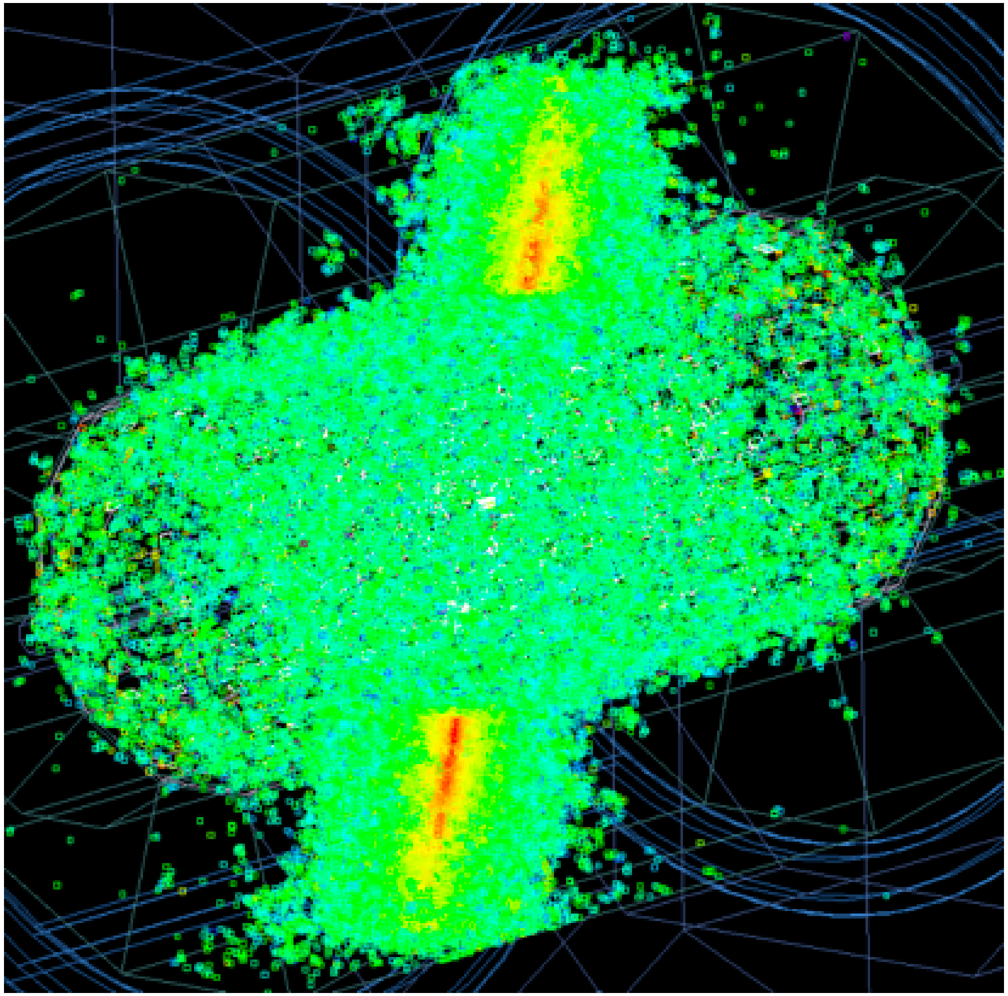
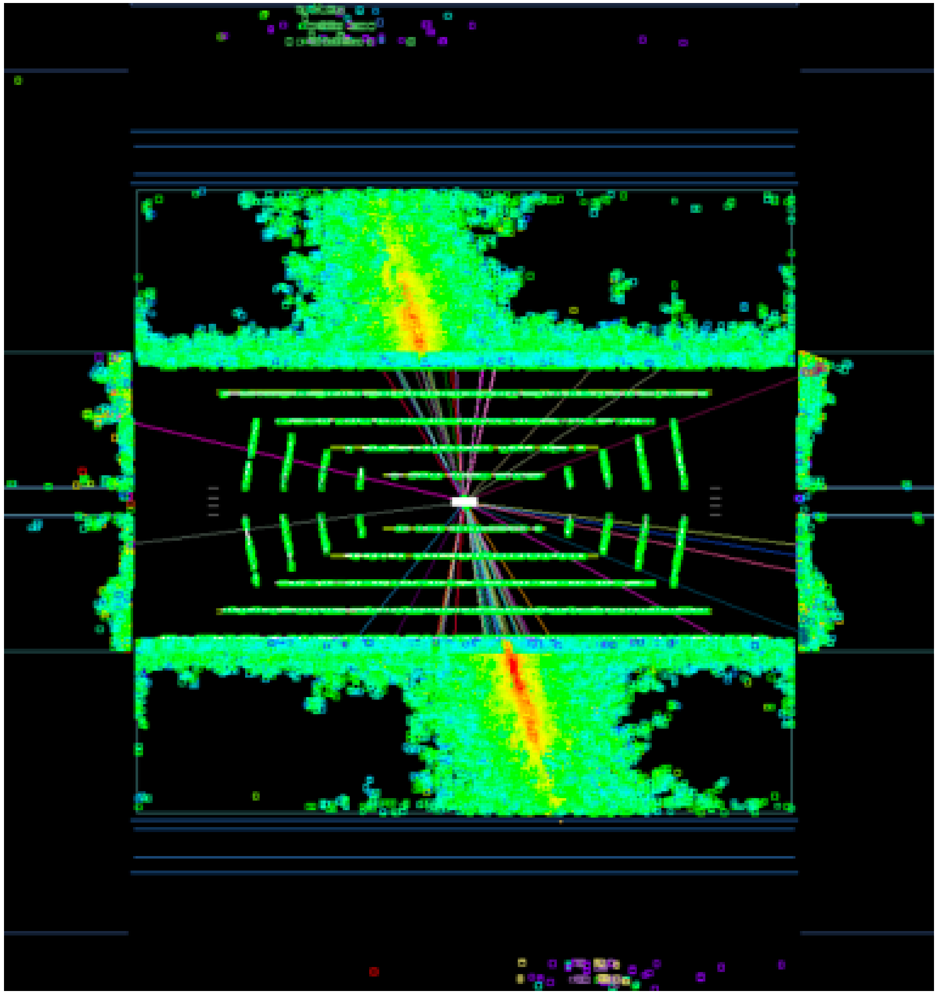
Physics and Experiments at a 100 TeV *pp* Collider

Ashutosh Kotwal
Duke University





USATLAS Workshop
Argonne National Laboratory
July 27, 2017

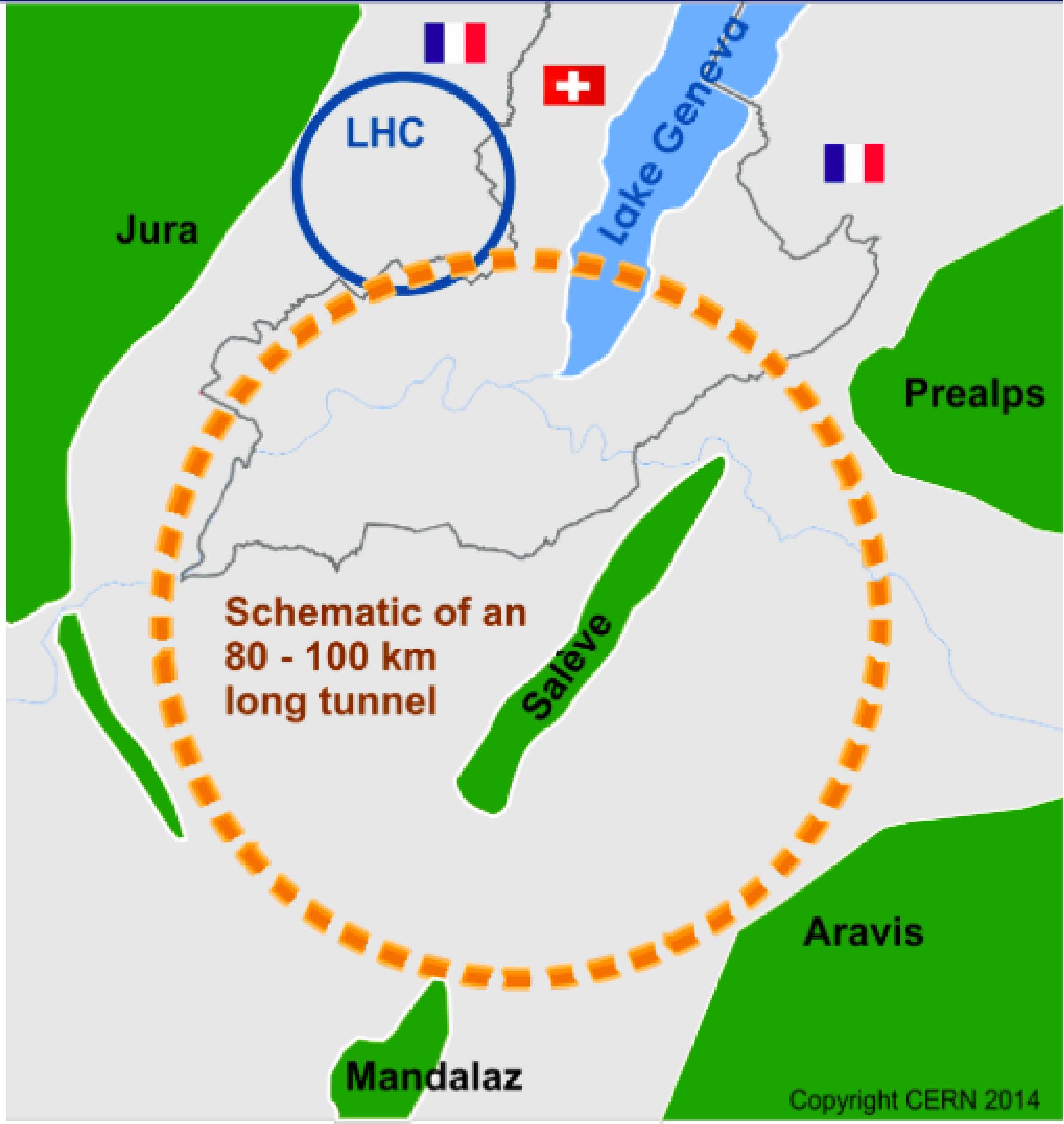
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

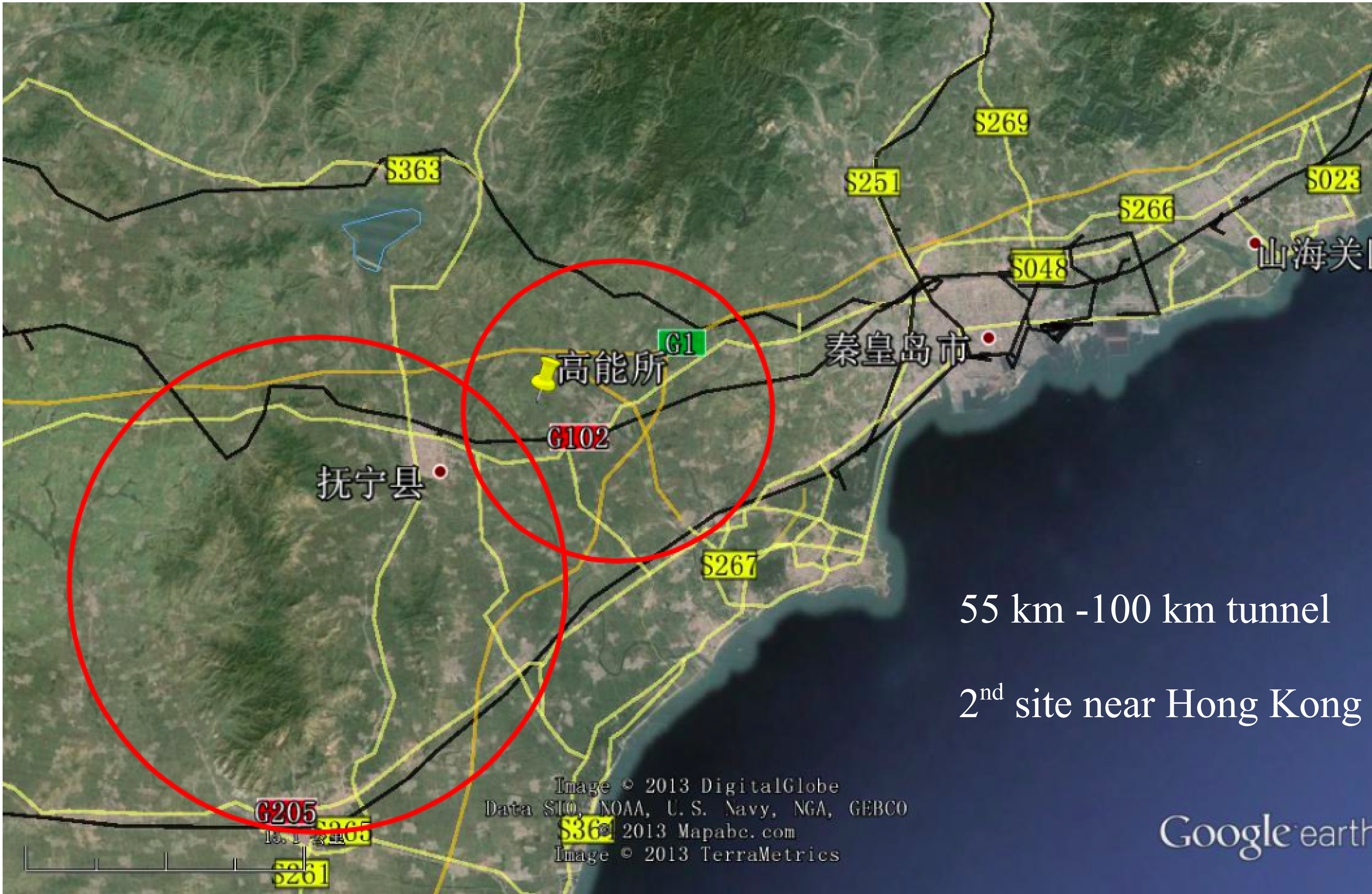
- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements

~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 CEPC-SPPC Site 300 km East of Beijing



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}

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. $gg \rightarrow HH$)
    - Going up to ~7 times the highest p_T probed at LHC
- Also large rapidity range for all objects due to higher longitudinal boost

Executive 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 was designed
  - We must prepare for a broader range of possible new physics
- Detectors will need to be more capable on all fronts
  - Faster
  - Much higher resolution
  - Much higher granularity
  - Much more forward-detection capability
  - Much higher bandwidth, smarter triggers
- HL-LHC upgrade will provide much experience and insights

All-Purpose 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

All-Purpose 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 τ2leptons
  - 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

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

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

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

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

Statistical precision:

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

Magnetic Tracking

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]:

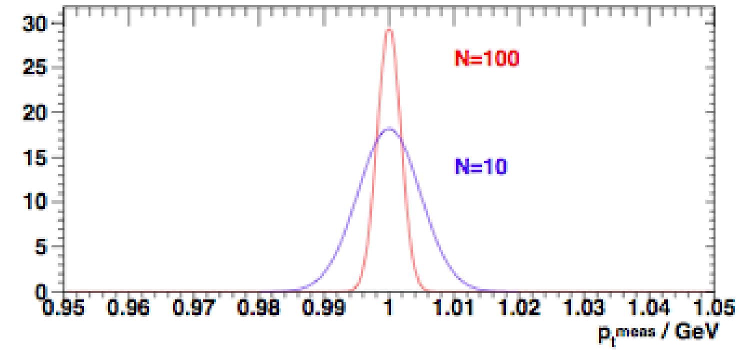
$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma(\kappa)}{\kappa} = \frac{\sigma_x \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{(N+4)}}$$

(for $N \geq 10$, curvature $\kappa = 1/\rho$)

Example: For $p_T = 1\text{GeV}$, $L = 1\text{m}$, $B = 1\text{T}$, $\sigma_x = 200\mu\text{m}$ and $N = 10$ one obtains:

$$\frac{\sigma(p_T)}{p_T} \approx 0.5\% \quad \text{for a sagitta} \quad s \approx 3.8\text{cm}$$

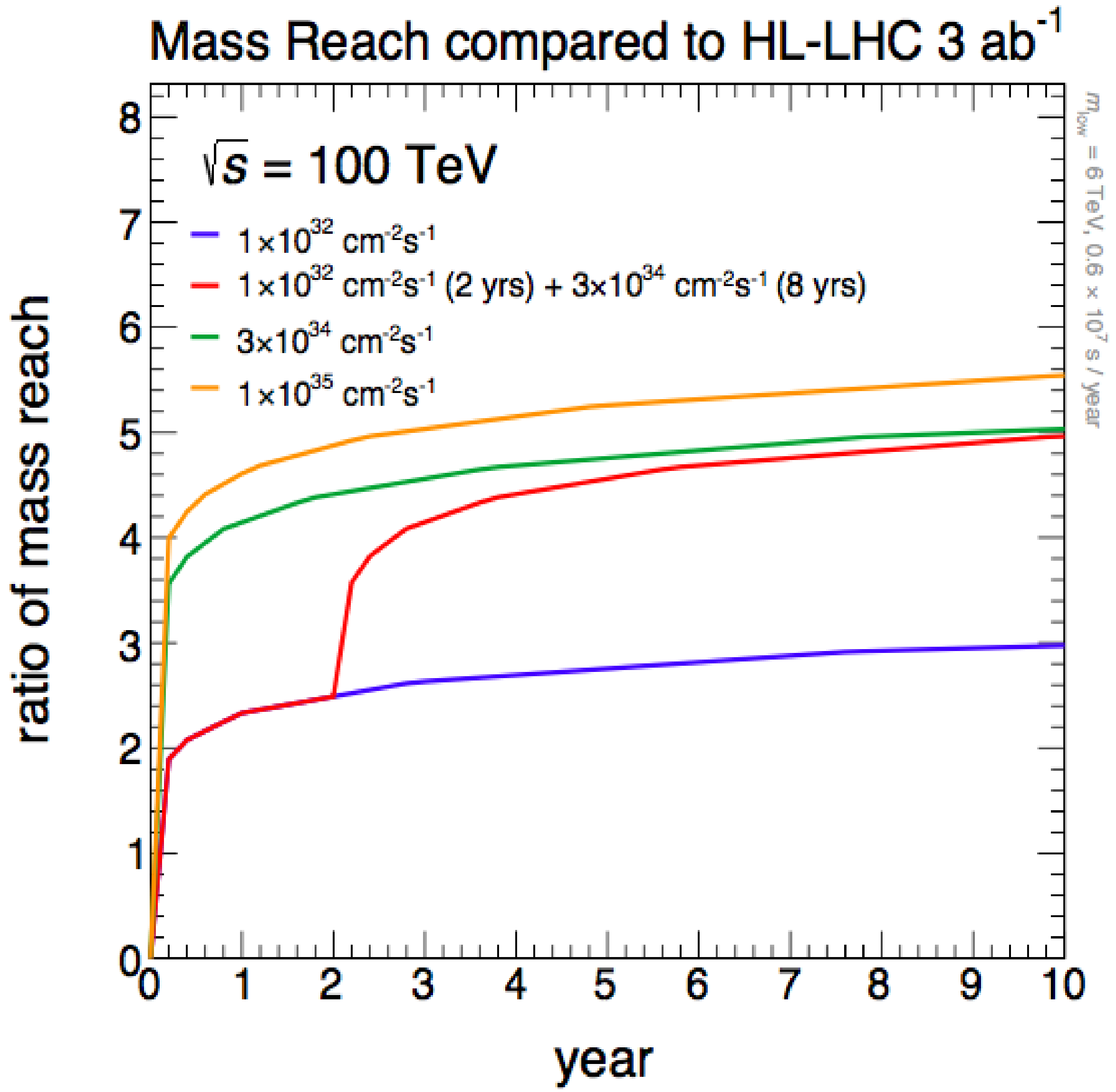
Important track detector parameter: $\frac{\sigma(p_T)}{p_T^2}$ (%/GeV)



