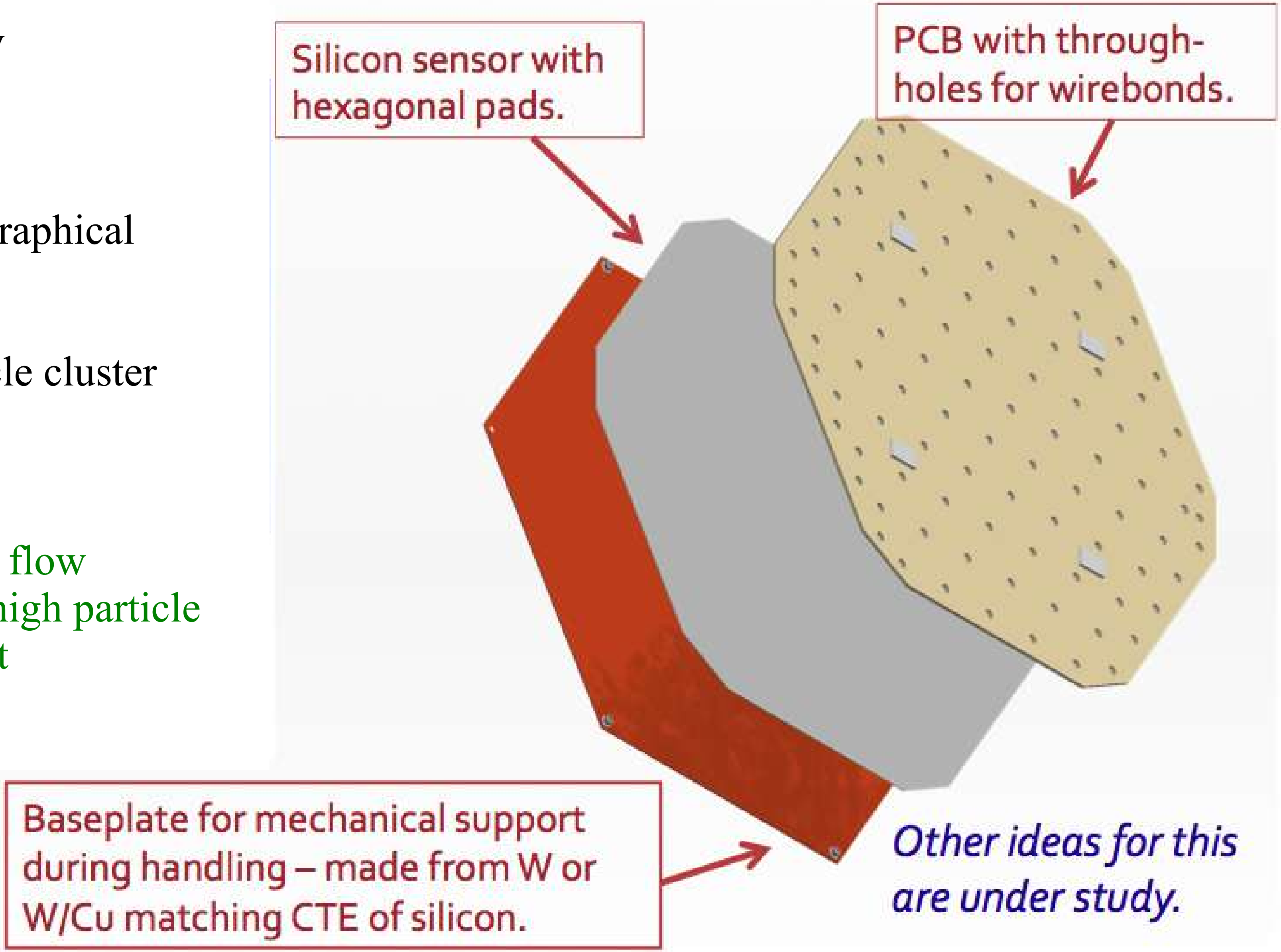
Proposal – Silicon High Granularity Calorimeter

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



Other ideas for this are under study.

Thanks to R. Rusack

Proposal – Silicon High Granularity Calorimeter

Good cluster energy resolution

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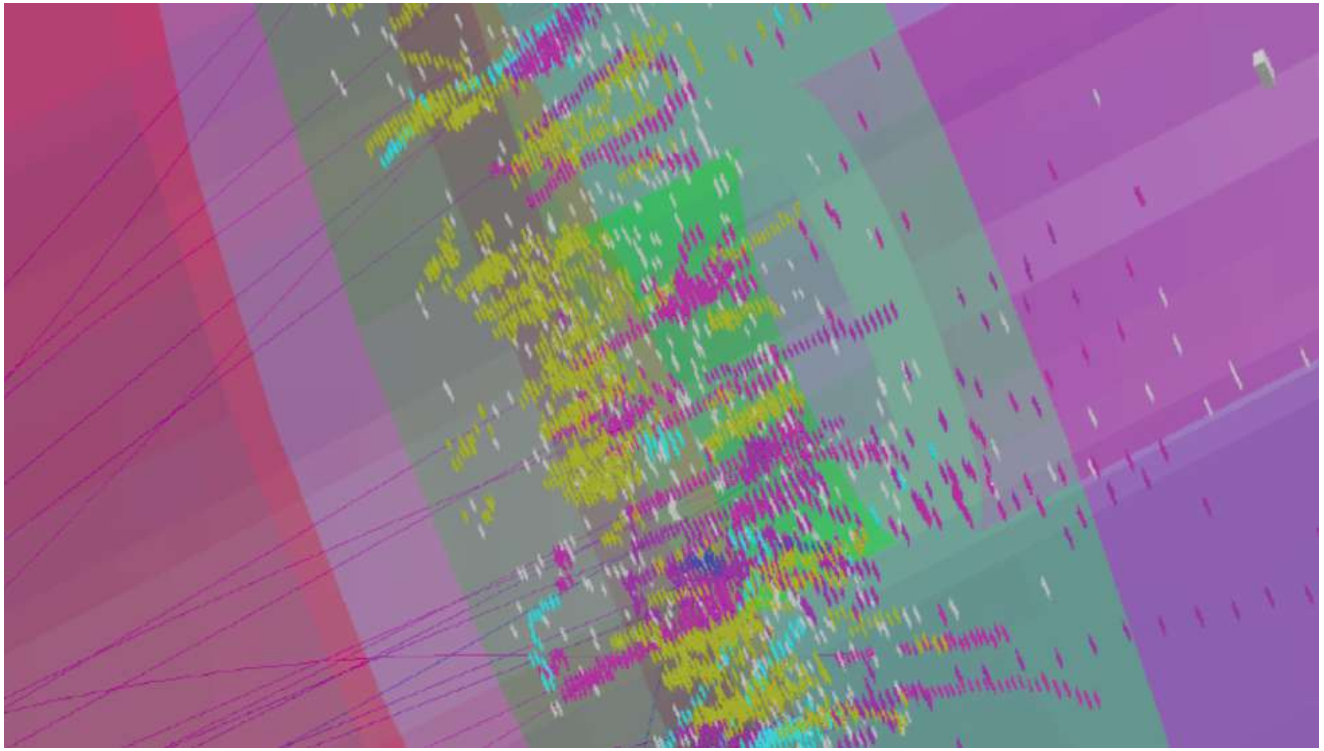
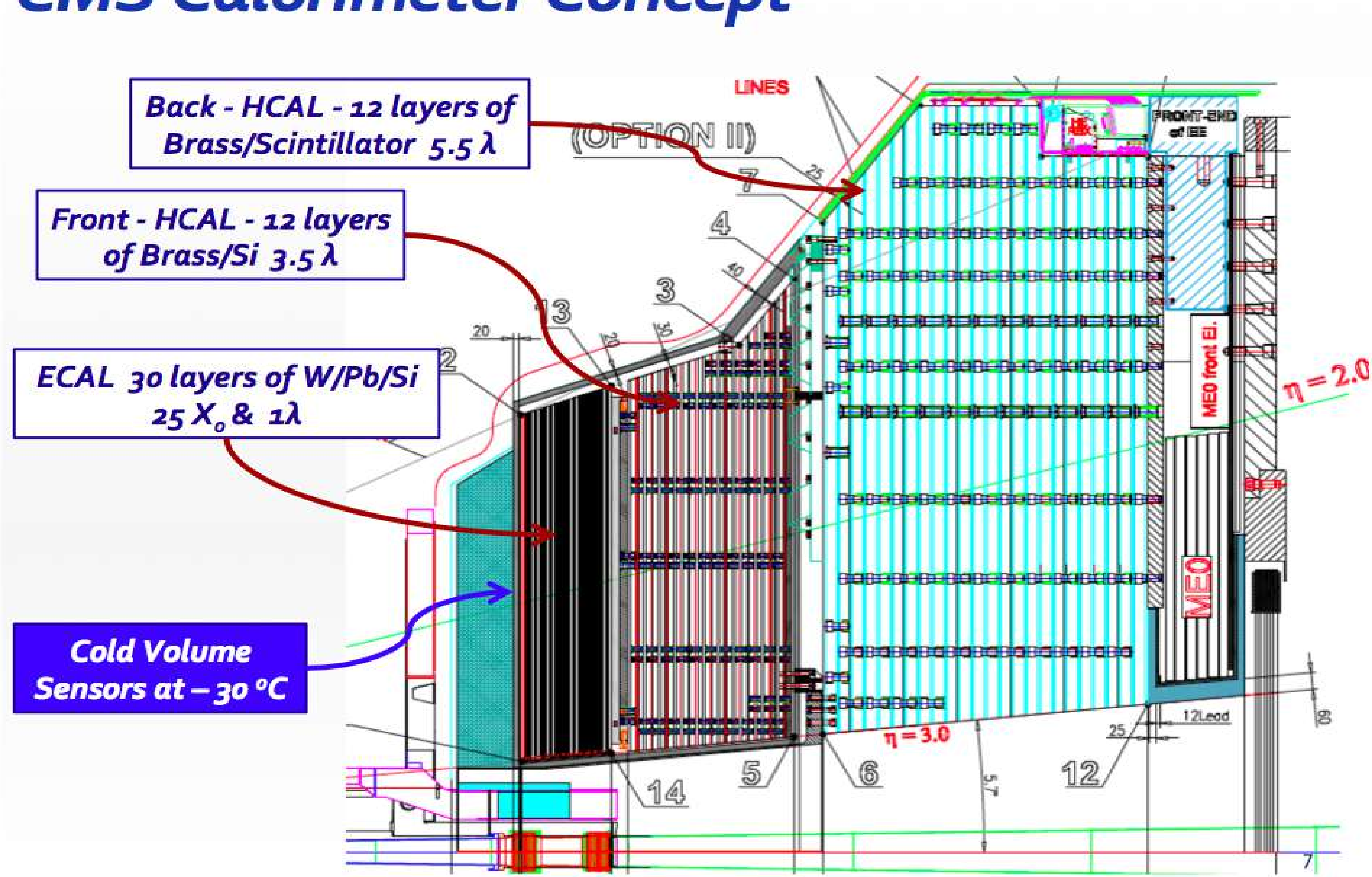


Thanks to R. Rusack

Proposal – Si-HGC for CMS Endcap

CMS Calorimeter Concept



Thanks to R. Rusack

Calorimeter Geometry Issues

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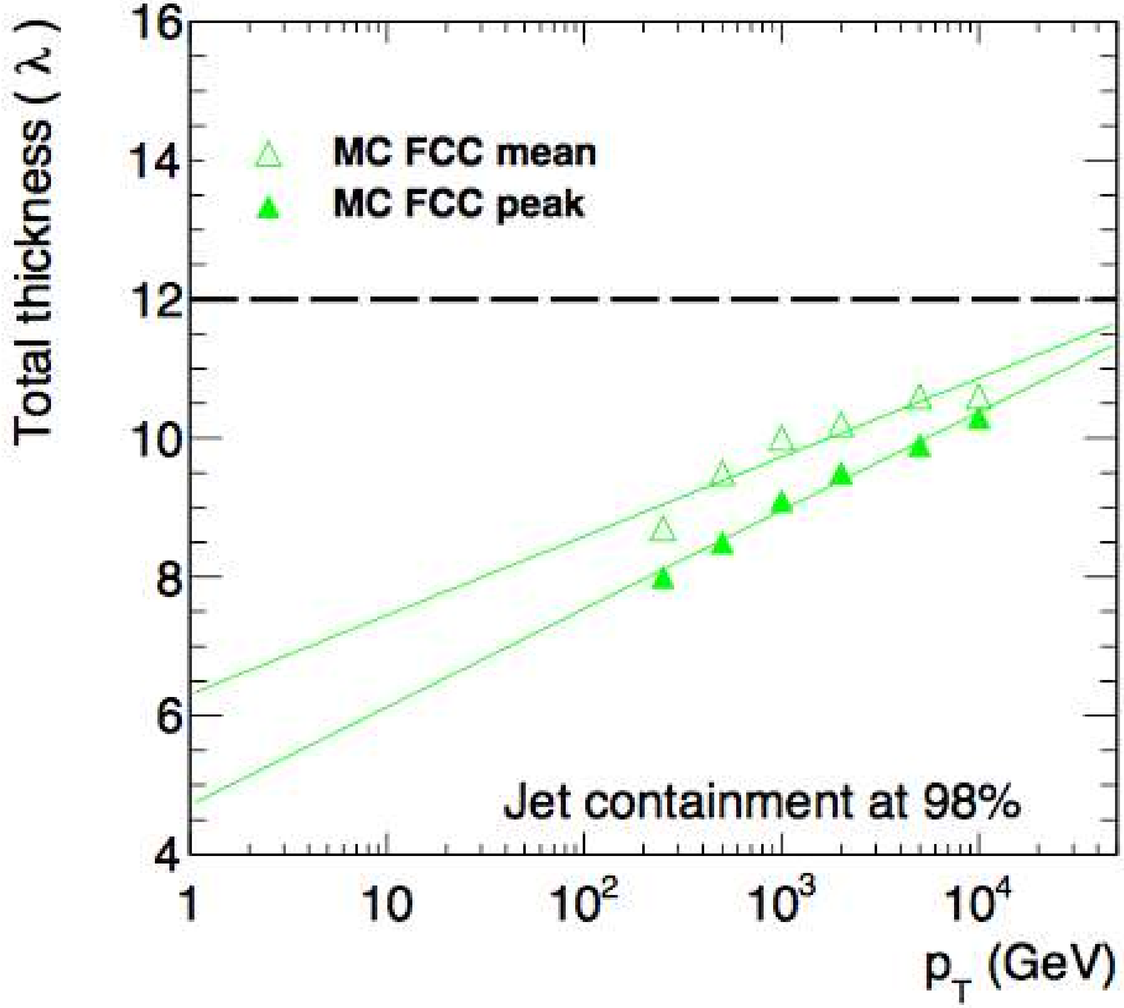
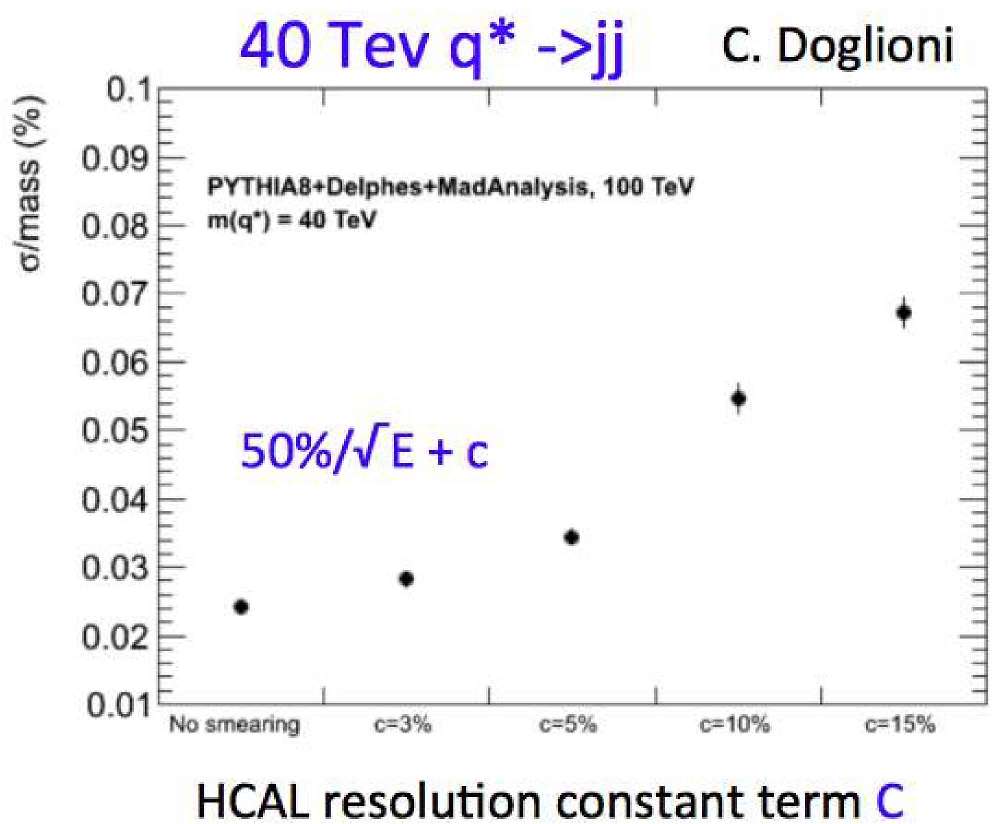


