Meeting Notes for Greg Bock, Mike Lindgren, Patty McBride and Rob Roser

25 May 1016

(Ashutosh Kotwal)

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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}

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)

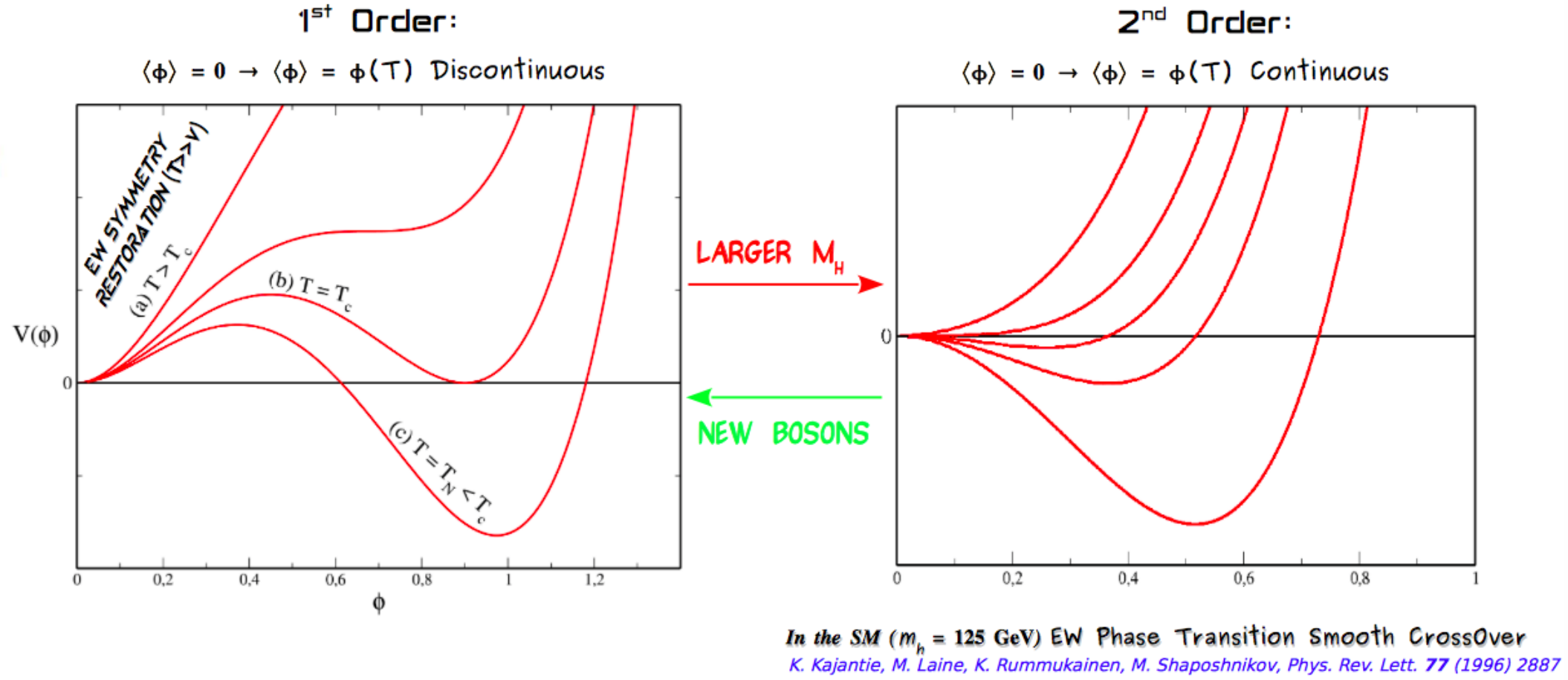
B Violation ✓ Sphalerons

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



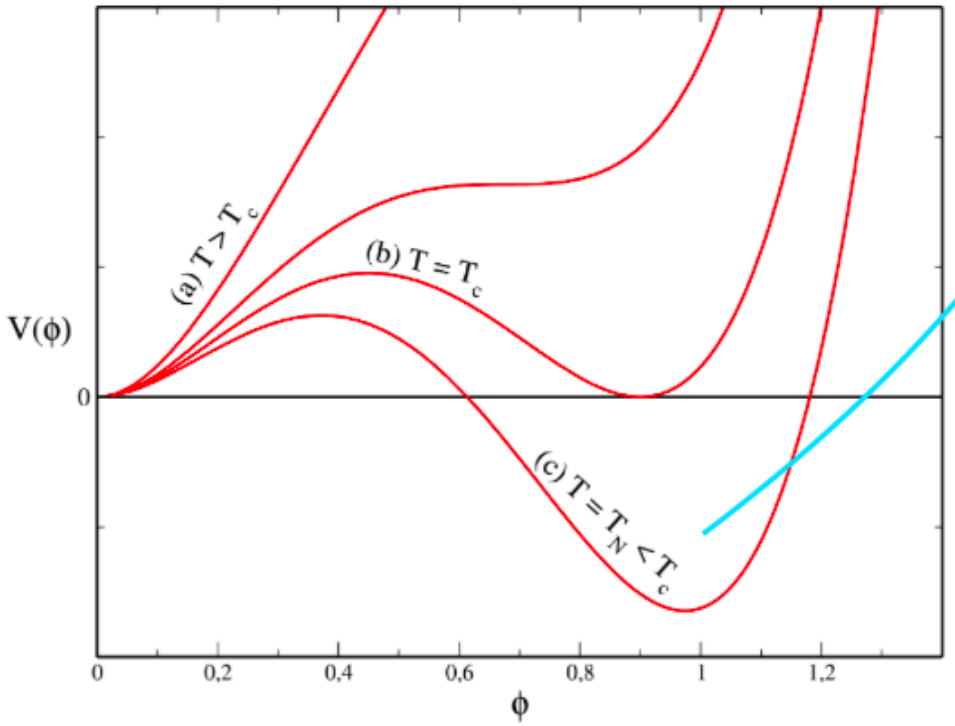
In the SM (m_h = 125 GeV) EW Phase Transition Smooth CrossOver

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

Baryon Asymmetry and Electroweak Phase Transition

1st Order:

