Theory Summary

Aspen Winter 2008

Scott Thomas

The Final Theory Summary of the Pre-LHC Era

Aspen Winter 2008

Scott Thomas

The Long Wait is Almost Over – But Let's Look Back One Last Time

Laboratory Experiments

Renomalizable Standard Model

Neutrino Masses M_L À TeV

Gravity M_P À TeV

Cosmological Observations

Dark Matter

Dark Energy

Primoridial Density Fluctuations (Inflation)

Baryon Asymmetry

What Good Are Theorists?

• Underlying Framework	Explain Hierarchies
• Model Building	Implement Framework (Within Constraints)
• Signal Building	Suggest Novel Signatures
• Search Strategies	Extract Signals from Data
• Measurement Techniques	Extract Information from Data
• Calculations	Compare Data with Theory

Electroweak Symmetry Breaking (Hierarchy)

Technicolor / Walking / Extended — (Technical) Naturalness

Supersymmetry

Warped Throat

Deconstruction/Little Higgs — (Mild) Technical Naturalness

Twin Higgs

Emergent / Composite Gauge Symmetry

Other

…….

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Other

…….

It Doesn't Solve Anything –

But it Has a Name,

Roni Harnik

The most Generic Form of Any of These Frameworks for EWSB is in Conflict with Observation

The Renormalizable Standard Model Works Too Well

(Supplement Only Neutrino Masses + Gravity)

No Evidence for Physics Beyond the Standard Model at the TeV Scale

Precision EW Chen

Higgs Sector Grojean, Pomarol

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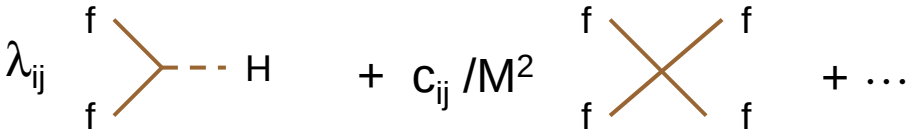
That's Interesting – We've Learned …..

1. There are Mechanisms Within a Framework which Suppress Processes in Conflict with Observation
2. These Frameworks Should be Abandoned

Perhaps the Ideology of Naturalness was Misguided

Flavor Hierarchies

Large Hierarchies Within the Quark and Lepton Yukawas



M À TeV Scale – No Observable Flavor Violating
Effects Beyond Renormalizable Standard Model

If M Near TeV Scale or Additional State Which Carry Flavor
Near the Weak Scale – Potential Conflict With Observation

Minimal Flavor Violation

Perez

$c_{ik} \gg \lambda_{ij}\, \lambda_{jk}$

Yukawas Characterize Magnitude of Flavor Violation

c_{ij} Bottom Quark Sector Aligned

$M \gg$ TeV - Almost Enough

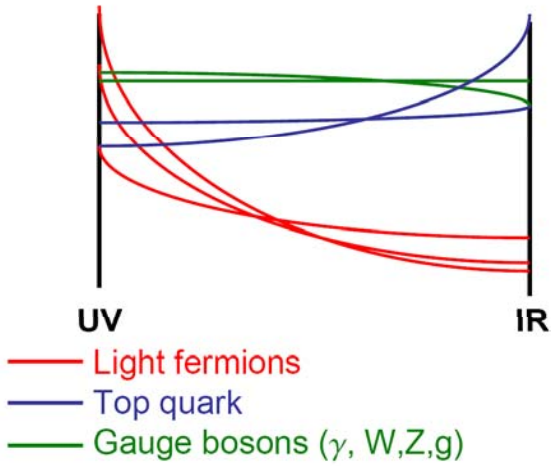
Interesting Levels of Flavor Violation in up-Quark Sector

$D\text{-}\bar{D}$ mixing , $t \rightarrow c\, Z$, ...

Warped Throat Flavor Violation

Csaki

Yukawa Hierarchies from fermion-fermion-Higgs Overlap in Bulk



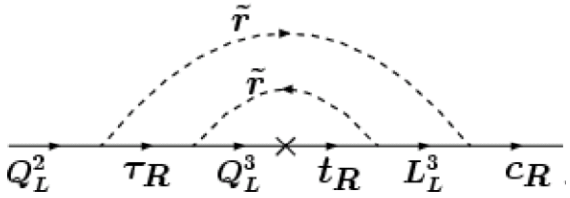
M » TeV

Mild GIM in Bulk Enough

Ingredients Generic in String Theory

Radiatively Generated Flavor Hierarchies

Dobrescu



Generational Hierarchy from Number of Loops

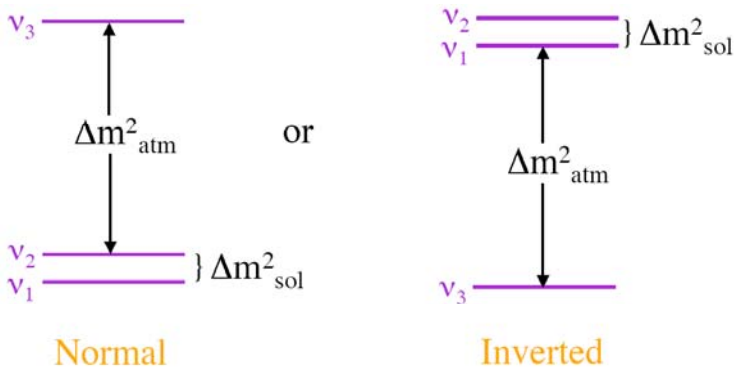
If M not too Large – Interesting Flavor Violation Possible

- $\mu \rightarrow e$ Conversion

Neutrino Masses

Kayser

- Mass Ordering in Spectrum
- θ_{13}
- Separating CP Violating and Matter Effects



We Have Beautiful Flavor Data in the Quark, Lepton, and Neutrino Sectors

Underlying Framework and Model for Origin of Flavor

Knowledge of Physics at the TeV Scale Necessary Ingredient to Extrapolate to Flavor Scale

New Flavor Horizons at the LHC

If any New States are Discovered with Carry Flavor –
Will Open Up a New Arena for Flavor Physics

SUSY: Squarks + Sleptons

Warped Throat: KK Quarks and Leptons

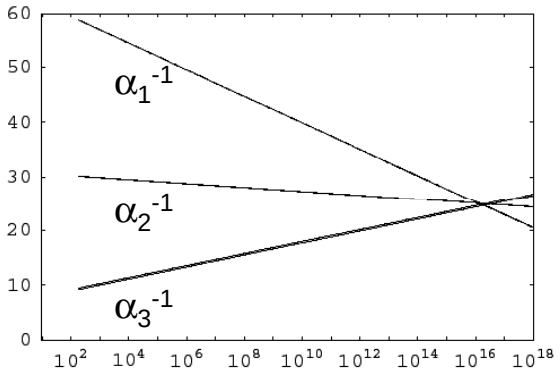
……..