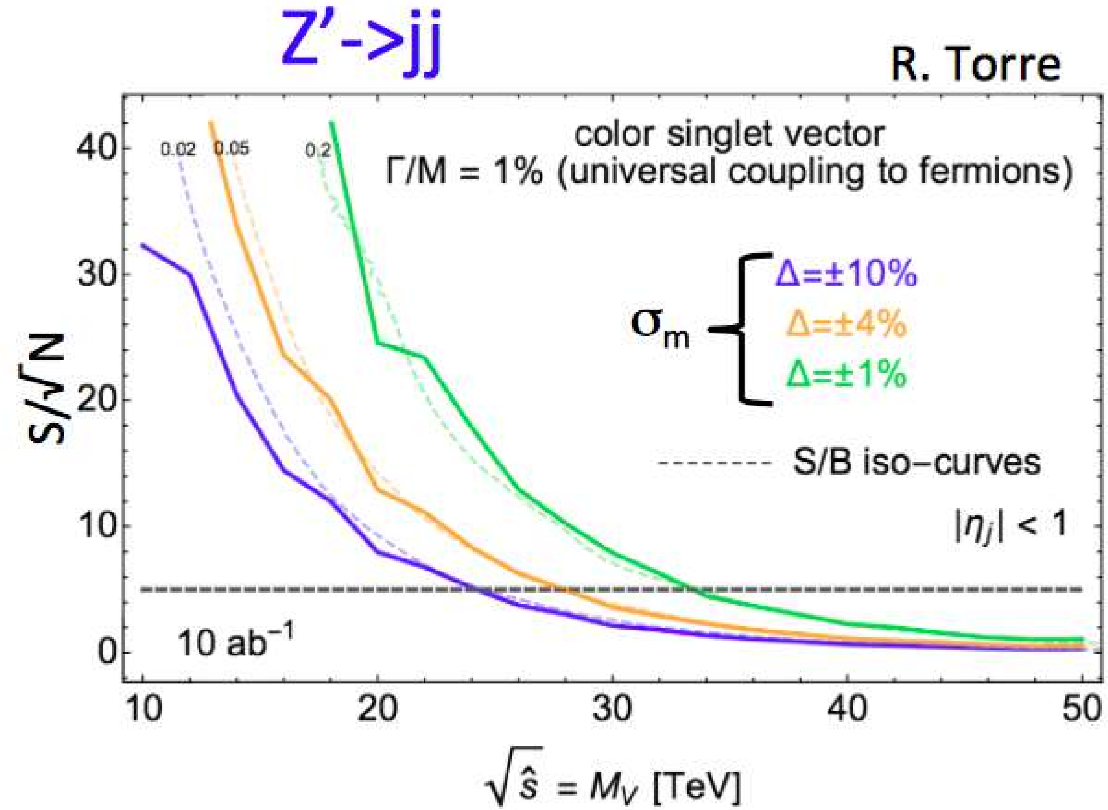
T. Carli *et al*, arXiv:1604.01415

11-12 interaction lengths needed – space constraints (coil radius is expensive)

- Dynamic range of electronics readout required scales linearly with collider energy

Effect of HCAL Energy Resolution on Dijet Resonances





Jet resolution ~2-3% needed for multi TeV dijet ressonances

- Extend Z'→jj discovery potential by 10TeV between σ_m=10% to 1%
- Constant term will dominate at TeV energies ($\sigma/E = a/\sqrt{E} \oplus c$)
- Good shower containment is mandatory!

(from Ana Henriques)

Calorimeter Granularity

- Granularity is a KEY issue: all decay products will be boosted closer together
  - 5 TeV resonance → HH → 4 τ produces 1 TeV τ-lepton
    - Photons within τ-jet are separated by ~2 mm
    - τ-leptons from Higgs separated by ~10 cm
  - 20 TeV resonance → *tt*, top decay products separated by ~3 cm
  - 10 TeV Zprime → WW, boosted W → jets separated by ~3 cm
- Tracking particles inside jets can be crucial
- Exploit particle flow algorithms to the fullest, push experience from CMS and ILC detector design effort

Geant4 simulation of a high-granular calorimeter for TeV-scale boosted particle

S. Chekanov
HEP/ANL

FCC Week. April 11-15, 2016
Rome, Italy

With contributions from:
A.Kotwal (Fermilab/Duke), L.Gray (Fermilab), J.Strube (PNNL), N.Tran (Fermilab), S. Yu (NCU), S.Sen (Duke), J.Repond (ANL), J.McCormick (SLAC),J.Proudfoot (ANL), A.M.Henriques Correia (CERN), C.Solans (CERN), C.Helsens (CERN)

See Sergei Chekanov's talk in BOOST2017

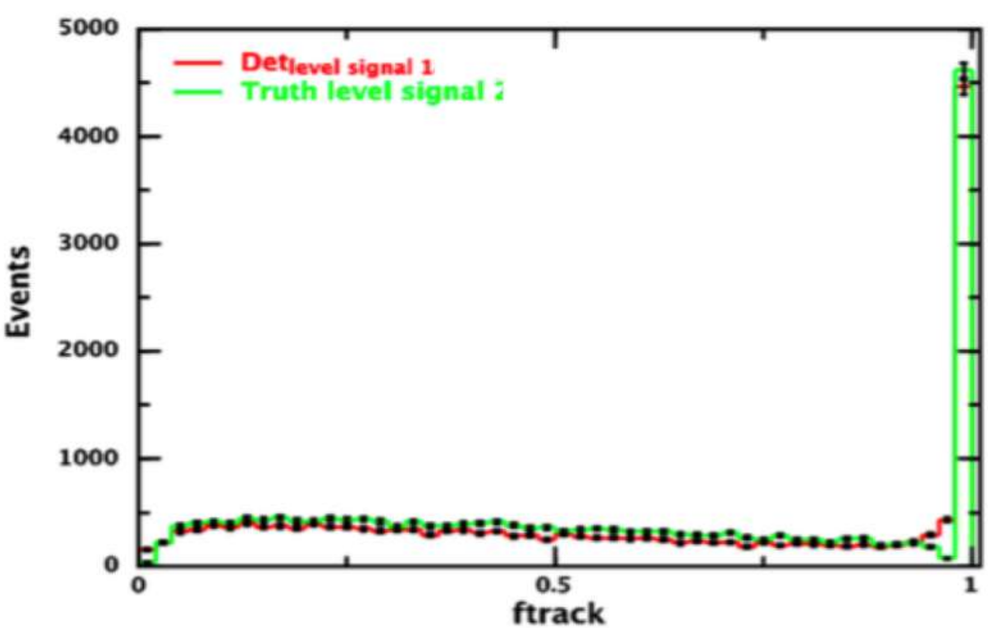
GEANT Simulation of Silicon/Tungsten EM Calorimeter

500 GeV hadronic τ-lepton decays with 4mm x 4mm silicon pads
Background simulation in progress, will investigate larger pad sizes and higher p_T

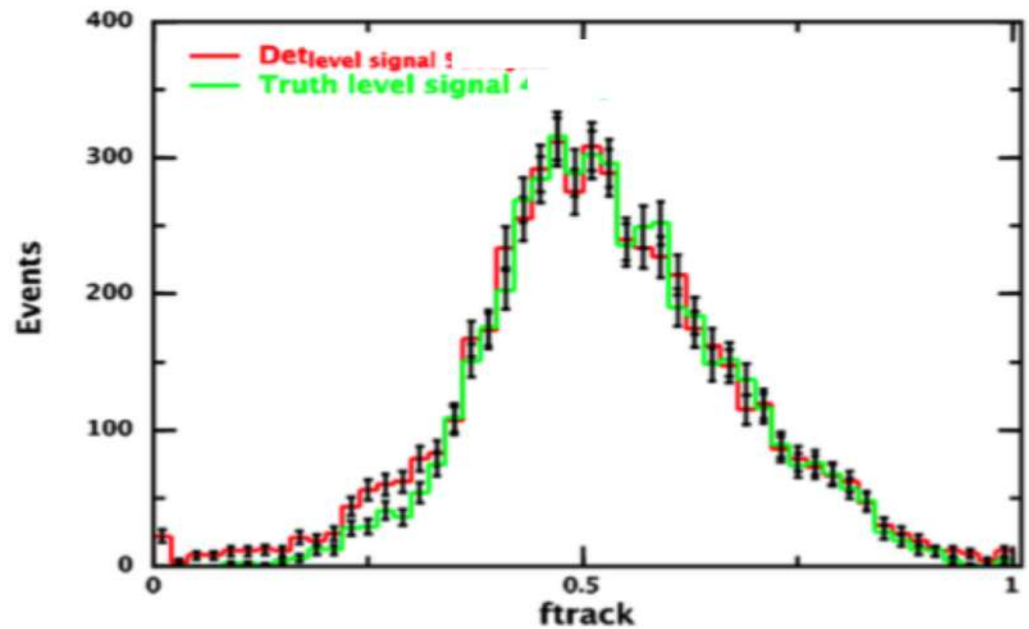
f_{track} (leading track momentum fraction)

=(pT of highest pT track in core region (ΔR < core)) / (Total E_T deposited in ΔR <core)

core = 0.1



1 prong



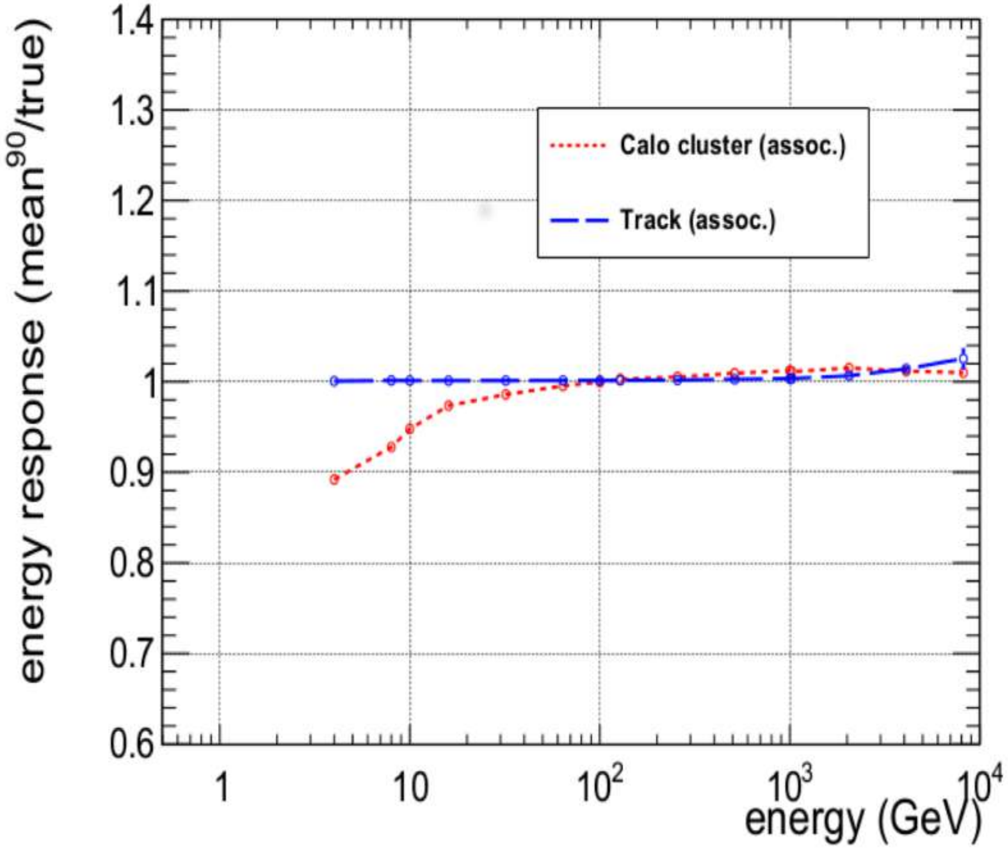
3 prong

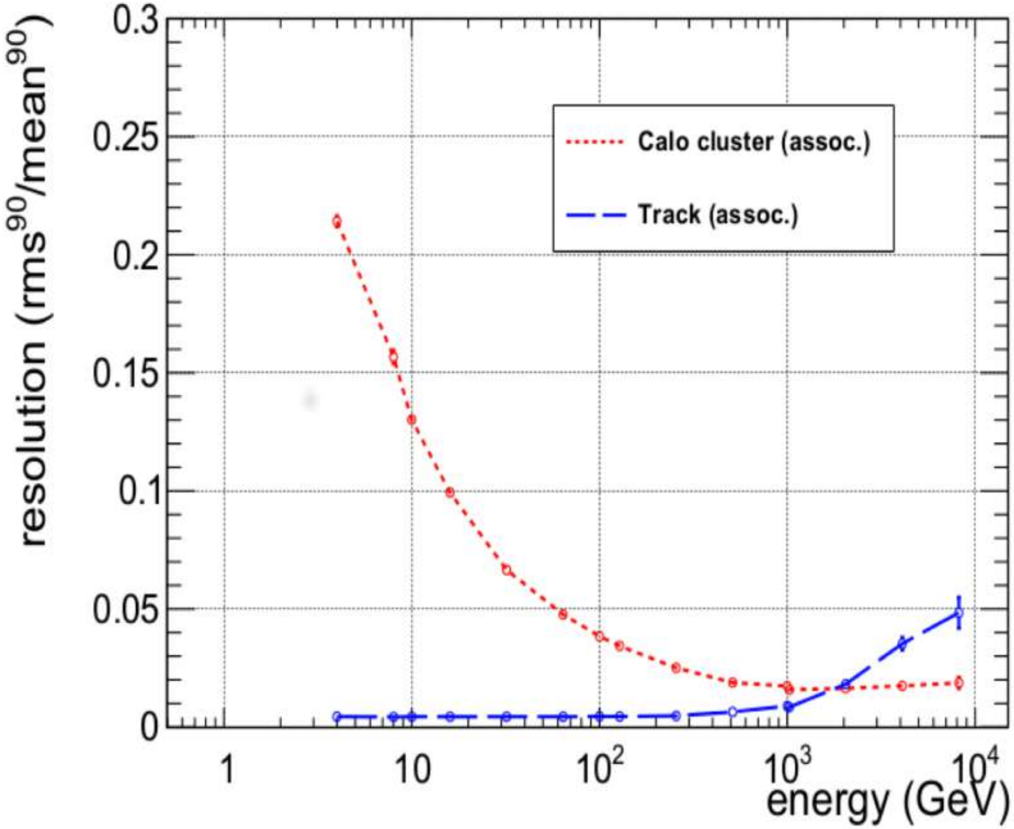
Analysis by Sourav Sen (Duke graduate student)

