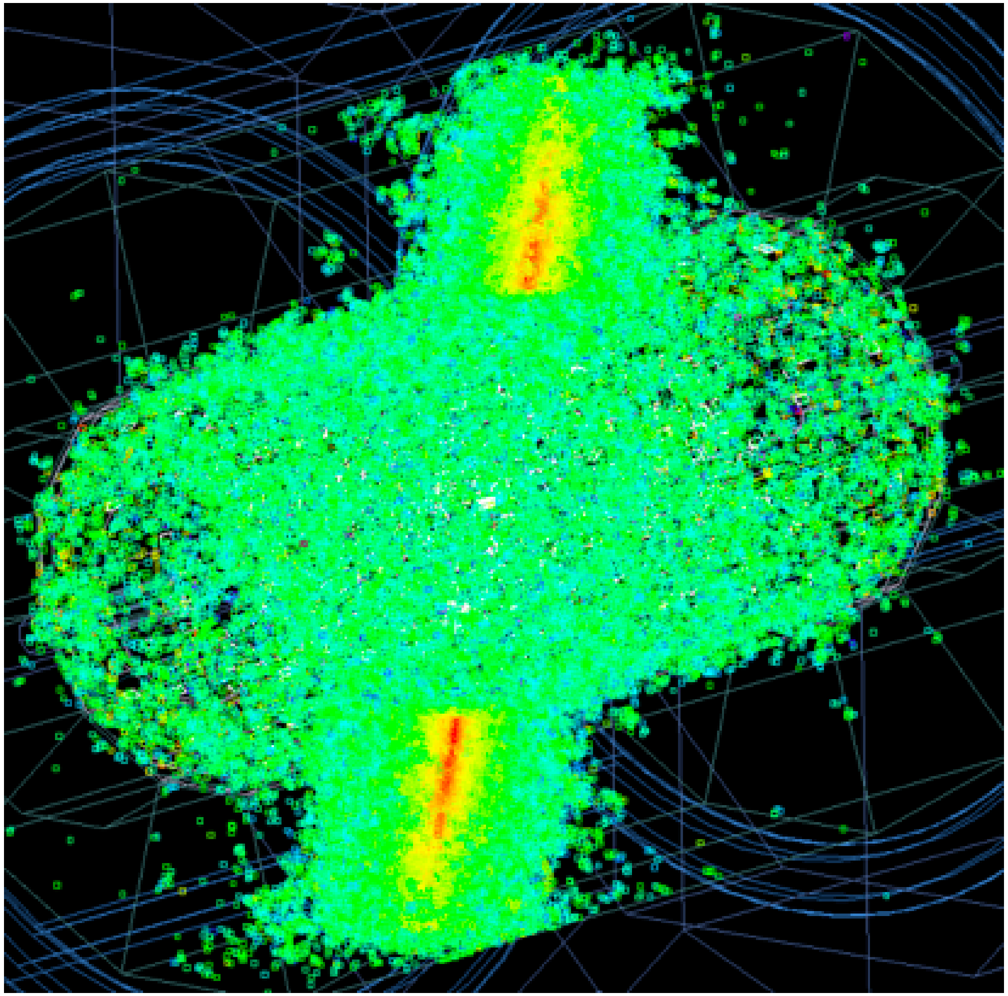
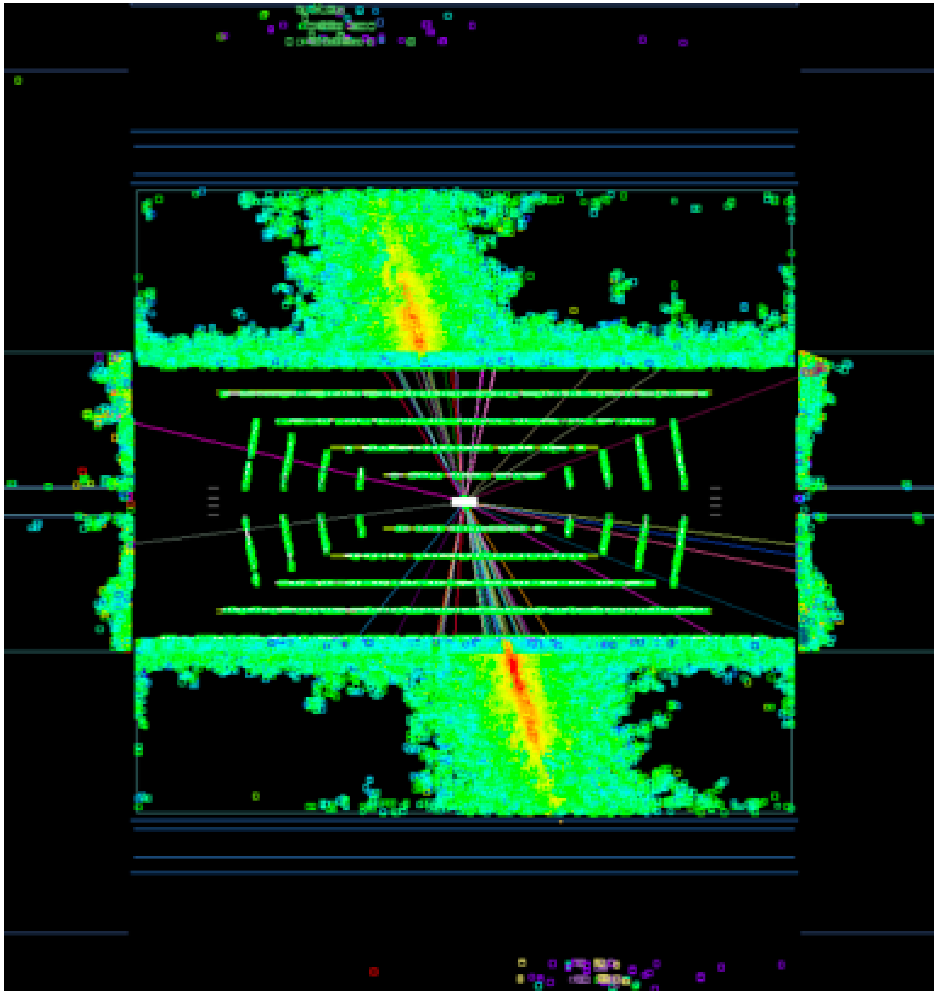
# Physics and Experiments at Future *pp* Colliders for Beyond-SM Physics

Ashutosh Kotwal
Duke University





Preparations for European Strategy
Fermilab
March 3, 2018

# 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

# GEANT Simulations

- Strategy:
  - Focus on high-granularity calorimeters
  - Resolve highly-boosted vector and Higgs bosons, top quarks, τ-leptons

- GEANT4 simulations with ILCSOFT (installed by S. Chekanov at Argonne with some help from SLAC, PNNL)
- Geometry tuning and sample generation (Chekanov and AVK)
- Analysis by Nhan Tran (Fermilab CMS postdoc), Shin-Shan Yu (Asst. Prof. in Taiwan), Chih-Hsiang Yeh (Yu's student at National Taiwan University), Sourav Sen (Duke graduate student)
- Samples created on OSG on 1-week timescale – need more analysts !