Thanks to Carsten Niubuhr

Collider Luminosity and Energy

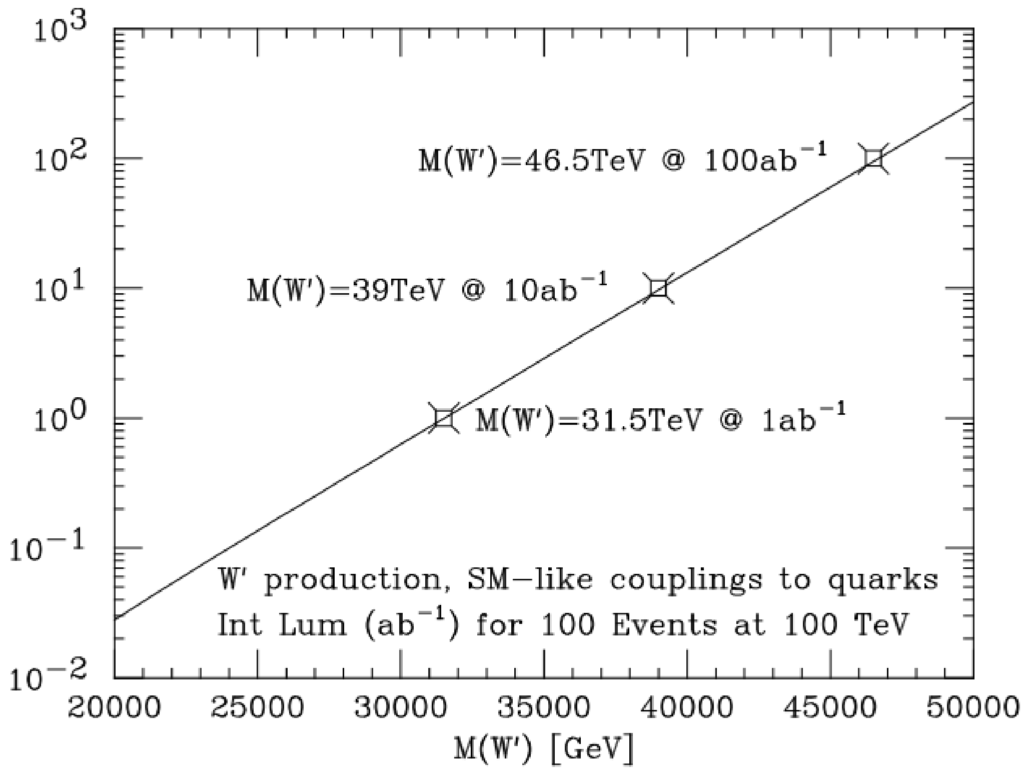
- Collider luminosity evolution for high-mass reach

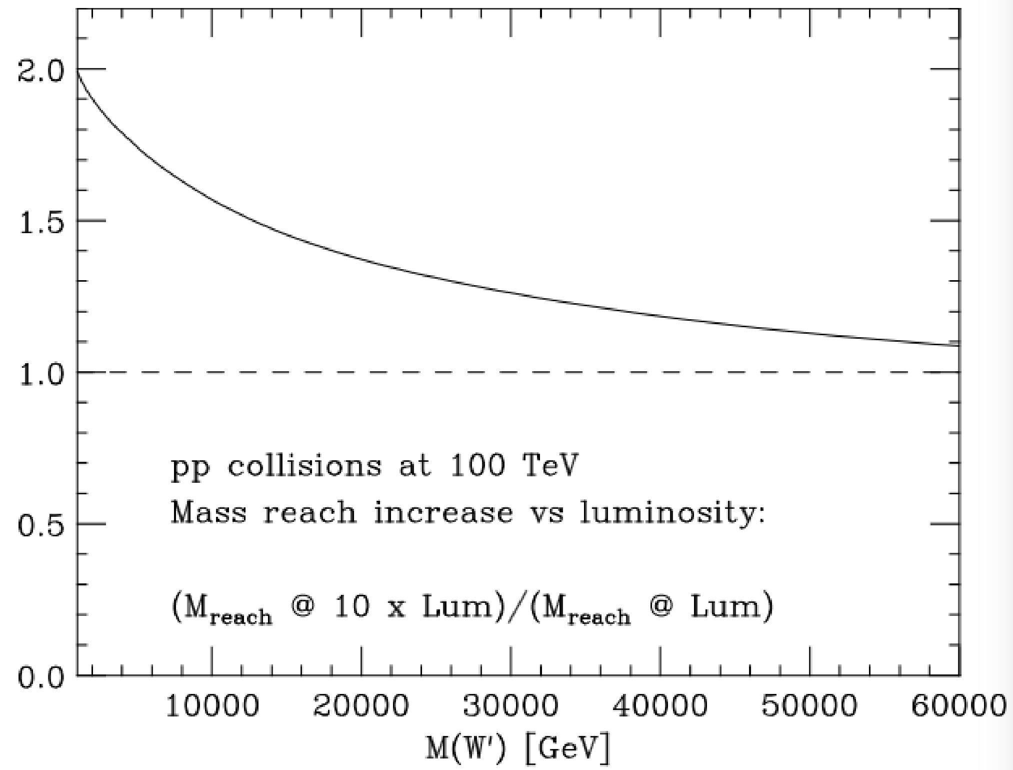


(from L-T. Wang)

Highest Mass Leptonic Resonances

- HL-LHC studies showed $Z' \rightarrow ll$ reach up to 6.5 TeV
- Scaling to 100 TeV collider => 45 TeV with 150 ab^{-1} or 38 TeV with 15 ab^{-1}
  - 7 TeV change in mass reach for factor of 10 change in luminosity



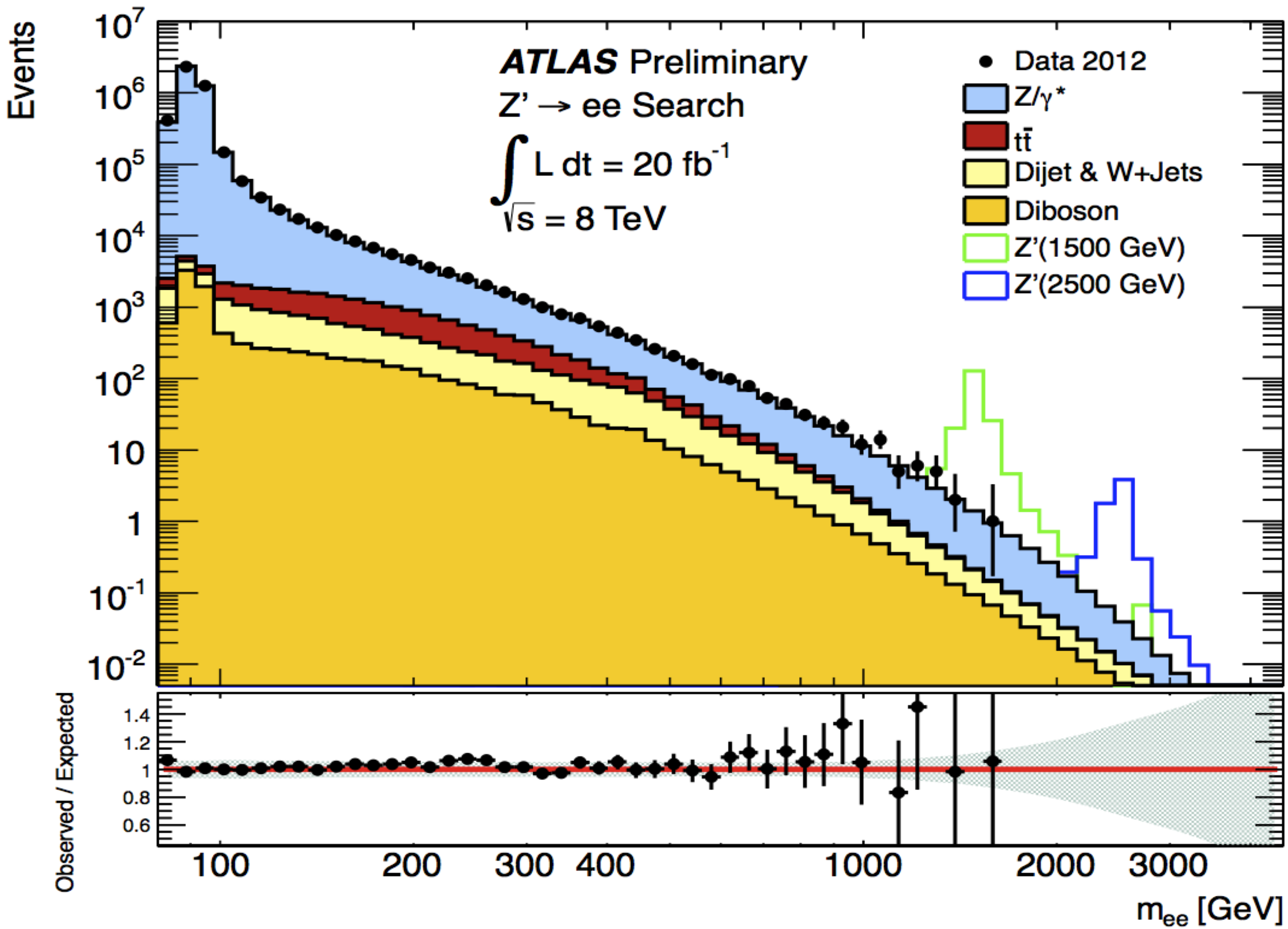


=> producing 20 TeV leptons

(from M. Mangano)

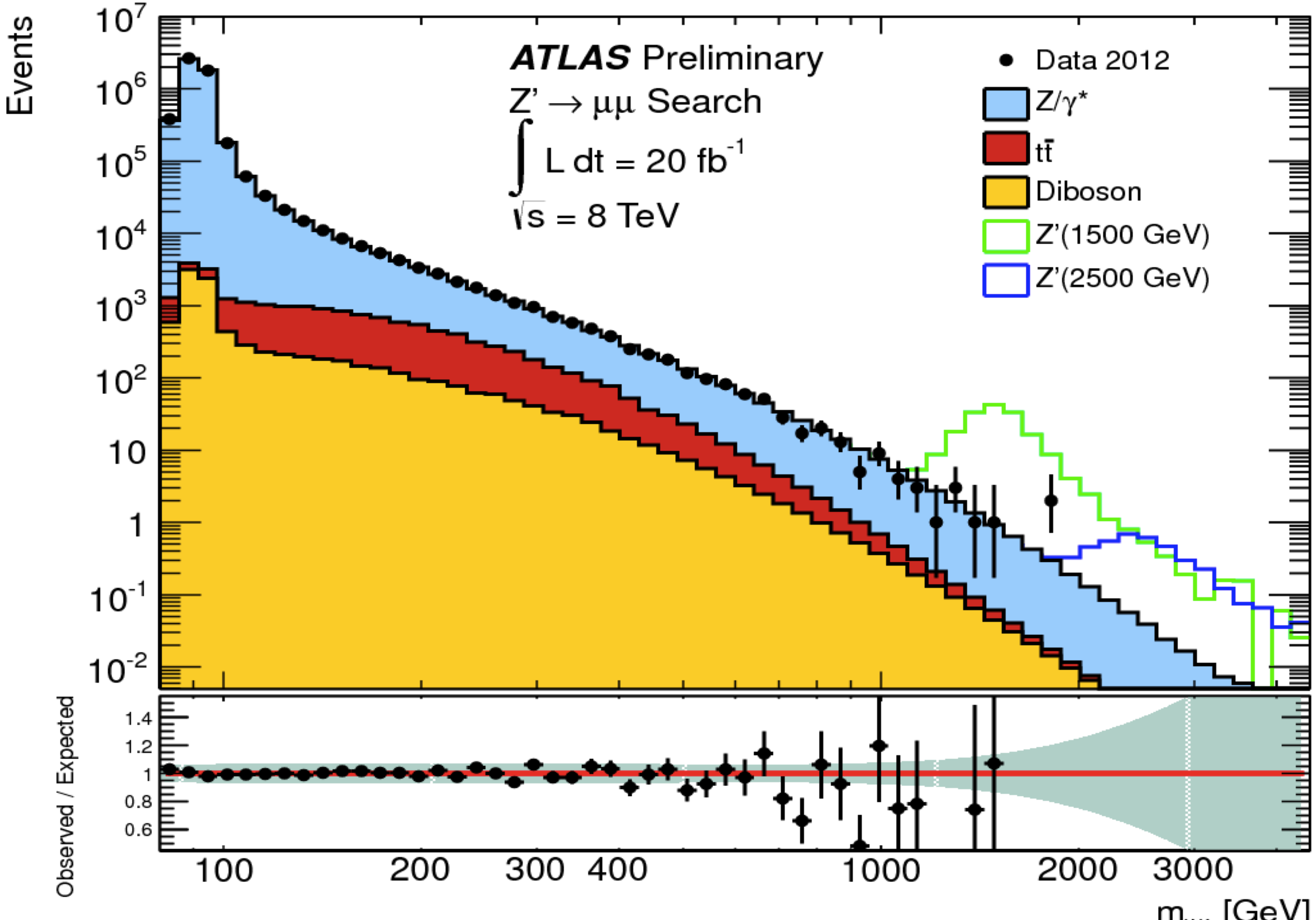
Dielectron Mass Spectrum

Multi-TeV masses probed at LHC

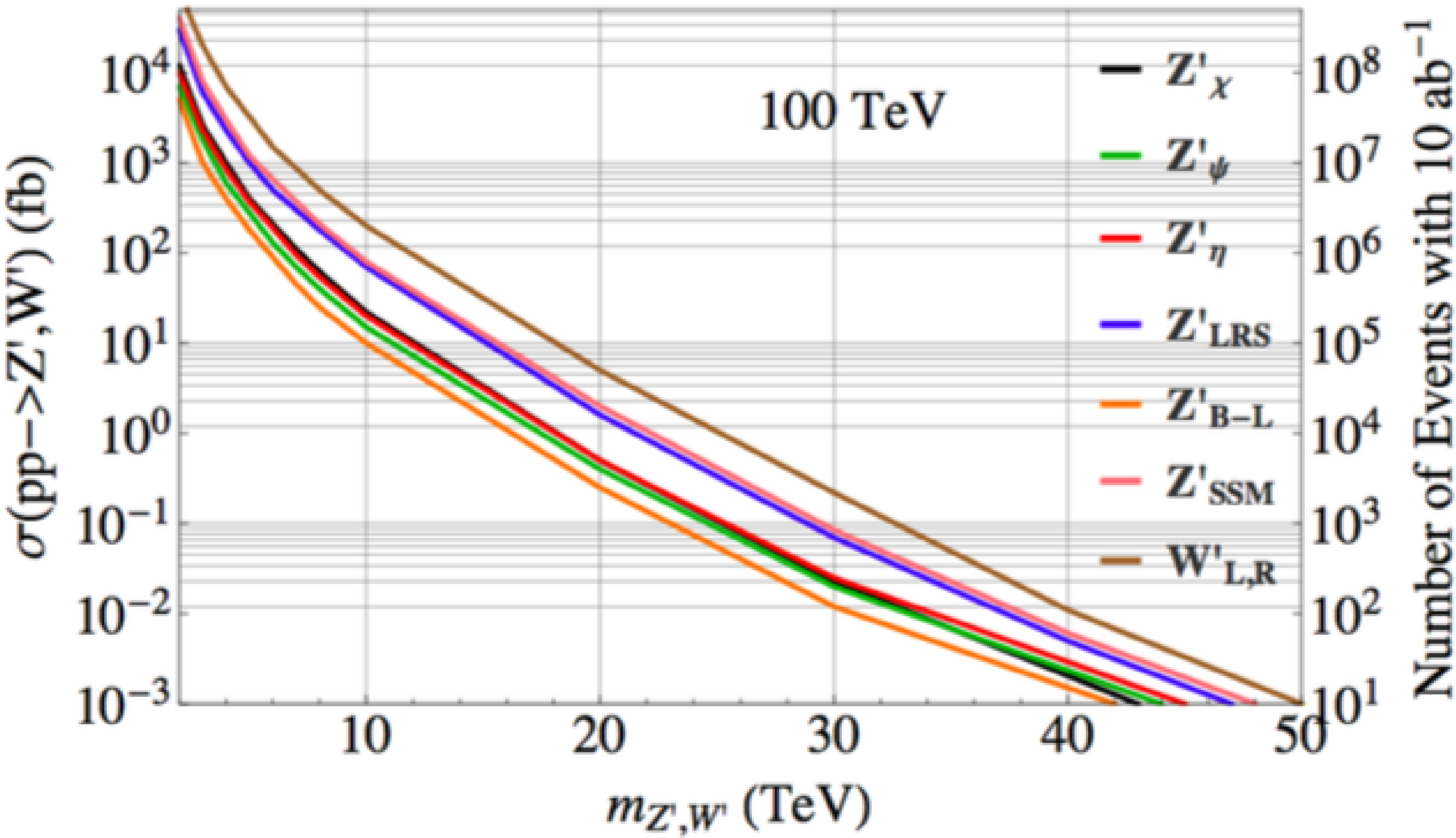


Dimuon Mass Spectrum

Multi-TeV masses probed at LHC



Exploring New Territory - New Weak Gauge Interactions



Discovery reach

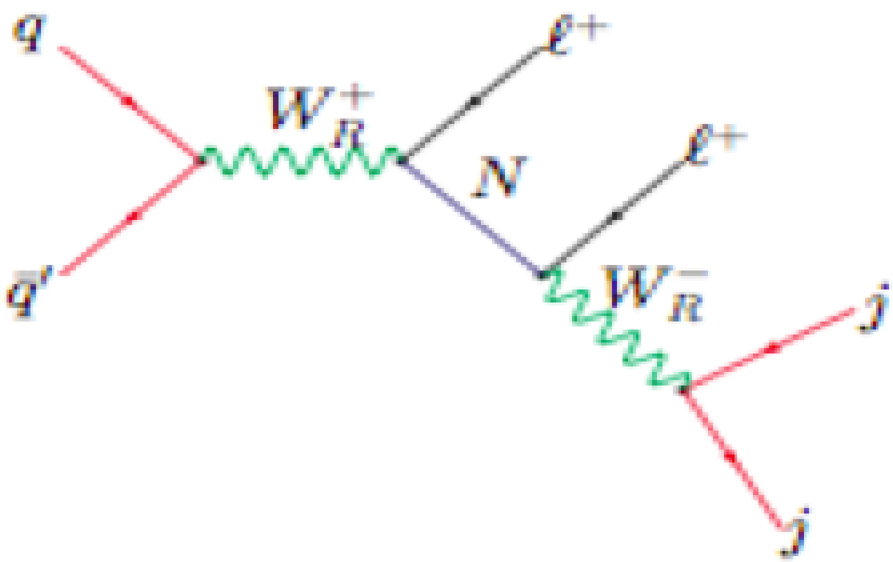
T.Rizzo, arXiv:1403.5465

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

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



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

(Keung, Senjanovic'83)