Higgs → ττ is an important channel to complement γγ and *bb*

GEANT Simulation: Si/W ECAL & Scintillator/Iron HCAL

Single pion response and resolution

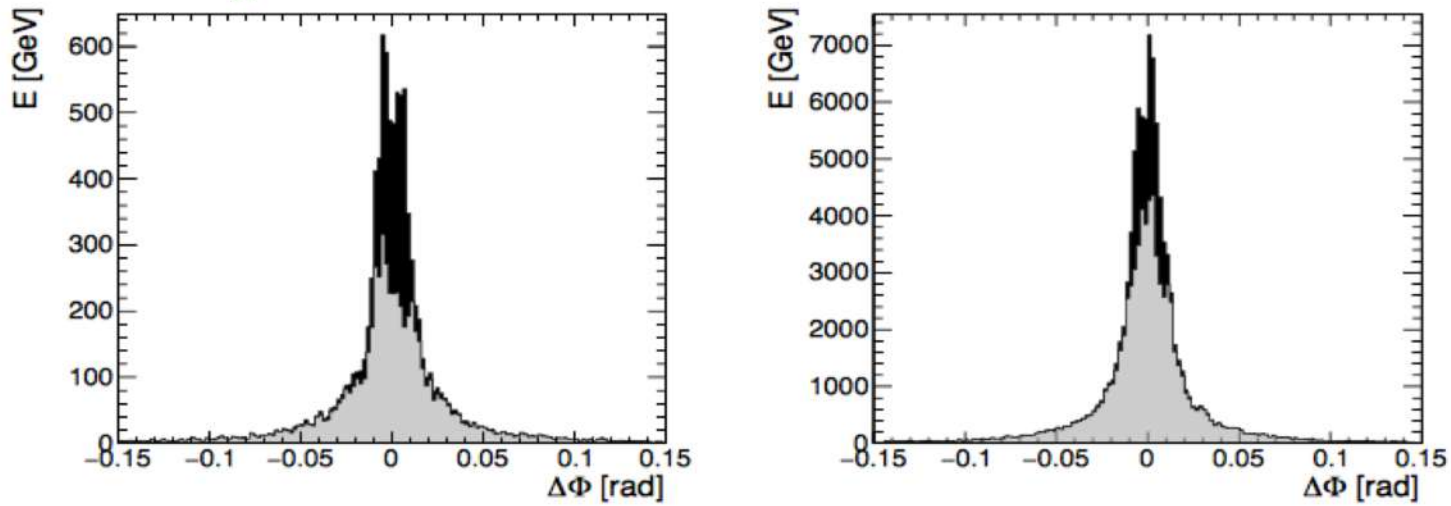




- Analysis by S. Yu, N. Tran and S. Chekanov
- First look at boosted object discriminating variables
- Published in **JINST 12 (2017) no.06, P06009**

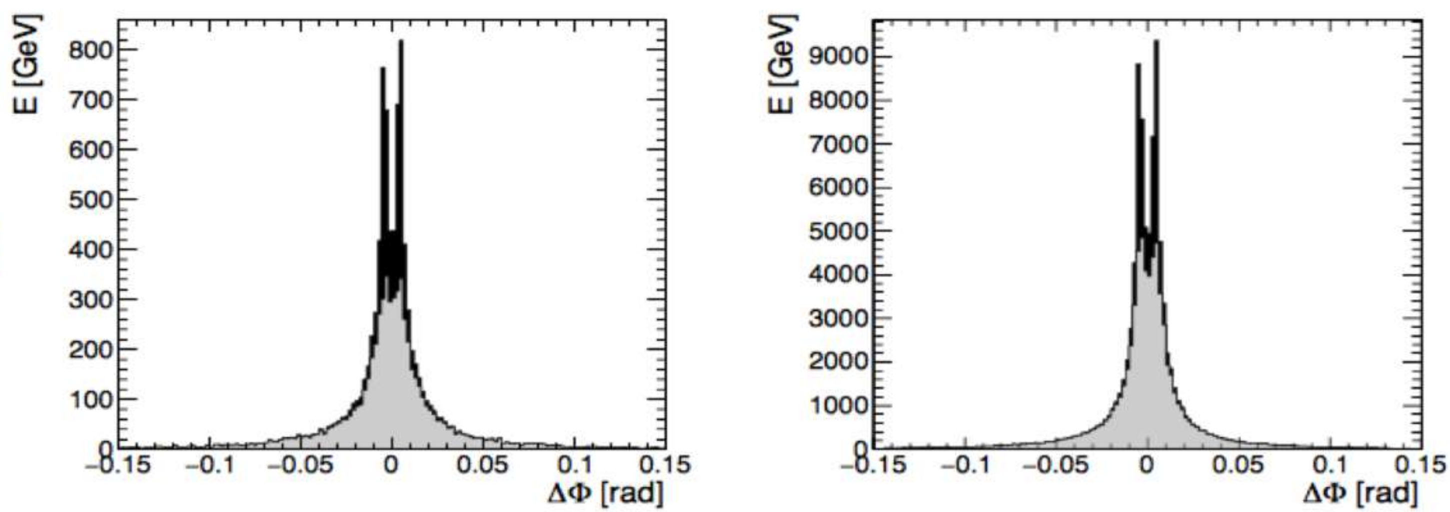
GEANT Simulation: Silicon/Tungsten EMCAL & Iron/Scintillator HCAL

Dual K^0_L spatial separation (generated $\Delta\phi$ = 10 mrad)



(b) 5 × 5 cm HCAL cells and 2 × 2 cm ECAL cells

- Analysis by Nhan Tran
- Published in **JINST 12 (2017) no.06, P06009**



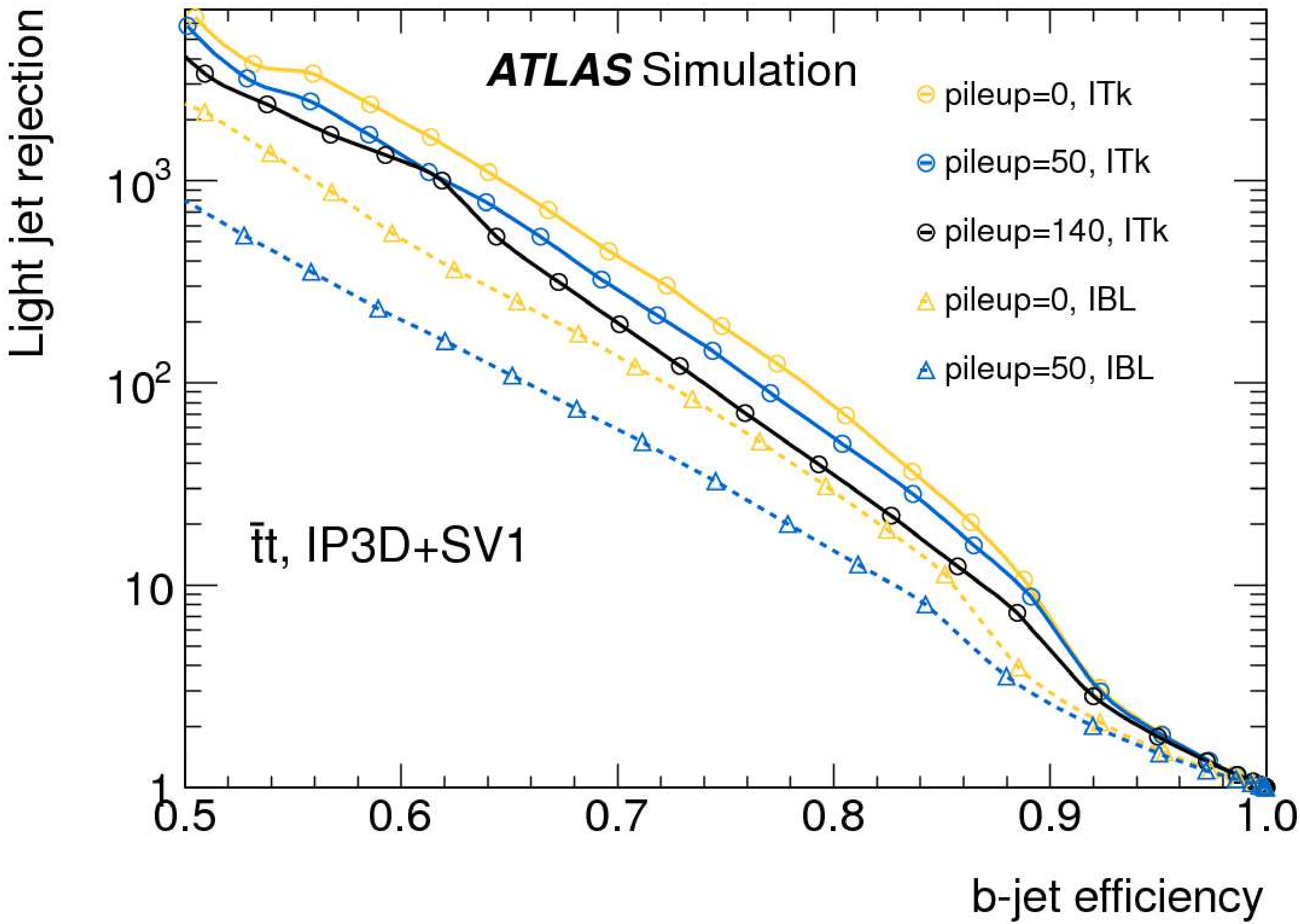
(c) 1 × 1 cm HCAL cells and 3 × 3 mm ECAL cells

Figure 14: Azimuthal distribution of energy deposition for pair of incident K_L^0 particles at 100 GeV (left) and 1000 GeV (right), with the angular separation of $\Delta\phi^K = 0.009$ rad. Electromagnetic calorimeter cells are indicated in black while hadronic calorimeter cells are indicated in gray.

b-tagging

CMS Barrel Pixel detector

Design Performance for HL-LHC



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

b-tagging

- FCC stage 1 plans to deliver ~3 ab^{-1}
  - Similar conditions as HL-LHC, pileup ~ 200 at 25 ns bunch crossing
- FCC stage 2 plans to deliver ~ 15 ab^{-1}
  - Pileup ~ 1000
    - or 5 ns bunch crossing? If very fast detectors have no out-of-time pileup

- Need to achieve same *b*-tagging performance in higher-density environments
  - Highly boosted top quarks and Higgs bosons from heavy resonance decays
  - Width of b-jet ~300 microns at 2 cm radius
  - Need to resolve tracks with factor x5 higher local density than LHC

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"

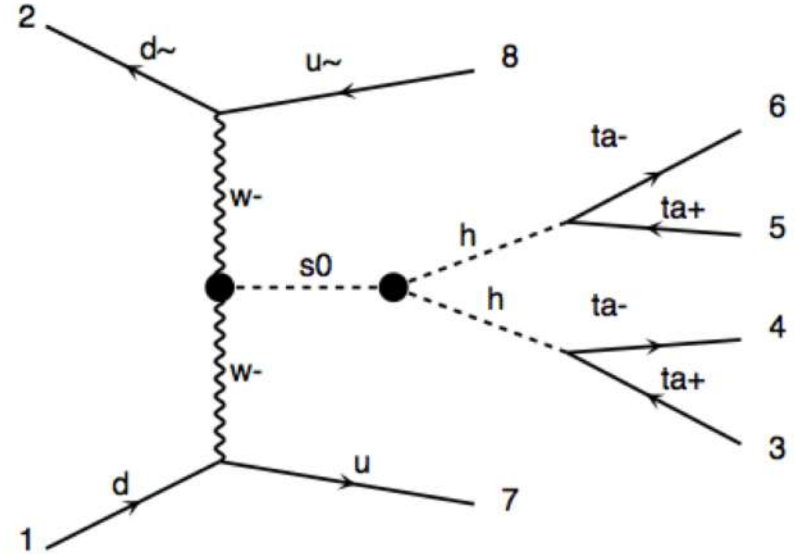
- Vector boson scattering topology
  - Quarks emit longitudinal vector bosons which interact with new (presumably strong) dynamics
  - Quarks scatter by small angle in the forward direction

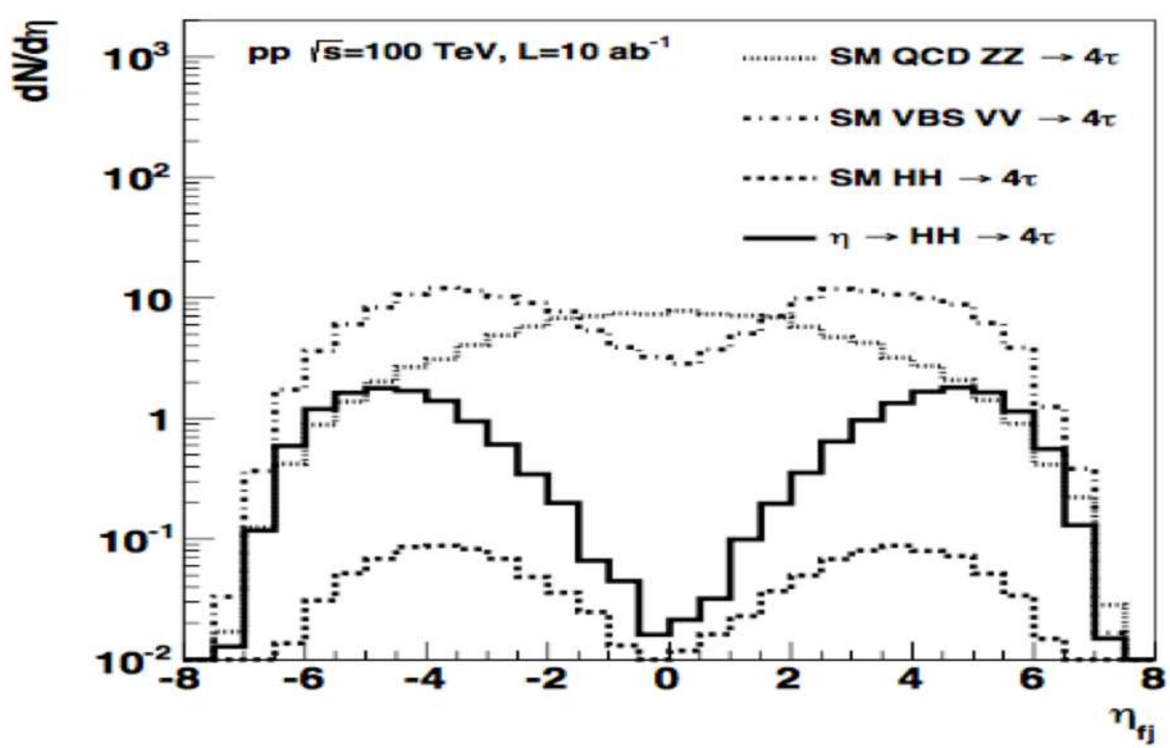
Vector Boson Scattering

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.