No Positive Hints for Physics Beyond the Standard Model at the TeV Scale in Non-Renormalizable / Irrelevant Interactions

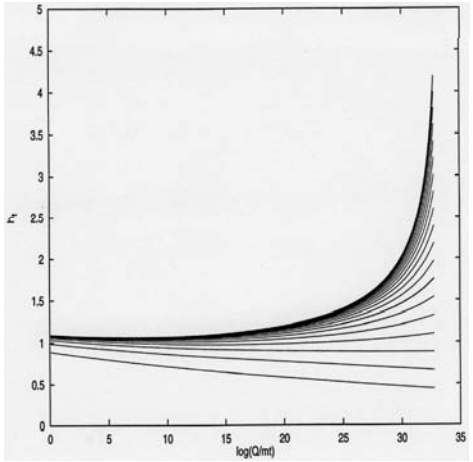
Any Positive Hints in Renormalizable / Relevant Interactions?

SUSY: 1. Gauge Coupling Unification

2. Top Quark IR Quasi-Fixed Point



Renormalization Scale (GeV)



Signal Building

Objects:

- Leptons
- Photons
- Missing Transverse Energy
- Jets

Exotic Objects: New (Long Lived) States

- Displaced Vertices - Leptons, Photons, Jets
- Highly Ionizing Tracks
- Highly Ionizing to Minimum Ionizing Kinks
- Highly Ionizing Stopped Track
- Out of Time Decays
- Charge Exchange Tracks
- Charge Changing Tracks
- Quirks
- Unparticles
- High Multiplicity Mush
- .....

Long Lived Stops

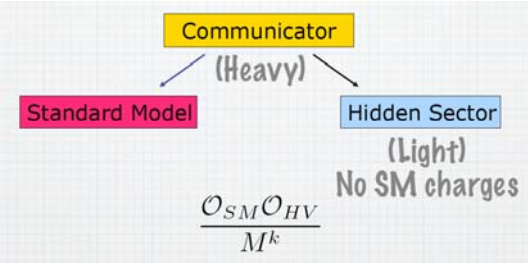
Canepa

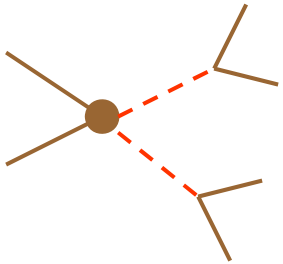
More General Context In Which to Consider Signals

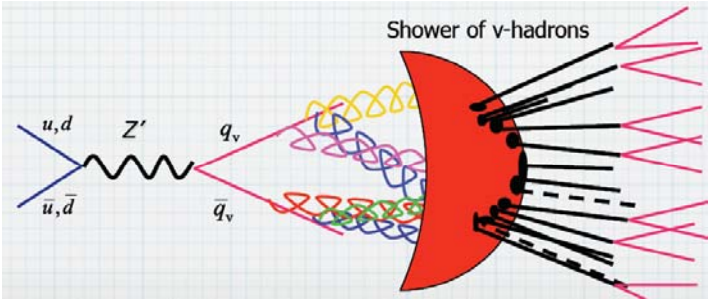
Fully Exploit the Discovery Potential of the LHC !

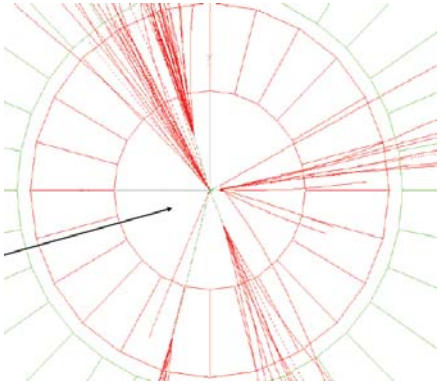
Hidden Valleys

Zurek



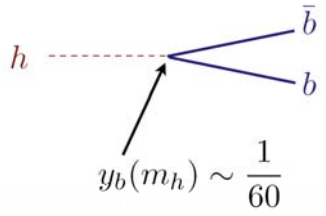




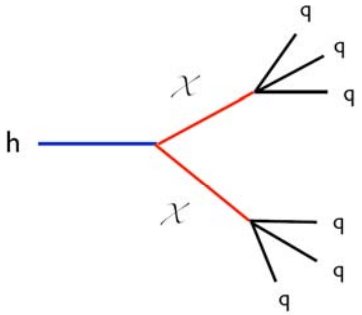


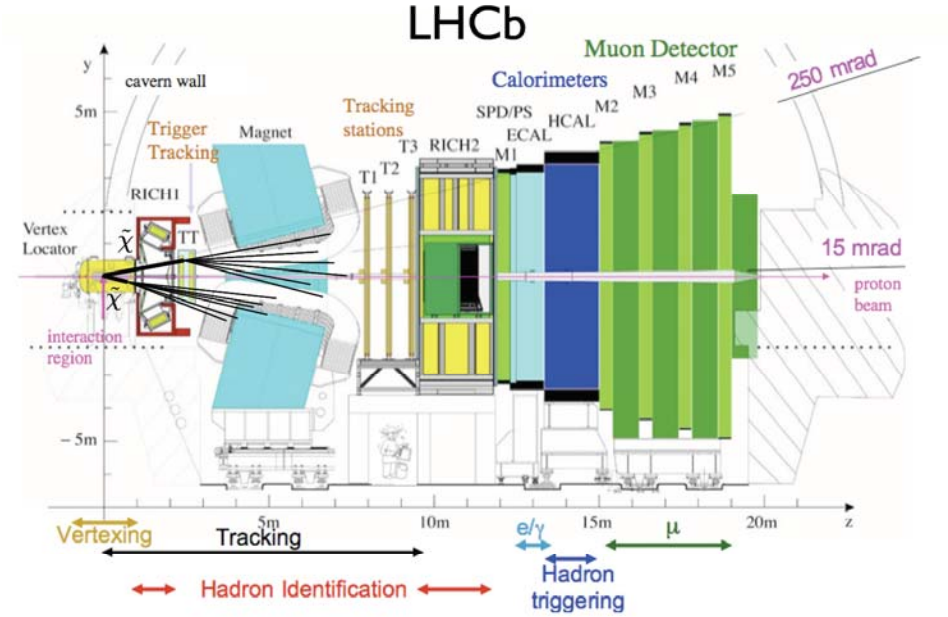
Non-Standard Higgs Decays

Kaplan



Higgs Branching Ratios can be Drastically Modified Compared with Standard Model Expectation