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

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

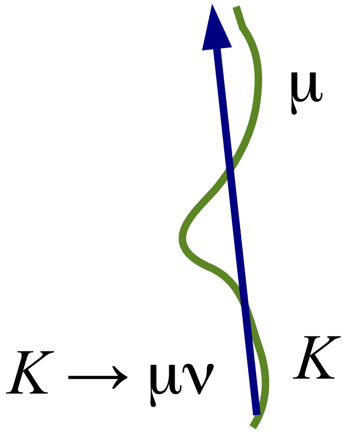
Three tracker/magnet geometries being considered:

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

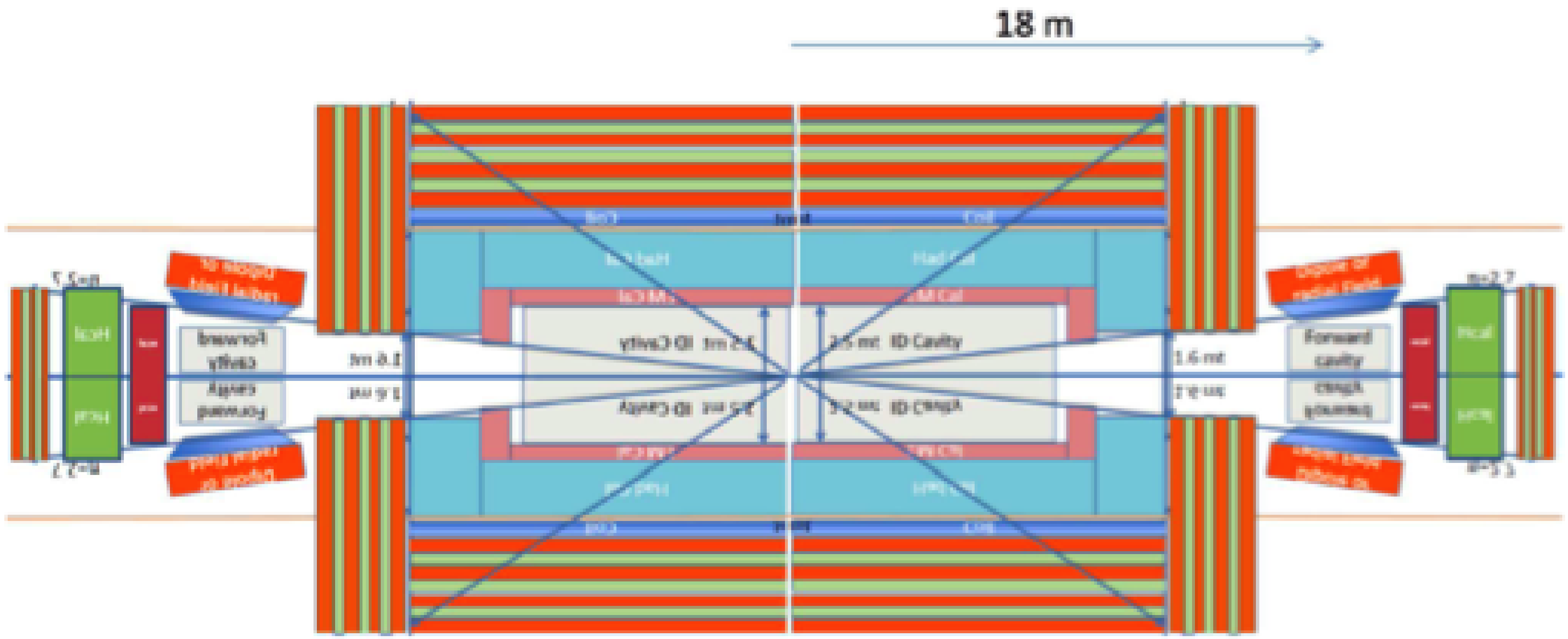
https://indico.fnal.gov/conferenceOtherViews.py?view=standard&confId=7864

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

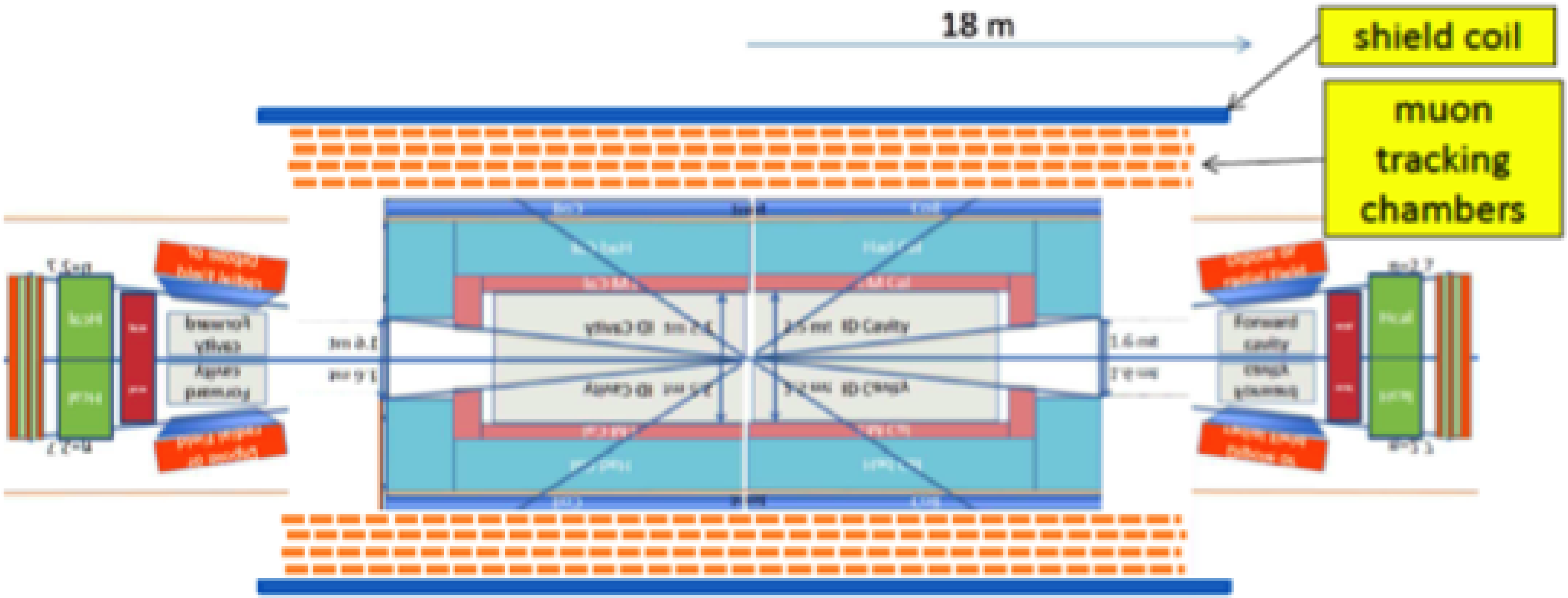


2. Option 1: Solenoid-Yoke + Dipoles (CMS inspired)



- **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

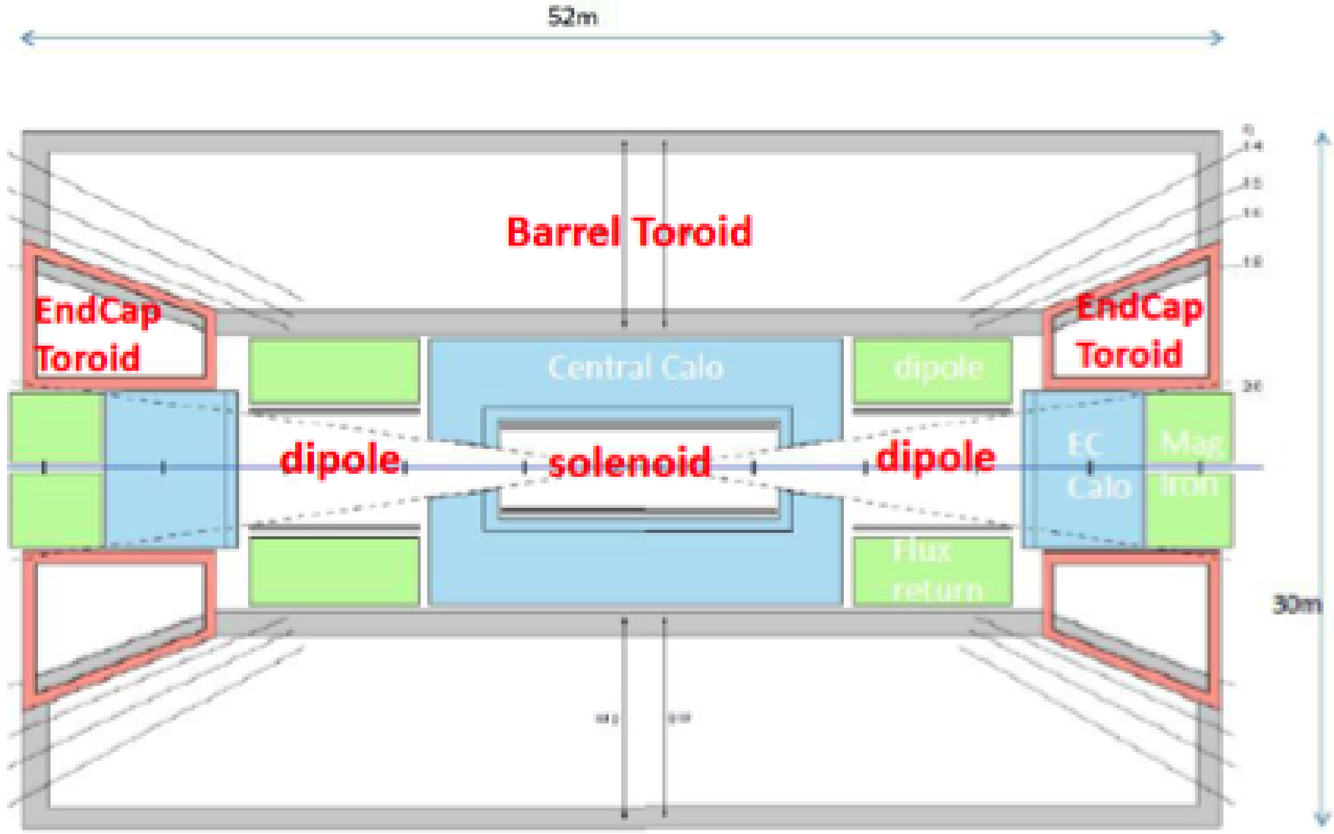


Twin Solenoid: a 6 T, 12 m dia x 23 m long main solenoid + an active shielding coil

Important advantages:

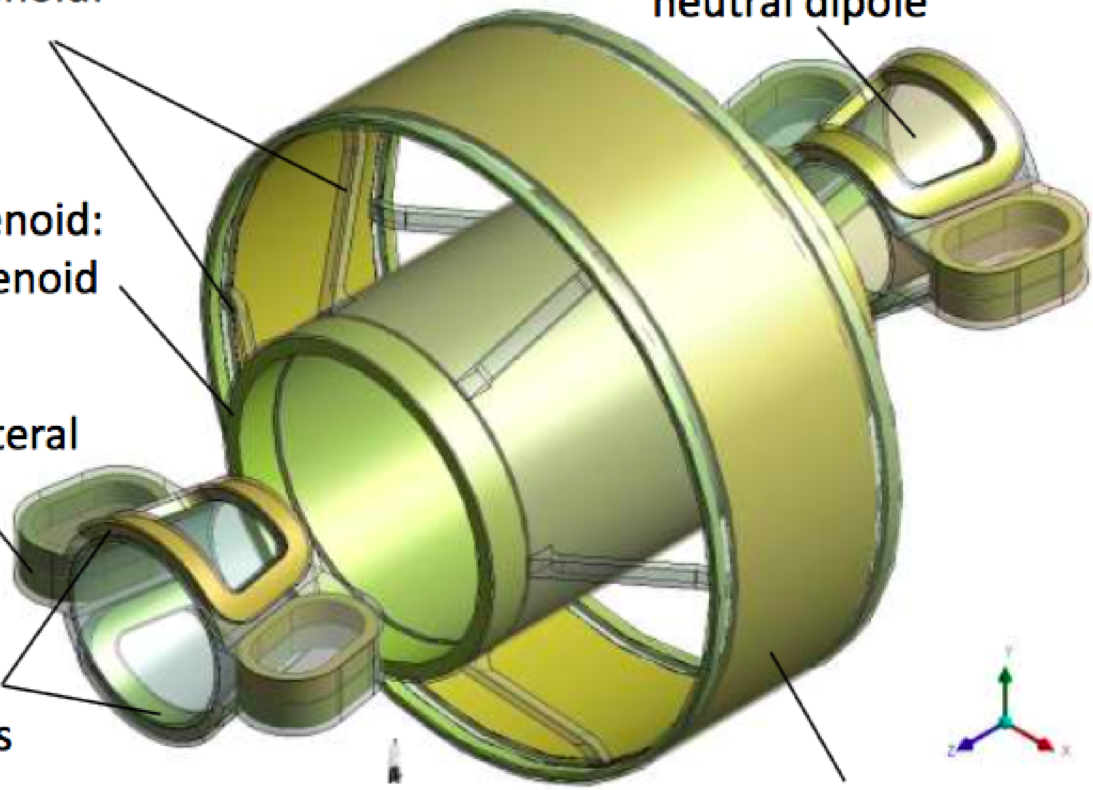
- ✓ **Nice Muon tracking space:** area with 2 to 3 T for muon tracking in 4 layers.
- ✓ **Very light:** 2 coils + structures, ≈ 5 kt, only ≈ 4% of the option with iron yoke!
- ✓ **Much smaller:** system outer diameter is significantly less than with iron .

2. Option 3: Toroids + Solenoid + Dipoles (ATLAS +)



- 1 Air core Barrel Toroid with 7 x muon bending power $B_z L^2$.
- 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

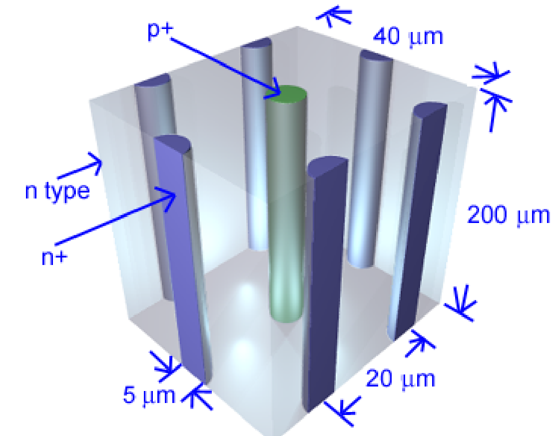


Property	Value
TS cold mass	3.2 kt
TS vacuum vessel mass	2.4 kt
TS stored energy	53 GJ
Dipoles cold mass	2x 380 t
Dipoles vac. vessel mass	To be det.
Dipoles stored energy	2x 1.5 GJ
Free bore	12 m
Outer diameter	27 m
System length	42 m
Total stored energy	**56 GJ**

(from Herman ten Kate)