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

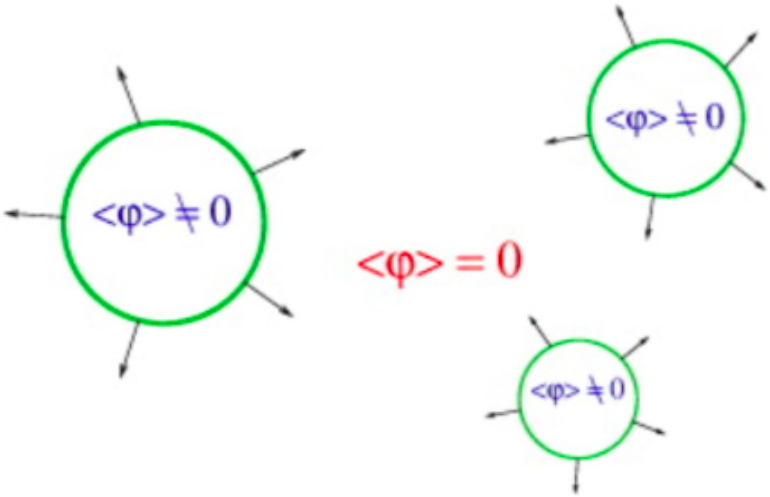


Nucleation of True Vacuum Bubbles (in False Vacuum Sea)