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

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

Vector Boson Scattering

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Phys.Rev. D91 (2015) 114018

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

Want jet rapidity coverage up to 6 at least

Forward Jet Coverage for Longitudinal VBS

$V_L V_L \rightarrow \eta \rightarrow HH$

AVK, S. Chekanov, M. Low

TABLE II. 5σ discovery mass reach for the $\eta \rightarrow HH \rightarrow 4\tau$ resonance, at a pp collider with $\sqrt{s} = 100$ TeV and $\mathcal{L} = 10$ 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

- Lower p_T threshold on forward tagging jets is preferred
  - Reject pileup jets with good tracking in forward direction
  - Resolve overlapping pileup jets with higher granularity / spatial resolution (*a la* CMS high-granularity endcap calorimeter for HL-LHC)

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

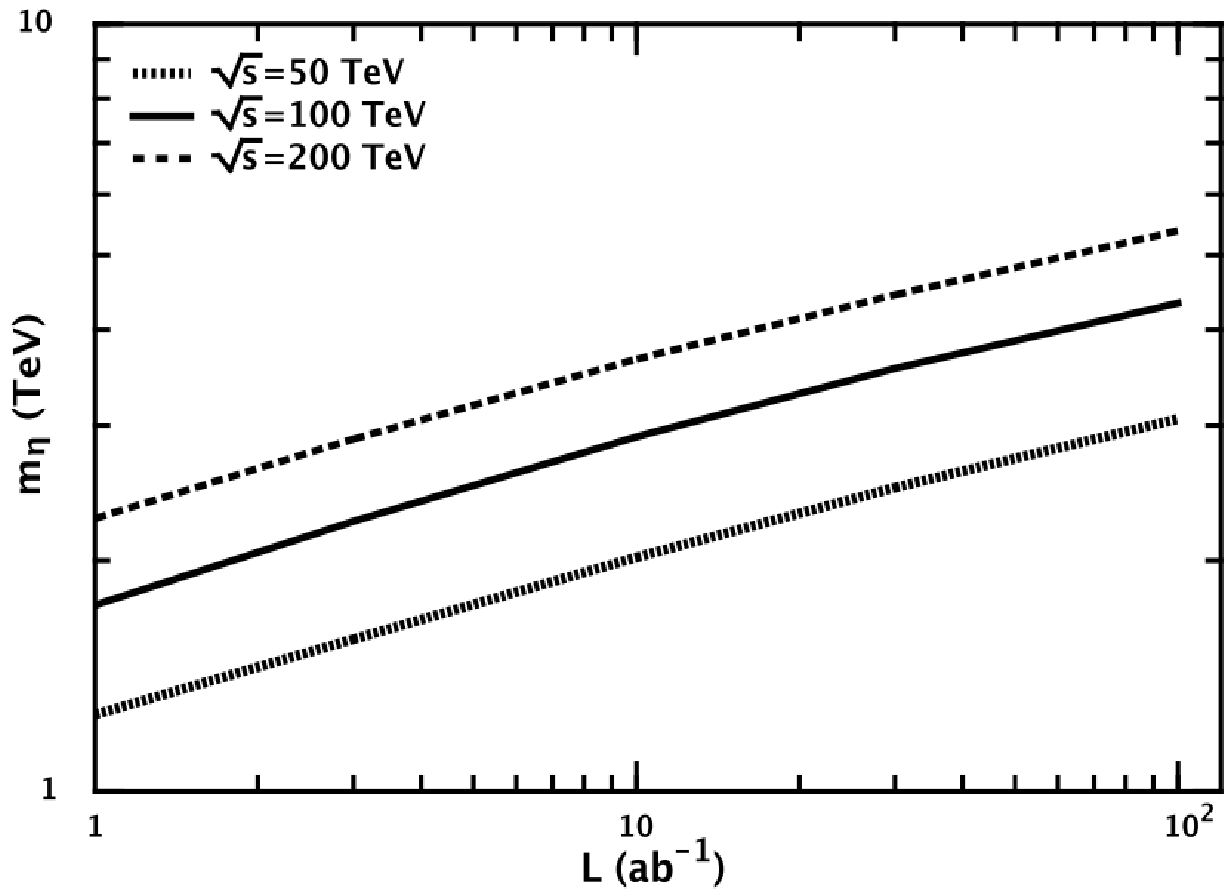
TABLE V. 5σ discovery mass reach for the $\eta \to HH \to 4\tau$ resonance, as a function of the $\sqrt{s}$ of a pp collider. The fractional resonance width Γ_η/m_η is fixed at 70%. These results are illustrated in Fig. 14.

$\mathcal{L}$	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

Forward Jet Coverage for Longitudinal VBS

$V_L V_L \rightarrow \eta \rightarrow HH$

M. Low,
S. Chekanov,
AVK



5σ discovery mass reach

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

Scaling behavior of sensitivity with integrated luminosity and collider energy

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

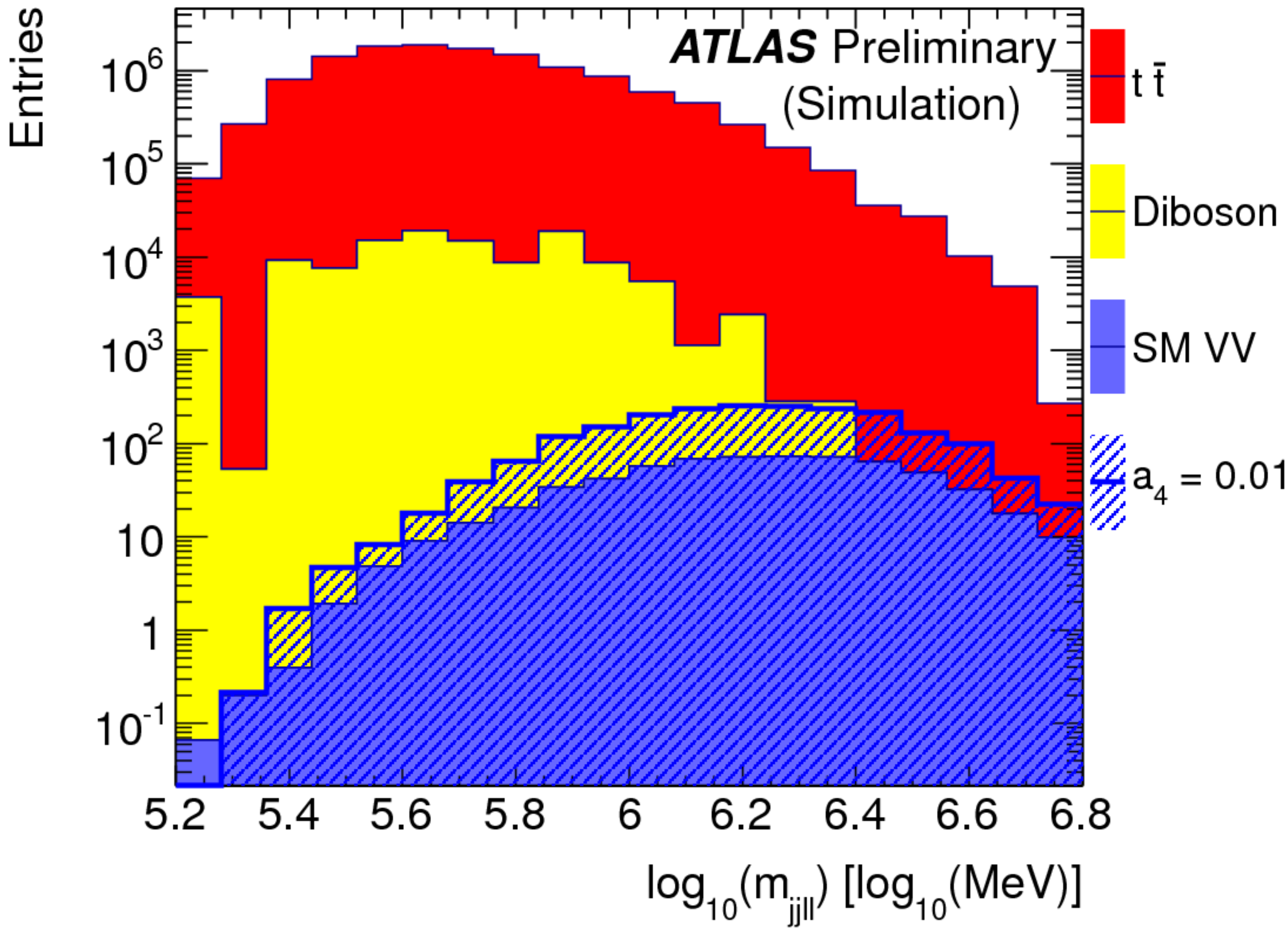
Find approximate scaling coefficients (with some dependence on resonance width)

Factor of 10 more luminosity: 50% higher mass reach

Doubling of collider energy: 40% higher mass reach

$VV \rightarrow WW$ Scattering

3 ab^{-1}



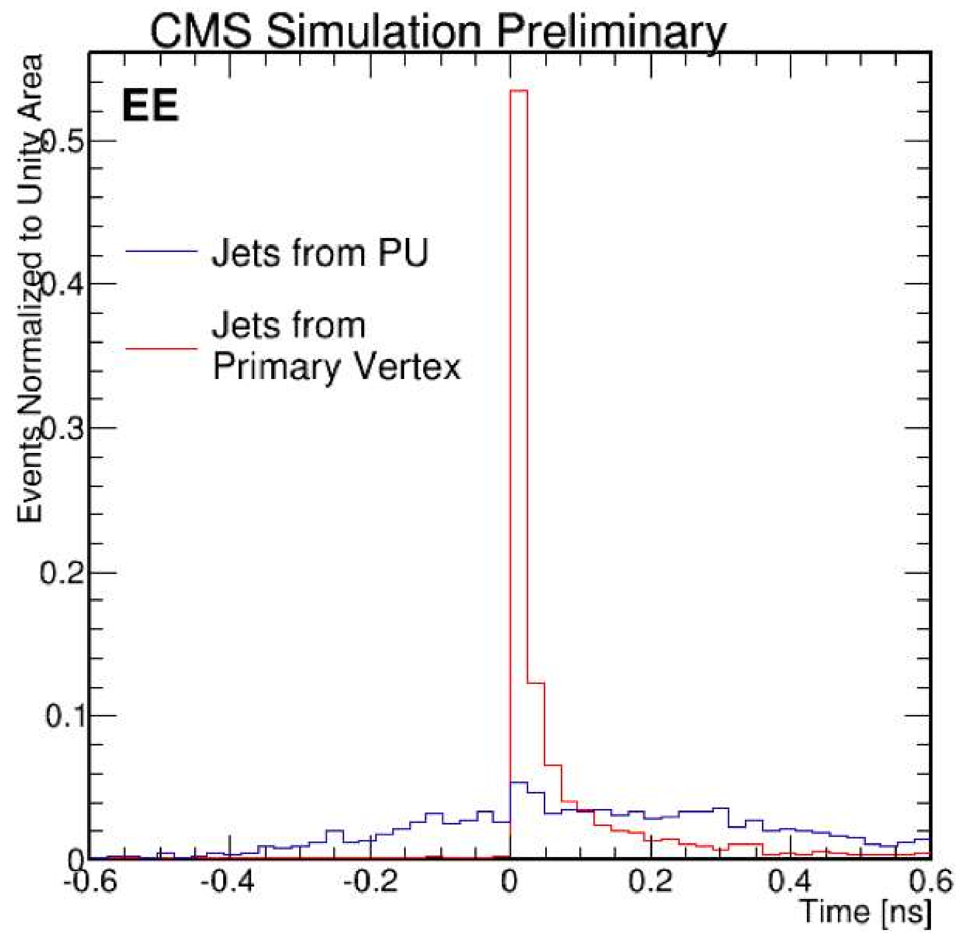
For W^+W^- final state in VBS, *tt* background is problematic

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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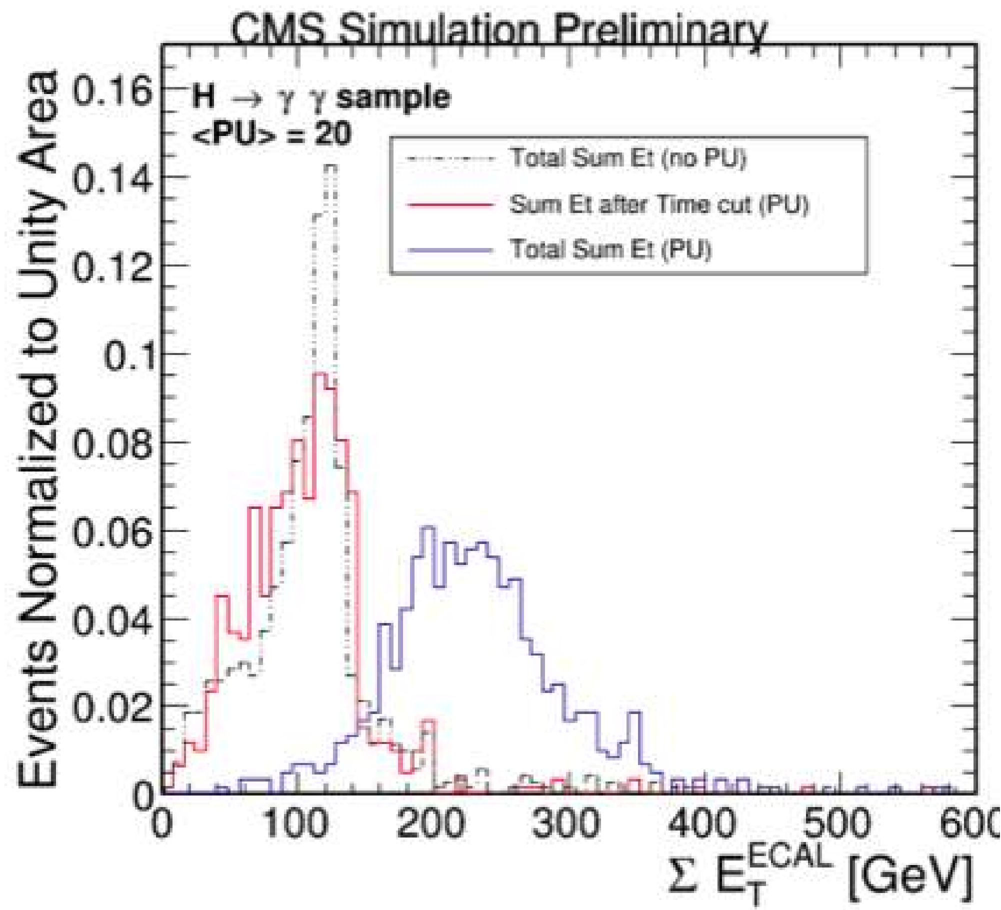
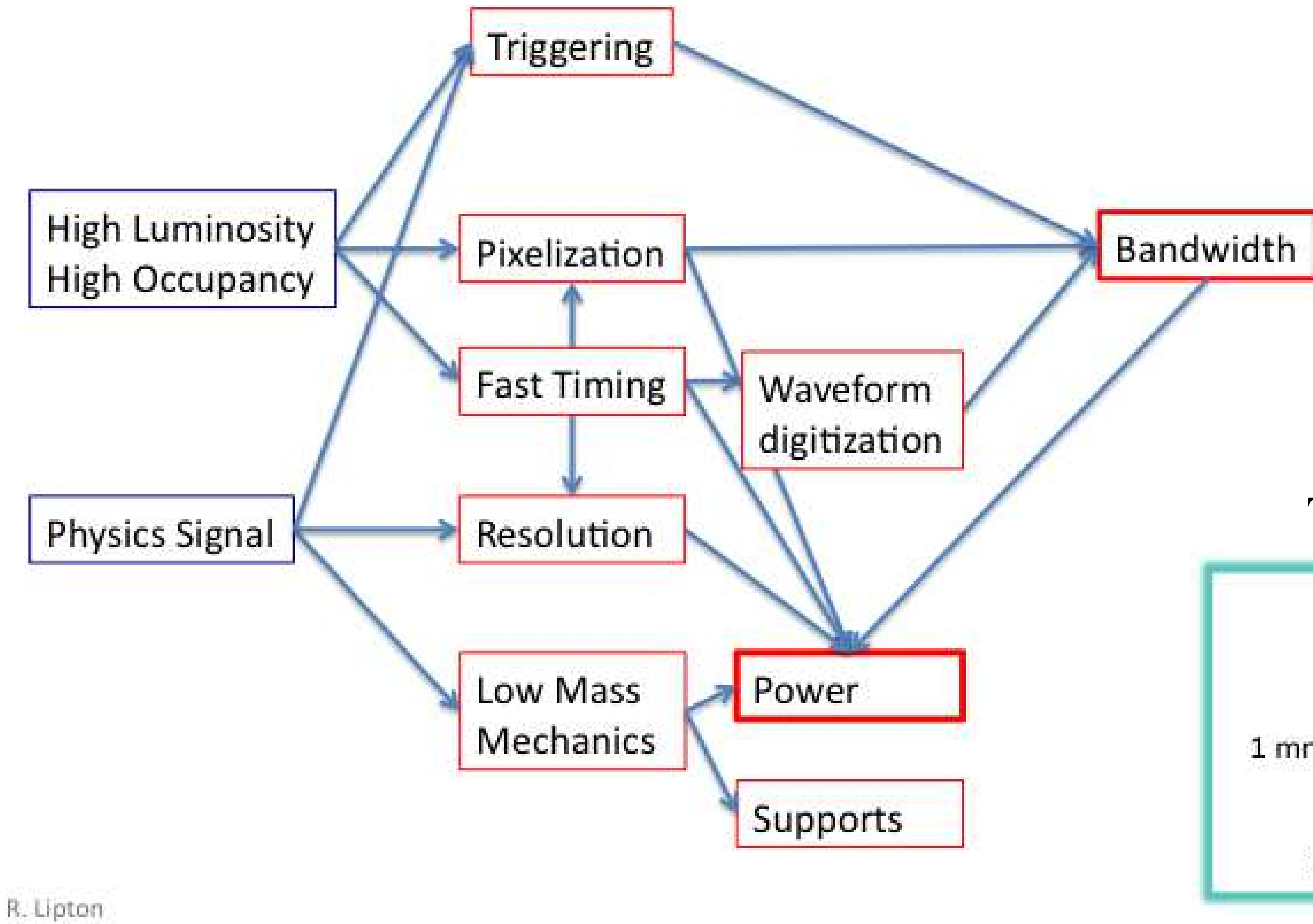
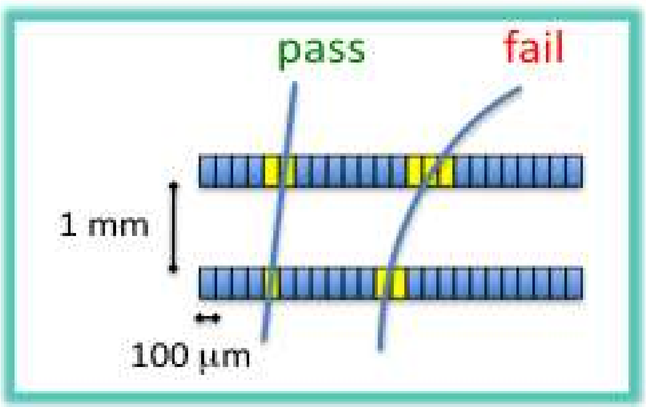