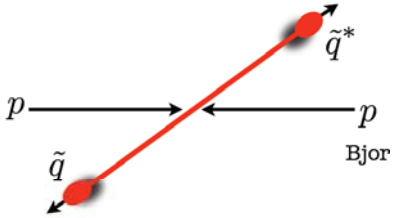


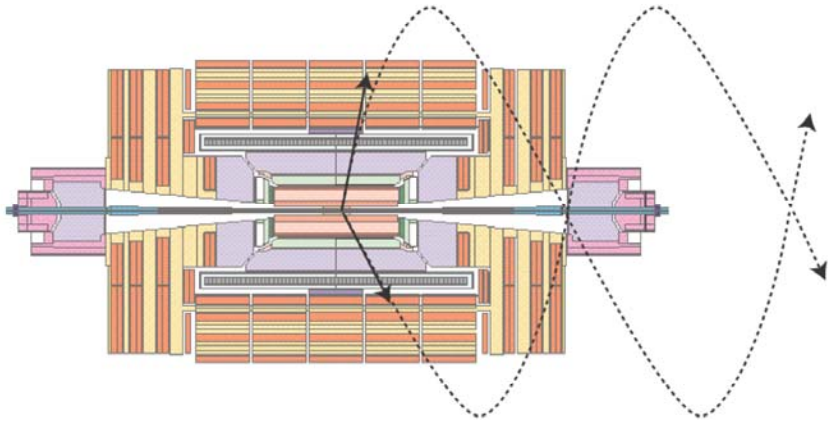


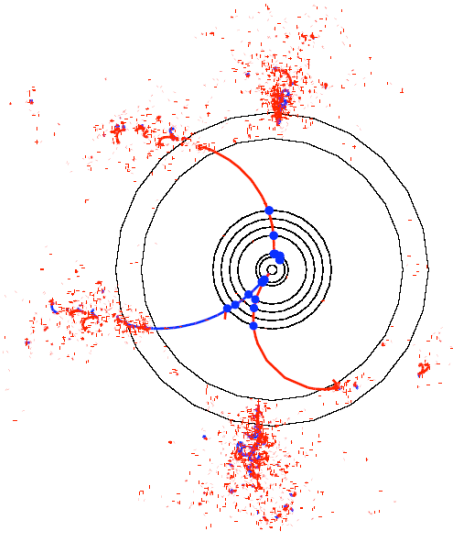
Quirks Harnik

Highly Excited Open String States

Hidden Sector $\Lambda \lesssim m_O$





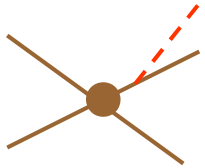


UnParticles

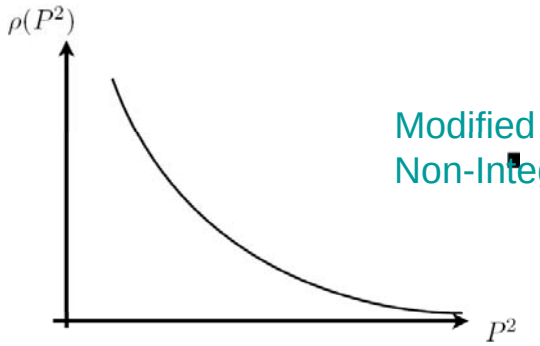
Fox (1st Place ACP 2008 Ski Race)

(Nearly) Conformal Sector

$$\langle \mathcal{O}(0)\mathcal{O}(x)\rangle \sim \frac{1}{x^{2D}}$$

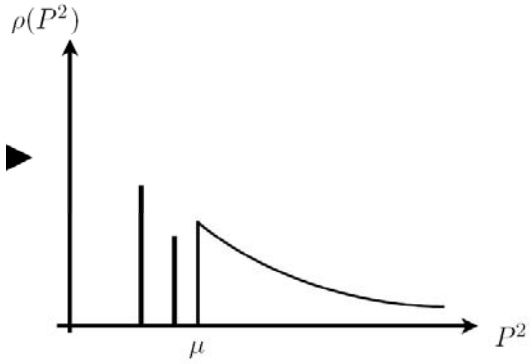


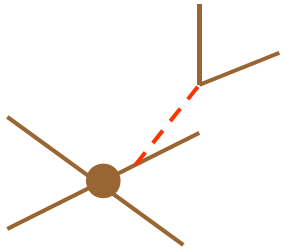
Free Particle



Modified Phase Space :
Non-Integer Dimension

Introduce Gap

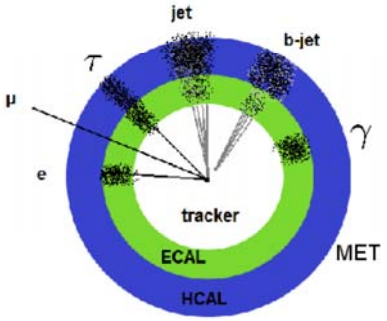




Hidden Valley

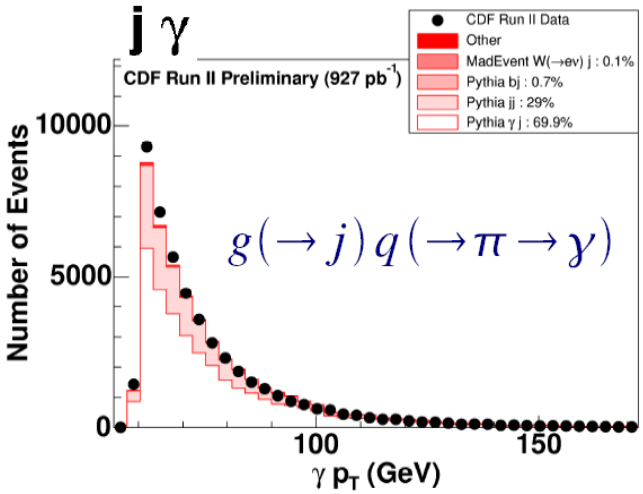
Search Strategies

Mrenna



Global Signature Based Search

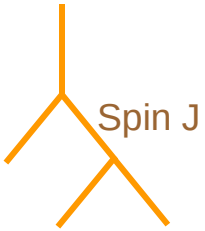
Large Number of kinematic Variables in Large Number of Final States