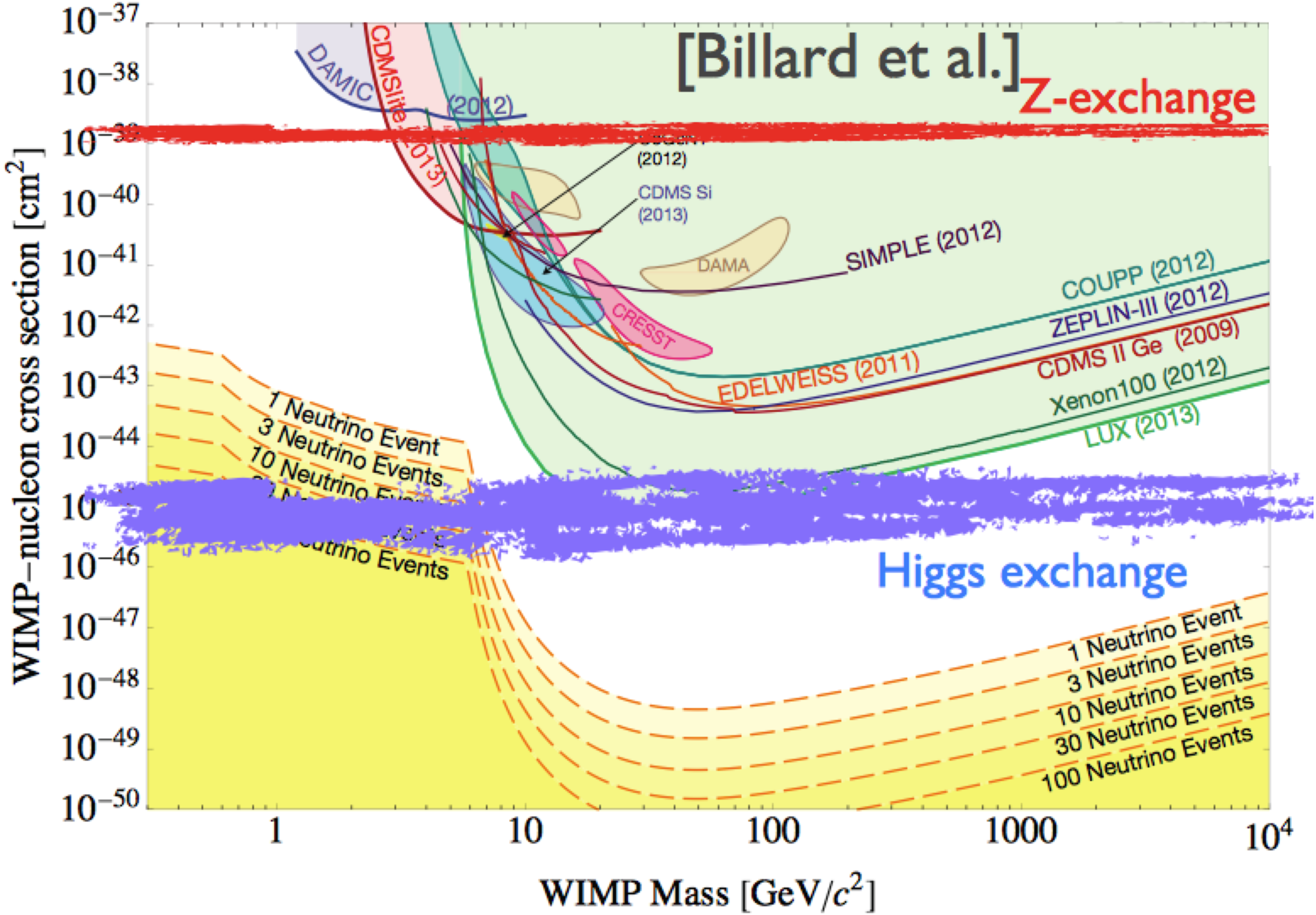
Improving Hit Resolution

- 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



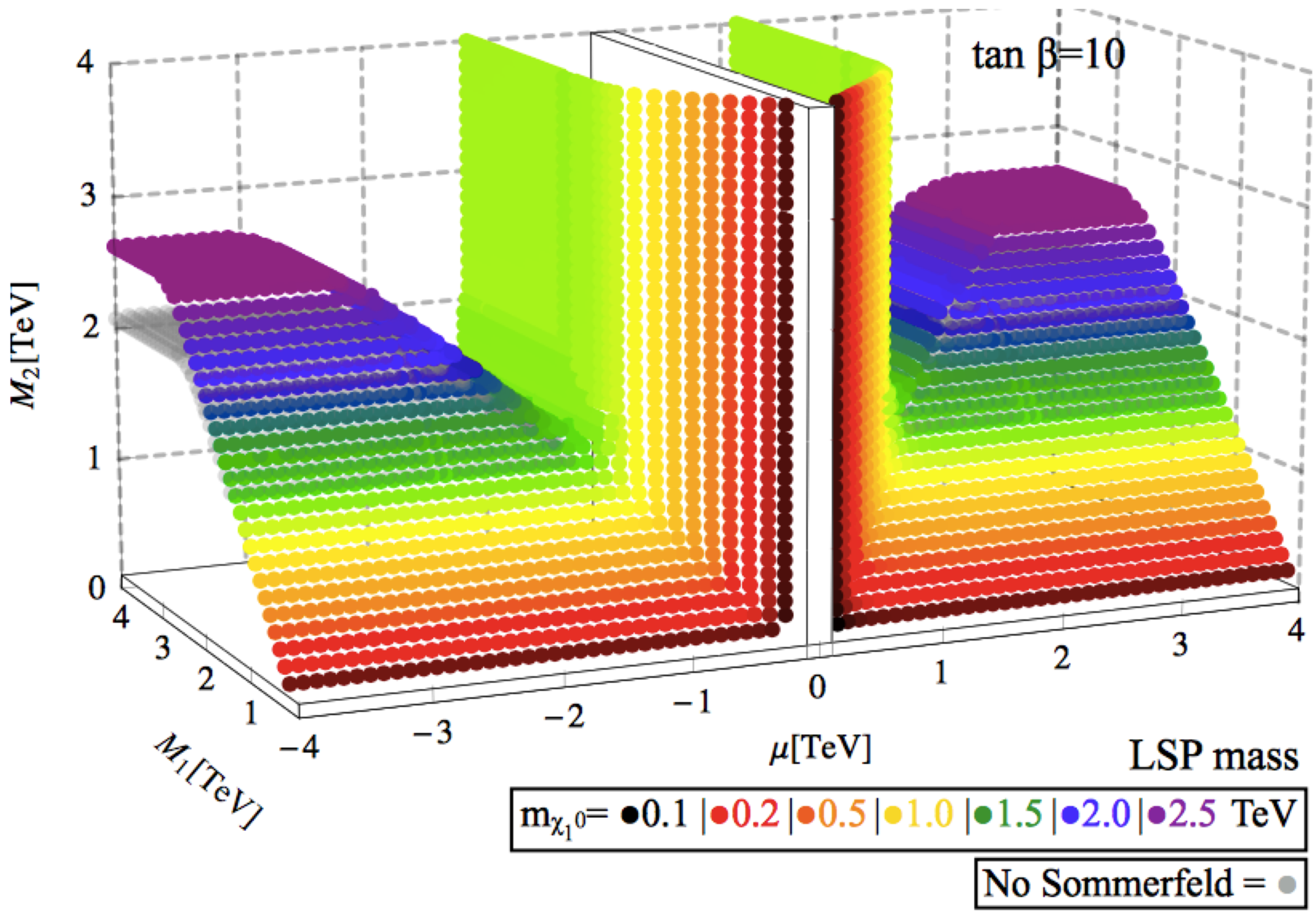
Dark Matter

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,*

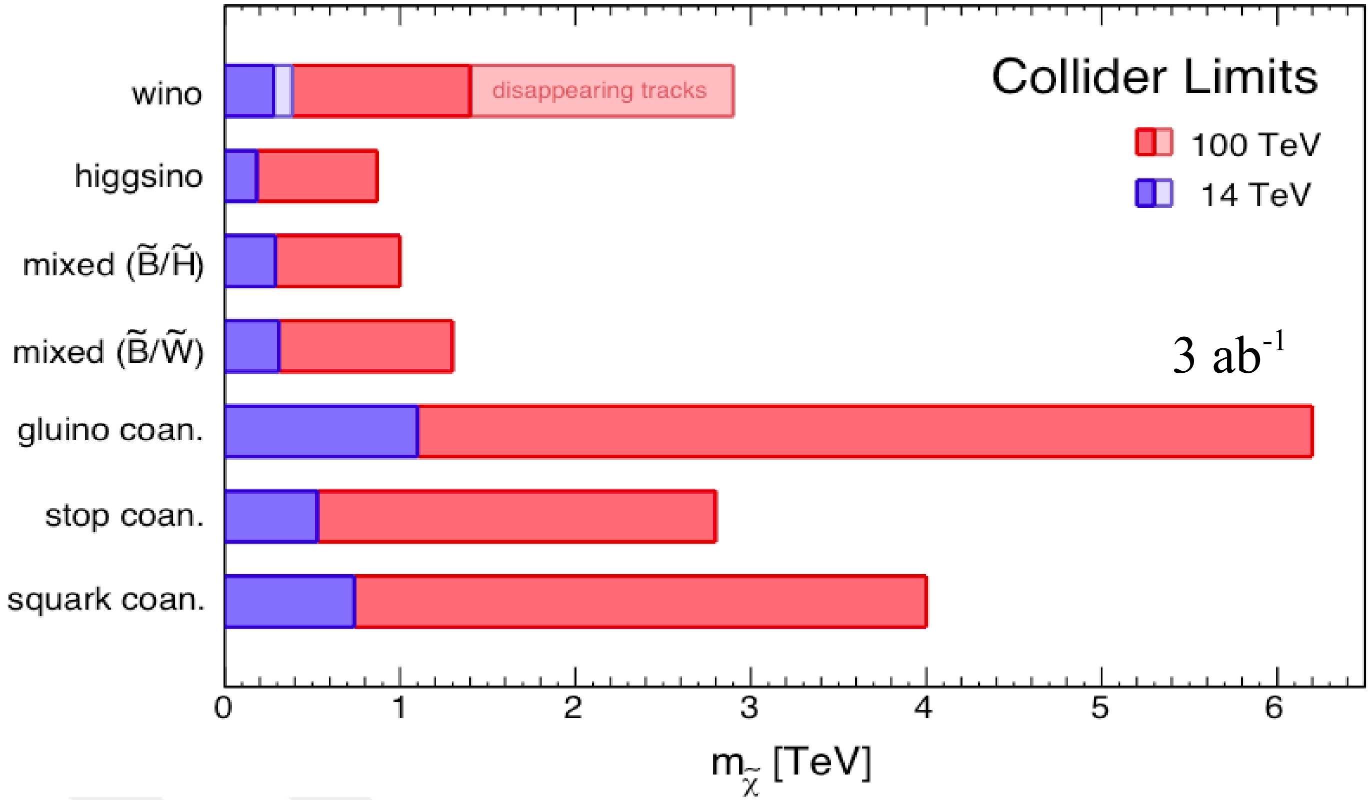
ArXiv:1510.03460

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

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**

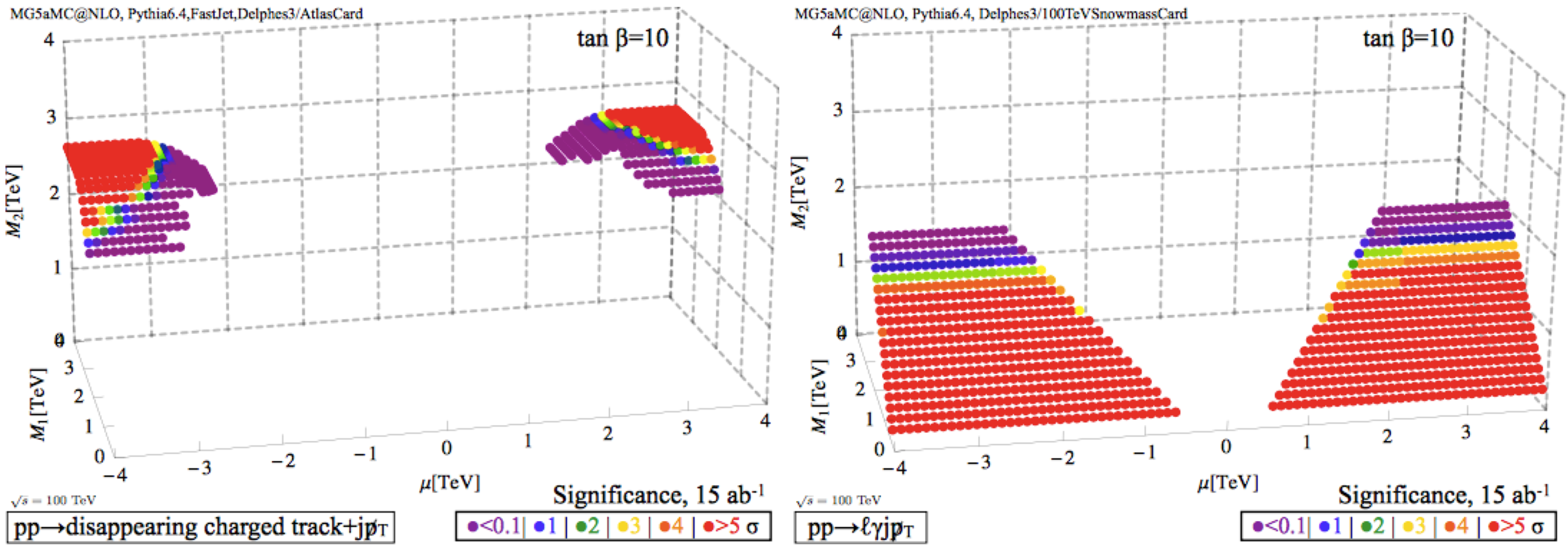


Figure 7. **Left panel:** Points on the relic neutralino surface, which will be excluded or discovered using a disappearing track search with 15 ab^{-1} at a 100 TeV collider. At smaller values of $|\mu|$ the higgsino still mixes enough to cause the mass splitting of the wino plateau to be too large for the disappearing track search to be effective. **Right panel:** Points which will be excluded or discovered using a compressed search for $pp \to \ell^\pm \gamma j \not{p}_T$.

Covering the WIMP Surface

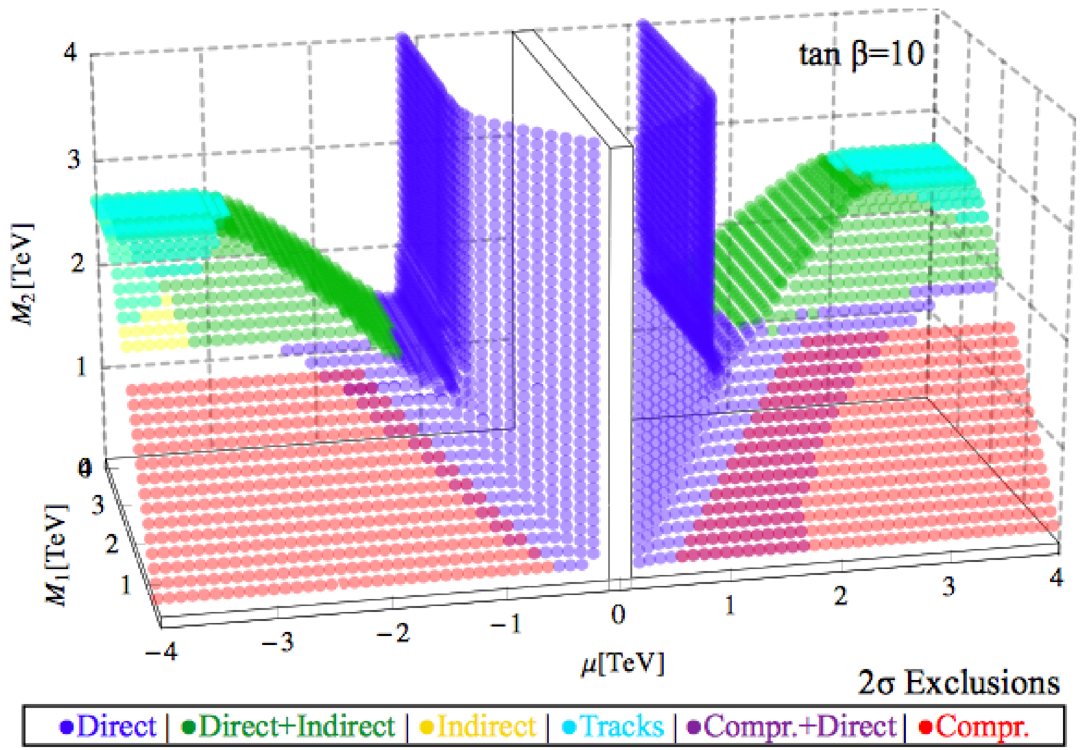


Figure 8. A combination of 2σ exclusions from future indirect (CTA and HAWC), direct (XENON1T and LZ), and collider searches (charged tracks and compressed events at 100 TeV) are shown over the surface of thermal relic neutralinos.

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

100 TeV *pp* collider, combined with direct and indirect searches, covers the parameter space of WIMP satisfying relic density

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**

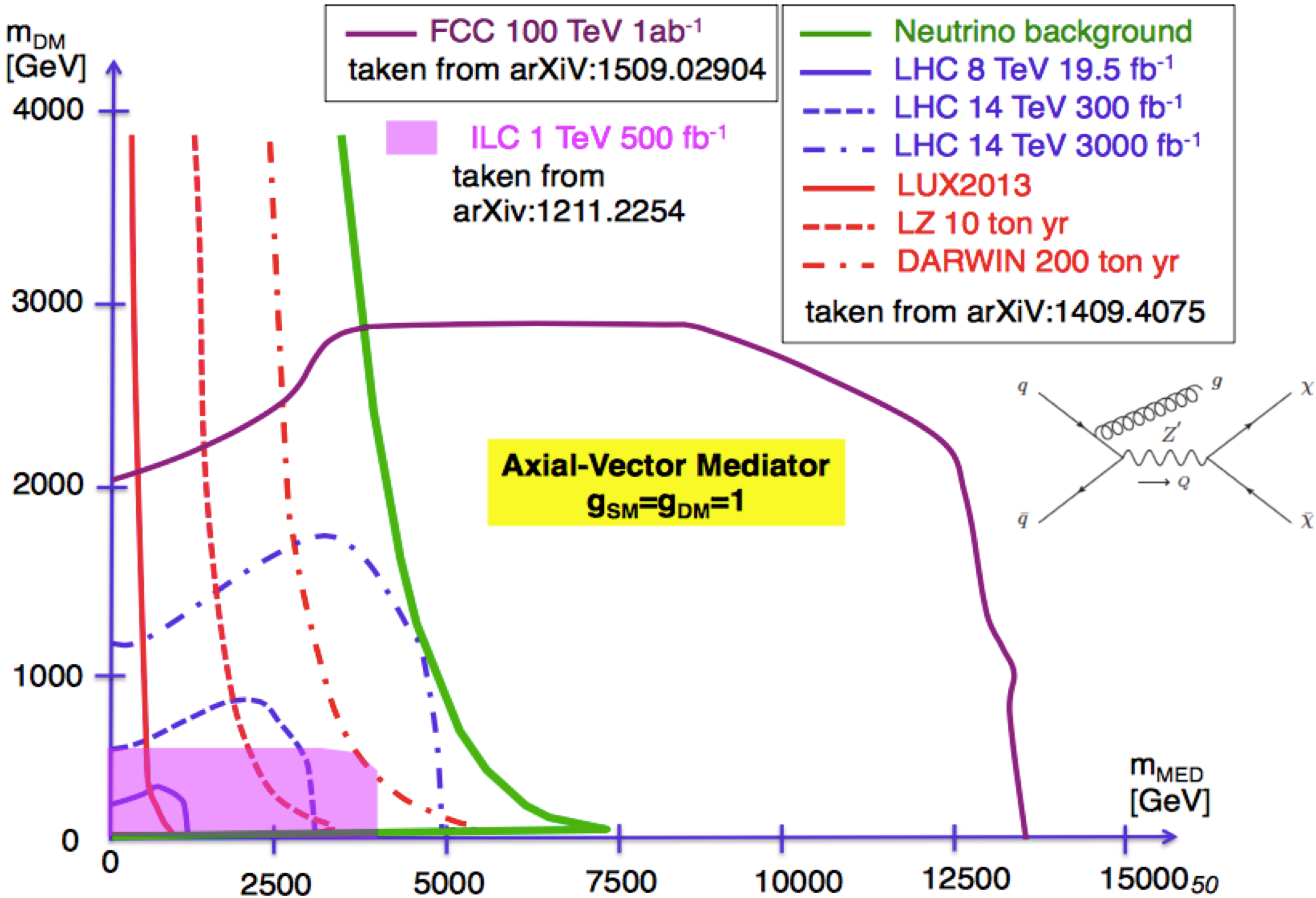
  Besides very low DM masses DD wins clearly over collider