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

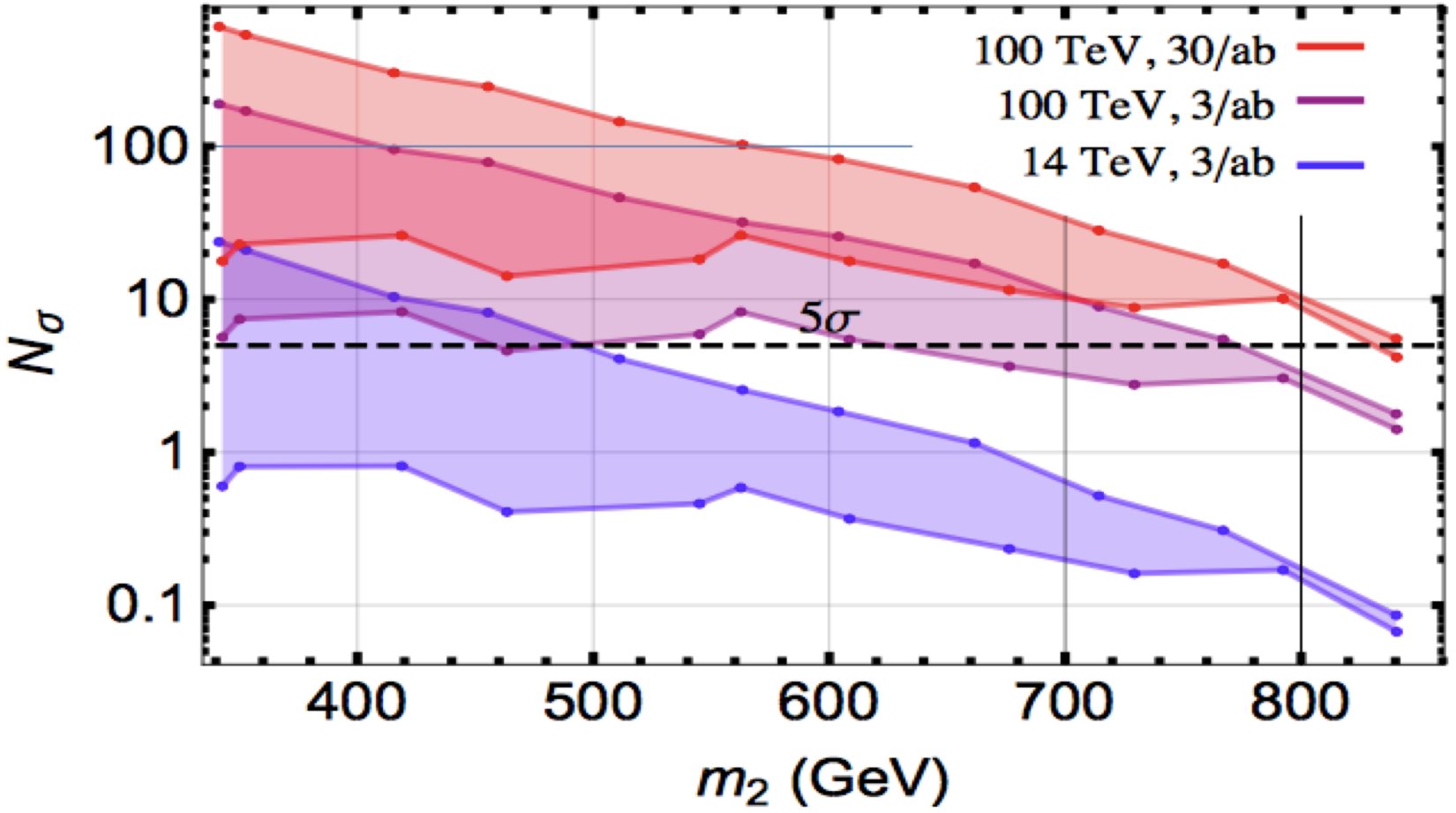


SUDDEN CHANGE IN HIGGS VEV

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 4τ



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

Discovery potential across entire parameter space with next collider

Inducing First-Order Electroweak Phase Transition

$$V(H,S) = -\mu^2 \left(H^\dagger H\right) + \lambda \left(H^\dagger H\right)^2 + \frac{a_1}{2} \left(H^\dagger H\right) S$$
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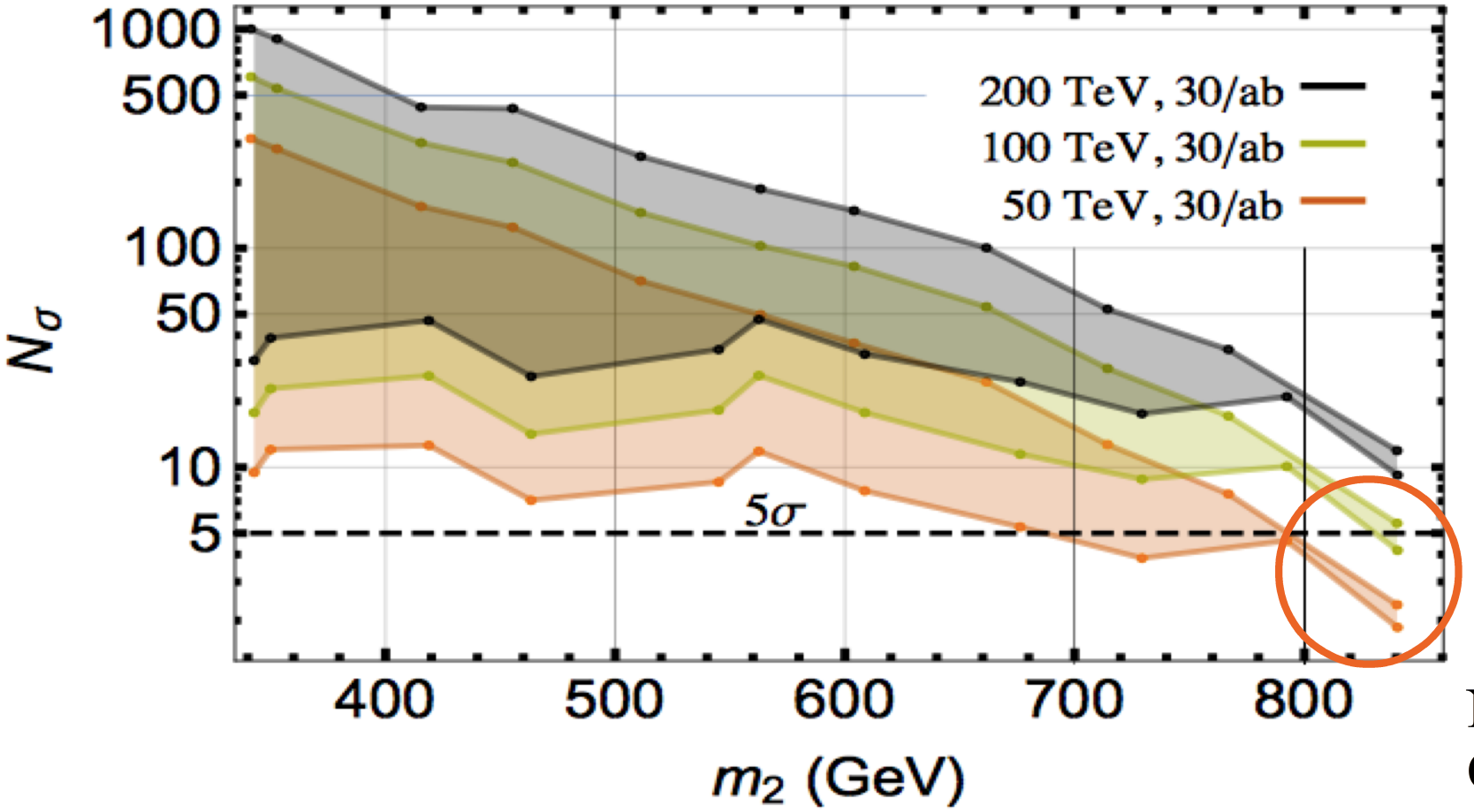
$S \to HH \to \gamma\gamma bb$ and 4τ

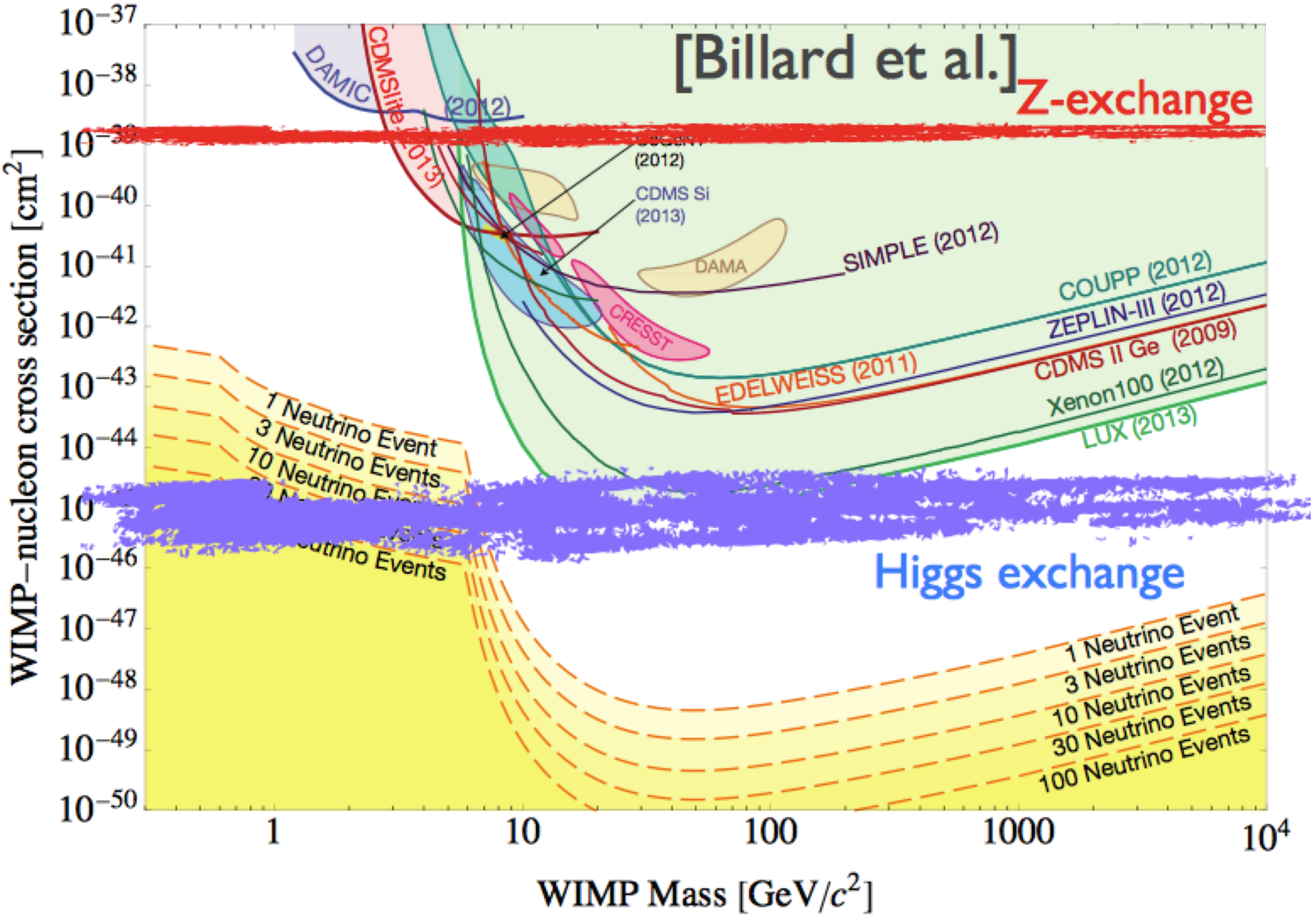


(AVK, P.Winslow, J.M. No, M.J.Ramsey-Musolf)

Next project:
Other channels?