Compare with MonteCarlo (Iteratively Tuned)

Measurement Techniques

Kong

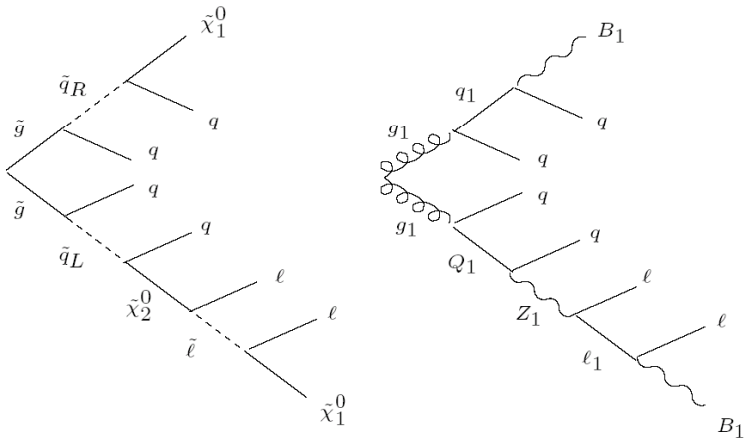


$(1 / \Gamma)(d \Gamma / dx) = f(x)$

Odd Order Polynomial Degree 4J+1

$x = m_{23}/m_{23}^{max}$

Partner Particles: $\Delta J = ½$, $\Delta J = 0$

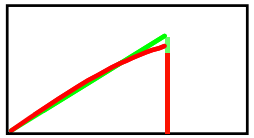


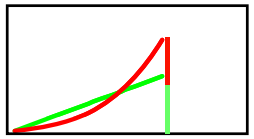
Superficially Similar Signatures

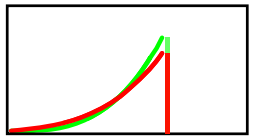
Determing the Spin of Partner Particles

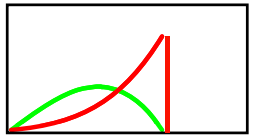
	Super-Partners	Same Spin-Partners (Nearly Degenerate)
Opposite-Sign Same-Flavor Lepton-Lepton	$2x$	$\frac{20}{9}x(1-\frac{1}{5}x^2)$
Jet-Lepton	$2x$	$\frac{2}{3}x(1+4x^2)$
Opposite-Sign b-Jet-Lepton	$4x^3$	$\frac{2}{3}x(1+4x^2)$
Same-Sign b-Jet-Lepton	$4x(1-x^2)$	$\frac{2}{3}x(1+4x^2)$

SUSY
Same Spin



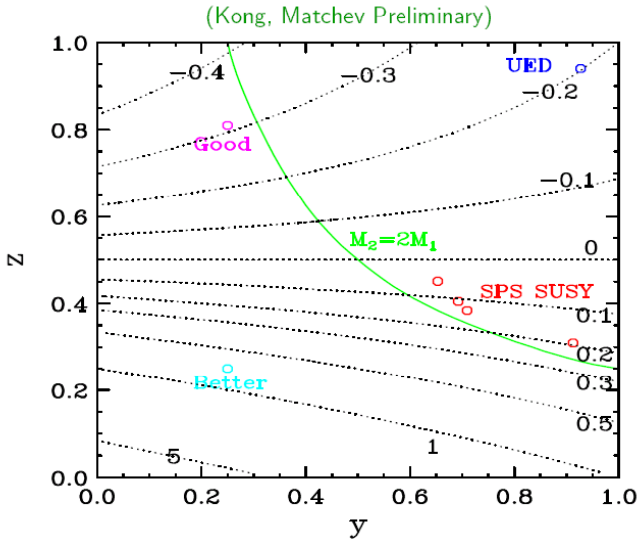






Note: No Initial state Charge Asymmetry Required
Better Discrimination with non-Degenerate States – $O(x^5)$ Polynomial
Even Easier with Other Mass Orderings

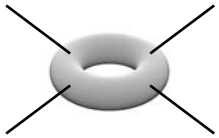
More General Spectrum – Same Ordering



Coefficient of x^3 term in Invariant Distribution

Additionally x^5 term Invariant Distribution

One-Loop Calculations Forde



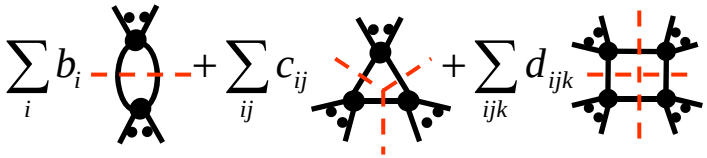
Started as Technological Application of String Theory

Cutting Techniques

Rational Terms D = 4- ε

Recursion Relations, Bootstrap

…….