Summary

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
  - ∫ PUΓ ΓΕΒΓ⌡ΞΞ⌡ΟΛΘΠΕΛΚ
  - ∫ PUΓ ΓΕΒΓ⌡ΞΒΞ∈ΚΡΘΞΞΦ
  - Much more forward-detection capability
  - Much higher bandwidth, smarter triggers
- Substantial knowledge & experience on design gained from HL-LHC upgrade

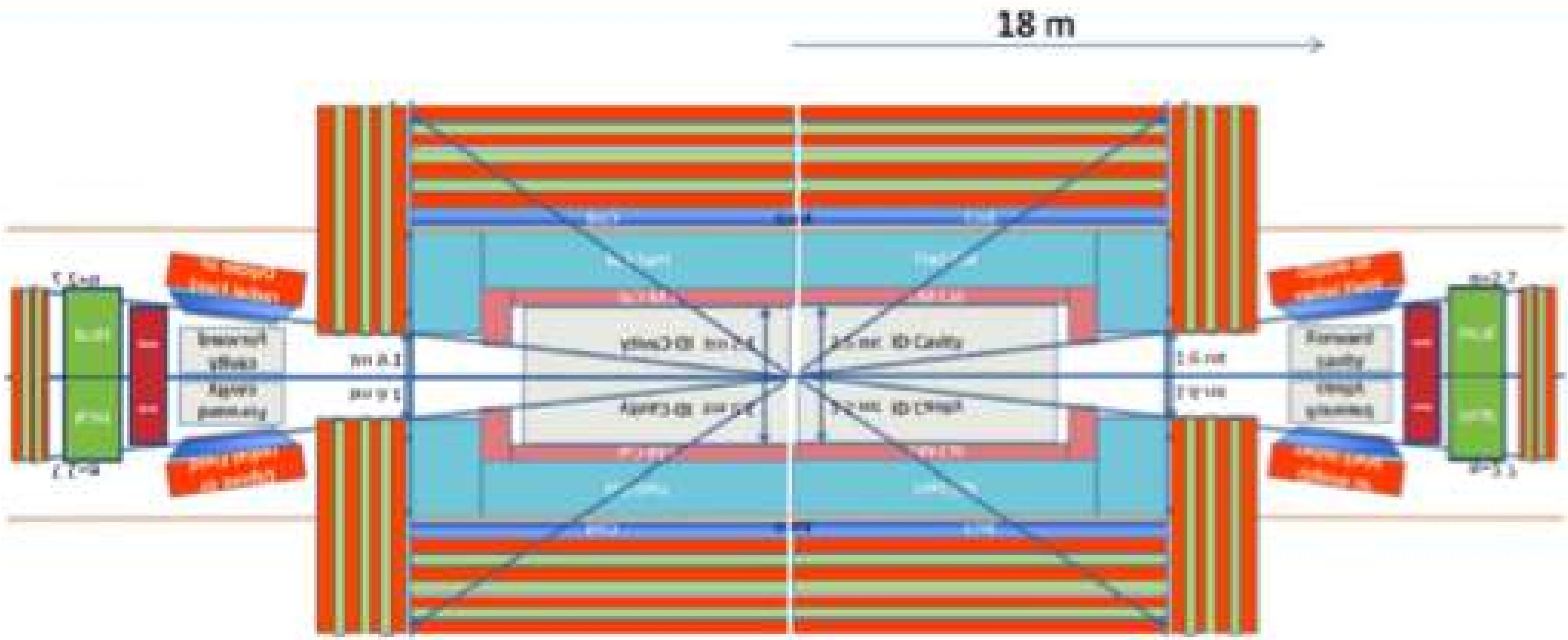
Summary

- 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 11 Tesla magnet with Niobium/Tin (Niobium/Titanium is industry standard)

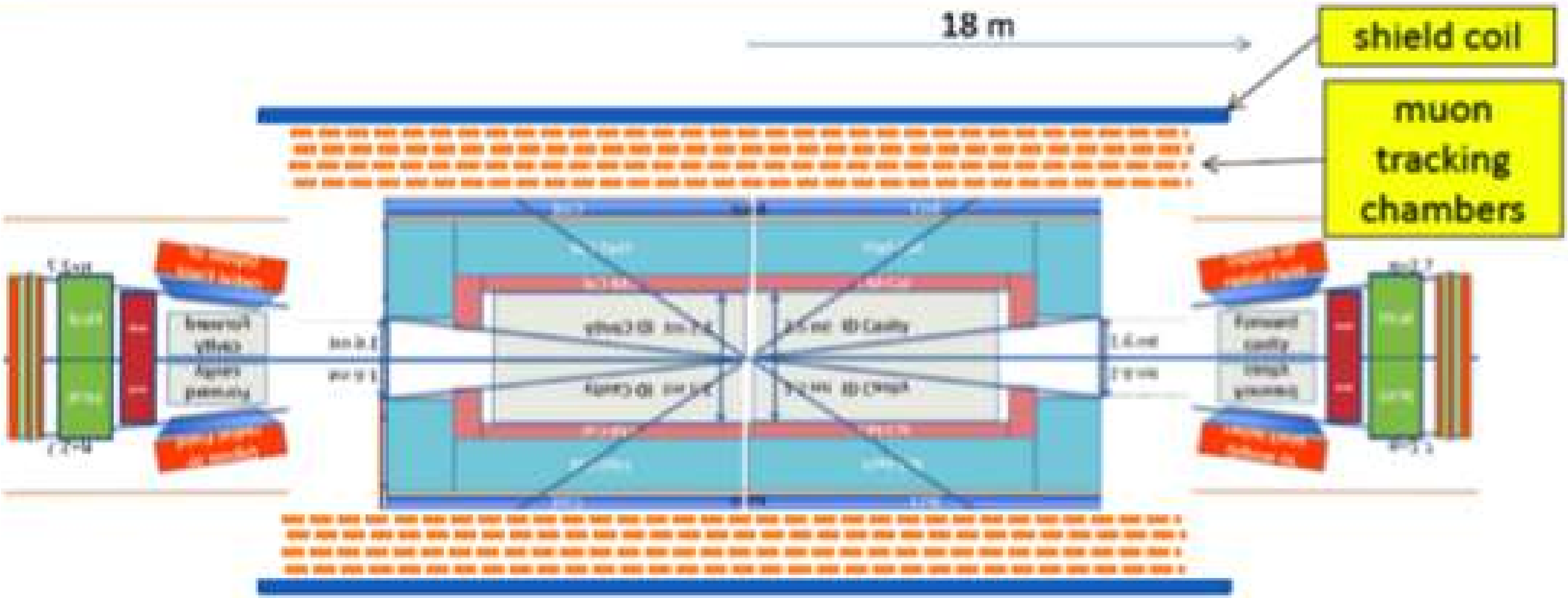
- Integrated luminosity
  - 10 ab^{-1} is a good starting point
  - CERN-FCC has proposed 17 ab^{-1} target
  - Useful to compare 3 ab^{-1}, 10 ab^{-1} and 30 ab^{-1} sensitivities
  - Motivate higher luminosity if needed to produce definitive answer

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

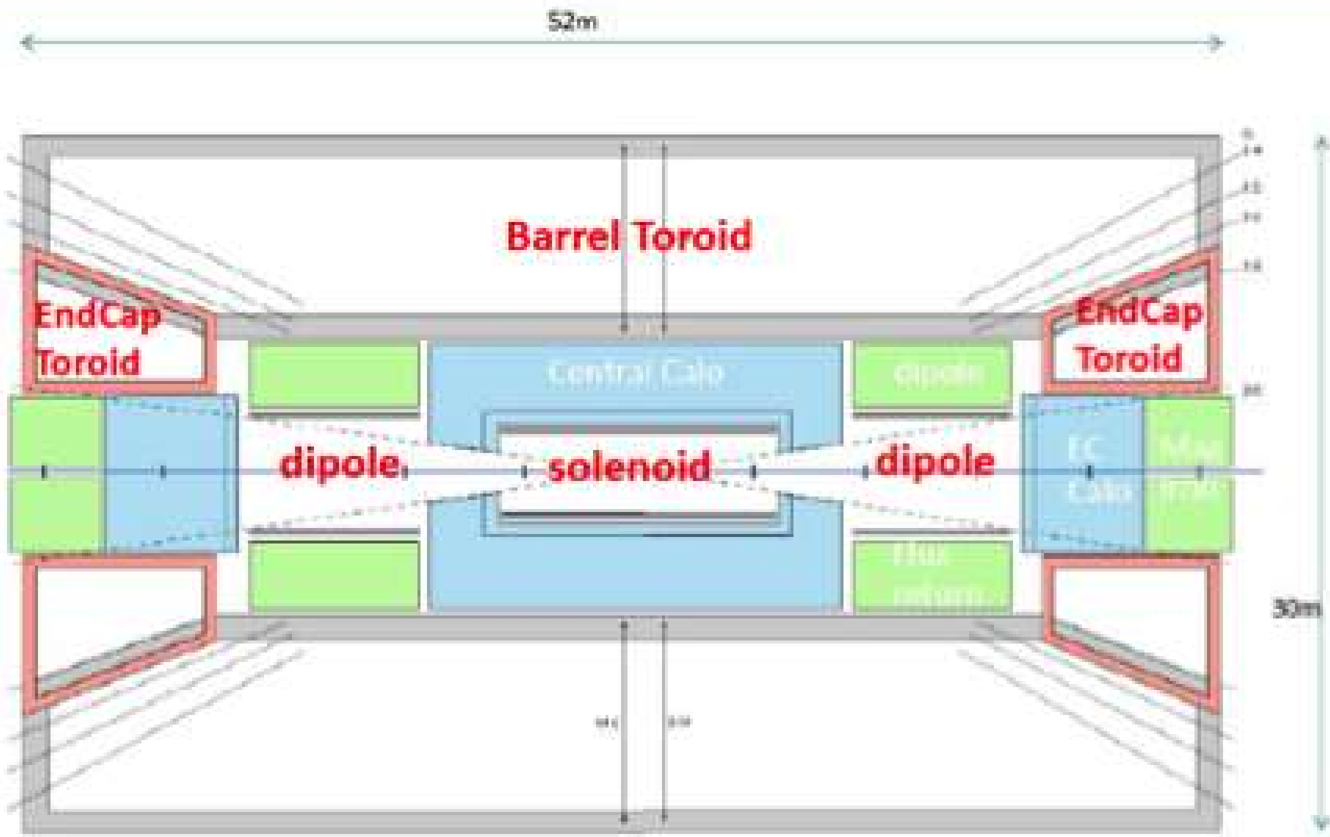


Twin Solenoid: a 6 T, 12 m dia x 23 m long main solenoid + an active shielding coil

Important advantages:

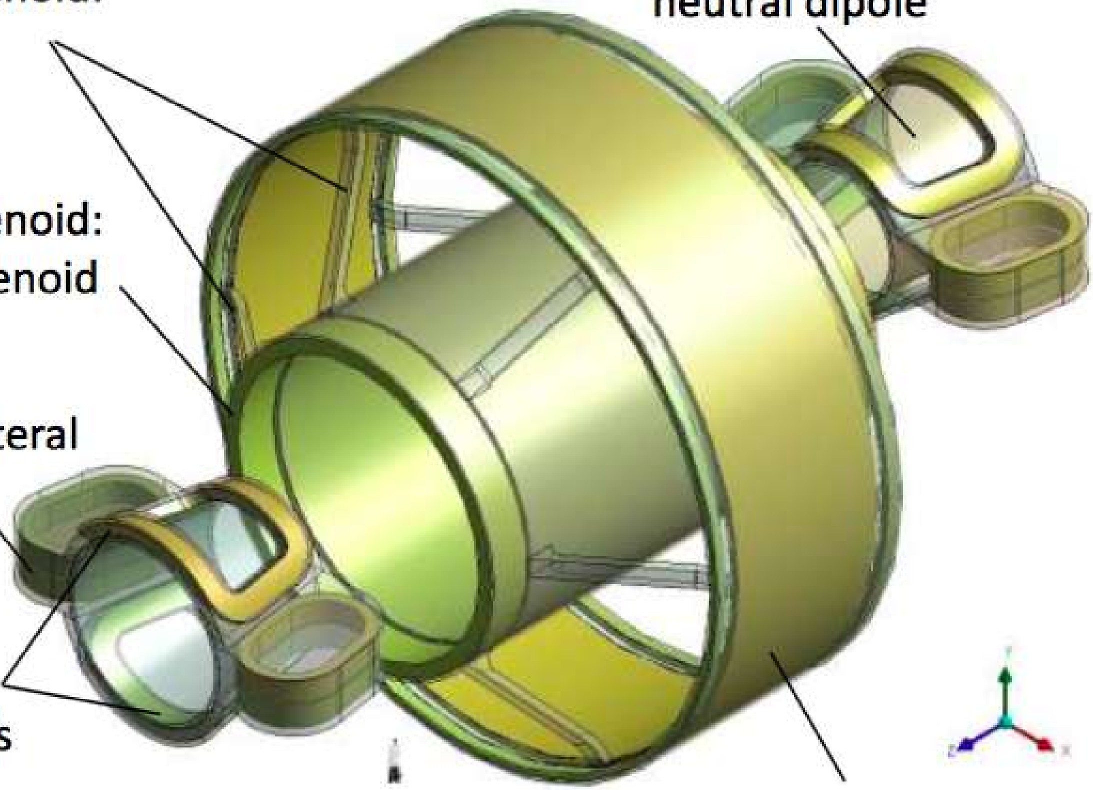
- ✓ **Nice Muon tracking space:** area with 2 to 3 T for muon tracking in 4 layers.
- ✓ **Very light:** 2 coils + structures, ≈ 5 kt, only ≈ 4% of the option with iron yoke!
- ✓ **Much smaller:** system outer diameter is significantly less than with iron .