- **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



Calorimetry

Requirements at 100 TeV collider

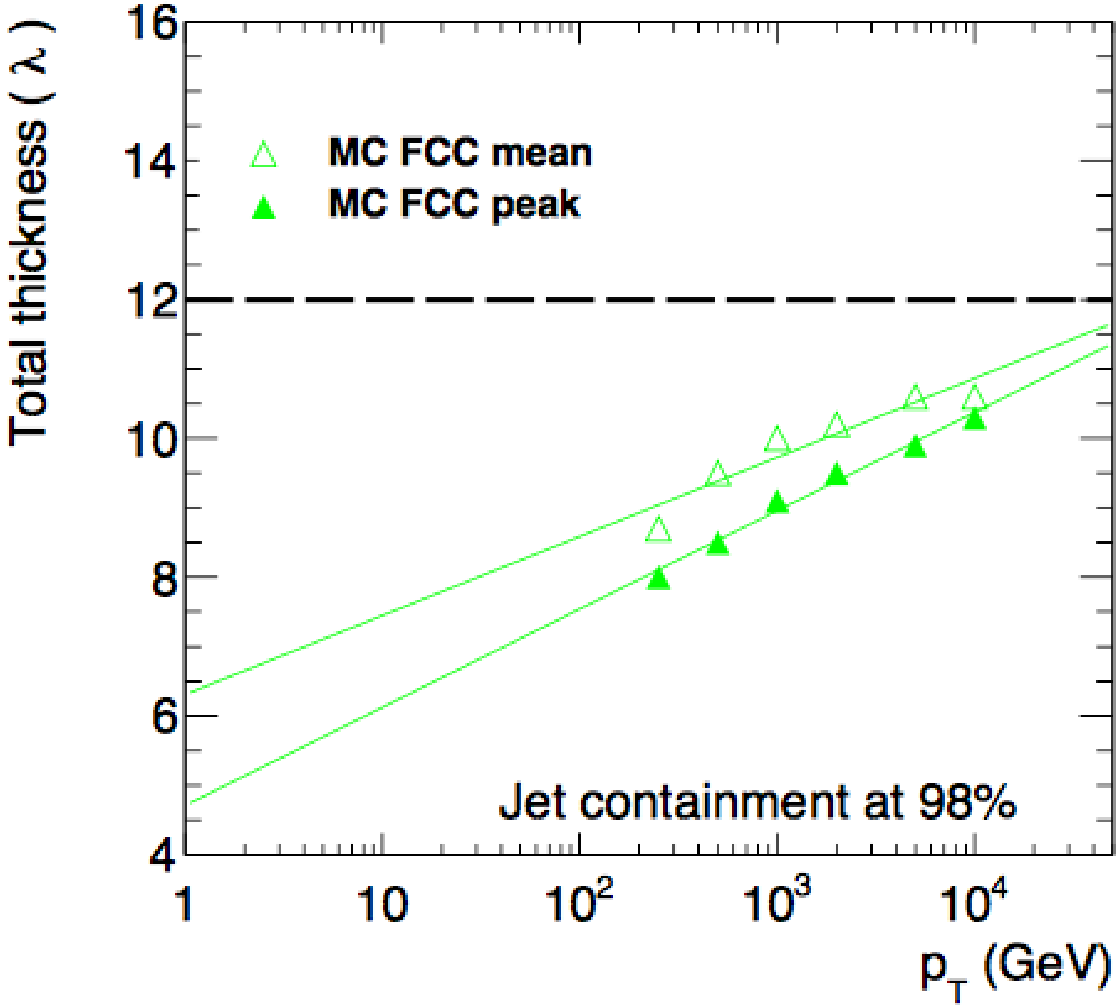
The detector has to cover wide range of signatures

- Detection of high mass states
  - Dijet resonances or compositeness, M_{q*} ~ 50 TeV
  - Z' or W' to leptons, $m_{Z'}$ ~ 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 $\sqrt{E}$

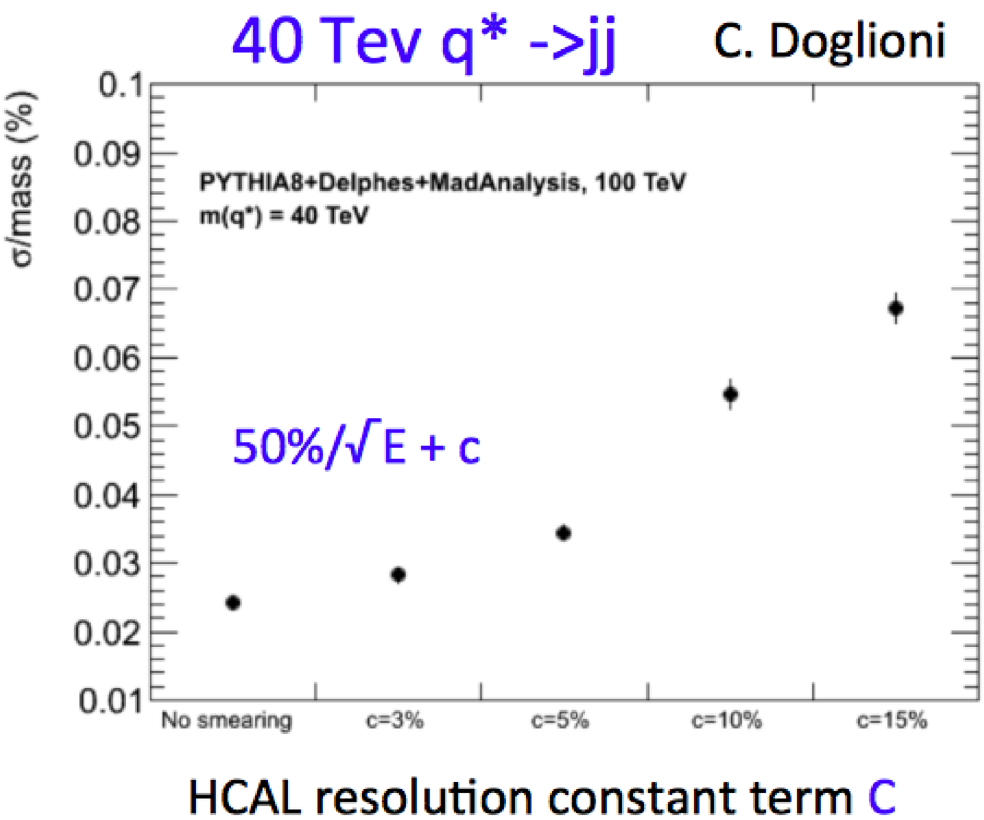


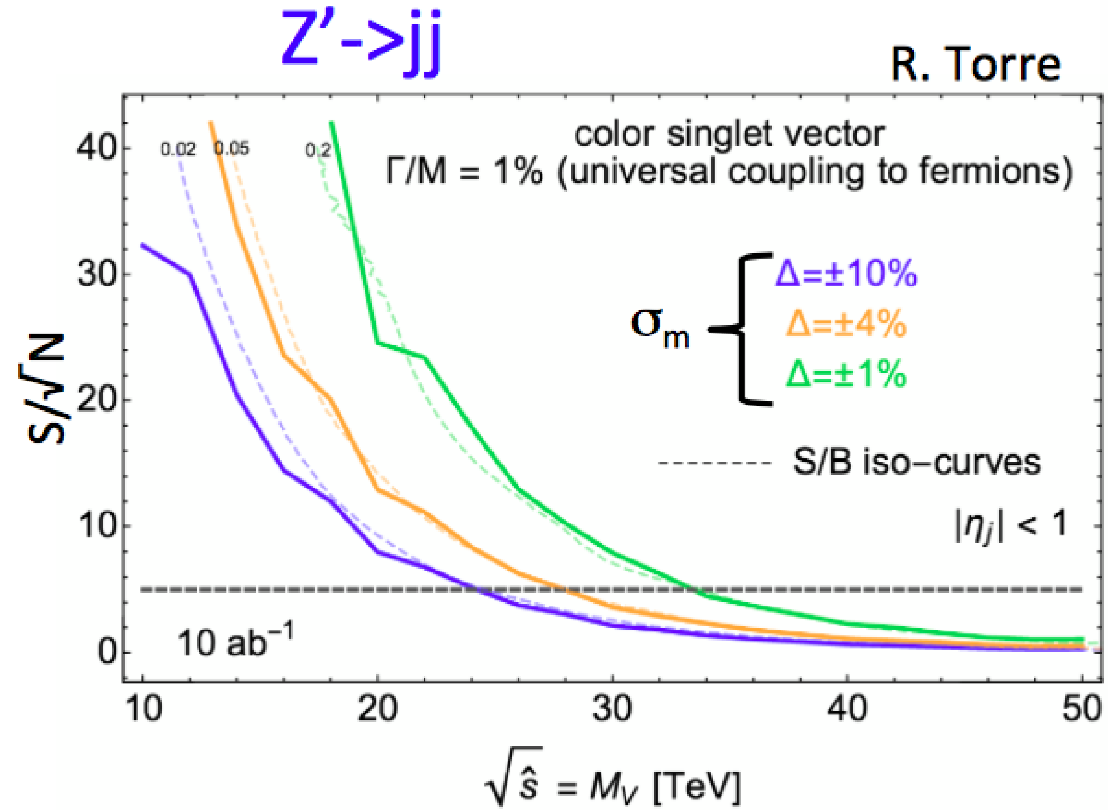
T. Carli *et al*, arXiv:1604.01415

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

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), Sourav Sen (Duke graduate student)
- Lindsey Gray (Fermilab CMS) is our Particle Flow Algorithm expert consultant
- Samples created on OSG on 1-week timescale – need more analysts !

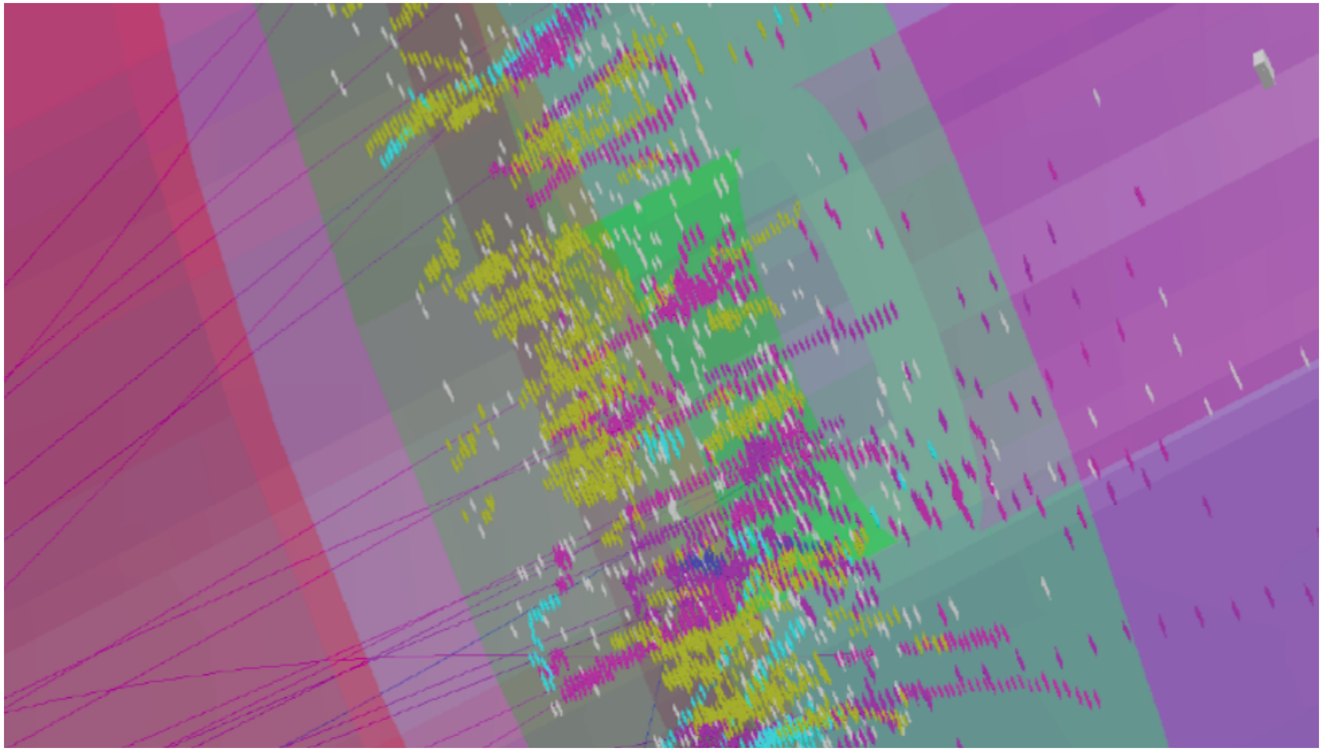
Silicon High Granularity Calorimeter

Good cluster energy resolution

Very detailed topographical information

Excellent two particle cluster resolving power

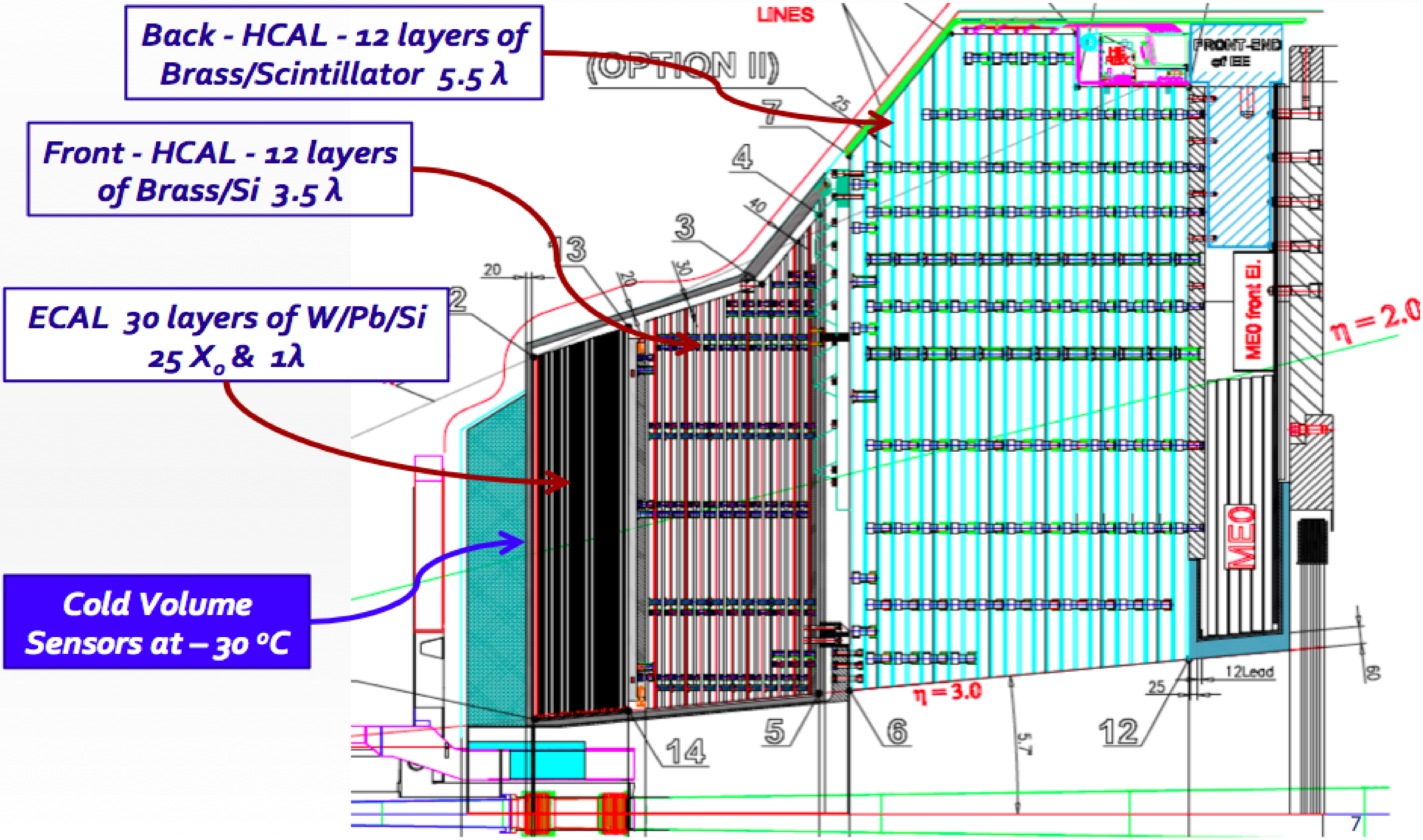
Suitable for particle flow reconstruction in a high particle density environment