Numerical Implemetation General One-Loop : Black Hat

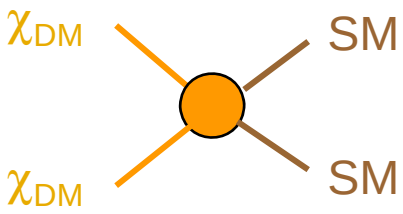
Feynman Diagram Techniques Are Rapidly Becoming Outdated

This Momentum Routing Based Organization of Diagrams Might be Well Adapted

1. An Effective Field Theory Approach to Resumation
2. Efficient Phase Space Monte Carlo Integration

Dark Matter

- Light Moduli - Axion
- Gapped Dark Sector
- Non-Thermal Relic
- WIMP Thermal Freeze Out Relic



WIMP with Electroweak Quantum Numbers

$\Omega_{CDM} h^2$ ' 0.1 for m » 1-3 TeV

SUSY with Bino-Like Neutralino LSP R-Parity Conservation

$\Omega_{CDM} h^2$ À 0.1 for m » few 100 GeV

Special Regions of SUSY Parameter Space $\Omega_{CDM}\, h^2 \,' 0.1$ Baer

- Co-LSP Enhancement $\Delta m / m < 1/20$

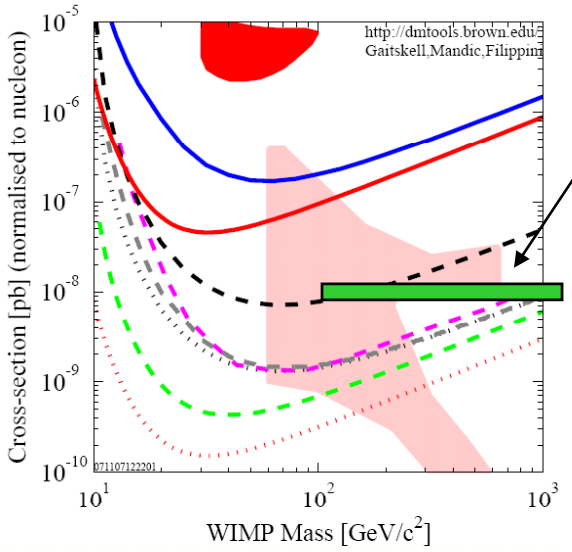
  Bino-Higgsino Neutralino $m_1 \,' \mu$

  Stau-Neutralino $m_\tau \,' m_\chi$

Particles Emitted from Bottom of Decay Chain Very Soft

- Resonant Enhancement

  $m_A \,' 2\, m_\chi$



Bino-Higgsino

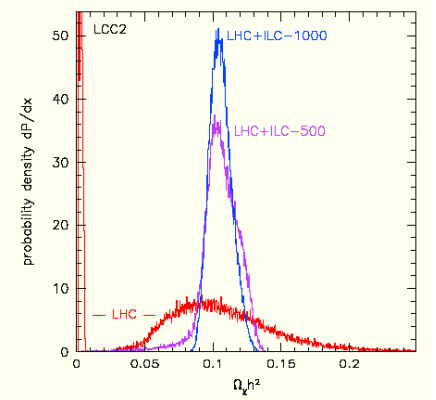
DATA listed top to bottom on plot
DAMA 2000 58k kg-days NaI Ann.Mod. 3sigma,w/o DAMA 1996 limit
CDMS (Soudan) 2004 + 2005 Ge (7 keV threshold)
XENON10 2007 (Net 136 kg-d)
SuperCDMS (Projected) 2-ST@Soudan
DEAP CLEAN 150kg FV (proj)
WARP 140kg (proj)
SuperCDMS (Projected) 25kg (7-ST@Snolab)
LUX 300 kg LXe Projection (Jul 2007)
XENON1T (proj)
Baer et. al 2003

A priori Calcualtion of $\Omega_{CDM}\, h^2$ from LHC Measurements

SUSY:

Assume Couplings

Use Masses + Mixing Angles



Model Independent:

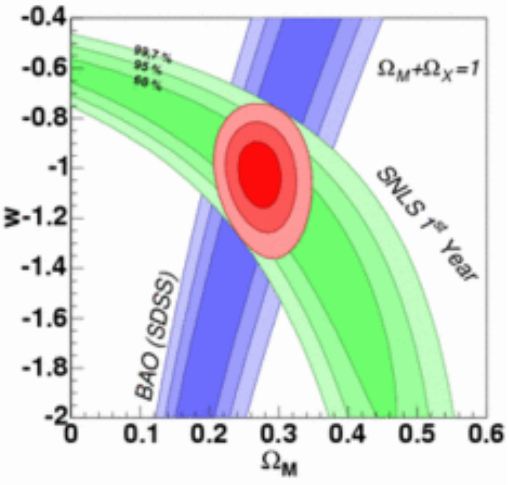
Very Difficult

ILC – Magnitude of Couplings May be Possible

Dark Energy

Probe Dark Energy Equation of State ρ / p - Precision Measurement of Expansion History

Carithers

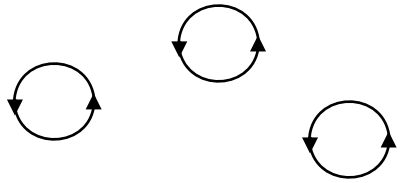


$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

$$3\frac{\ddot{a}}{a} = -4\pi G\left(\rho + 3p\right)$$

Quantum Contribution to Dark Energy

- Quantum Gravity - Local Quantum Field Theory



Zero Point Energy Of Fields : $\pm\frac{1}{2}\hbar\omega$

States = Π_i | n_i i

Volume Extensive

UV sensitive

$$\delta\rho_o \sim \Lambda^4$$

- Quantum Gravity – Holographic Ultraviolet-Infrared Mixing

Holographic Screen
(FRW - Apparent Horizon)

$$N_{\text{dof}} \sim \frac{R^{D-2}}{\ell_P^{D-2}} \qquad E_{\text{dof}} \sim \frac{\hbar}{\ell_P} \qquad \ell_P^{D-2} = G_D\hbar$$

Redshift

$$\sqrt{g_{00}} \sim \frac{\ell_p}{R}$$

$$\delta\rho \sim \frac{1}{G_D R^2} \sim \rho$$

(Very) High Precision Measurement of Expansion History z » 1 - 2
Might Probe Holographic UV-IR Nature of Gravity Through Quantum Dark Energy

Non-Perturbative Quantum Gravity at the TeV Scale

R^{-1} » TeV M_P À R^{-1} (Tuned)

R^{-1} » M_P » TeV

$E/M_P > 1$ Non-Perturbative Quantum Gravity Processes

- Ultraviolet – Infrared / Holographic Properties

  Fixed Angle Cross Section Grows with Energy

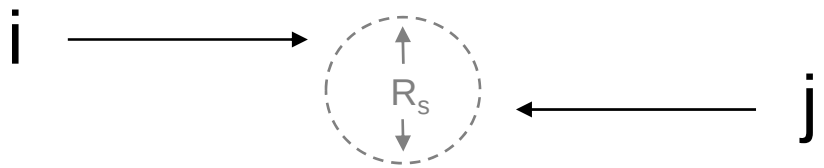
  Space – Time Uncertainty Relation

  Inconsistent with Local Quantum Field Theory

  Area Extensive Degrees of Freedom (Volume Extensive No Operational Meaning)