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

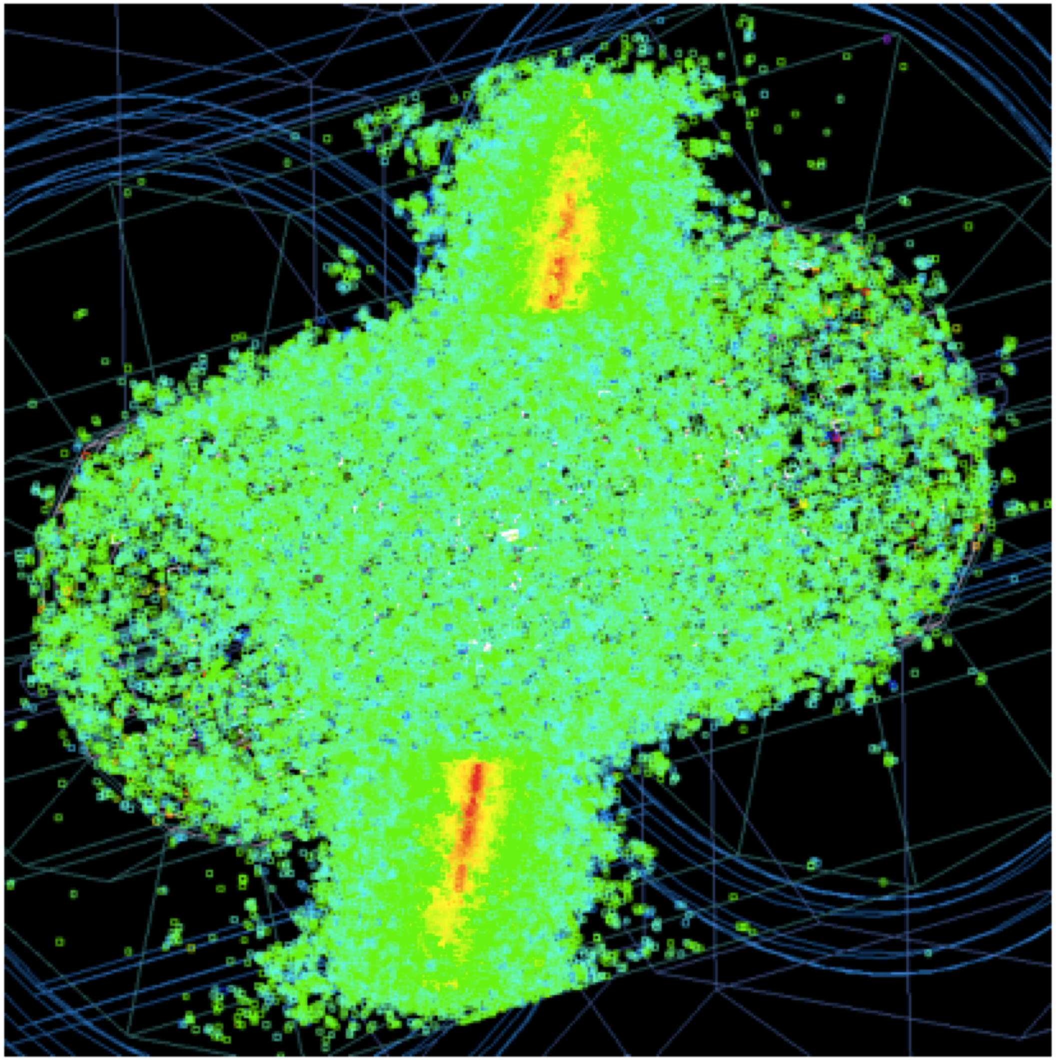
**S. Chekanov**
*HEP/ANL*

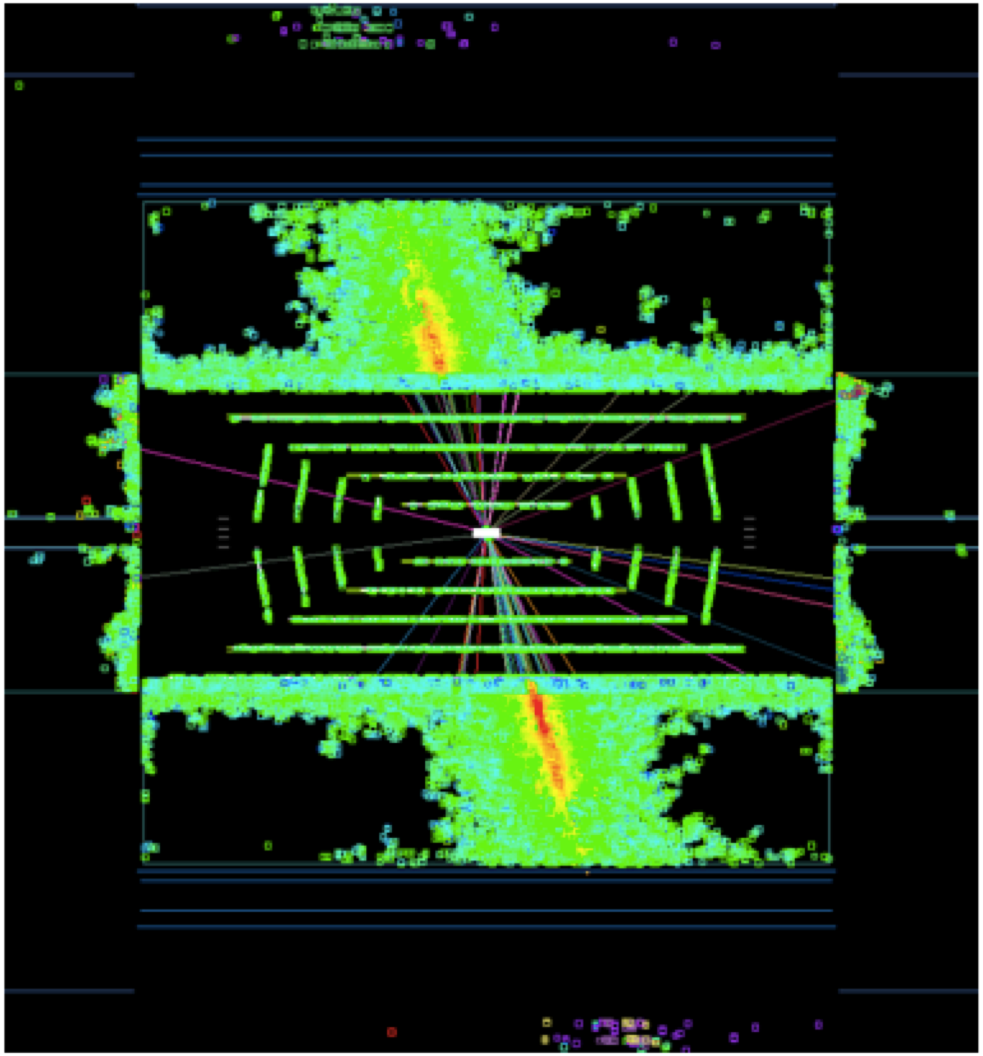
*FCC Week. April 11-15, 2016*
*Rome, Italy*

*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)

# GEANT Simulation of Scintillator / Iron HCAL and Silicon Tracker

5 TeV hadronic W → dijet decay with 4 cm x 4 cm scintillator readout
Background simulation in progress, will investigate different pad sizes and higher $p_T$