Thanks to R. Rusack, ECFA 2014

Proposal – Si-HGC for CMS Endcap

CMS Calorimeter Concept



Thanks to R. Rusack, ECFA 2014

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

S. Chekanov
HEP/ANL

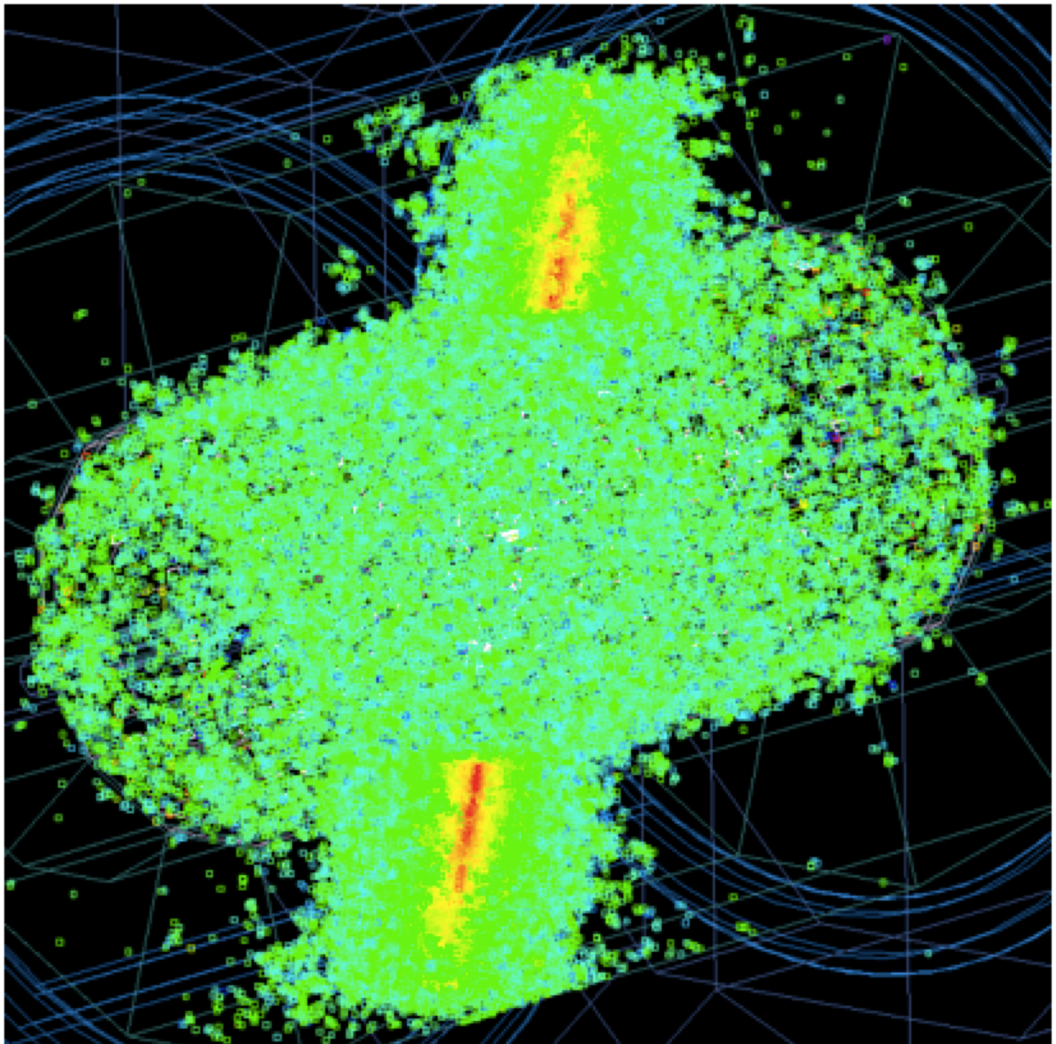
FCC Week. April 11-15, 2016
Rome, Italy

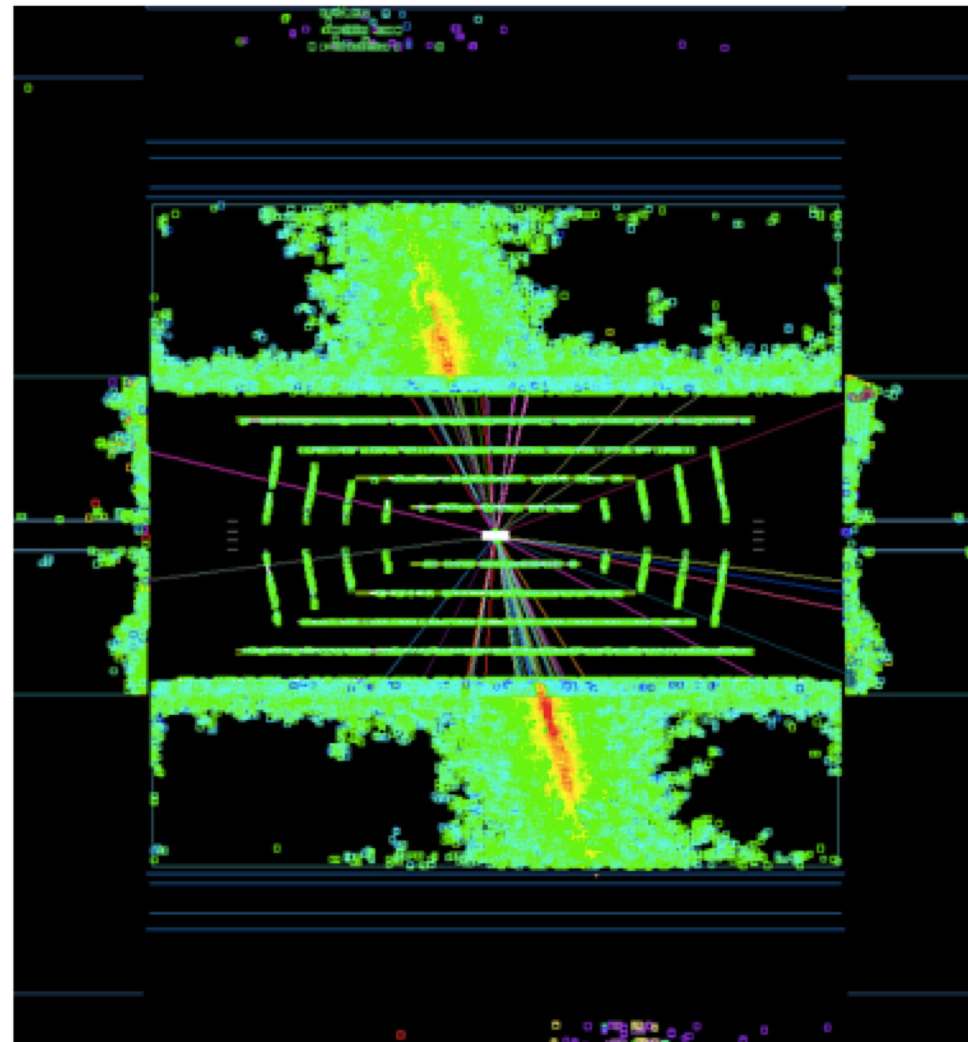
With contributions from:
A.Kotwal (Fermilab/Duke), L.Gray (Fermilab), J.Strube (PNNL), N.Tran (Fermilab), S. Yu (NCU), S.Sen (Duke), J.Repond (ANL), J.McCormick (SLAC),J.Proudfoot (ANL), A.M.Henriques Correia (CERN), C.Solans (CERN), C.Helsens (CERN)

See Sergei Chekanov's talk in BOOST2017

GEANT Simulation of 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





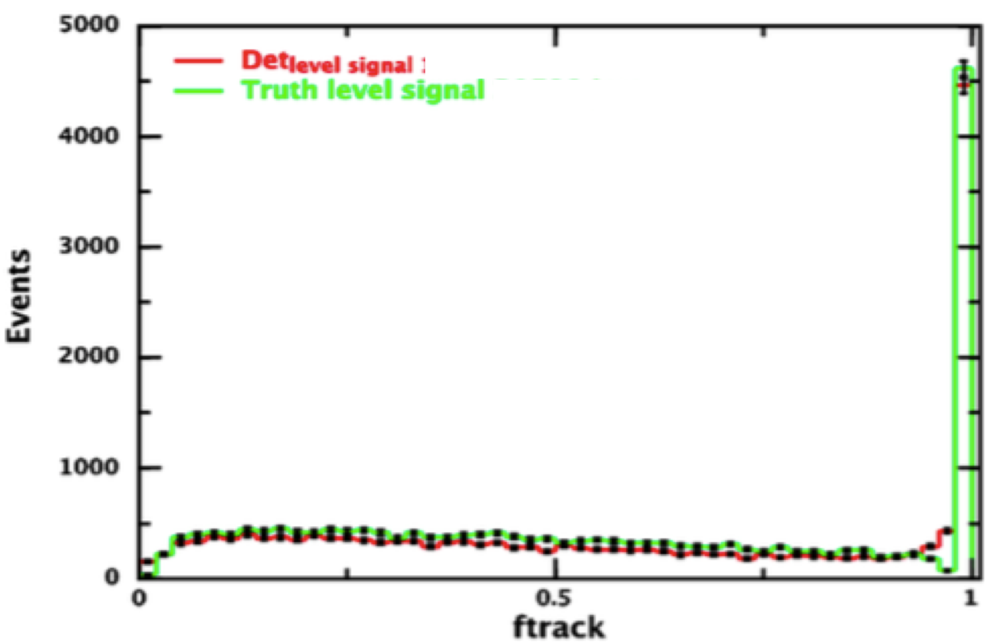
Generated on OSG by S. Chekanov

GEANT Simulation of Silicon/Tungsten EM Calorimeter

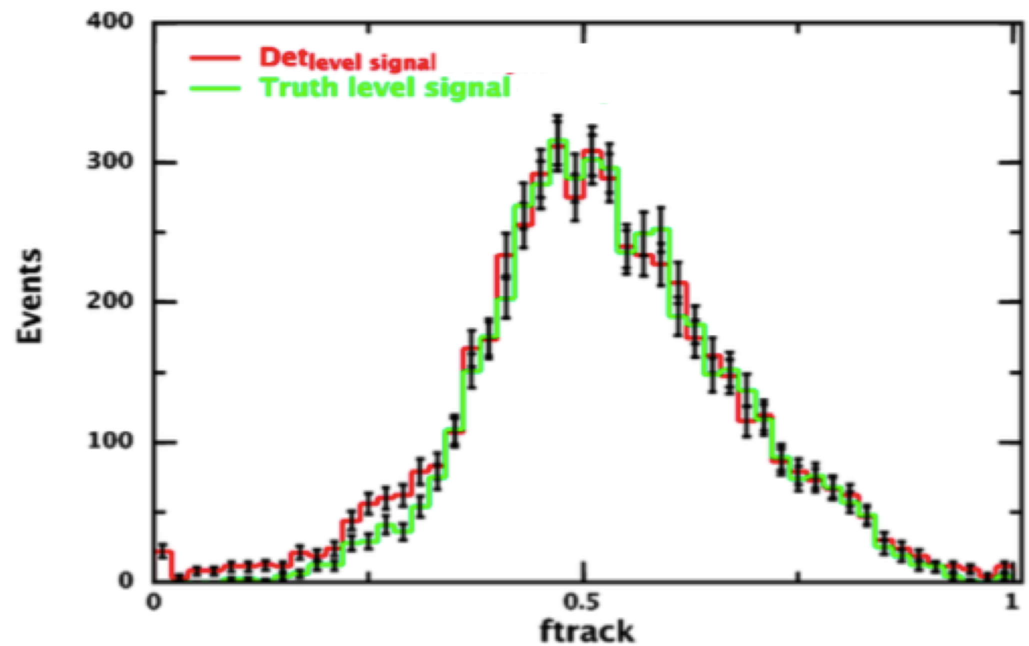
500 GeV hadronic τ-lepton decays with 4mm x 4mm silicon pads
Background simulation in progress, will investigate larger pad sizes and higher p_T

f_{track} (leading track momentum fraction)
=(pT of highest pT track in core region (ΔR < core)) / (Total E_T deposited in ΔR <core)

core = 0.1



1 prong



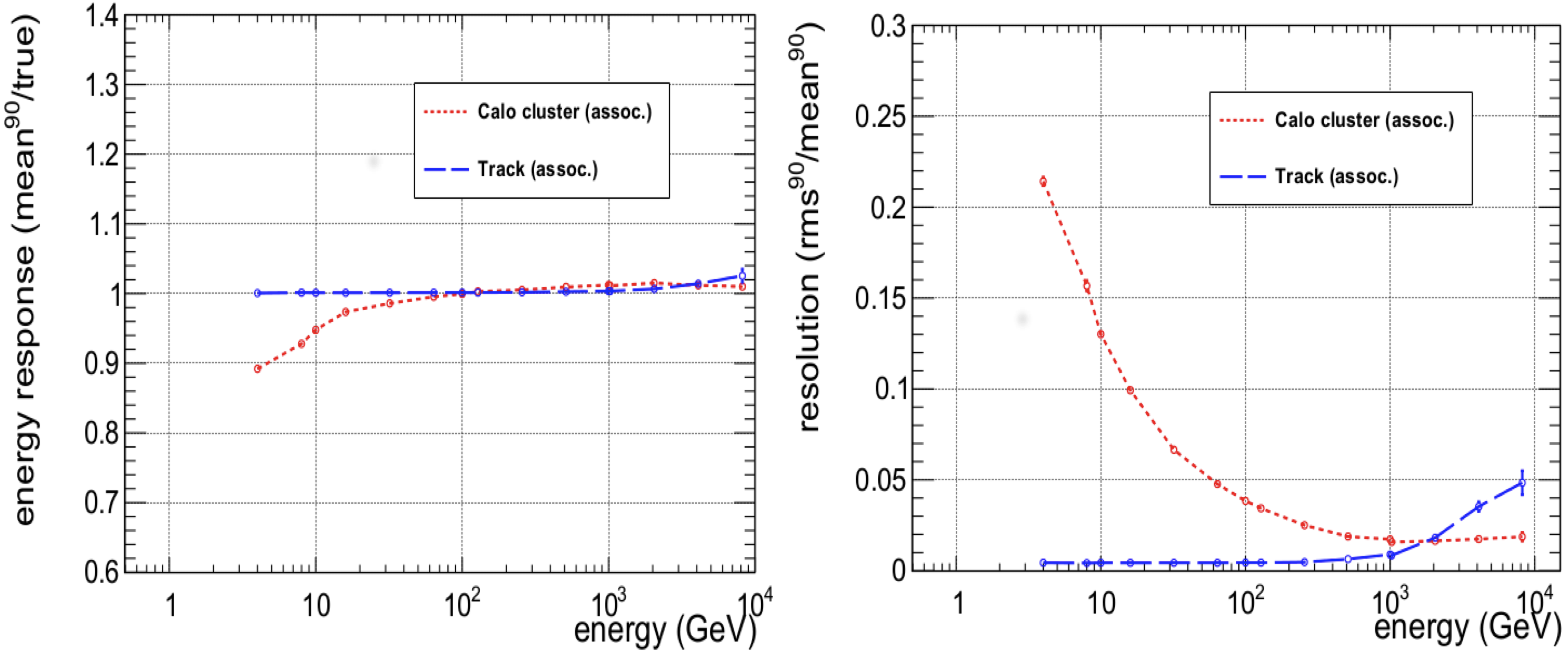
3 prong

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

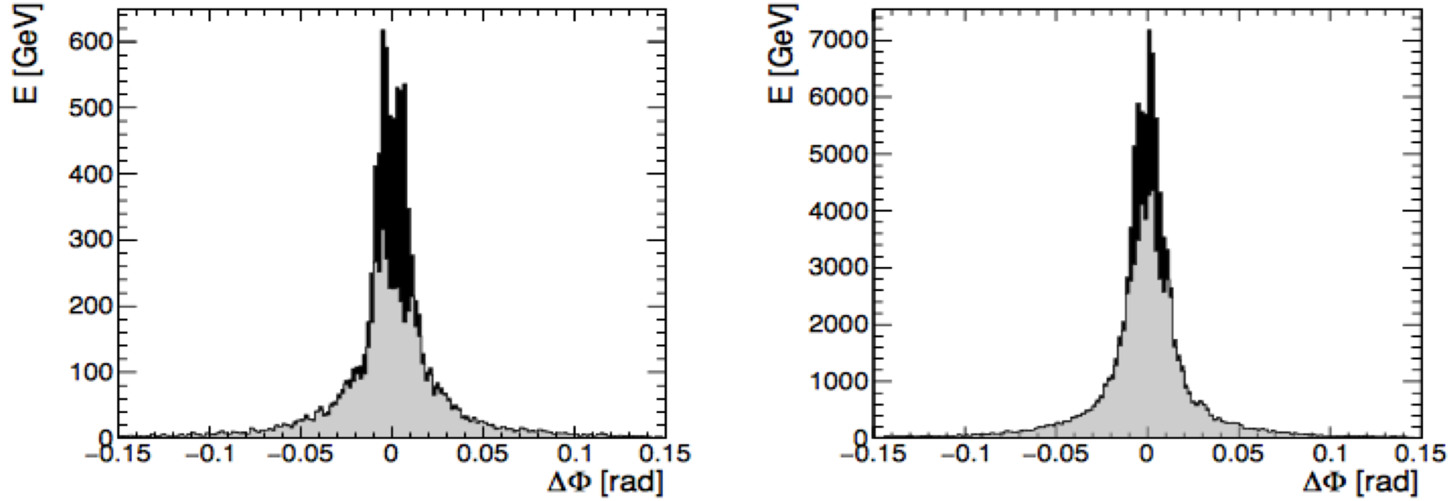
Single pion response and resolution



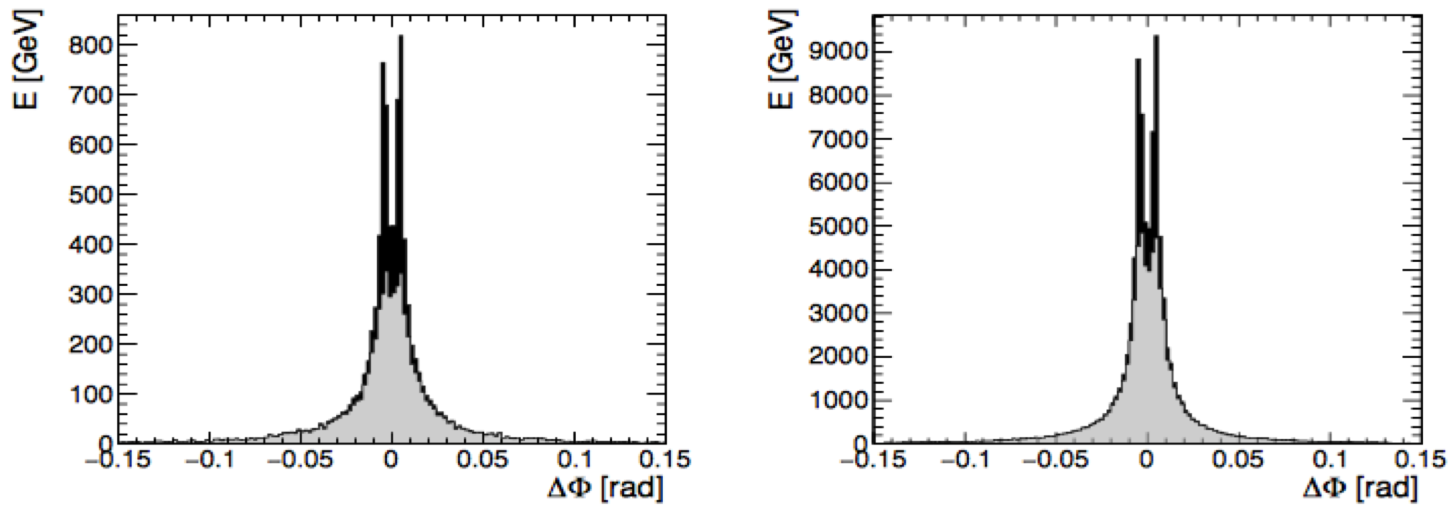
- Analysis by S. Yu, N. Tran and S. Chekanov
- First look at boosted object discriminating variables
- Published in **JINST 12 (2017) no.06, P06009**

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

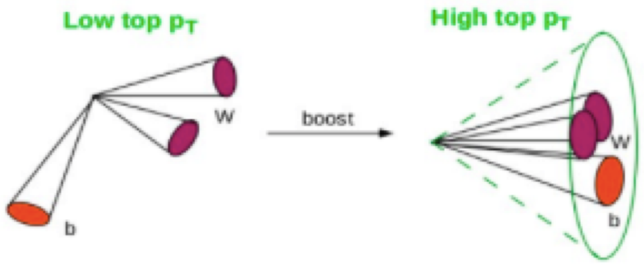


(c) 1 × 1 cm HCAL cells and 3 × 3 mm ECAL cells

Analysis by
Nhan Tran

Figure 14: Azimuthal distribution of energy deposition for pair of incident K^0_L 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.