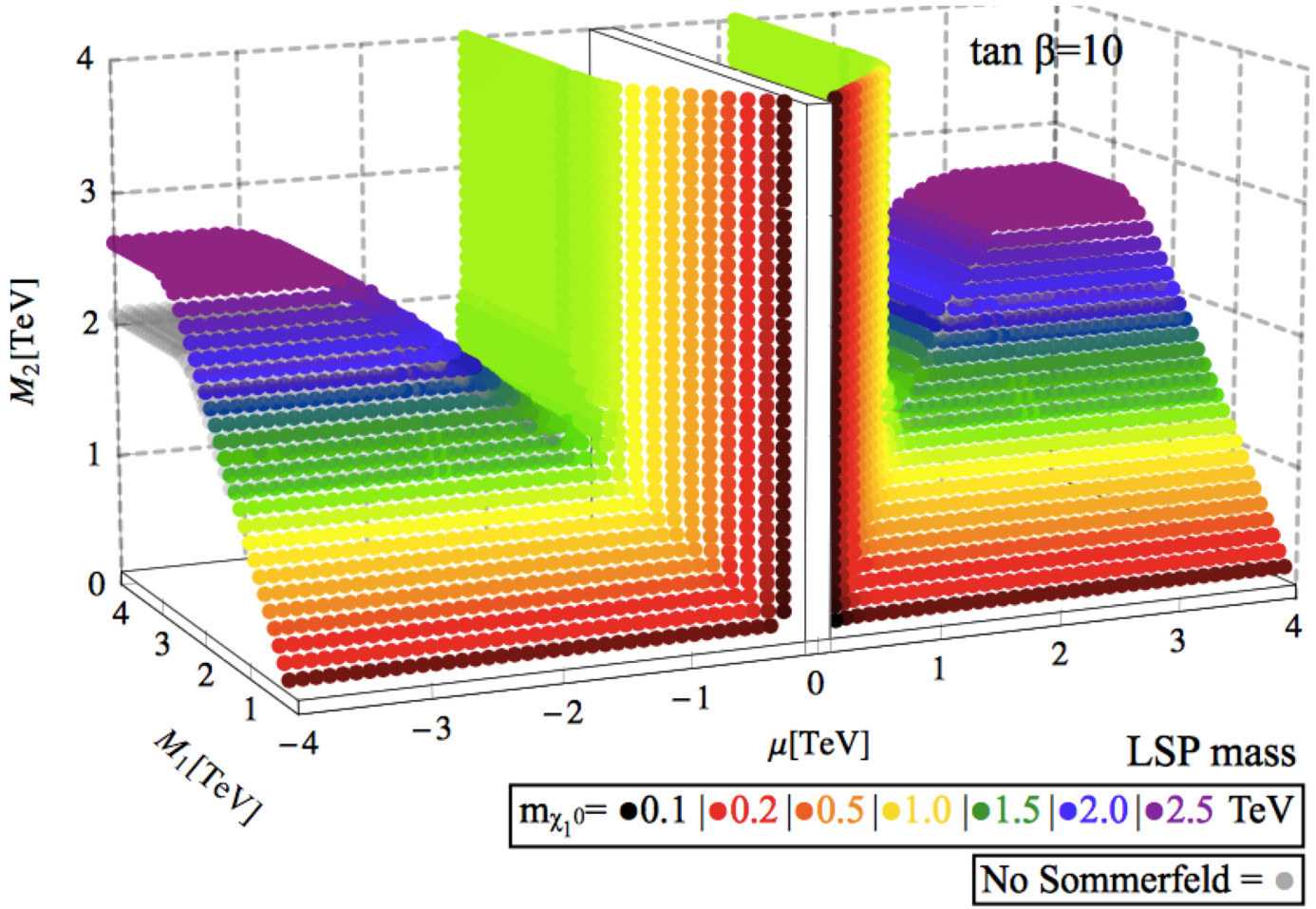
Discovery potential across entire parameter space