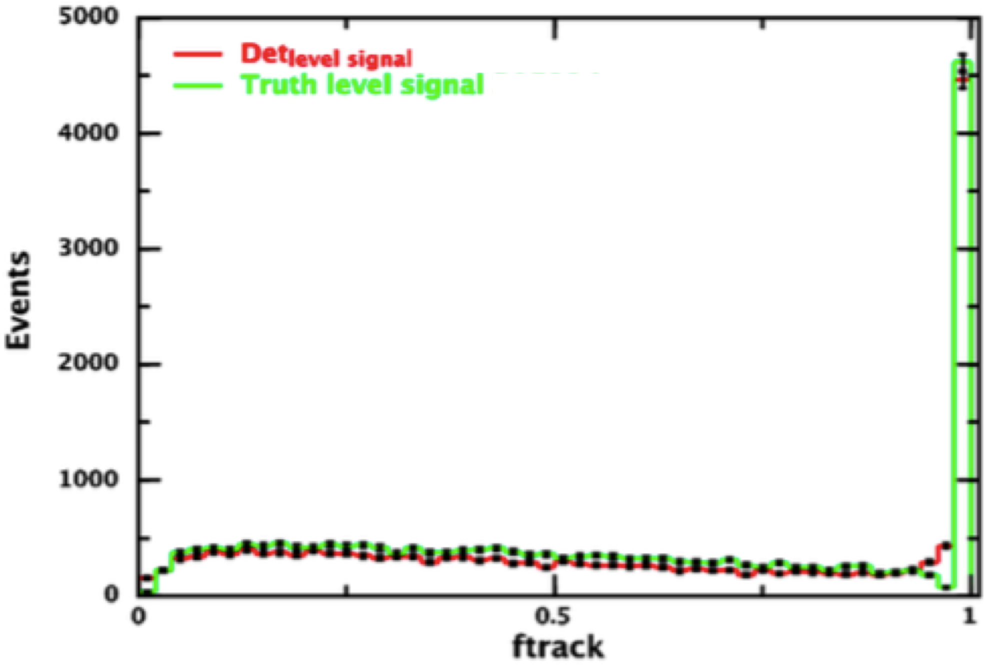
Generated on OSG by S. Chekanov

# GEANT Simulation of Silicon/Tungsten EM Calorimeter

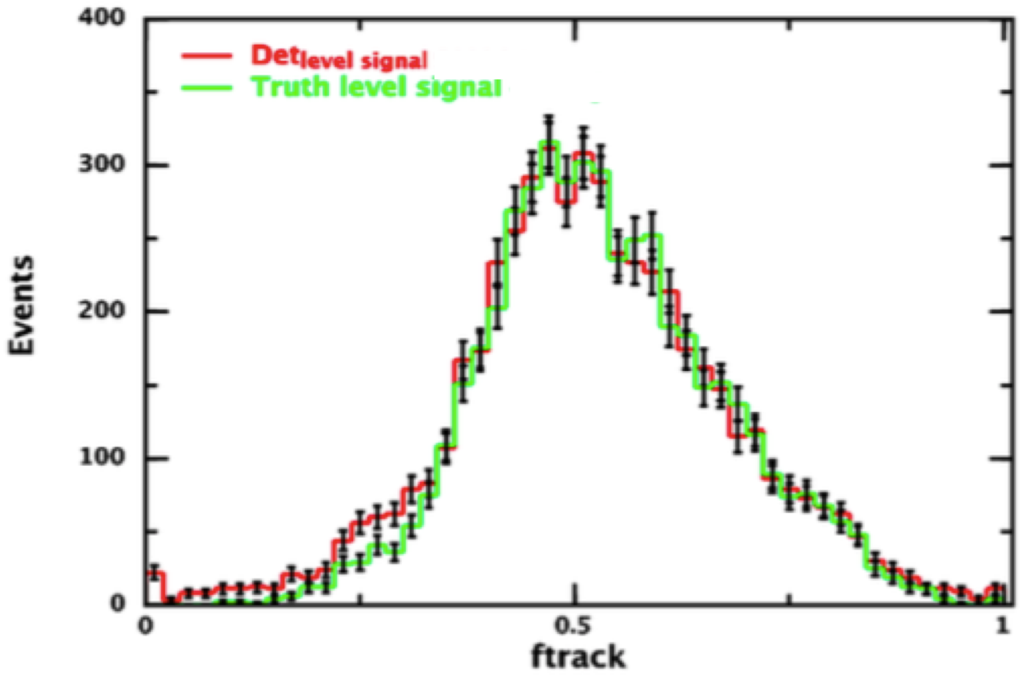
500 GeV hadronic τ-lepton decays with 4mm x 4mm silicon pads
Background simulation in progress, will investigate larger pad sizes and higher $p_T$

**$f_{track}$ (leading track momentum fraction)**
**=(pT of highest pT track in core region ($\Delta R <$ core)) / (Total $E_T$ deposited in $\Delta R <$core )**

core = 0.1



**1 prong**

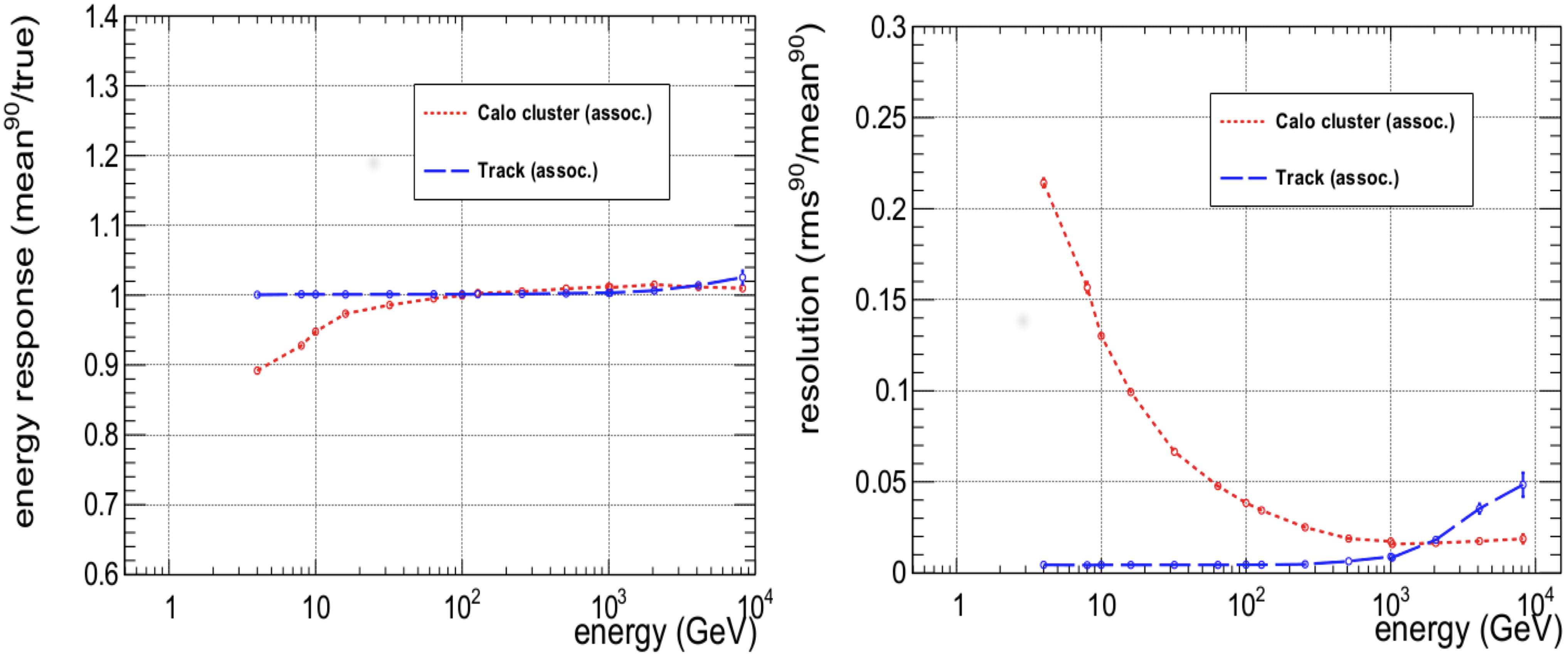


**3 prong**

Analysis by Sourav Sen (Duke graduate student)