  Boundary Hologram – Gravitating Space-Time Emergent Concept

Very High Energy Scattering



Einstein Gravity at Long Distances

- Hoop Conjecture) If Impact Parameter l_P ¿ b · R_s
  i,j Fall Through Horizon → Form Black Hole →
  Black Hole Decays by Hawking Evaporation to
  High Multiplicity Low Energy Quanta

$$\sigma \geq \Omega_{D-2} R_s^{D-2}$$

Very High Energy Scattering → Long Distance → Low Energy

- Holographic UV-IR Properties of Gravity Evident

Cross Section and Multiplicity Grow with Energy

!!→ Exclusive Hard Scattering Processes Shut off
(Cloaked Behind Horizon)

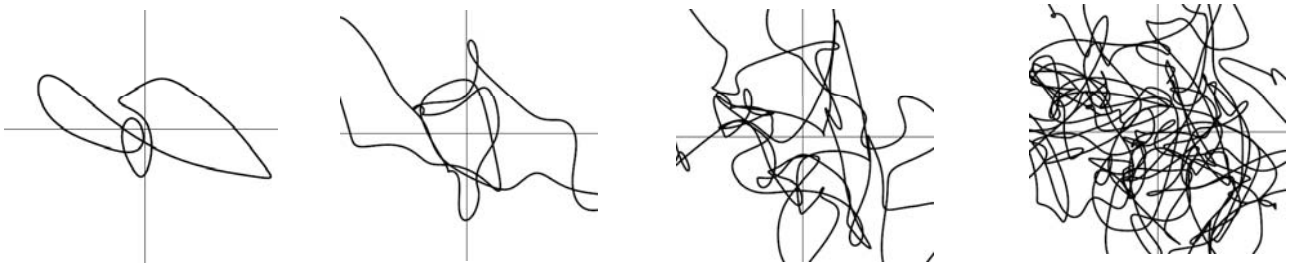
Heralds the End of the Experimental Investigation of
Short Distance Physics

High Energy Scattering Perturbative String Theory

l_p ¿ b ¿ l_s b À R_s

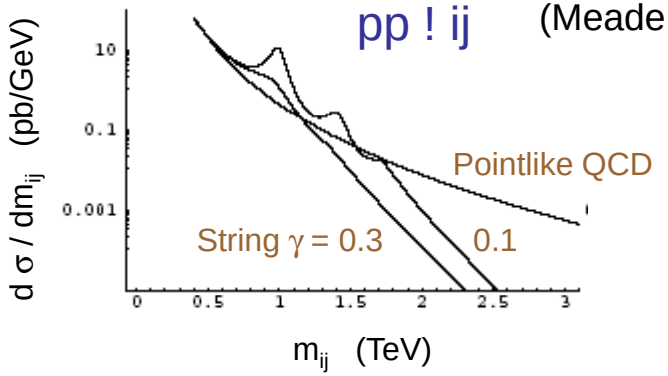
Higher Energy Scattering Resolves More
String Oscillator Mode Zero Point Fluctuations

String Fire Ball



(Susskind, Uglum)

pp ! ij (Meade, Randall)