Effect of HCAL transversal segmentation on jet sub-structure



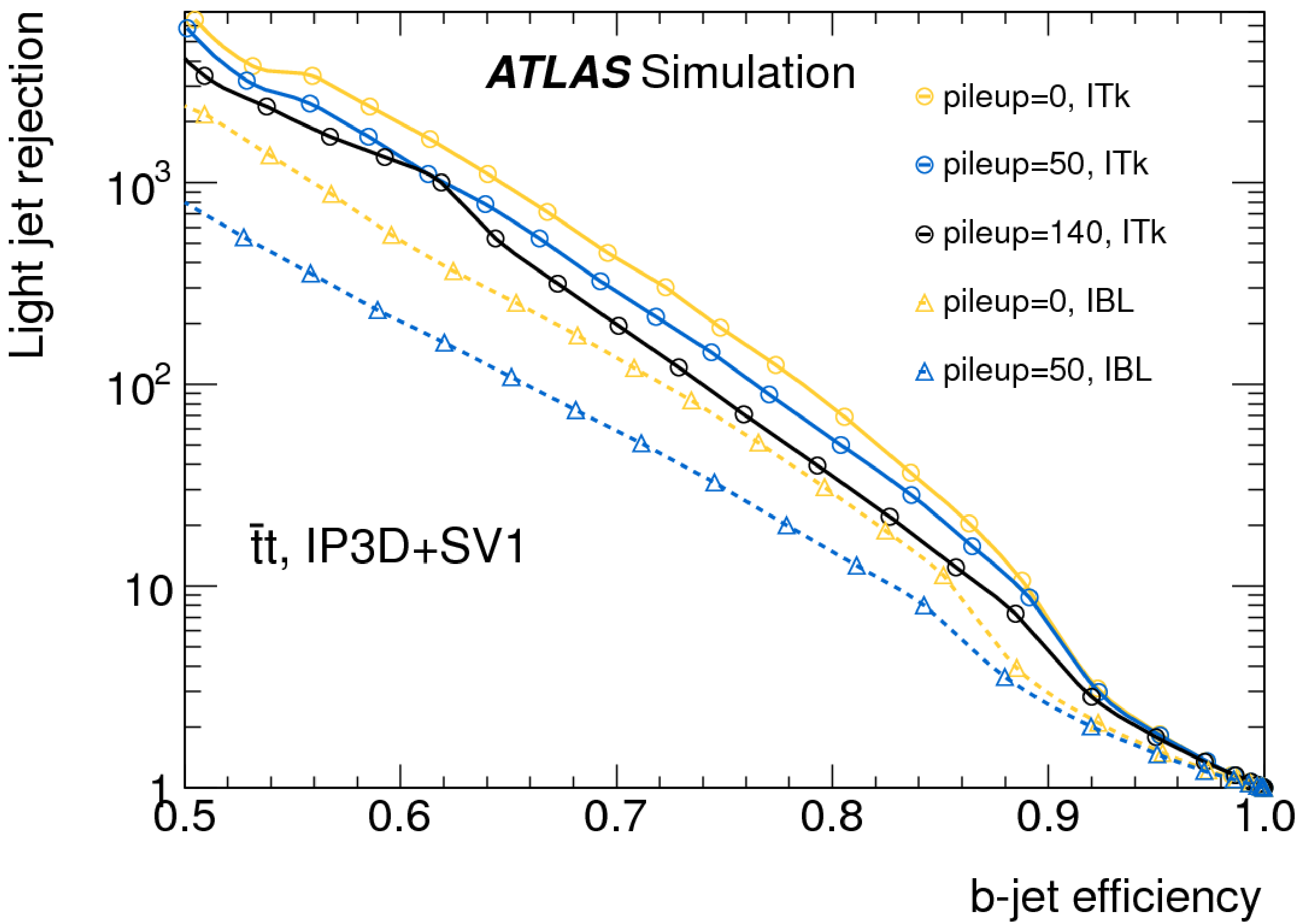
Full GEANT simulations of jet response, resolution and substructure discrimination in progress by Shin-Shan Yu, Nhan Tran, S. Chekanov *et al*

- Improve σ_m of sub-jettiness variables compared to $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ for high P_T jets by:
  - 80% for $\Delta\eta \times \Delta\phi = 0.05 \times 0.05$
  - 120% for $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$

Need at least 2-4 times better granularity than ATLAS/CMS $\Delta\eta \times \Delta\phi$=0.1x0.1-> 0.025x0.025

b-tagging

b-tagging 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?

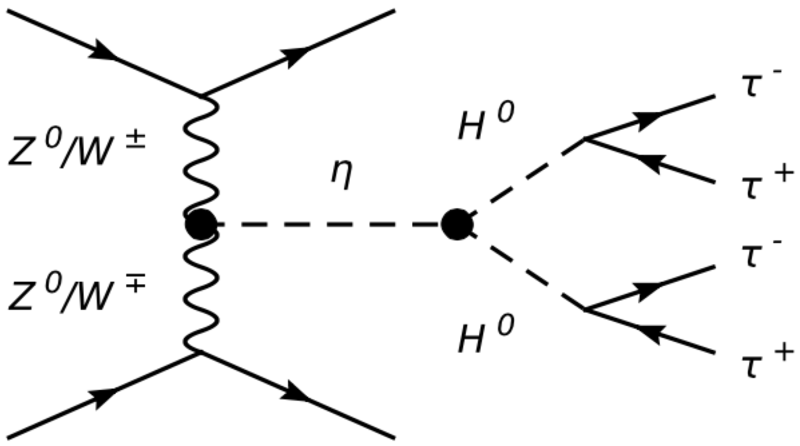
- Old idea: Higgs doublet (4 fields) is a Goldstone mode generated from the spontaneous breaking of a larger global symmetry
  - Higgs boson and W_L, Z_L are all Goldstone bosons from, eg. Spontaneously breaking global SO(5) → SO(4)
  - Examples: Holographic Higgs, Little Higgs models...
  - Electroweak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

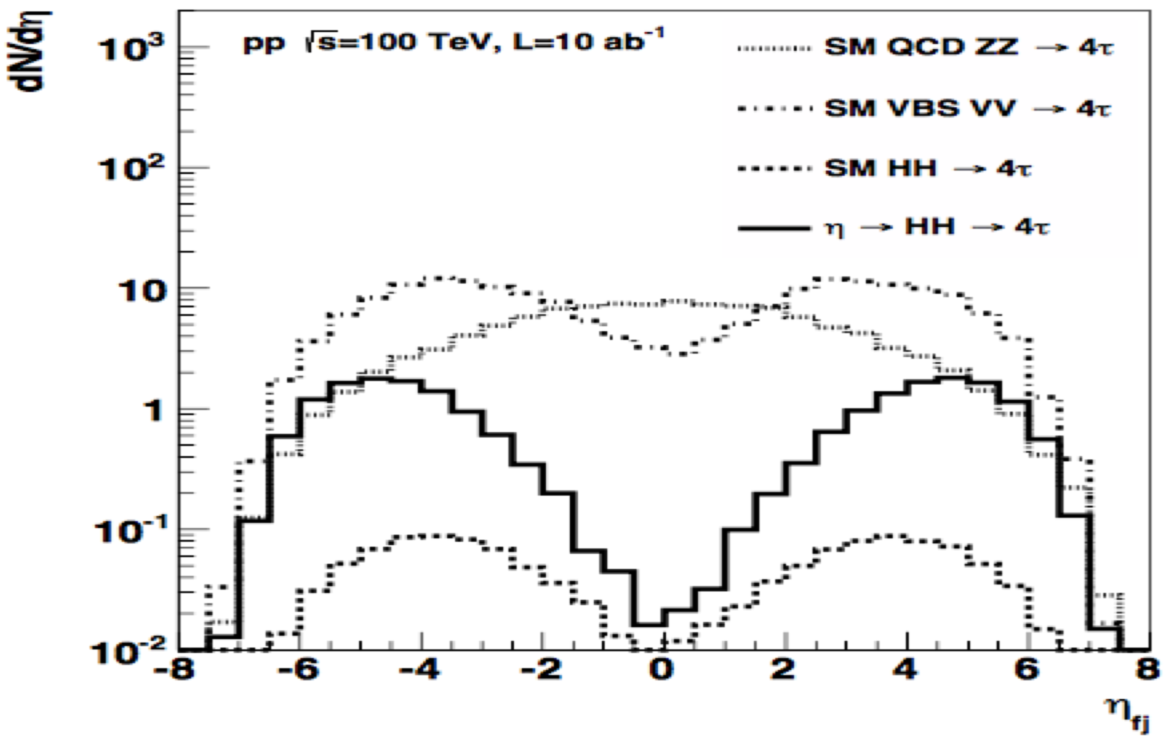
- Vector boson scattering topology
  - Quarks emit longitudinal vector bosons which interact with new (presumably strong) dynamics
  - Quarks scatter by small angle in the forward direction

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

$V_L V_L \rightarrow \eta \rightarrow HH$

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 $\Gamma/M = 20\%$.

$p_T^{\rm min}$ (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 III. 5σ discovery mass reach for the $\eta \to HH \to 4\tau$ resonance, at a pp collider with $\sqrt{s} = 100$ TeV and $\mathcal{L} = 10\ \mathrm{ab}^{-1}$, 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

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*)

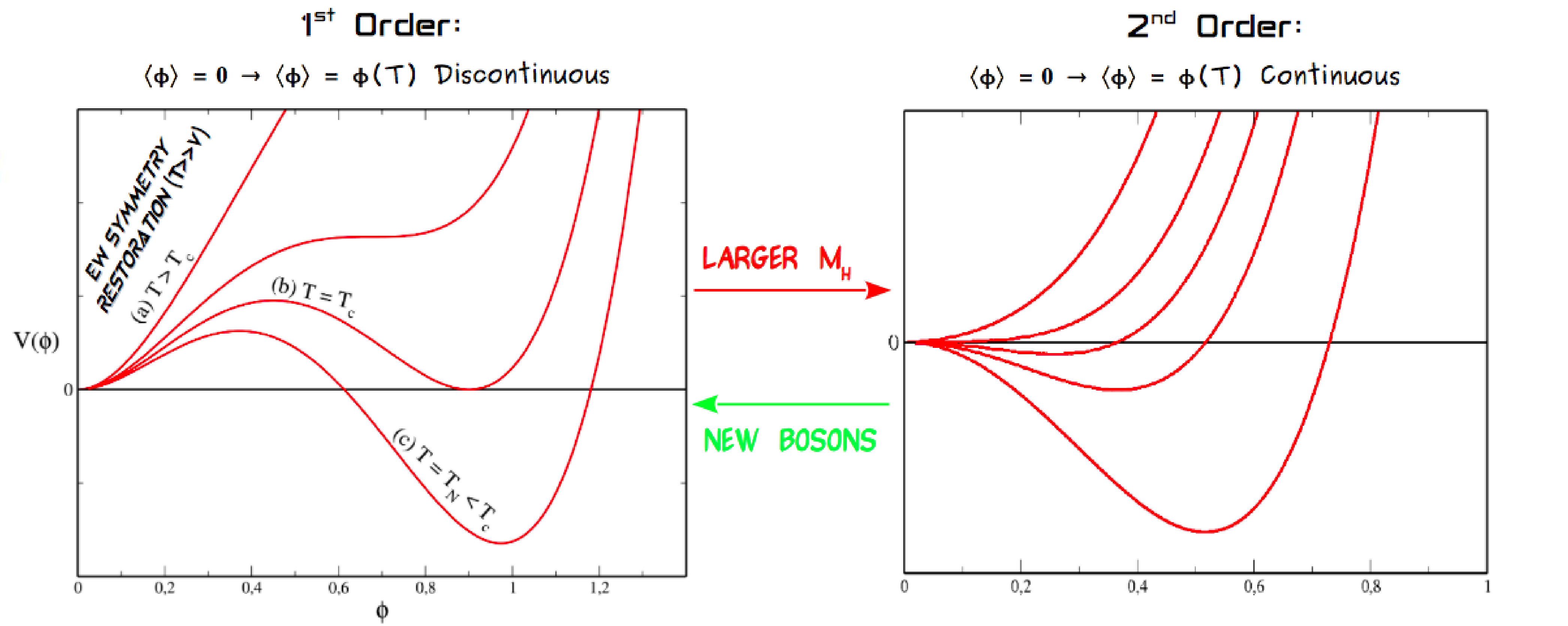
B Violation ✓ *Sphalerons*

*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



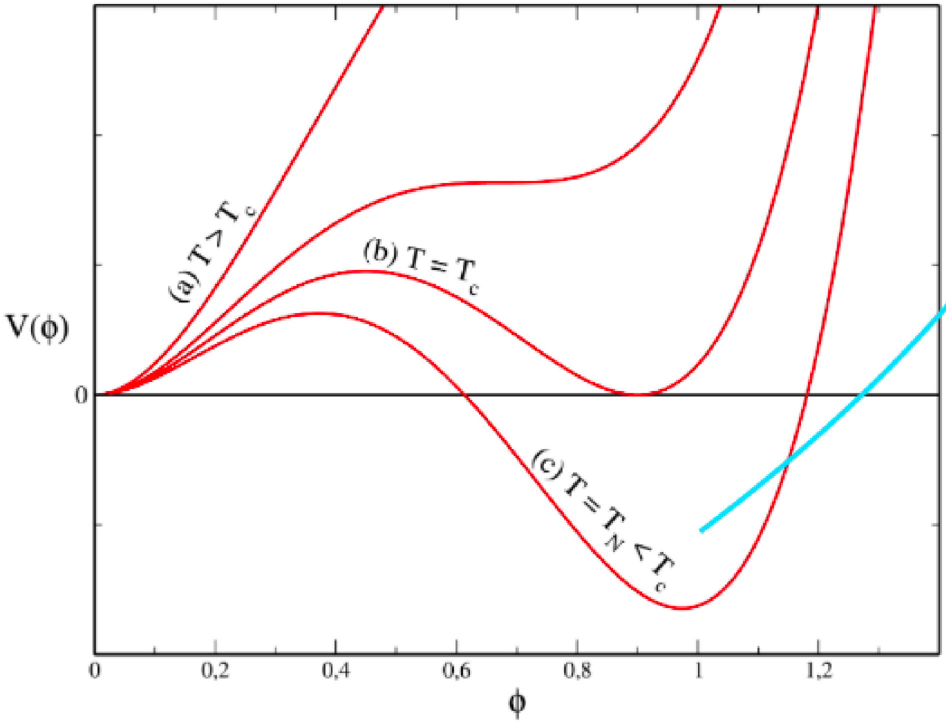
In the SM (m_h = 125 GeV) EW Phase Transition Smooth CrossOver

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

Baryon Asymmetry and Electroweak Phase Transition

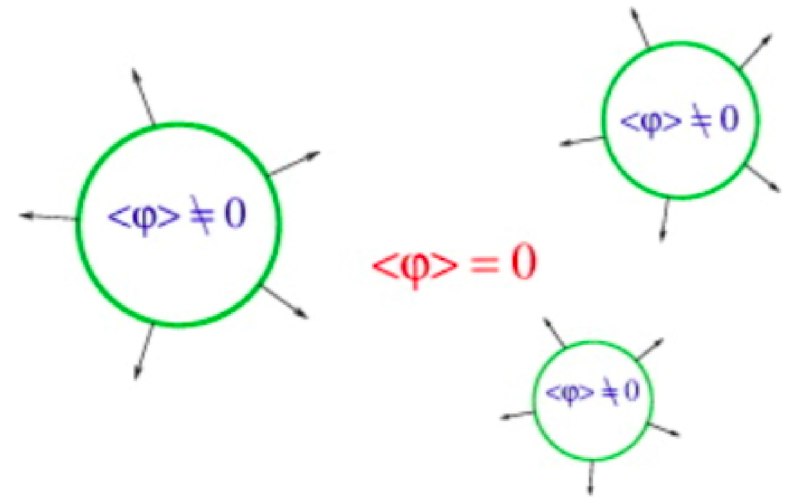
1st Order:

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



Nucleation of True Vacuum Bubbles
(in False Vacuum Sea)

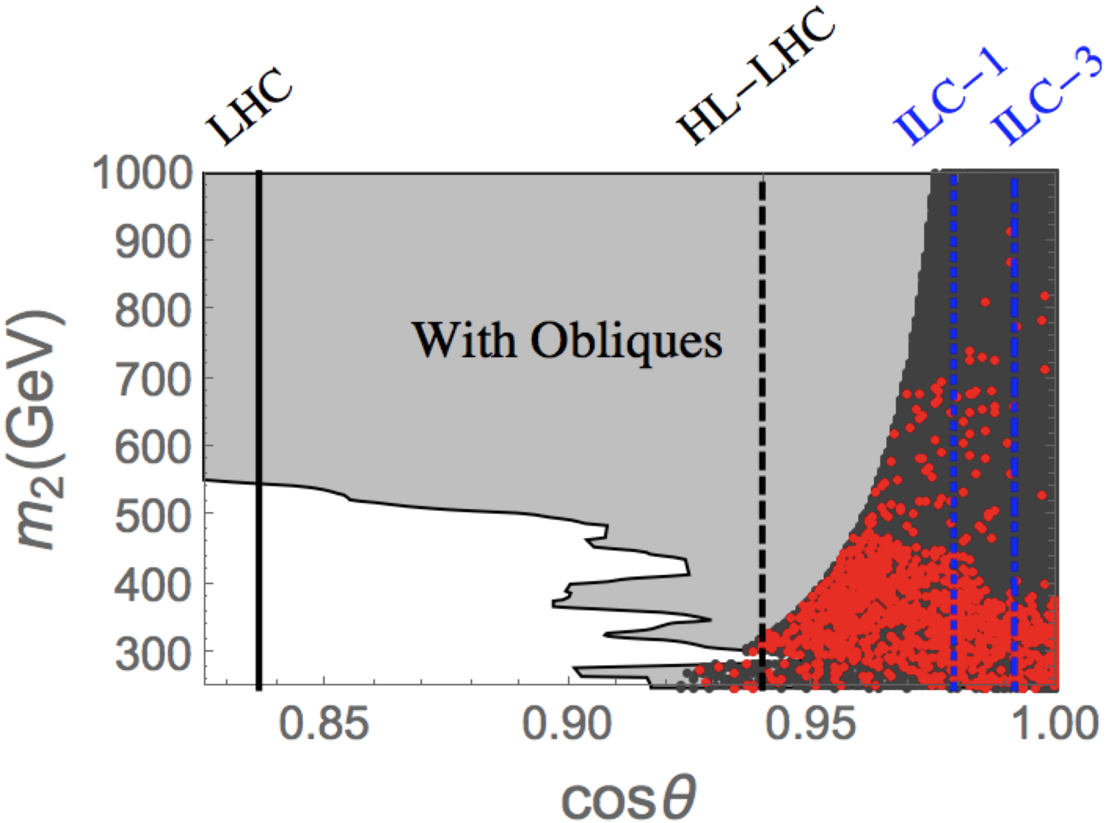
J. S. Langer, Ann. Phys. ***54*** *(1969) 258*
S. R. Coleman, Phys. Rev. D ***15*** *(1977) 2929*
A. D. Linde, Nucl. Phys. B ***216*** *(1983) 421*