# GEANT Simulation of Scintillator / Iron HCAL

## Single pion response and resolution



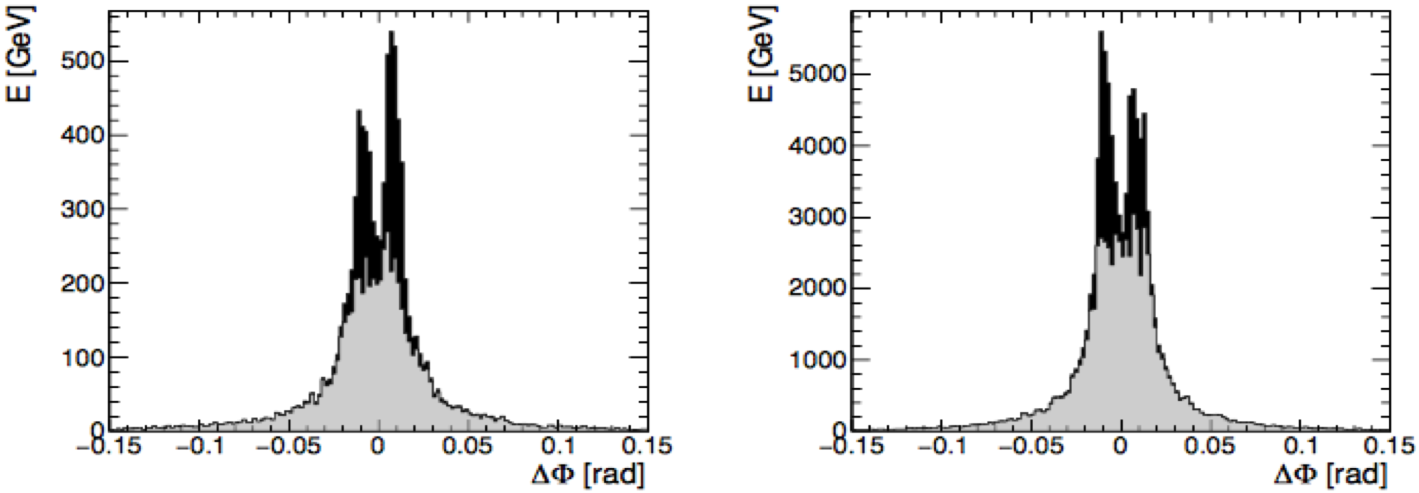
JINST paper published: **JINST 12 (2017) no.06, P06009**

*Initial performance studies of a general-purpose detector for multi-TeV physics at a 100 TeV pp collider*

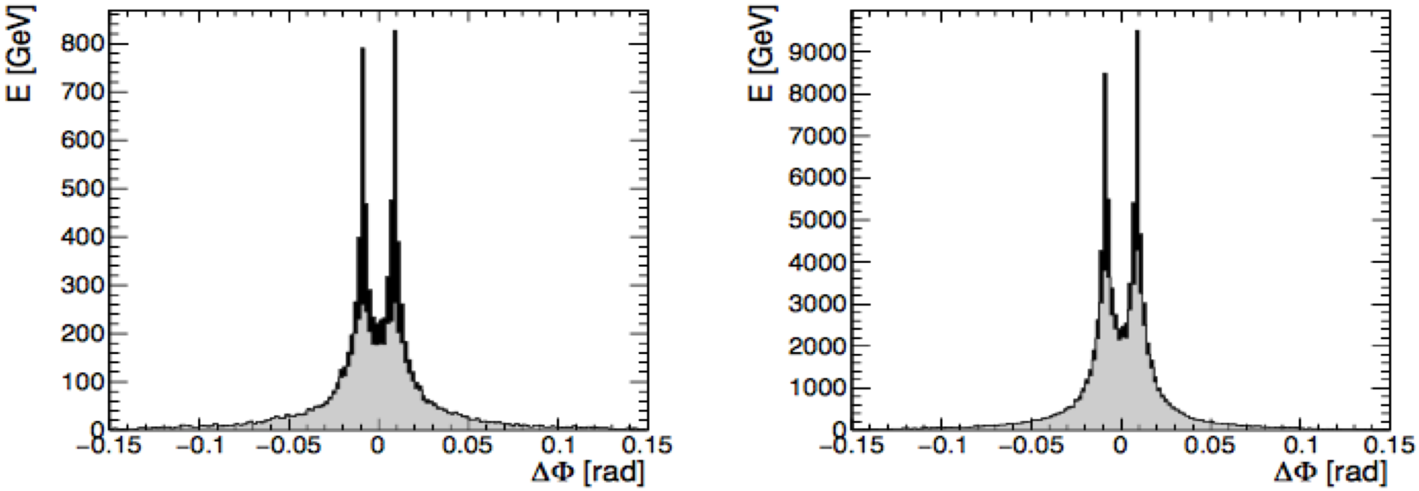
**S.V. Chekanov**, **M. Beydler (Argonne), A.V. Kotwal (Duke U. & Fermilab), L. Gray (Fermilab), S. Sen (Duke U.), N.V. Tran (Fermilab), S. -S. Yu (Taiwan, Natl. Central U.), J. Zuzelski (Michigan State U.).**

