FCC and the Future of Fundamental Physics
Particle Physics

What is
What is an article?
Spacetime Symmetries

\[ \hat{\text{trans}} \rightarrow \hat{\text{rot}} \rightarrow \hat{\text{boosts}} \]

Quantum Mechanics

\[ |p^\mu, \sigma \rangle \rightarrow U(\Lambda) |p^\mu, \sigma \rangle = D_\nu \Big| \Lambda p^\nu, \sigma \Big\rangle \]

"Particles are Unitary reps of Poincaré group"
Particle Physics = Study of
Fundamental Laws of Nature
governed by still-mysterious union of
Quantum Mechanics + Spacetime
17th → 20th Century Physics

March of REDUCTIONISM

March of SYMMETRIES
Whatever the Ultimate Theory

Relativity

Quantum Mechanics

Massless particles interacting as line

Symmetries

A

B

C

Gravitational

Unique

"Gravity"

Spins 0, 1/2, 3/2, 2, 5/2
Massless Particles

\[ p_{\alpha \tilde{\alpha}} = (p_0 + p_3, p_1, p_2) = \lambda_\alpha \tilde{\lambda}_{\tilde{\alpha}} \]

Either \( \lambda_A \alpha \beta \gamma \chi \) or \( \tilde{\lambda}_A \tilde{\lambda}_B \chi \gamma \)

\( h_1, h_2, h_3 \)

Completely Determined

By Poincaré–Spacetime
Spin 1

\[ (g \cdot f_{abc}) \] 

\[ \langle 12 \rangle \]

\[ \langle 13 \rangle \langle 23 \rangle \]

\[ \Rightarrow f_{abc} \text{ satisfies Jacobi} \]

QM Unitarity

\[ \Rightarrow \text{Gauge Theory} \]
Spin of $X$: $x$, $x'$, $x''$, $x'''$

Spin must be 0

$X = H^{+95}$

Diagram with vertices and edges representing interactions or processes.
At very high energies, $H$ and $W_L, Z_L$ are all united into $S$. Higgs: interpolation of low-E, massive $\phi$ to high-E, massless $\phi$.

Higgs: determined by consistency of Spacetime + $\mathbb{E}^+$.
Belief in Principles Paid Off

0, \frac{1}{2}, 1, \frac{3}{2}, 2

Higgs is first “really new” particle we’ve seen!
21st Century Reactions

Doom of Spacetime, End of Relativism

Why is the Universe Big?

Really Needed, New Ideas Needed

beyond paradigms of spacetime - internal symmetries
Reductionism + Wilsonian EFT Paradigm is False
Fundamental Laws Nothing like that of Condensed Matter Physics — FAR DEEPER and MORE RADICAL
[But maybe only at Planck Scale?]
Photon MUST stay massless, because

\[ 2 \neq 3 \]

This is why gauge fields + chiral fermions can be easily engineered in Cond. Matter!
Higgs

\[ \text{massless spin 0} \quad 1 \quad = \quad 1 \quad \text{massive spin 0} \quad \text{NO DIFFERENCE} \]

WHY ISN'T HIGGS ENORMOUSLY MASSIVE? PLANCKIAN?

[Higgs is Special! Does NOT naturally arise in Cond. Matter!]

Huge irony: we understand why all elementary particle masses are pegged to mass of the Higgs— but not the mass of the Higgs itself!
\( (E_A) = \int \frac{d^3 k}{2} \left[ \frac{1}{k^2 + m_b^2} - \frac{1}{k^2 + m_f^2} \right] \phi^* \phi \)

\( \Lambda_{\text{UV}} \chod \Lambda_{\text{IR}} \)

\( + \left( 3 - \xi \right) \left( \frac{\Lambda_{\text{UV}}}{\Lambda_{\text{IR}}} \right)^2 \Lambda_{\text{UV}} \Lambda_{\text{IR}} \)

\( \overset{\text{Hierarchy Problem}}{\downarrow} \)

\( \overset{\text{Cosmological Constant Problem}}{\downarrow} \)

\( \overset{\text{Why is there a macroscopic universe?}}{\downarrow} \)
\[ \Lambda + \text{Higgs} \rightarrow \text{Beyond Symmetries} \]

- 1 d.o.f. whether \( m_h^2 > 0, = 0, < 0 \)
  - NO DIFFERENCE
  - Hierarchy Problem

- \( \Lambda > 0 \)
- \( \Lambda = 0 \)
- \( \Lambda < 0 \)

- Same amount of symmetry
  - \[ \text{SO(5,1)} \rightarrow \text{Poincaré} \rightarrow \text{SO(4,2)} \]
- Cosmological Constant Problem
Emergent Spacetime

We are clearly missing something HUGE about Quantum Mechanics of our Relativistic Vacuum in the Macroscopic Universe.
Higgs Discovery Crucial

Our Relativistic Vacuum is qualitatively different than anything we've seen elsewhere in physics

Not just @ Planck scale
Already @ TeV scale
The Higgs is the most important character in this drama—we can put it under most incisive and precise experimental scrutiny.
Higgs is Really New Physics!

* We've never seen anything like it
* Harbinger of Profound New Principles at work in quantum vacuum
* MUST LOOK AT IT CLOSER!
Never Seen Point-Like Scalar

So, how pointlike is it?
But with LHC resolution, Higgs could be about as elementary as a "pion".
Never Seen Point-Like Scalar

\[ m_W \]

Higgs Factory

FCC-ee

We will know FOR SURE if it's "like a Pion"
Never Seen Self-Interacting Fundamental Particles

100 TeV Collider

Measured to $\sim 5\%$
Higgs + Gravity: Unique in Self-Interaction!

YM, GR: charges helicity! + Color

\[ \langle 12 \rangle \langle 23 \rangle \langle 31 \rangle \]

\( n = 0 \) Higgs

\( n = 1 \) Violates Bose!

\( n = 2 \) Grav.

\{ But miniscule \( R \) corr \}
Also, 100 TeV collider blasts into the high energy frontier. New particles ~ 10 X LHC reach. Probes vacuum quantum fluctuations with power 100 X LHC.
The Challenge for EXPERIMENT is totally clear. Meanwhile for THEORY, the mystery of the origin of $\Lambda + m^2$—why is there a macroscopic universe?—continues to pose (an even more) radical challenge.
WIMP Dark Matter

* Still our only calculable model of DM

* Simplest models are alive and well!
  Doublet “Higgsinos” ~ 1 TeV
  Triplet “Winos” ~ 3 TeV

* Too heavy to be produced @ LHC, have tiny (\(\sim 10^{-46} - 10^{-47}\) cm\(^2\)) direct detection rate.

* Needs 100 TeV pp collider to make them!
Robust Coverage For WIMPS
Outlook

In (not just) my view, the scientific issues we face today are the most difficult and profound ones our field has seen since the 1930s.
The questions raised by the accelerating universe, and the Higgs discovery, both go to the heart of our understanding of the nature of spacetime, quantum mechanics, and the vacuum.
MOST CRITICAL

GREAT BIG CIRCULAR COLLIDERS

EXPERIMENTAL PROGRAM

$e^+$

$\bar{e}$

240 GeV

$\sim 100 \text{ km}$

$100 \text{ TeV}$

$P$