Direct Searches for Dark Matter



SUSY Neutralino 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,*

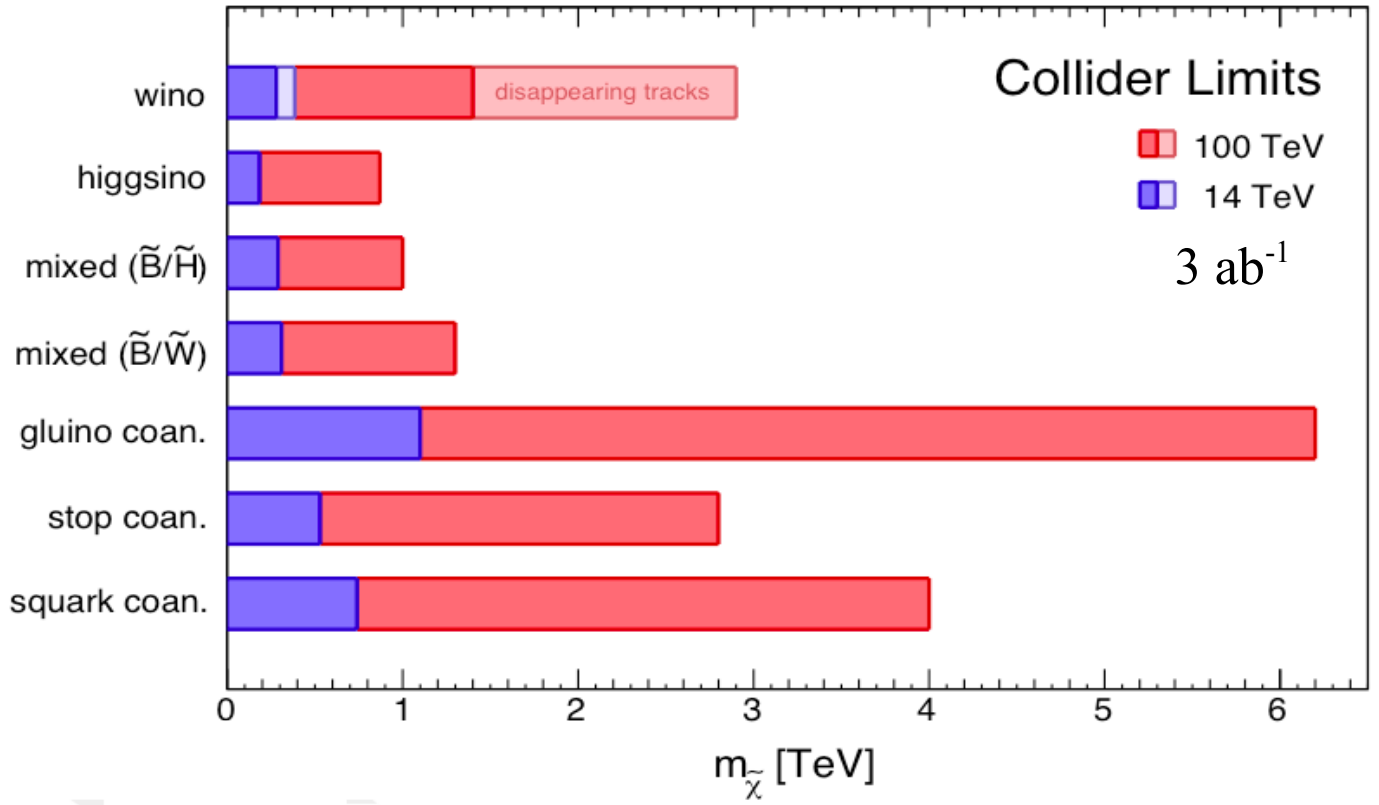
ArXiv:1510.03460

(collaborators of Paddy Fox)

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

WIMP Dark Matter

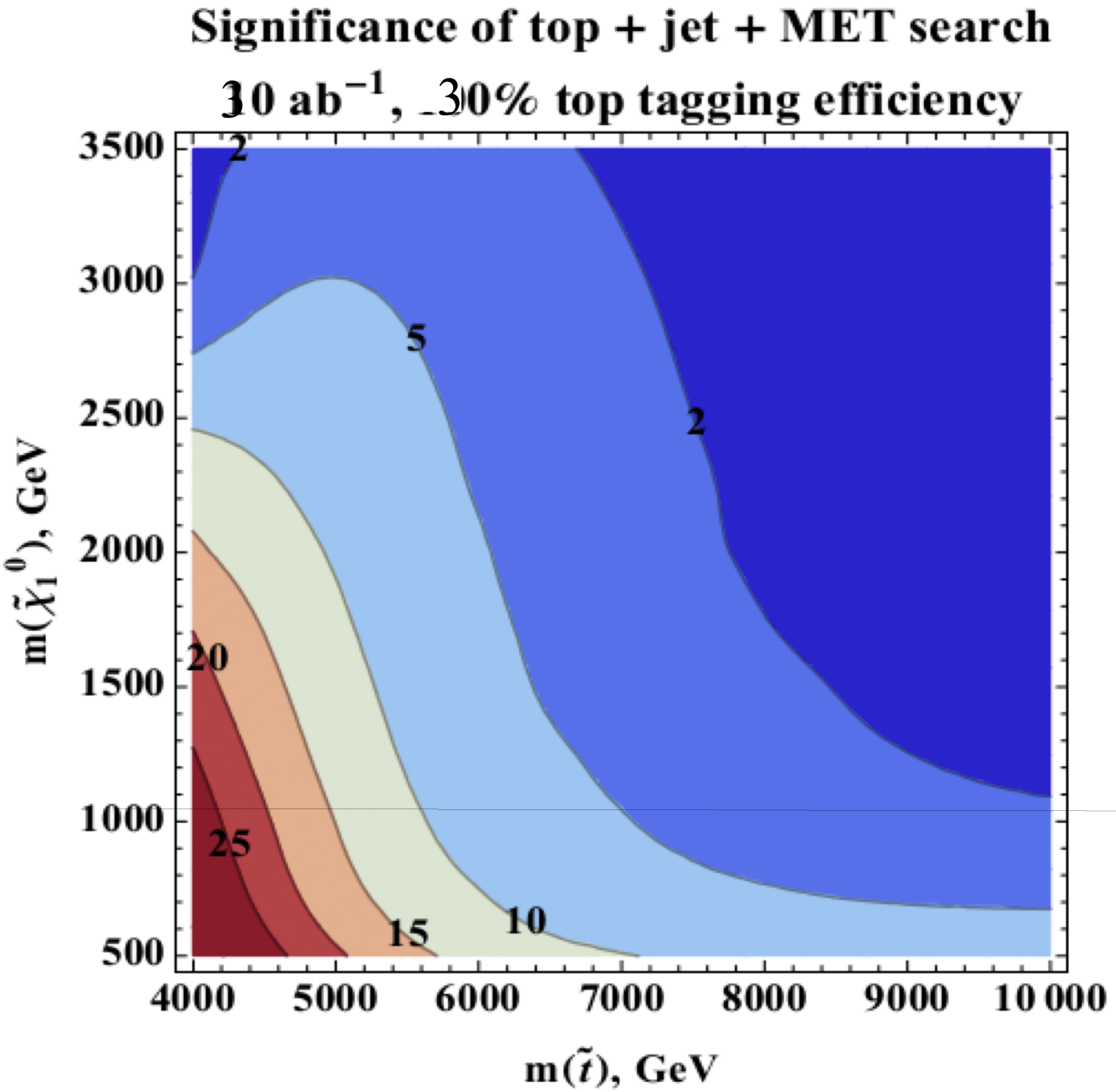
- $M_{\text{Dark Matter}} < 1.8$ TeV $(g_{DM}^2/0.3)$ based on WIMP thermal relic hypothesis



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

100 TeV *pp* collider covers most of the parameter space
Higgsino Dark Matter is the most difficult scenario to access

Higgsino Dark Matter at 100 TeV pp Collider



(Ahmed Ismail, AVK)