# GEANT Simulation of Scintillator / Iron HCAL and Silicon/Tungsten EMCAL

## Two-hadron position resolution



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

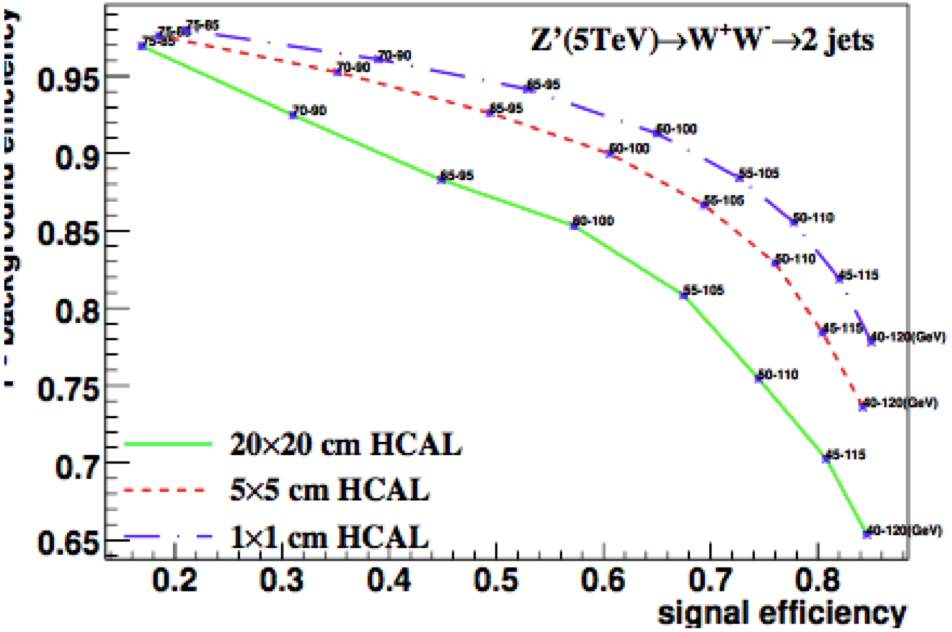


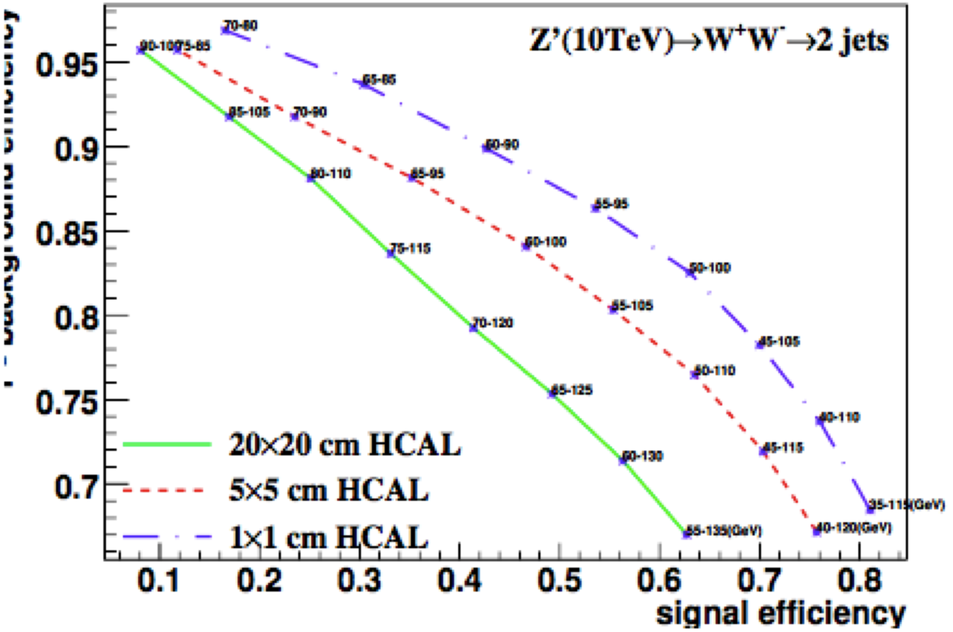
(c) 1 × 1 cm HCAL cells and 3 × 3 mm ECAL cells

Figure 15: 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 $\Delta\phi^K = 0.018$ rad. Electromagnetic calorimeter cells are indicated in black while hadronic calorimeter cells are indicated in gray.

# GEANT Simulation of Scintillator / Iron HCAL and Silicon/Tungsten EMCAL

Boosted boson mass resolution:
improvement with higher granularity calorimetry





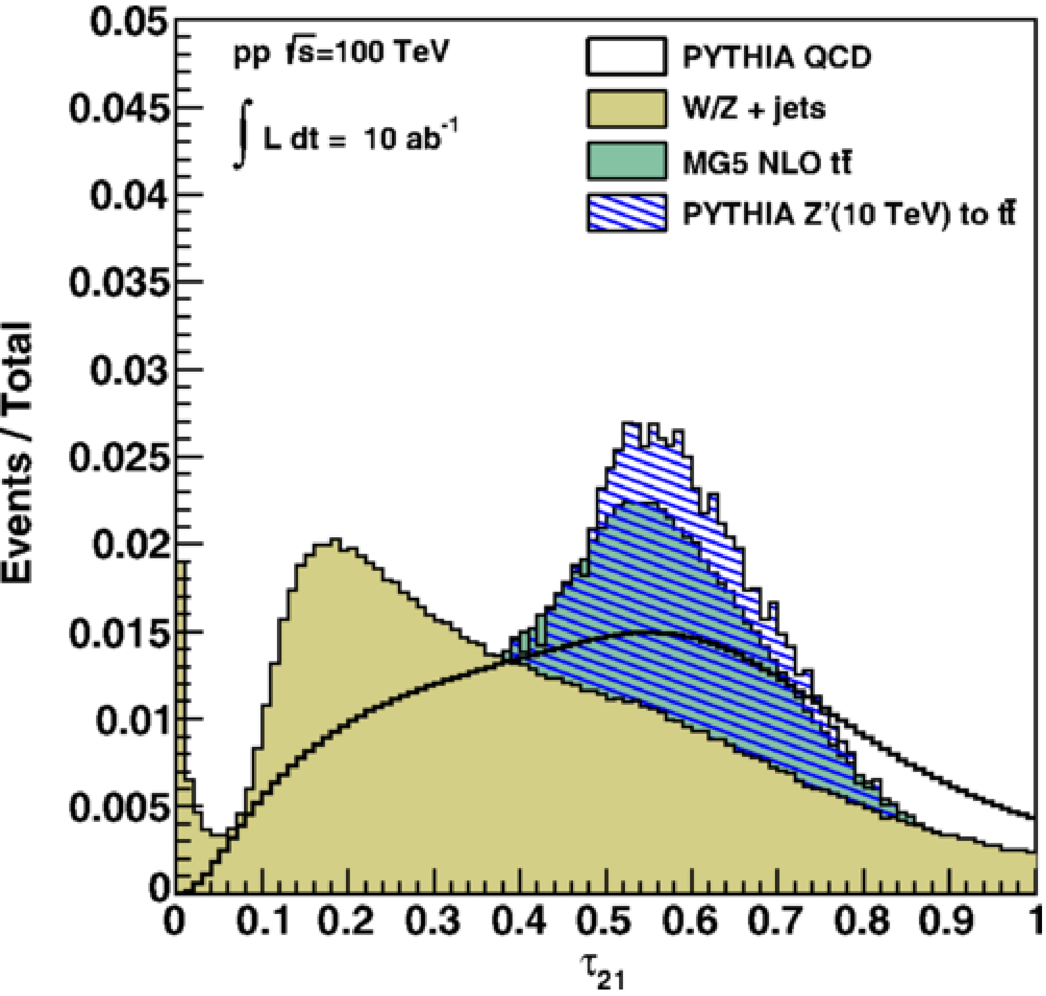
Publishing second paper on jet substructure variables

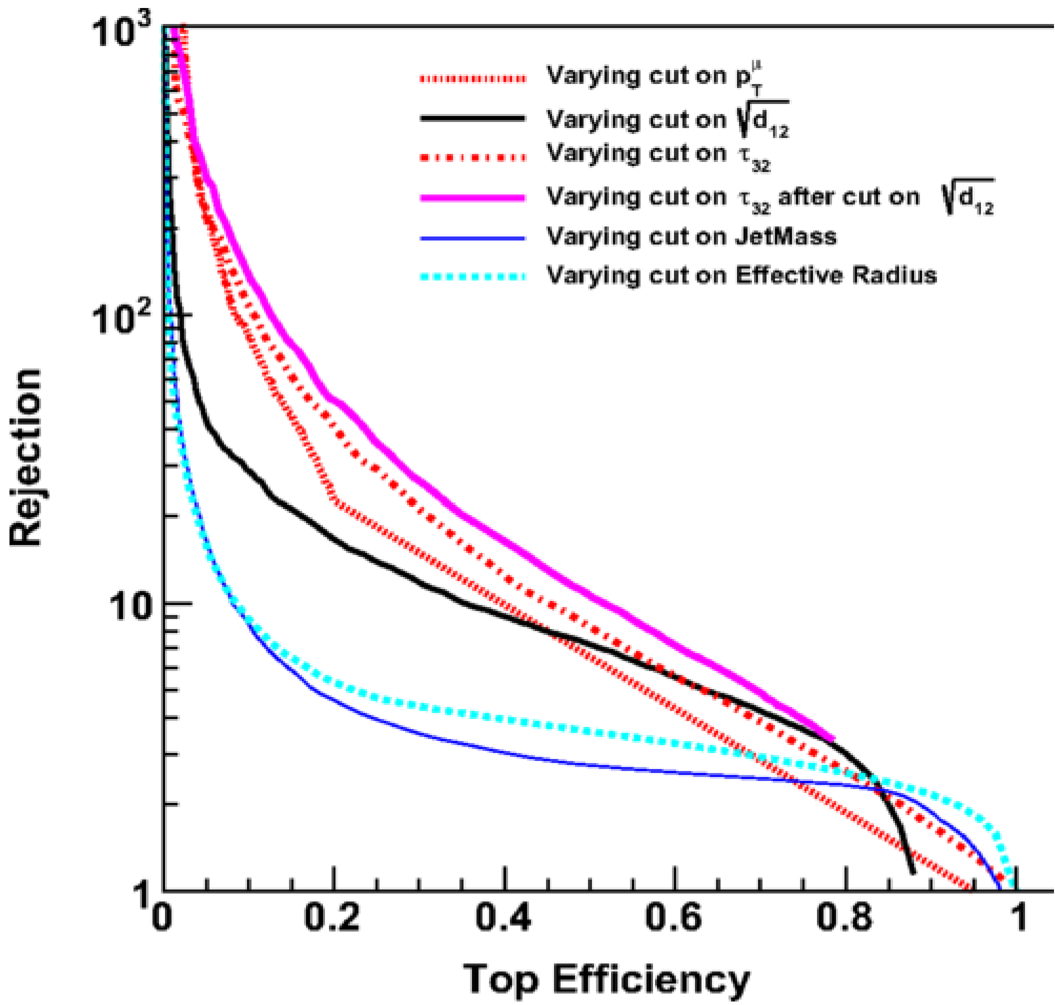
# Granularity Requirements for Boosted Top Quarks