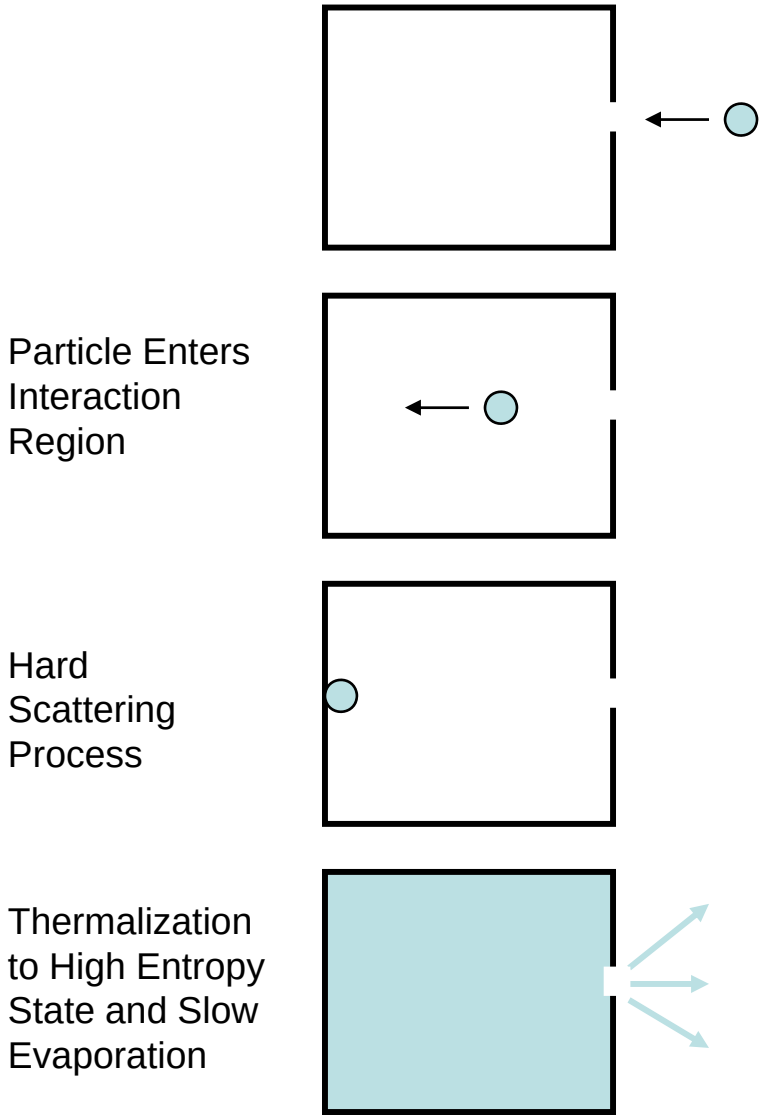
Exclusive 2→2 Shuts Off

Inclusive 2→ String Fire Ball

Current Model Independent Bound: Tevatron Monojet Search M_P > 800 GeV

Black Holes / High Entropy Fire Balls Could be Produced at LHC

Black Hole / High Entropy Object Formation in Collision



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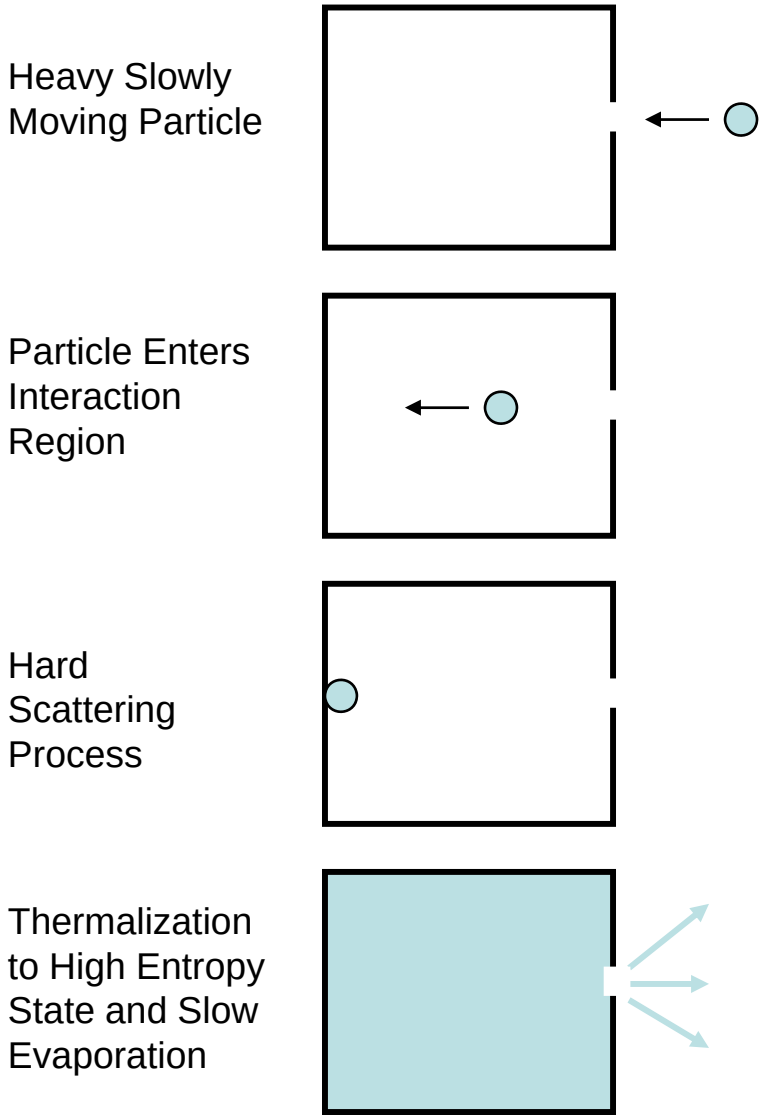
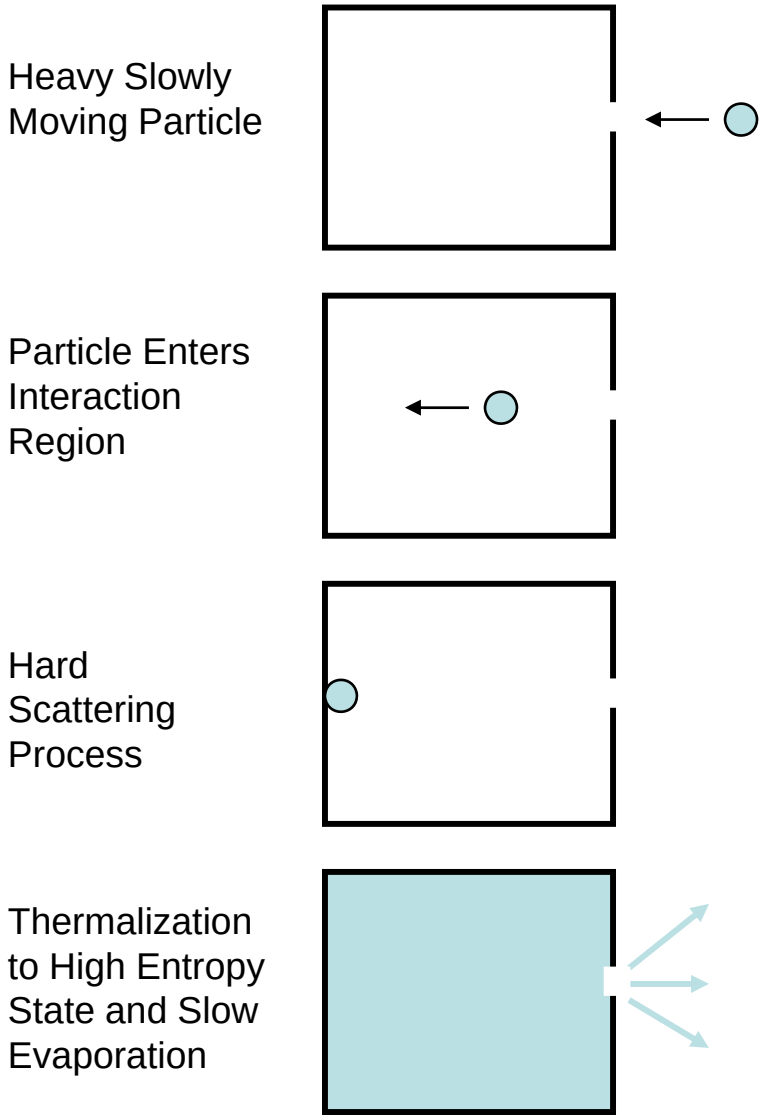


Black Hole / High Entropy Object Formation in Collision

Full Simulation (Landsberg)