Higgsino mass limit from relic density

Exploit large top Yukawa coupling to access Higgsino
Working with Ahmed Ismail (Argonne theory postdoc)

Other Sensitivity Studies in Progress

With Caterina Vernieri (CMS postdoc) and Roni Harnik –
exploring Neutral Naturalness in twin Higgs scenario using multi-*b* jet final state

Also talking with Caterina to Paddy Fox regarding his model to explain gamma ray excess from galactic center → multi-*b* jet final state

With Matthew Low (Nima Arkani-Hamed's post-doc at IAS, Princeton) on accessing composite Higgs resonances using boosted top quarks

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 Simulations

- Strategy:
  - Focus on high-granularity calorimeters
  - Resolve highly-boosted vector and Higgs bosons, top quarks, τ-leptons
  - 5 TeV resonance → HH → 4 τ produces 1 TeV τ lepton
    - photons within τ-jet are separated by ~3 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

- 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 (CMS postdoc), Shin-Shan Yu (Asst. Prof. in Taiwan), Sourav Sen (Duke graduate student)
- Lindsey Gray (CMS) is our Particle Flow Algorithm expert consultant

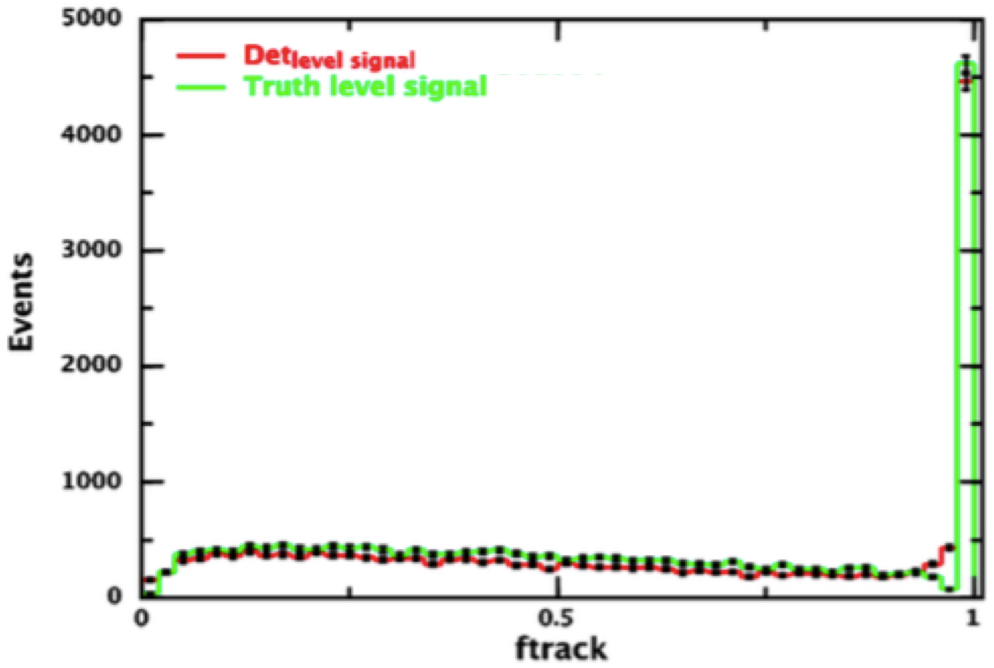
GEANT Simulation of Silicon/Tungsten EM Calorimeter

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

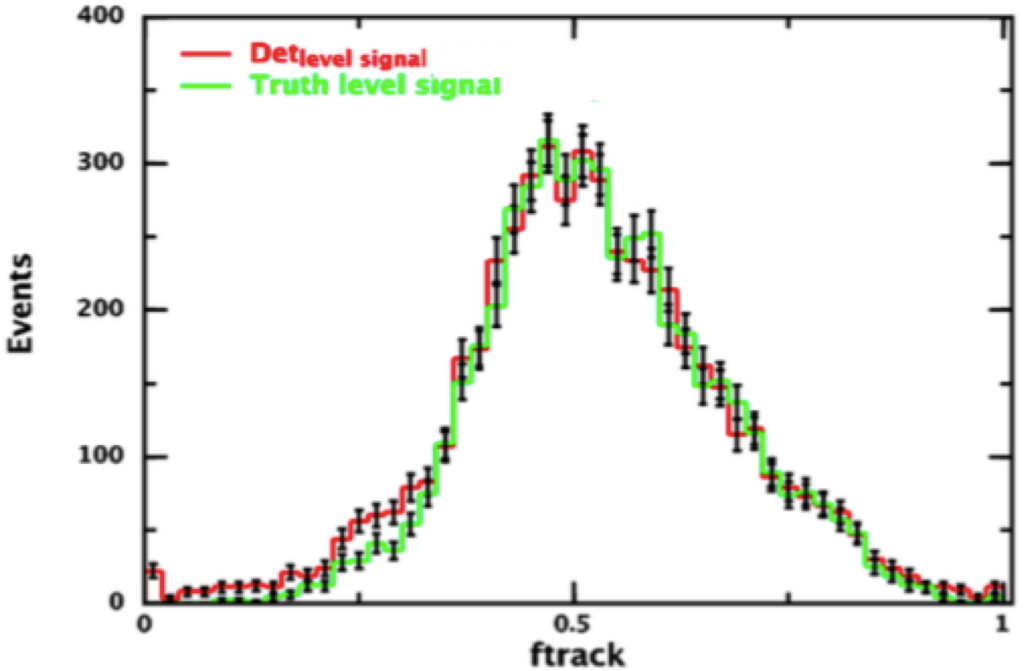
f_{track} (leading track momentum fraction)