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

20 TeV colored resonances discoverable





# Forward rapidity coverage

# Why is the Higgs Boson So Light?

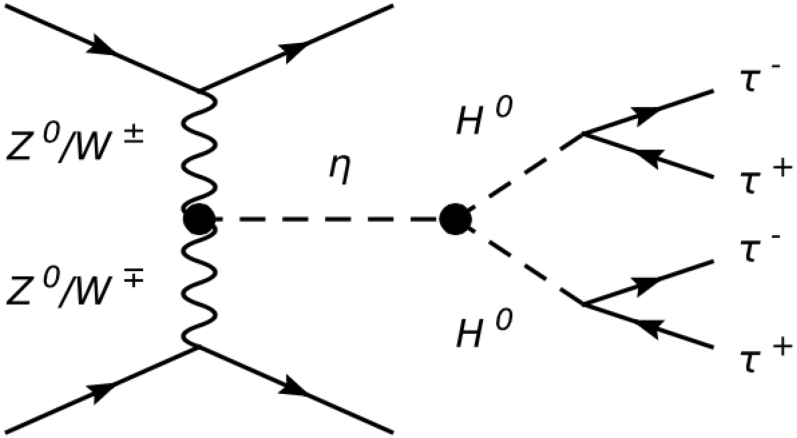
- Old idea: Higgs doublet (4 fields) is a Goldstone mode generated from the spontaneous breaking of a larger global symmetry
  - Higgs boson and $W_L$, $Z_L$ are all Goldstone bosons from, eg. Spontaneously breaking global SO(5) → SO(4)
  - Examples: Holographic Higgs, Little Higgs models...
  - Electroweak vev "$v$" is small compared to SO(5) breaking scale "$f$"

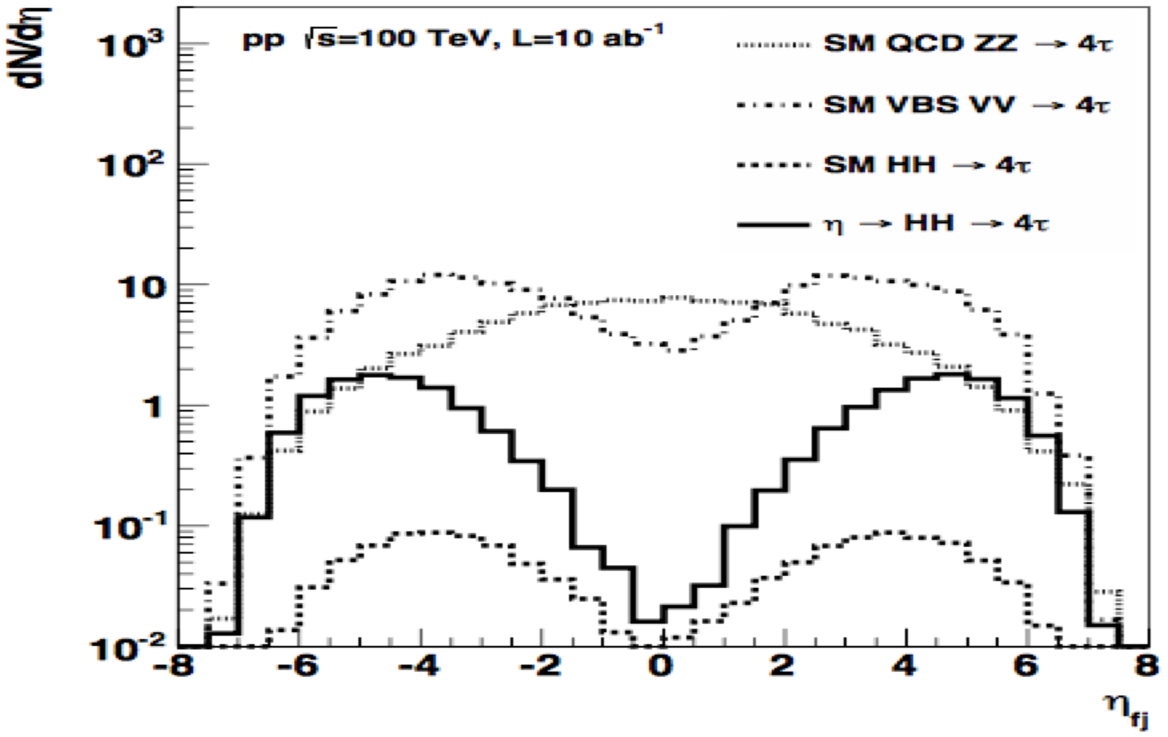
- Vector boson scattering topology
  - Quarks emit longitudinal vector bosons which interact with new (presumably strong) dynamics
  - Quarks scatter by small angle in the forward direction

# Longitudinal 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.

# Forward Jet Coverage for Longitudinal VBS

$V_L V_L \to \eta \to HH$

AVK, S. Chekanov, M. Low

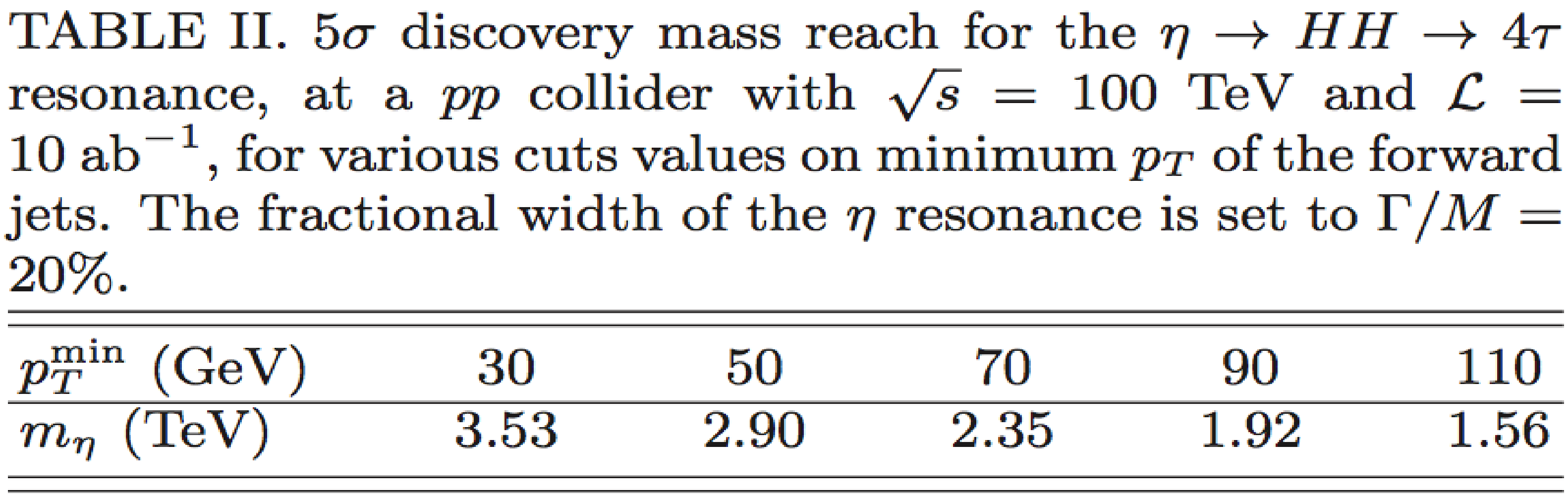


TABLE II. 5$\sigma$ discovery mass reach for the $\eta \to HH \to 4\tau$ resonance, at a $pp$ collider with $\sqrt{s} = 100$ TeV and $\mathcal{L} = 10$ ab$^{-1}$, for various cuts values on minimum $p_T$ of the forward jets. The fractional width of the $\eta$ resonance is set to $\Gamma/M = 20\%$.