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).

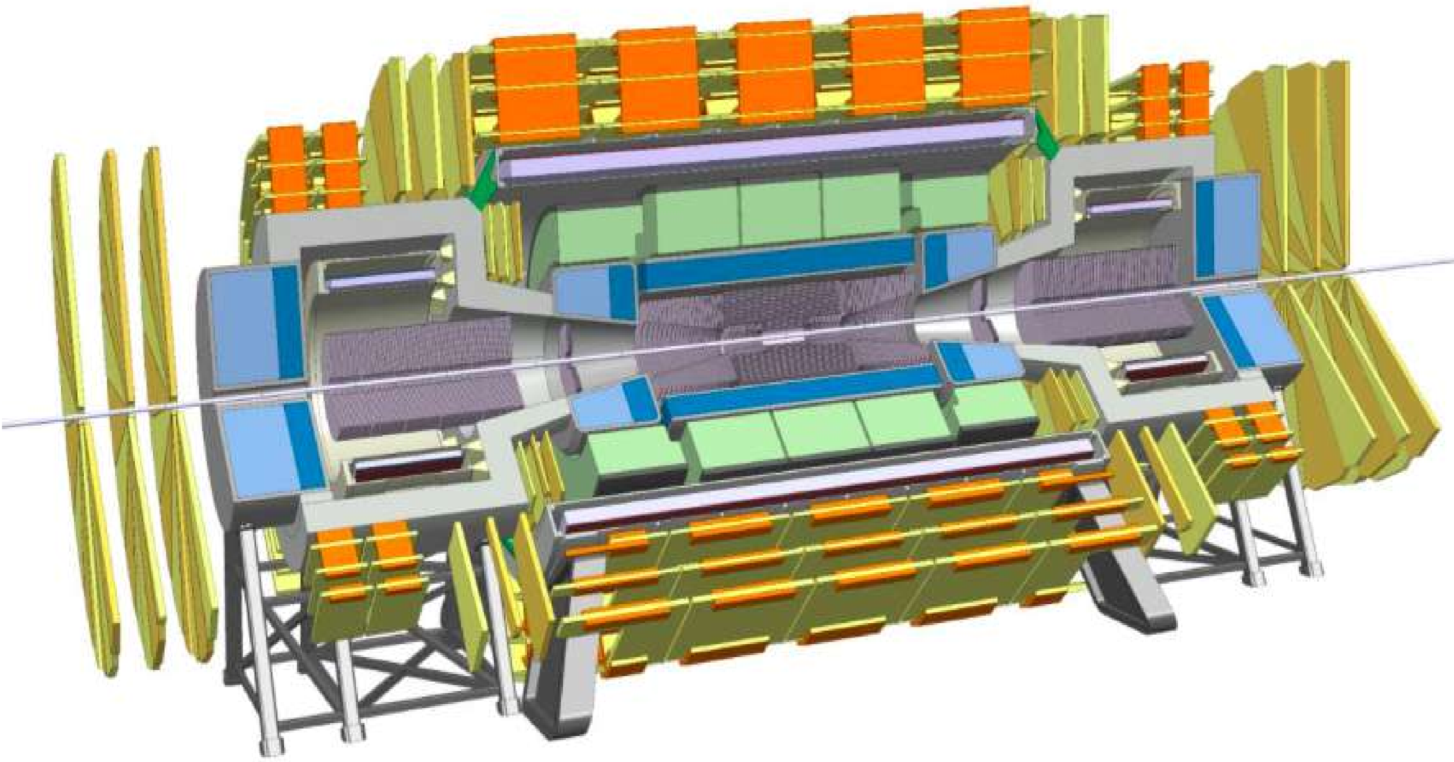
Twin Solenoid & Dipole system – bare coils



Property	Value
TS cold mass	3.2 kt
TS vacuum vessel mass	2.4 kt
TS stored energy	53 GJ
Dipoles cold mass	2x 380 t
Dipoles vac. vessel mass	To be det.
Dipoles stored energy	2x 1.5 GJ
Free bore	12 m
Outer diameter	27 m
System length	42 m
Total stored energy	**56 GJ**

(from Herman ten Kate)

Reference detector for the CDR



- 4T 10m solenoid
- Forward solenoids
- Silicon tracker
- Barrel ECAL Lar
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

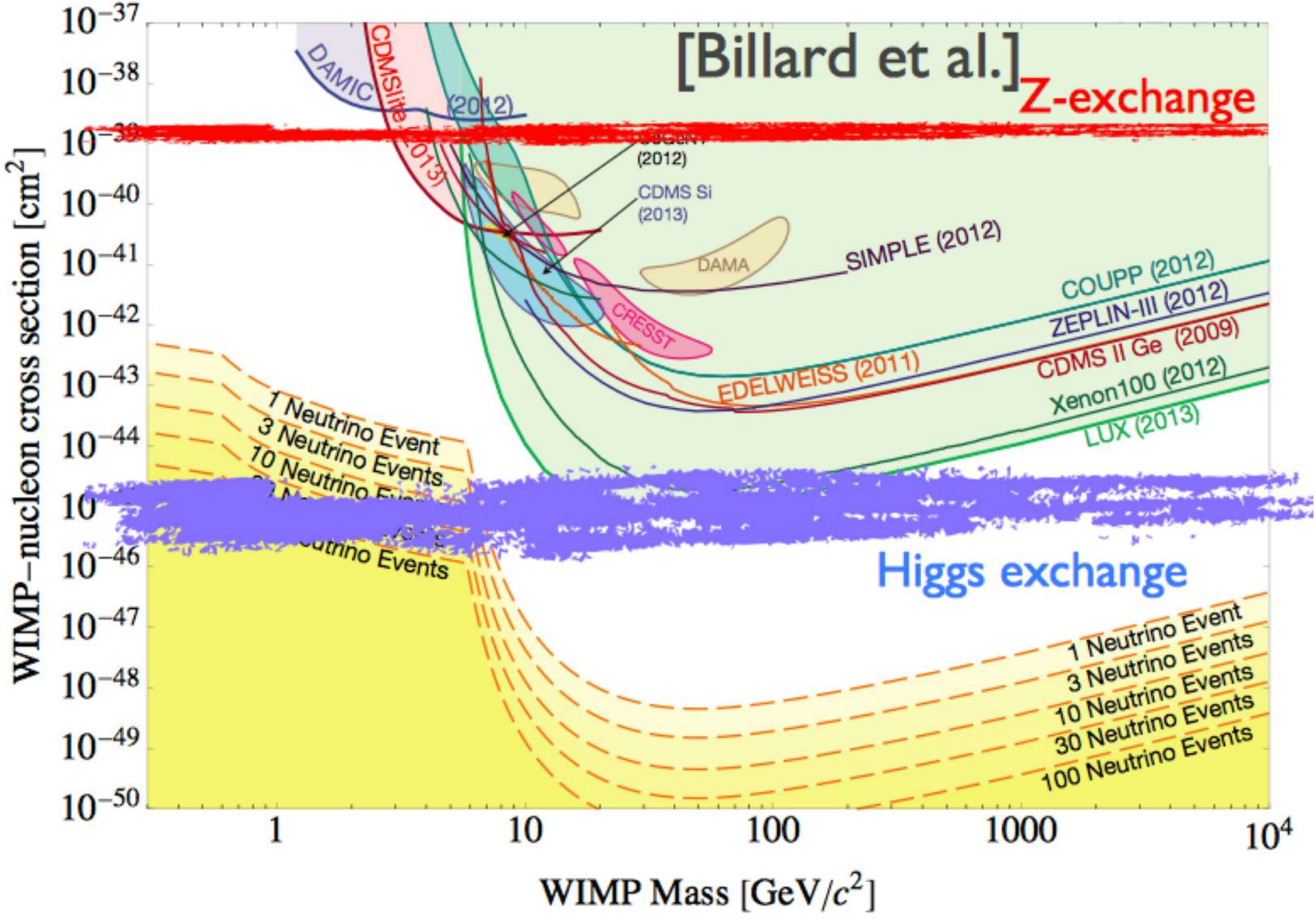
This is a reference detector that 'can do the job' and that is used to define the challenges.
The question about the specific strategy for detectors at the two IPs is a different one.

Skip outer coil for baseline cost estimates...

(from Werner Riegler)

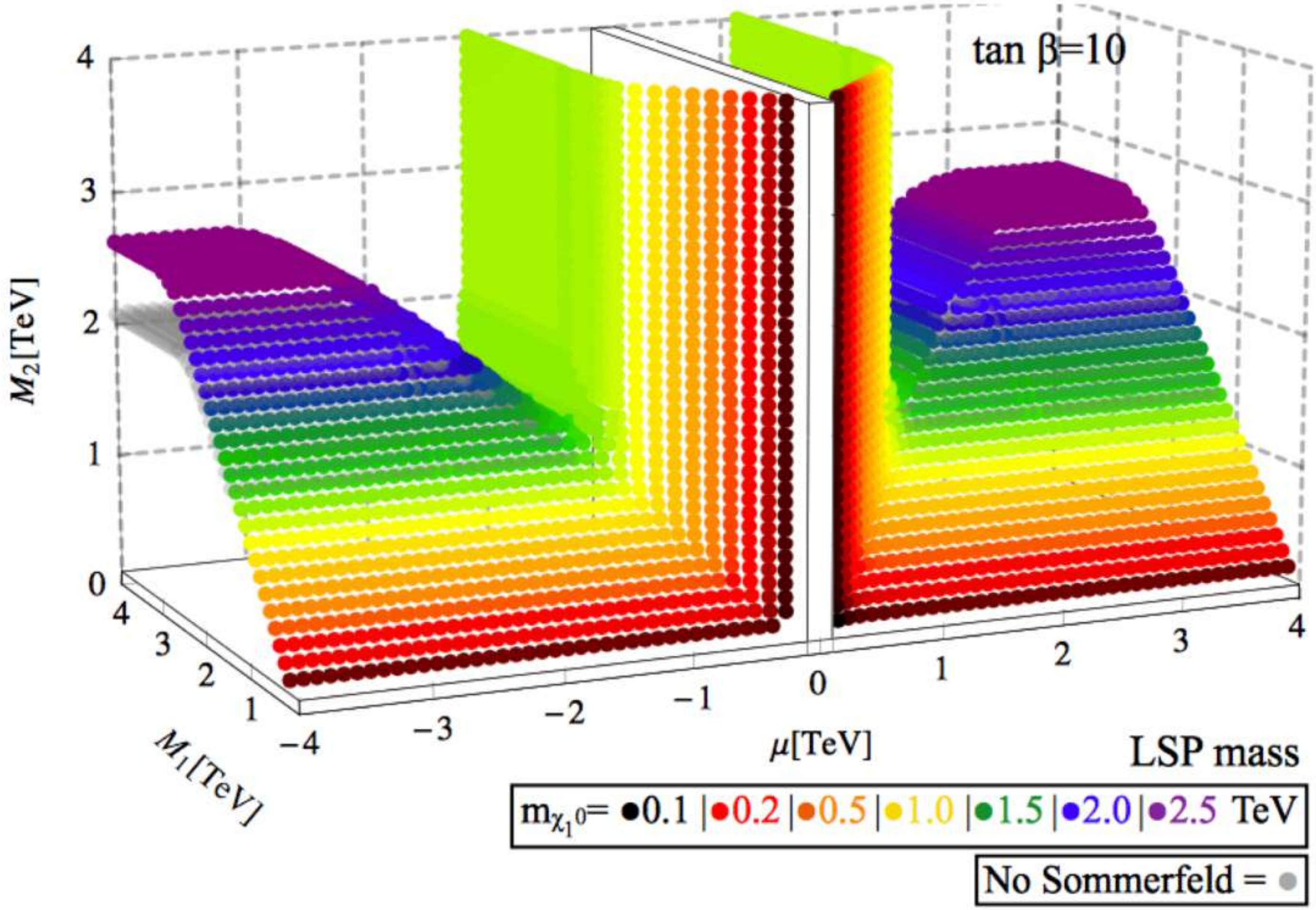
Dark Matter

Direct Searches for Dark Matter



SUSY Neutralino WIMP Relic Surface

- Supersymmetric partners of photon, Z boson or Higgs boson provide generic model of weakly interacting Dark Matter
- Combinations of Neutralino mass parameters that produce the correct relic abundance, along with Dark Matter particle (LSP) mass