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

core = 0.1



1 prong

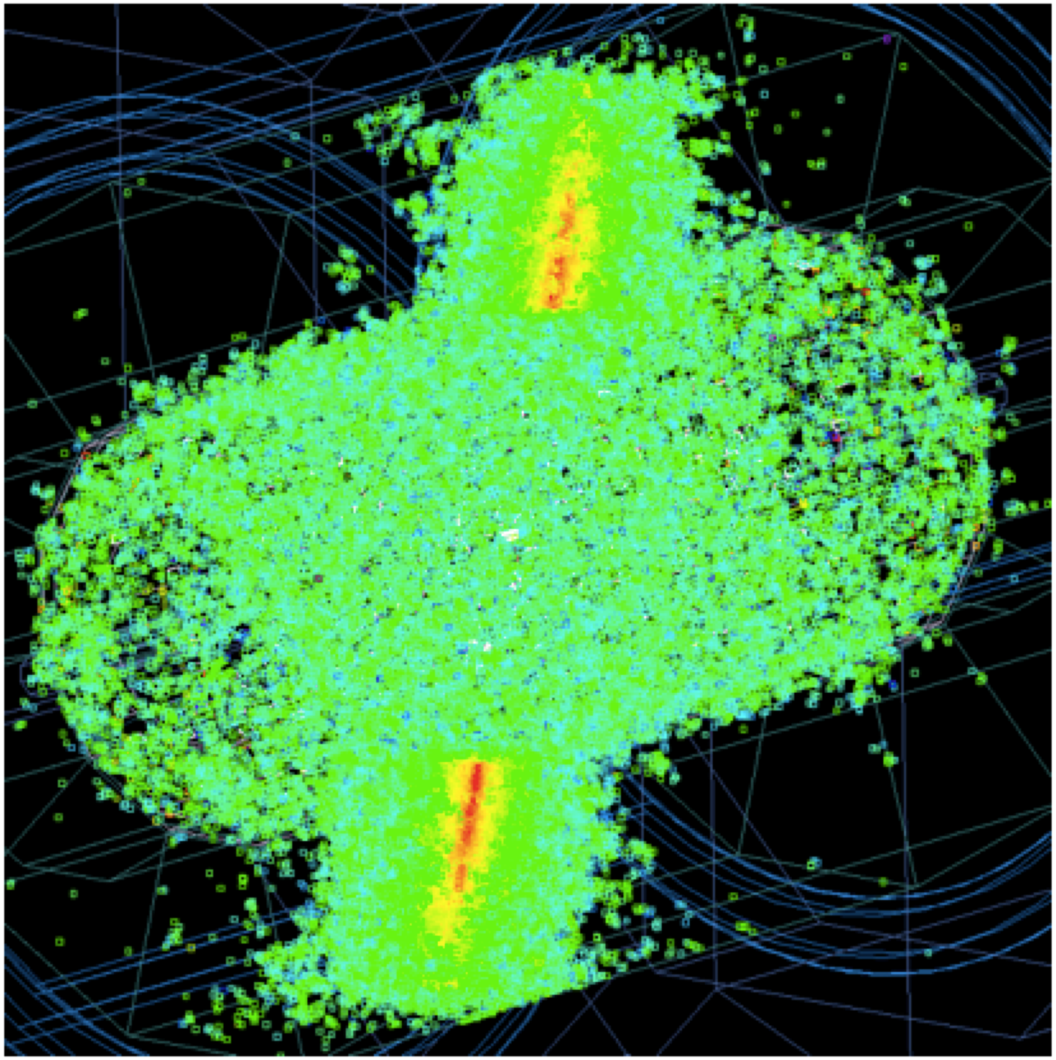


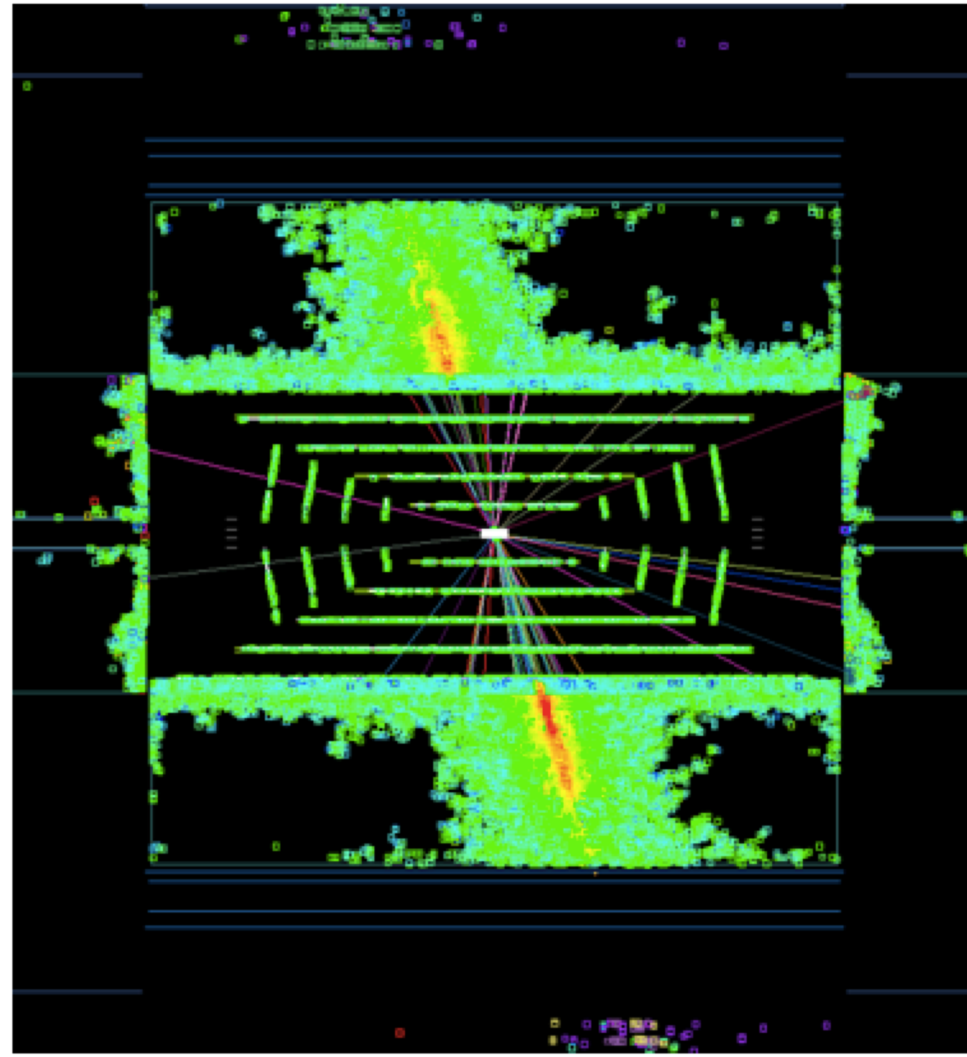
3 prong

Analysis by Sourav Sen (Duke graduate student)