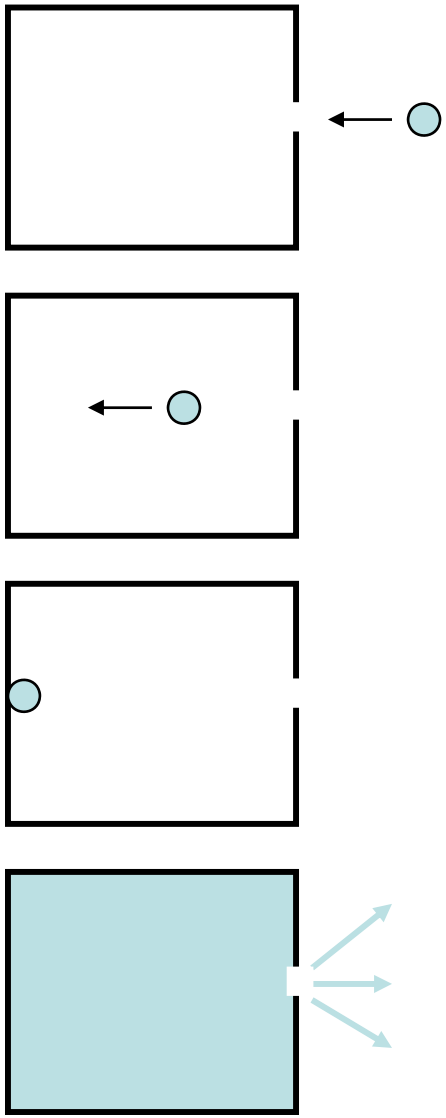
Black Hole / High Entropy Object Formation in Collision

Heavy Slowly Moving Particle

Particle Enters Interaction Region

Hard Scattering Process

Thermalization to High Entropy State and Slow Evaporation



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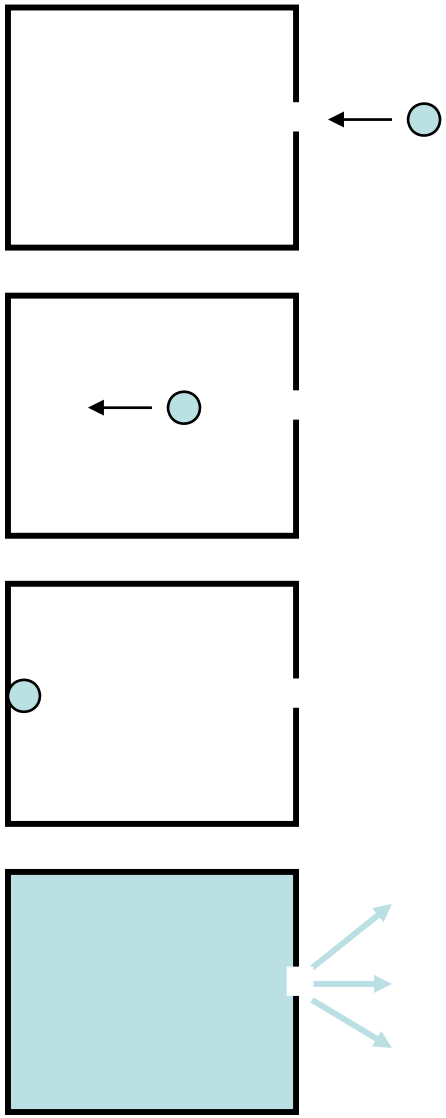

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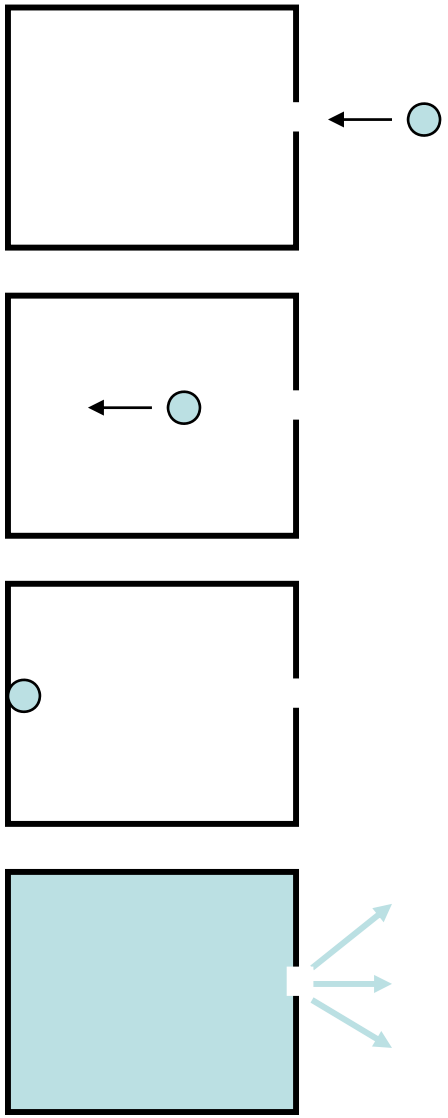

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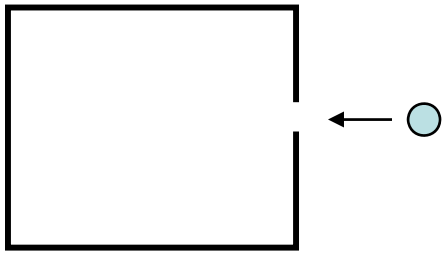

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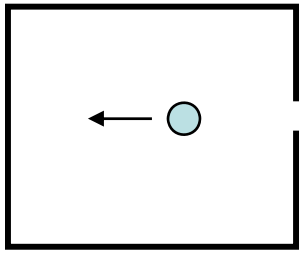

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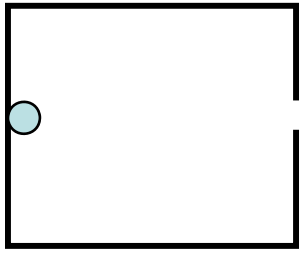

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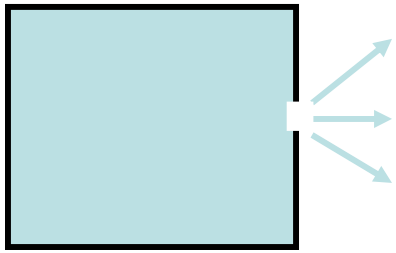

The Long Wait is Almost Over .....

We Are About to Enter a New Era of Discovery in High Energy Physics !

We Should All Look Forward to Future Theoretical Summaries at Aspen Winter Conferences in the LHC Era