Bramante *et al,*

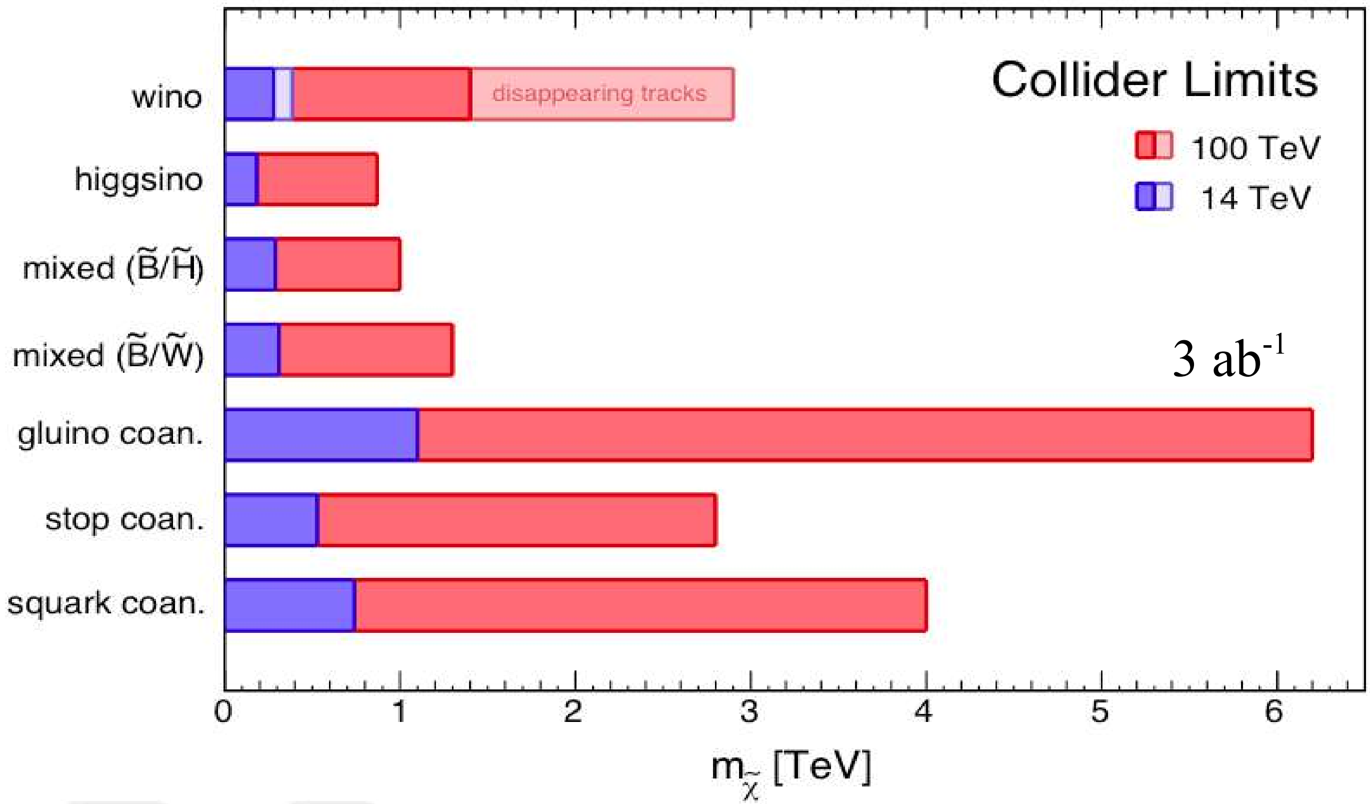
ArXiv:1510.03460

Phys. Rev. D91 (2015) 054015

(in the limit that other SUSY is heavy and decoupled)

Disappearing Track from Wino WIMP Decay

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



M. Low, L-T Wang,
ArXiv:1404.0682
(mono-jet channel)

100 TeV *pp* collider covers most of the parameter space – 30 ab^{-1} will double the mass reach

Disappearing track: almost degenerate, long-lived Wino^{+} → Wino^{0} requires robust tracking for reconstructing partial-length tracks

Compressed Spectrum WIMPs

$$pp \to (\tilde{\chi}_2^0 \to \gamma \tilde{\chi}_1^0)\,(\tilde{\chi}_1^\pm \to \ell^\pm \nu_\ell \tilde{\chi}_1^0) j \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^\pm \nu_\ell \gamma j$$

Bramante *et al*, **Phys. Rev. D93 (2016) no.6, 063525**

$p_{T,\ell} = [10 - 60]$ GeV	$\lvert\eta_\ell\rvert < 2.5$	
$p_{T,\gamma} = [10 - 60]$ GeV	$\lvert\eta_\gamma\rvert < 2.5$	$\Delta R_{\ell\gamma} > 0.5$
$p_{T,j} > 0.8$ TeV	$\lvert\eta_j\rvert < 2.5$	$M_{T2}^{(\gamma,\ell)} < 10$ GeV
$\not{p}_T > 1.2$ TeV .		

Soft leptons and photons are crucial for this signature

Collider vs Direct Detection Complementarity

Common ground (almost)

- Axial-Vector mediator

  DD and collider are equal in overall sensitivity but probe different regions of parameter space!

- Scalar mediator

  DD and collider are equal in overall sensitivity but probe different regions of parameter space!

Exclusive domains (almost)

- Vector mediator

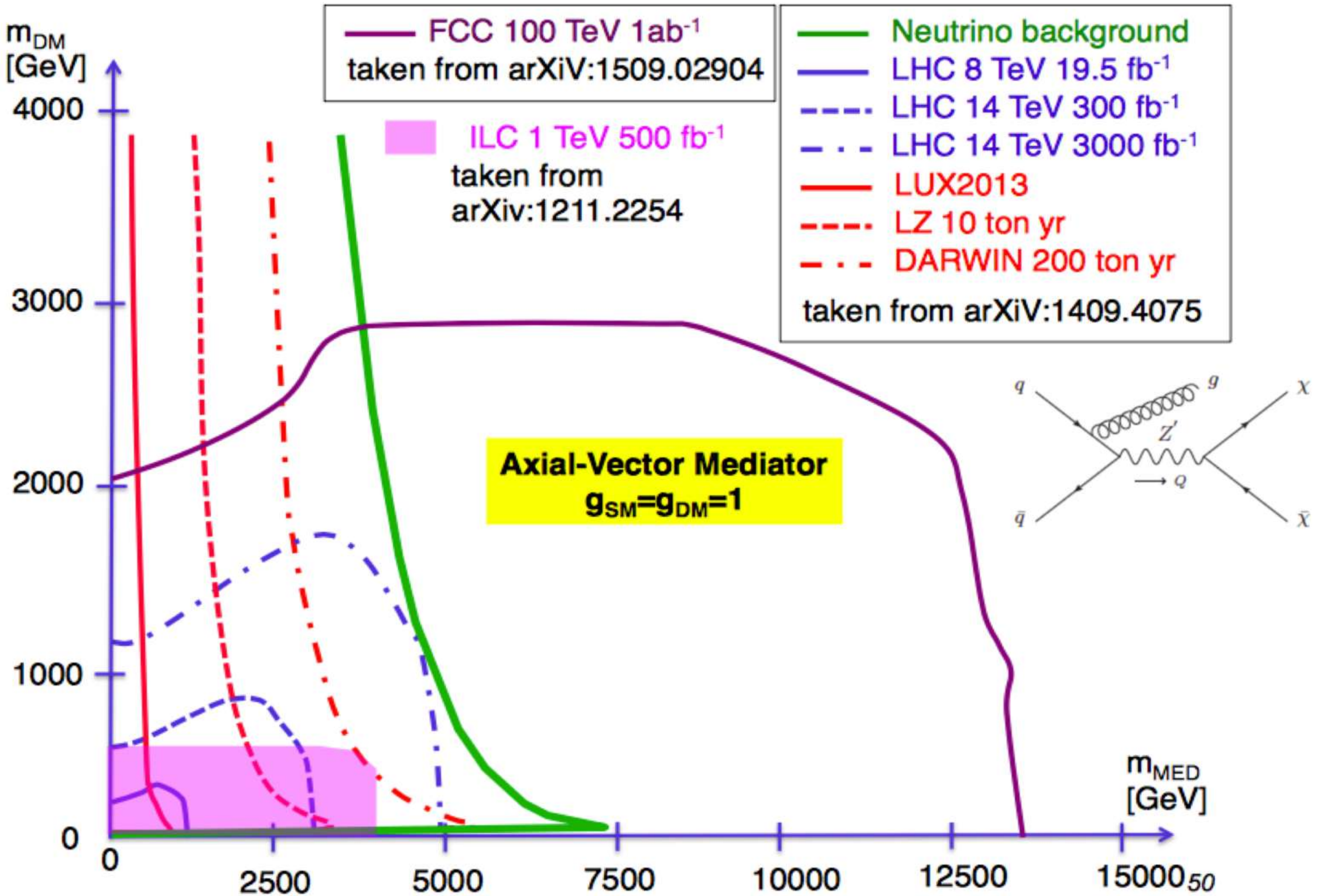
  Besides very low DM masses DD wins clearly over collider

- Pseudo-Scalar mediator

  No competitive limits from DD (only from indirect detection). Collider provides limits similar in sensitivity to scalar limits

(from O. Buchmuller)

Collider Searches – Large Mediator Mass



Physics Conclusions

Physics Conclusions

- Circular proton-proton colliders at very high energy provide unprecedented discovery potential

- New territory explored with precision measurements and direct searches is strongly motivated for
  - Solving the mysteries associated with the Higgs boson
  - Discovering WIMP Dark Matter
  - Understanding the electroweak phase transition and discovering the conditions for electroweak bryogenesis

- Potential for big surprises and discovery of unexpected new principles of nature

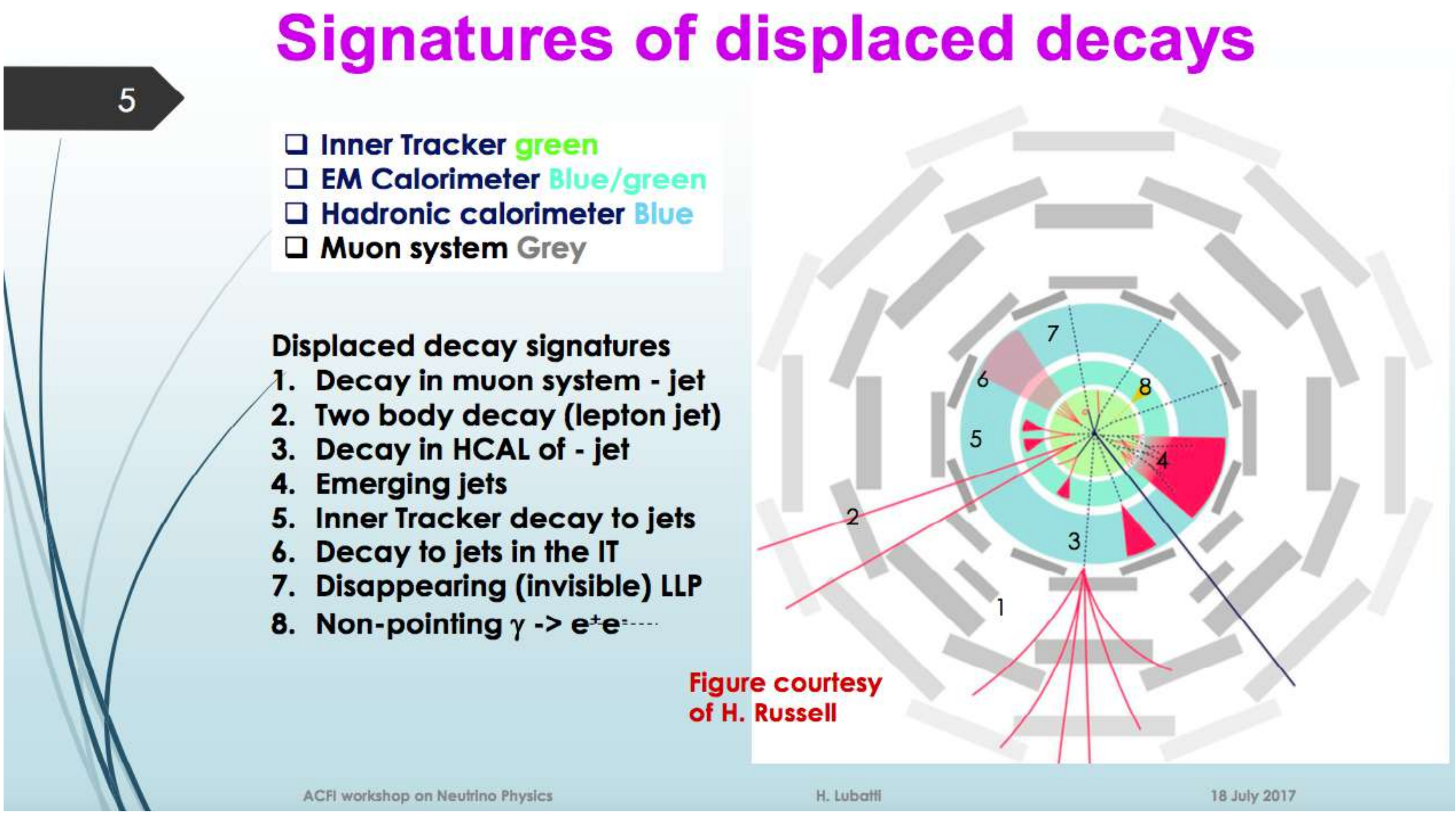
Detector Summary

- Entering new regime on detector design and technology
- 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 was designed
  - We must prepare for a broader range of possible new physics
  - Specialized, targeted detectors risky as target signatures are unconstrained
  - Prudent to continue CDF & D0 (Run 2), ATLAS & CMS general-purpose detector philosophy

- Need improved capabilities
  - Better track momentum resolution
  - Maintain/improve *b*-tagging at high jet p_T and high track density
  - Improve hadronic τ-lepton identification efficiency $\rightarrow$ high-granularity EMCAL
  - Boosted H/W/Z/top substructure $\rightarrow$ high-granularity HCAL
  - Extend forward jet coverage to rapidity ~ 6 for vector boson scattering
  - Extend forward tracking for rejecting top quark background and suppressing forward pileup jets

More Challenges

- Readout bandwidth driven by high granularity
  - Wireless transmission ???
- Pileup of ~1000 additional interactions: handle with precision timing?
- Triggering
  - challenging to trigger on disappearing tracks and long-lived particles



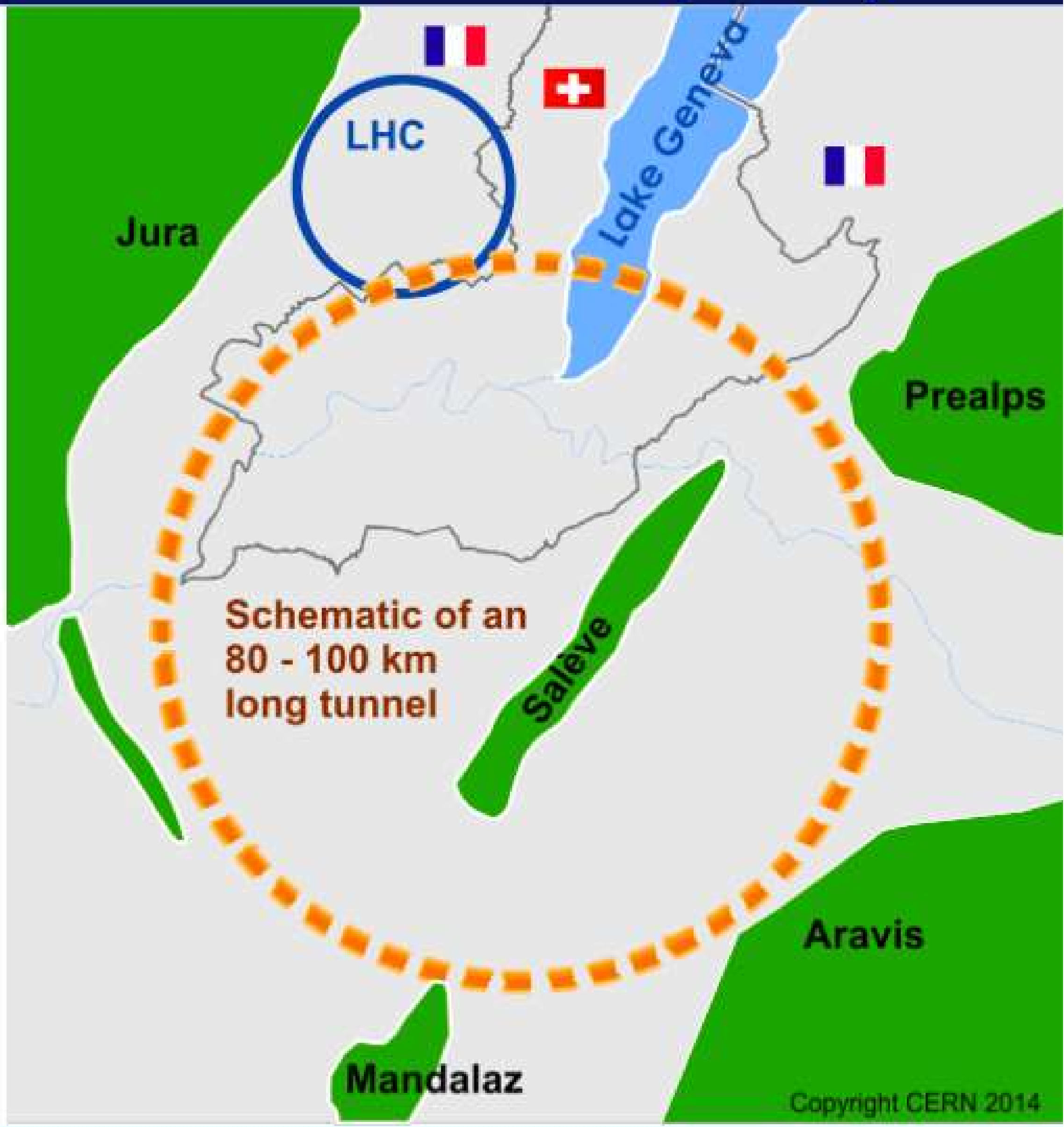
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