GEANT Simulation of Scintillator / Iron HCAL

5 TeV hadronic ⁄ → ∫EZ∫Π decay with 4 cm x 4 cm scintillator readout
Background simulation in progress, will investigate different pad sizes and higher p_T

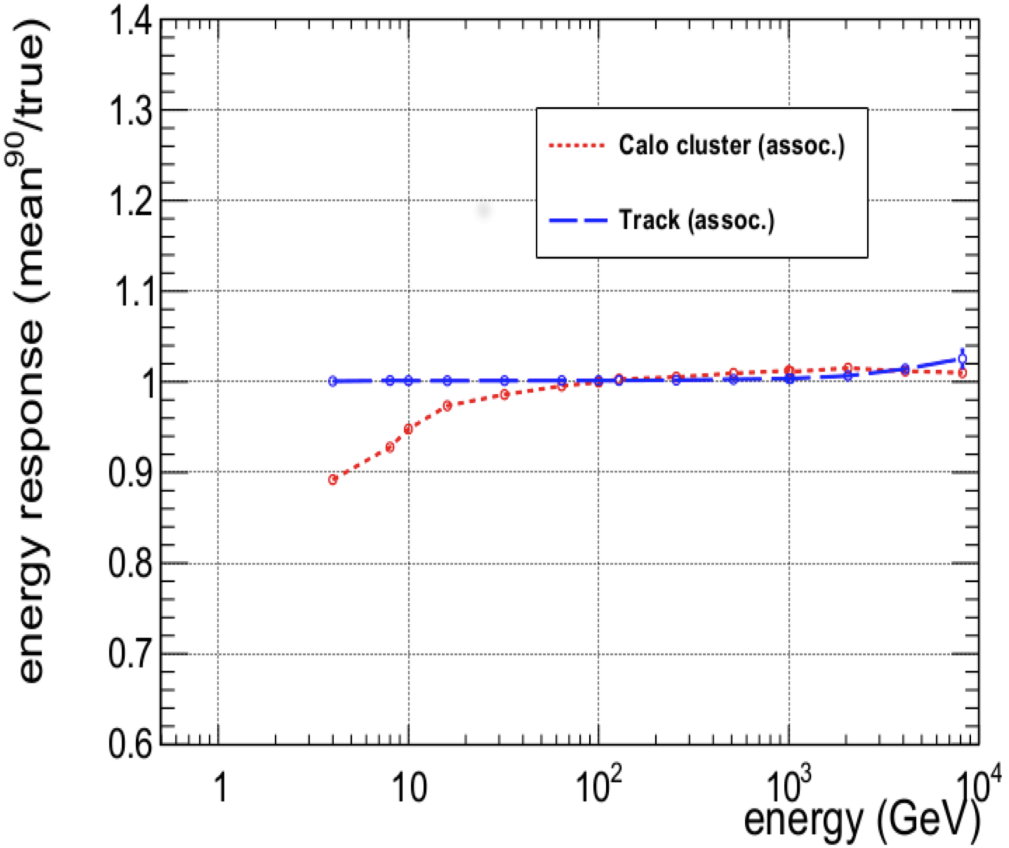


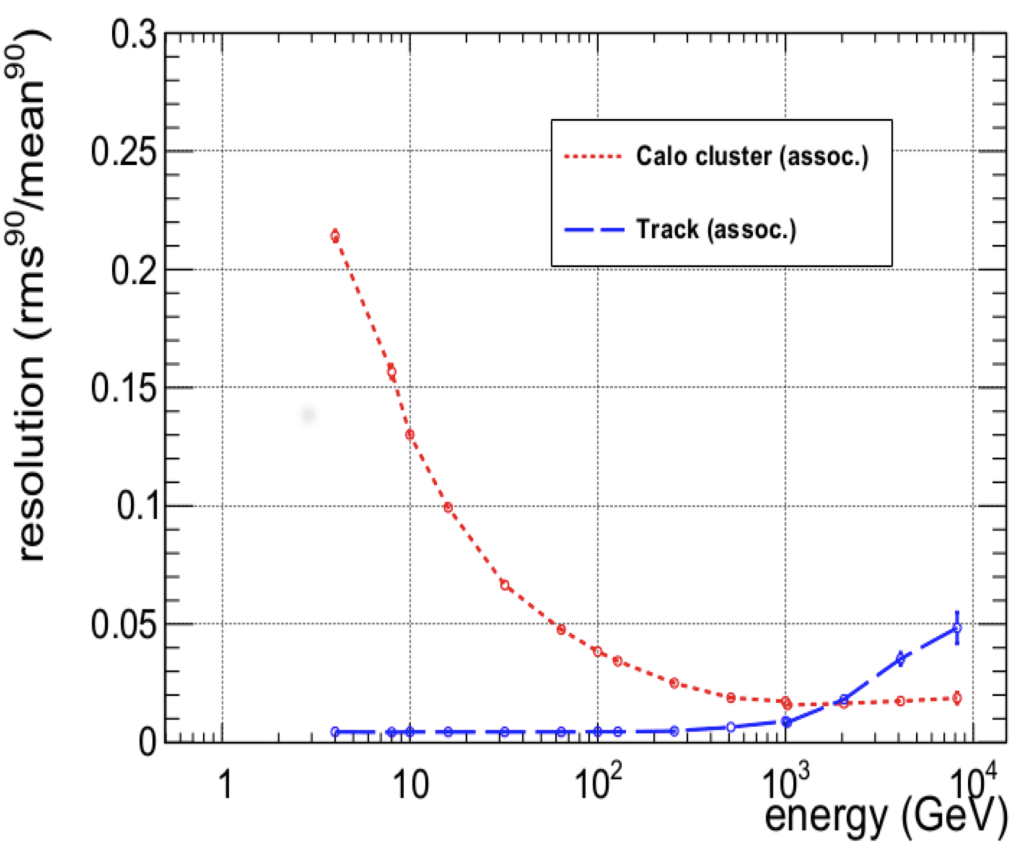


Generated on OSG by S. Chekanov

GEANT Simulation of Scintillator / Iron HCAL

Single pion response and resolution





- Analysis by Nhan Tran → now looking at two-particle separating power *versus* granularity
- Lindsey consulting on particle flow algorithm issues
- Shin-Shan Yu → jet response and resolution
- First look at boosted object discriminating variables
- Targeting NIM paper