| $p_T^{\mathrm{min}}$ (GeV) | 30 | 50 | 70 | 90 | 110 |
|---|---|---|---|---|---|
| $m_\eta$ (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

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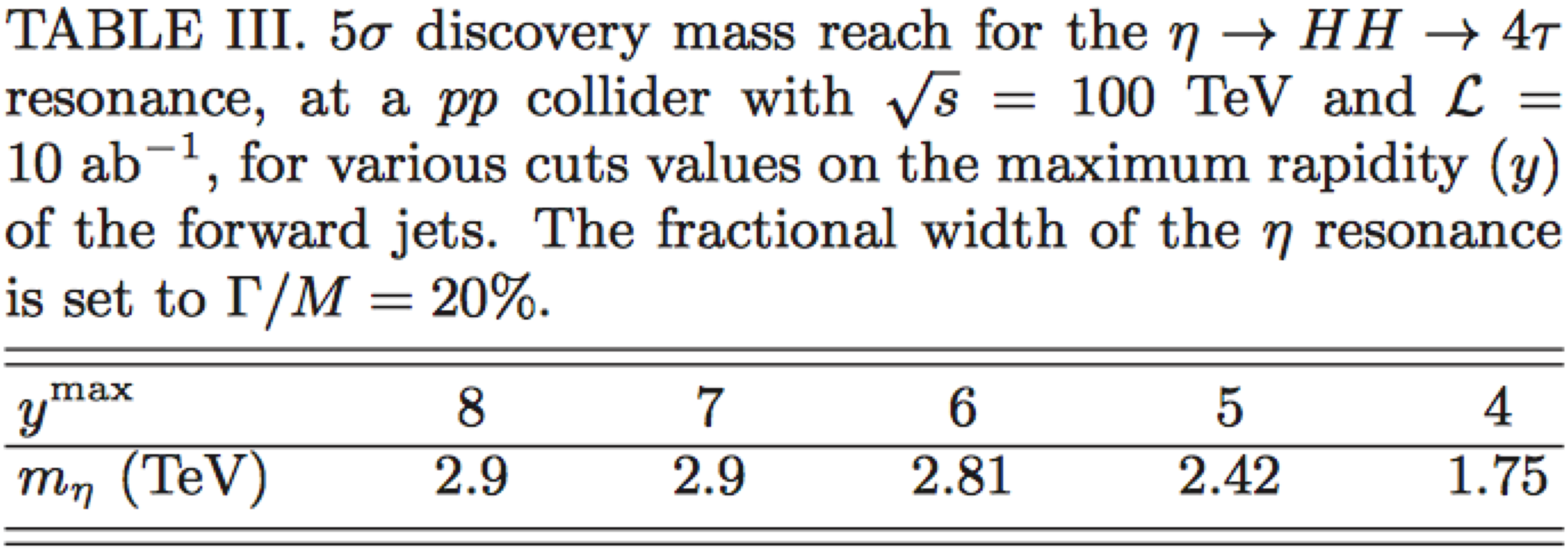

TABLE III. $5\sigma$ discovery mass reach for the $\eta \to HH \to 4\tau$ resonance, at a $pp$ collider with $\sqrt{s} = 100$ TeV and $\mathcal{L} = 10\ \mathrm{ab}^{-1}$, for various cuts values on the maximum rapidity ($y$) of the forward jets. The fractional width of the $\eta$ resonance is set to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

| $y^{\max}$ | 8 | 7 | 6 | 5 | 4 |
|---|---|---|---|---|---|
| $m_\eta$ (TeV) | 2.9 | 2.9 | 2.81 | 2.42 | 1.75 |

Want jet rapidity coverage up to 6 at least

# Vector Boson Scattering

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## 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

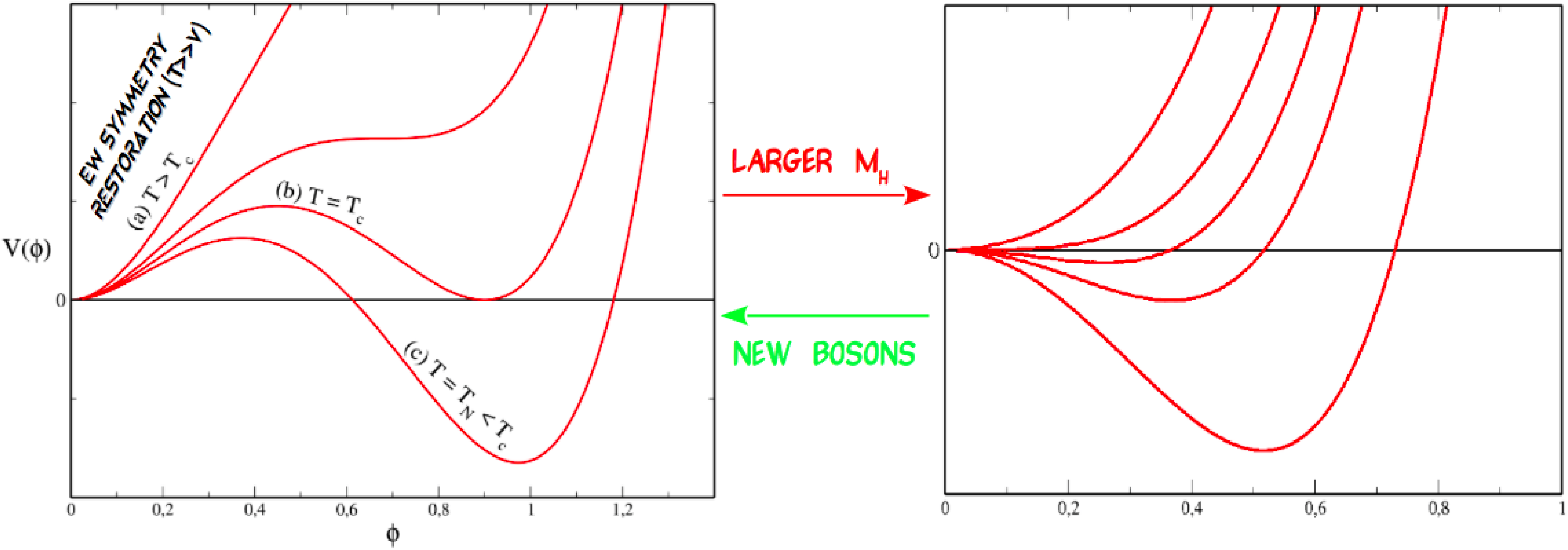
# Baryon Asymmetry and Electroweak Phase Transition