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

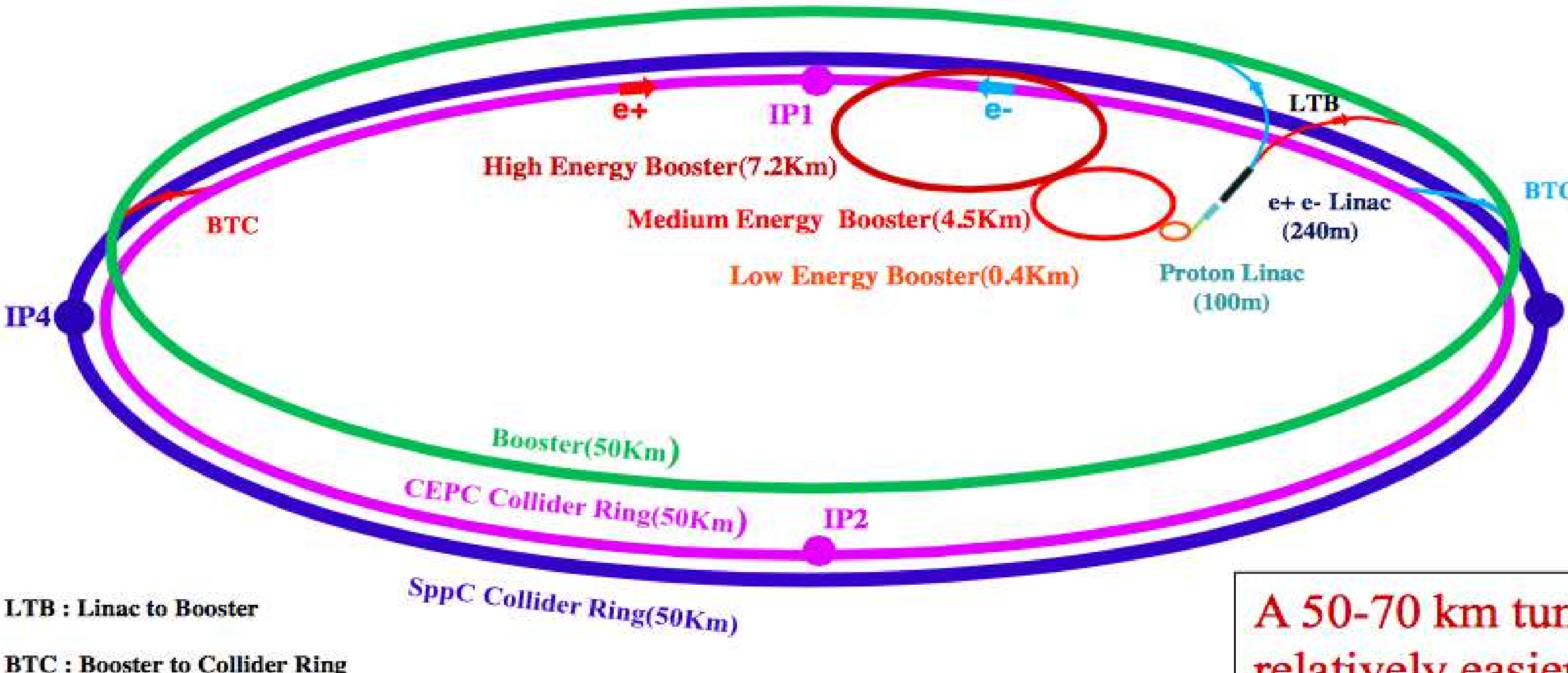


Chinese Site 300 km East of Beijing

From Yifang Wang lecture

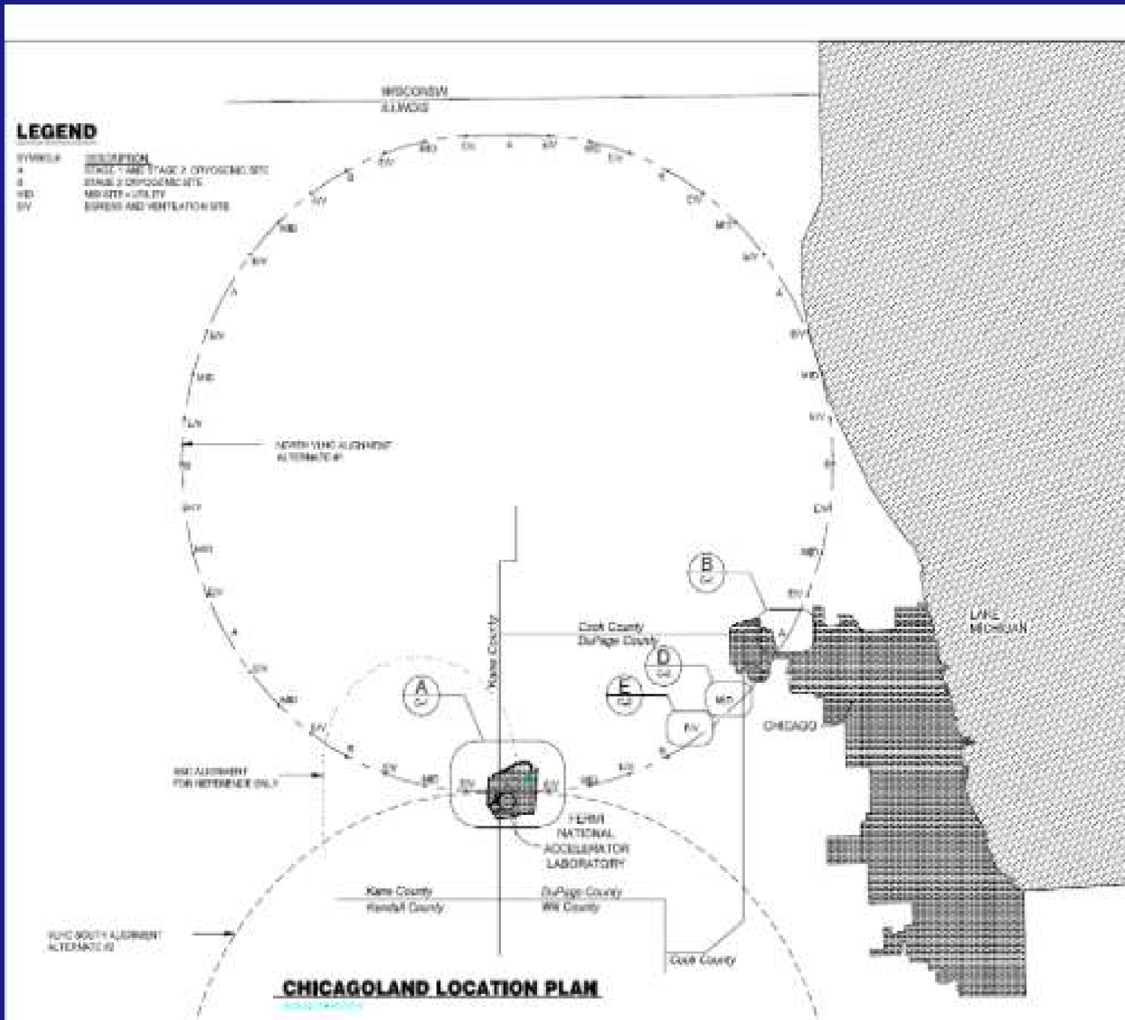
The Future: CEPC+SppC

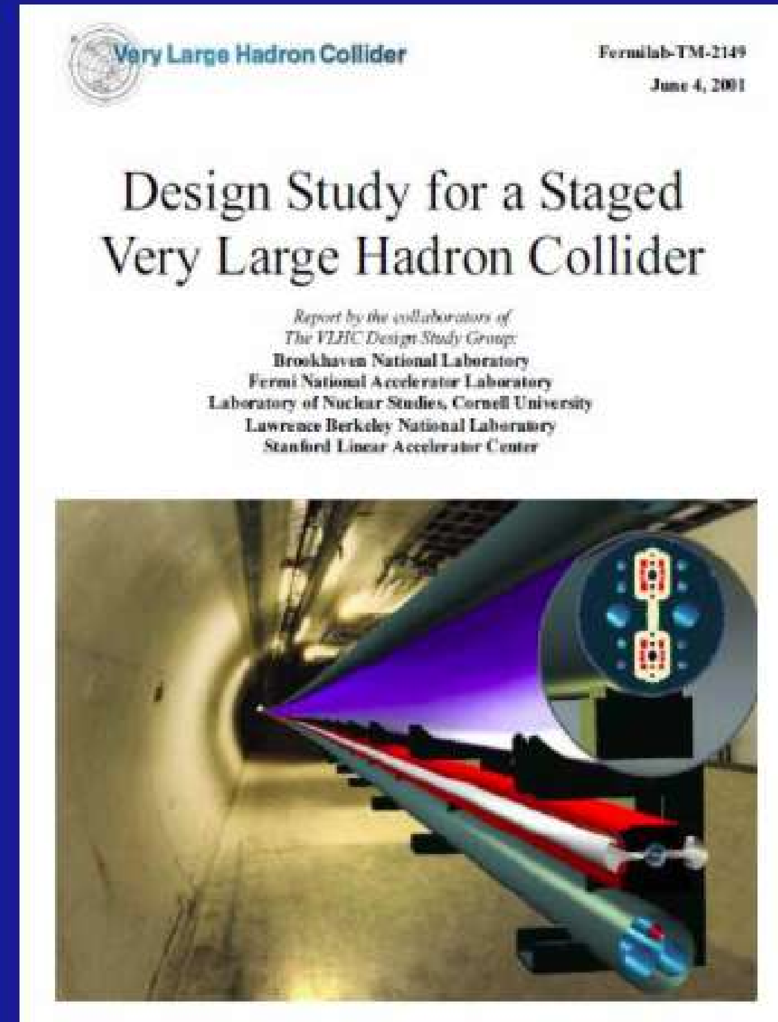
- For about 8 years, we have been talking about "What can be done after BEPCII in China"
- Thanks to the discovery of the low mass Higgs boson, and stimulated by ideas of Circular Higgs Factories in the world, CEPC+SppC configuration was proposed in Sep. 2012



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

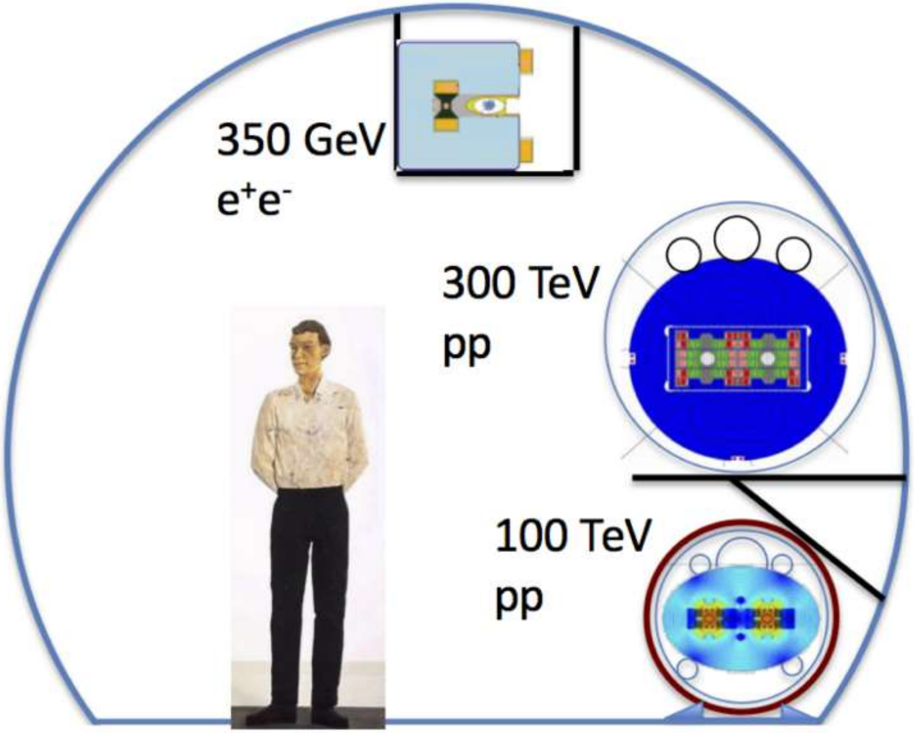
273 Pages VLHC Technical Proposal

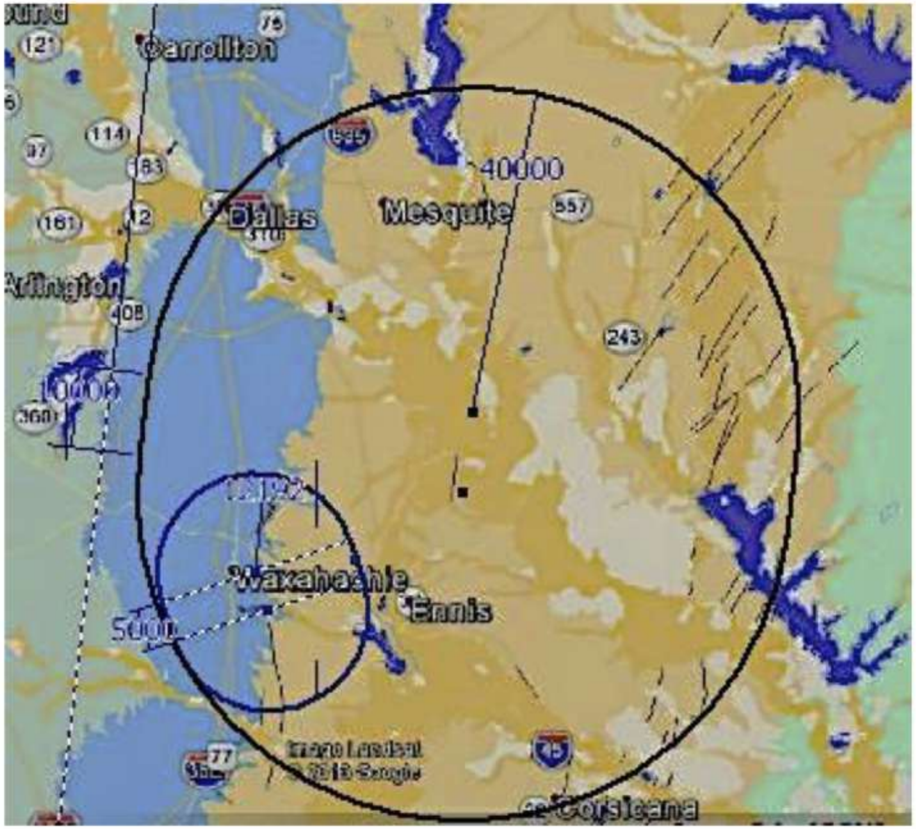




- **The VLHC proposal was well developed with all major technical solutions documented, including many details on the tunneling**
- **Very important outcome was that there are no technical "show stoppers" in building 175 TeV pp collider**

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