**$1^{st}$ 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*

# Baryon Asymmetry and Electroweak Phase Transition

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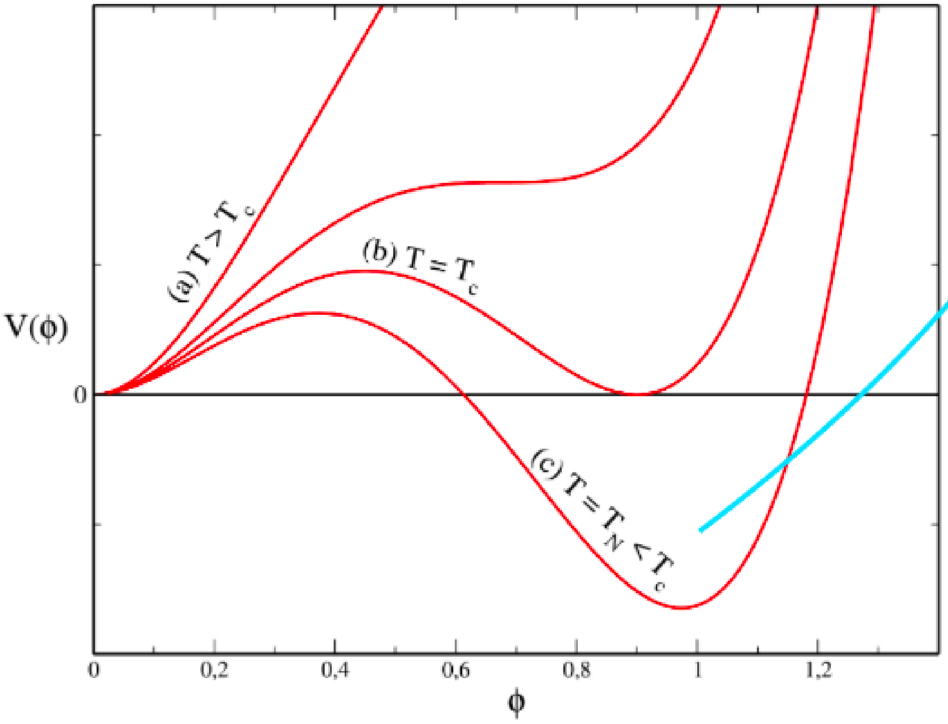
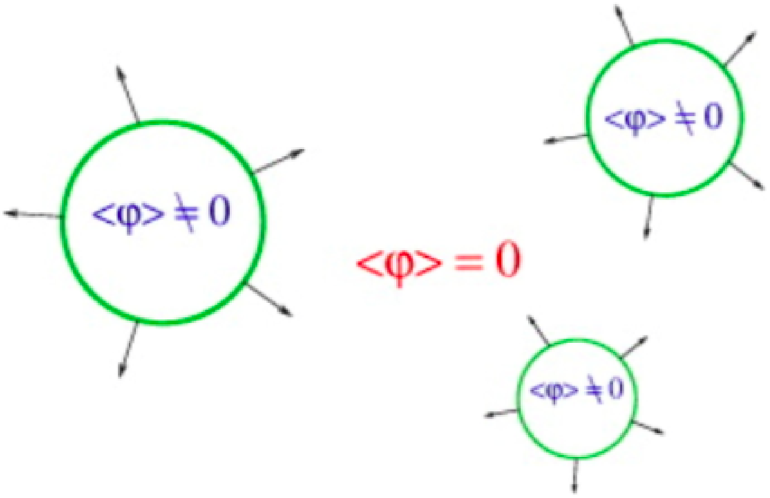


Nucleation of True Vacuum Bubbles
(in False Vacuum Sea)

*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*

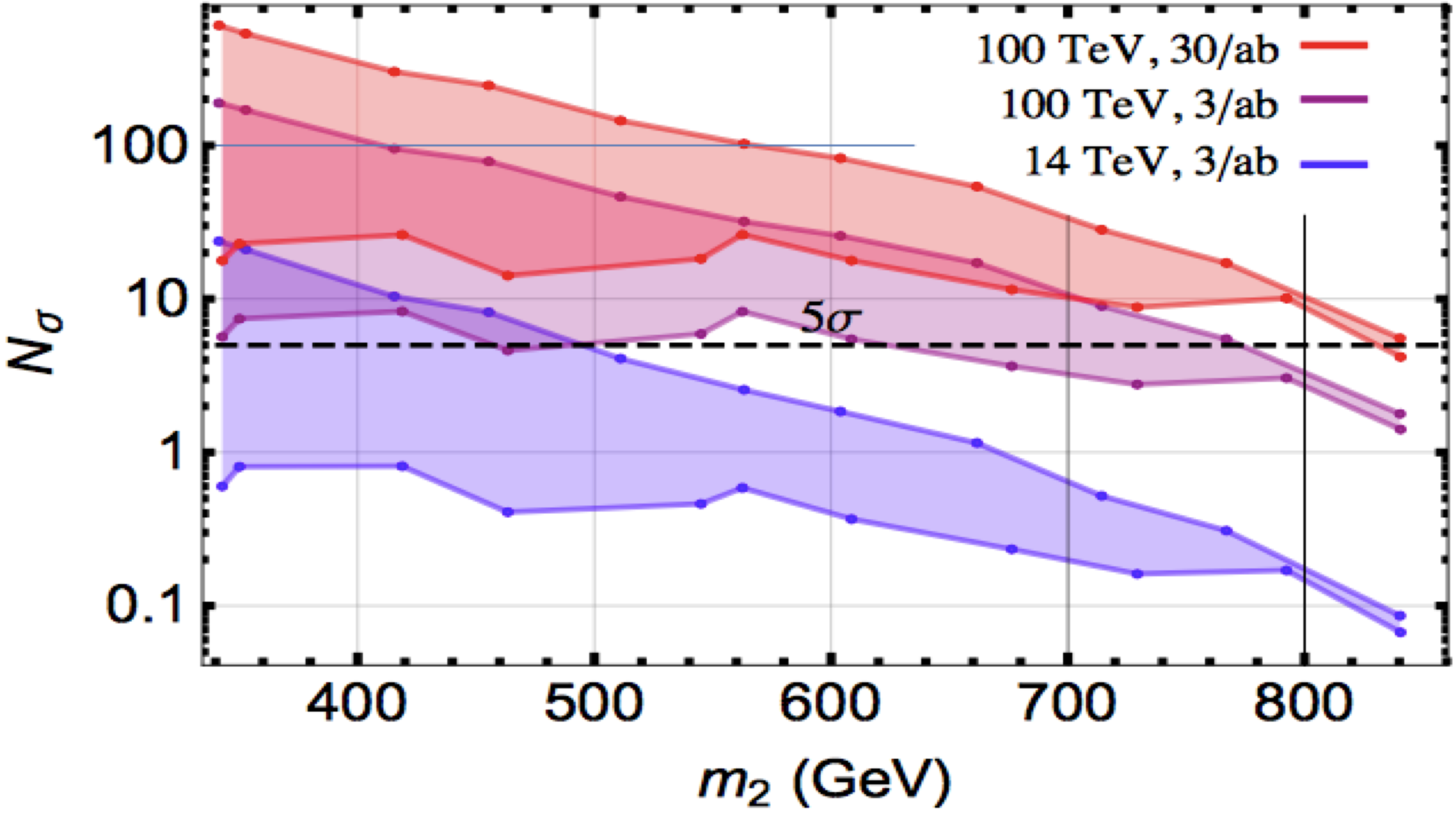


**SUDDEN CHANGE IN HIGGS VEV**

# Inducing First-Order Electroweak Phase Transition

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

$S \to HH \to \gamma\gamma bb$ and $4\tau$



(AVK, P. Winslow,
J. M. No,
M. J. Ramsey-Musolf,
**Phys.Rev. D94 (2016) no.3, 035022** )

Discovery potential across entire parameter space with next collider