SUDDEN CHANGE IN HIGGS VEV

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)

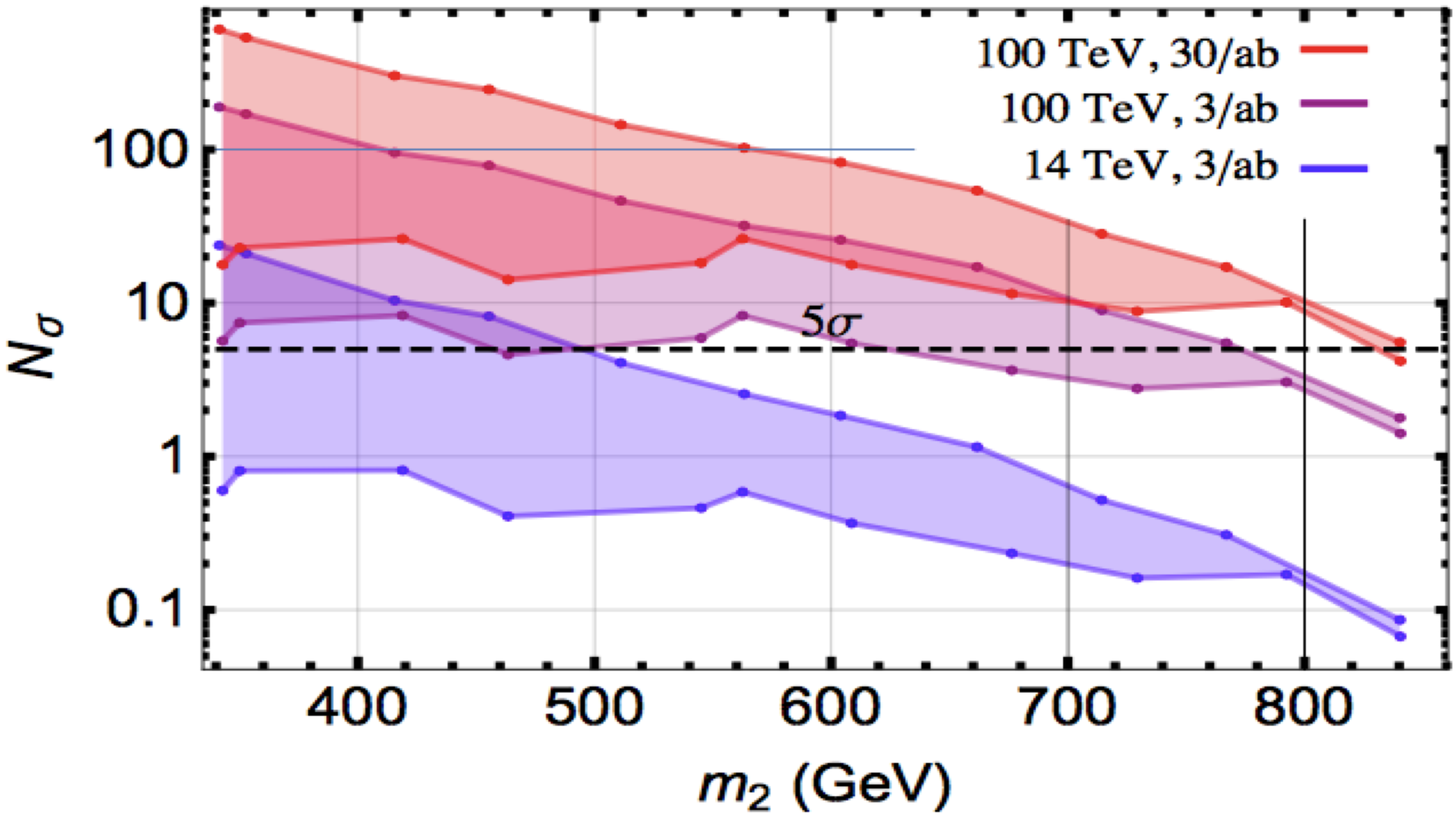
S. Profumo, M. J. Ramsey-Musolf, C. L. Wainwright and P. Winslow, arXiv:1407.5342

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

Inducing First-Order Electroweak Phase Transition

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

$S \to HH \to \gamma\gamma bb$ and 4τ



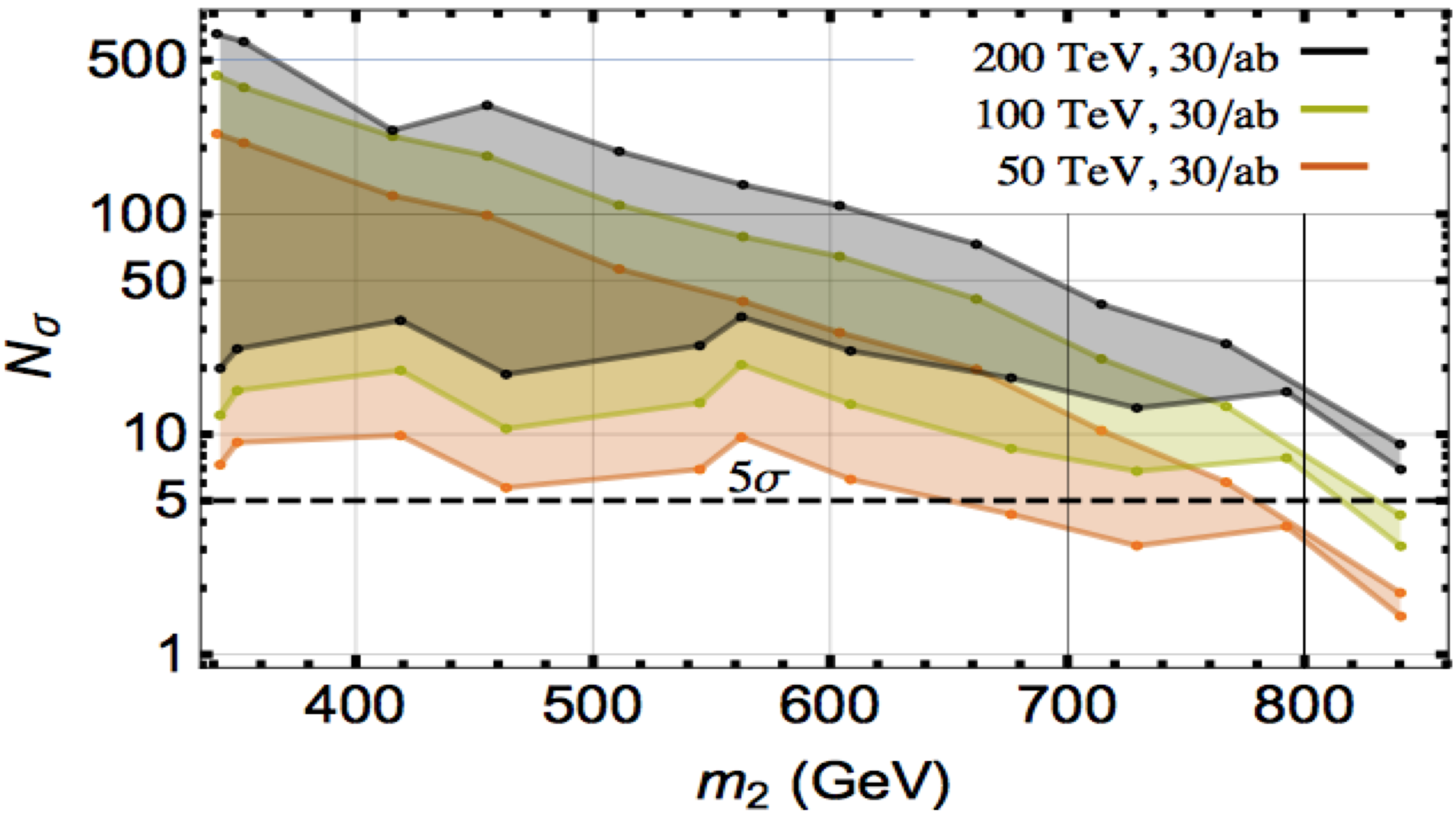
(AVK, P. Winslow, J. M. No, M. J. Ramsey-Musolf, **Phys.Rev. D94 (2016), 035022**)

Discovery potential across entire parameter space with next collider

Inducing First-Order Electroweak Phase Transition

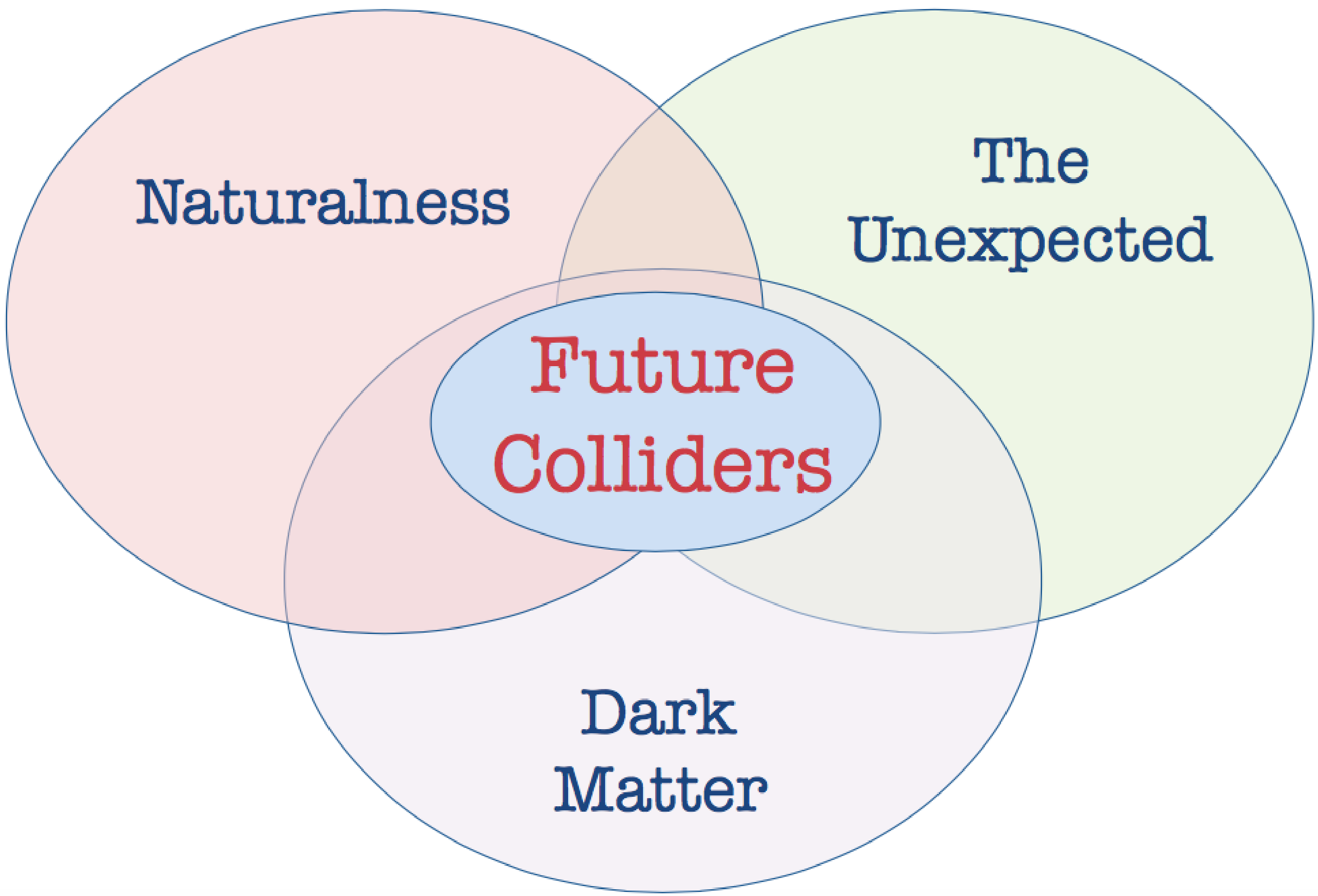
Assumptions: photon, b-quark and τ-lepton efficiency = 75%
Jets → b-quark and τ-lepton fake rate = 2%

$S \to HH \to \gamma\gamma bb$ and 4τ



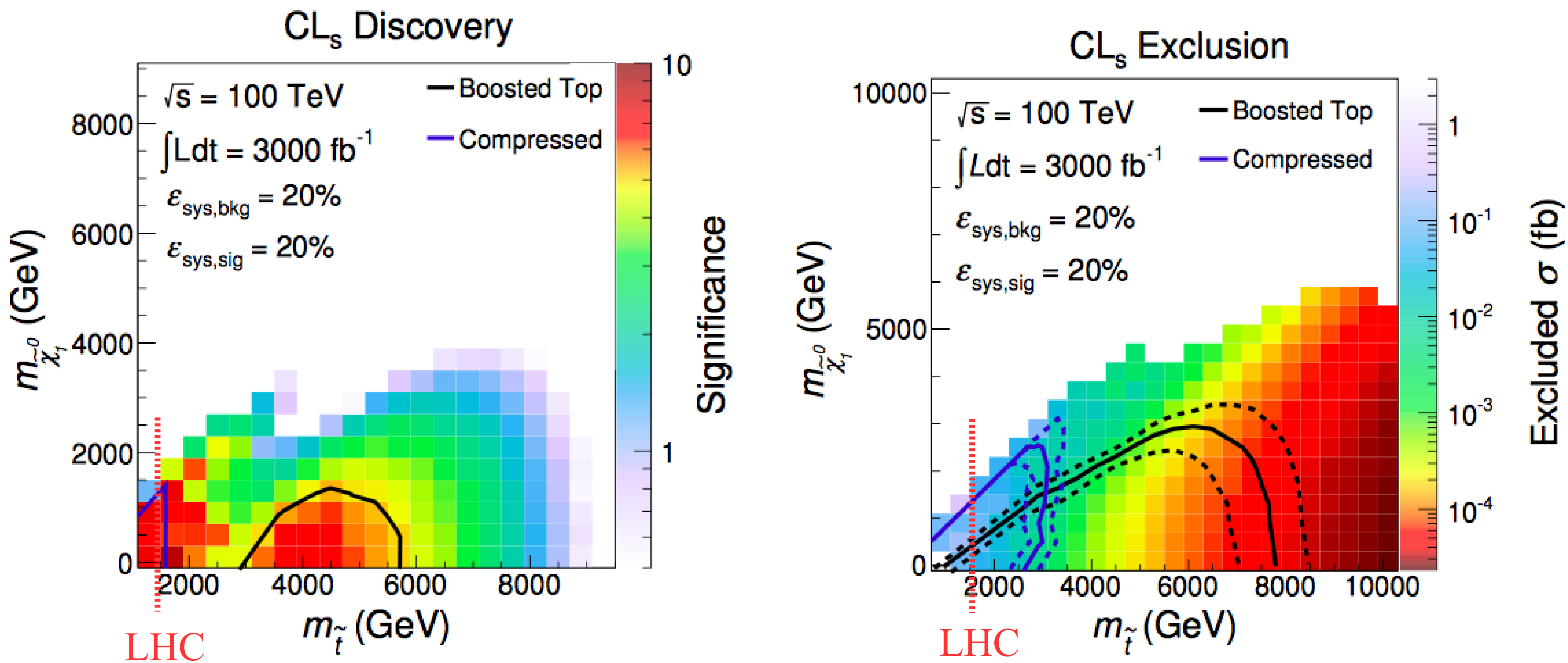
(AVK, P. Winslow, J. M. No, M. J. Ramsey-Musolf, **Phys.Rev. D94 (2016), 035022**)

Discovery potential across entire parameter space with next collider


Naturalness
The
Unexpected
Future
Colliders
Dark
Matter

Supersymmetric Colored Top Partner Sensitivity

(Cohen *et al*, 2014)

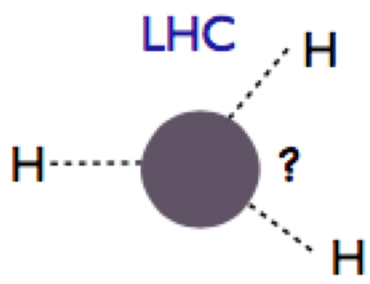


Fine-tuning ~ m_{stop}^{2} ~ 10^{-4}

A big jump beyond LHC

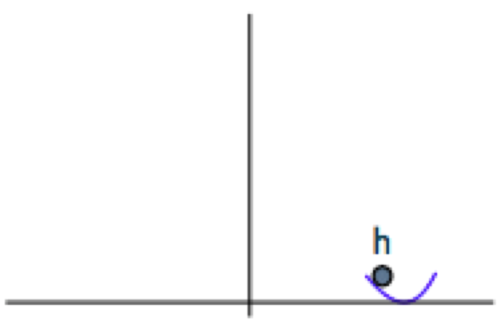
Discovering or eliminating “natural” low-energy SUSY

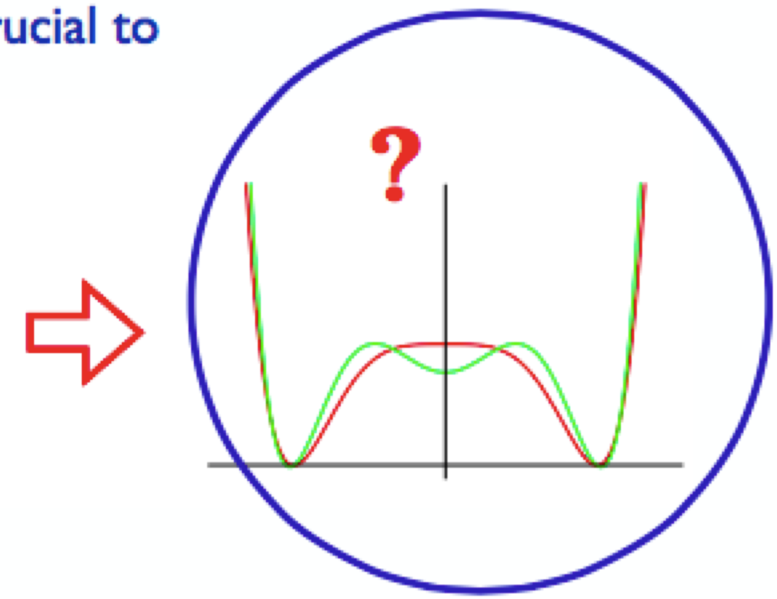
Higgs Self-Coupling



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

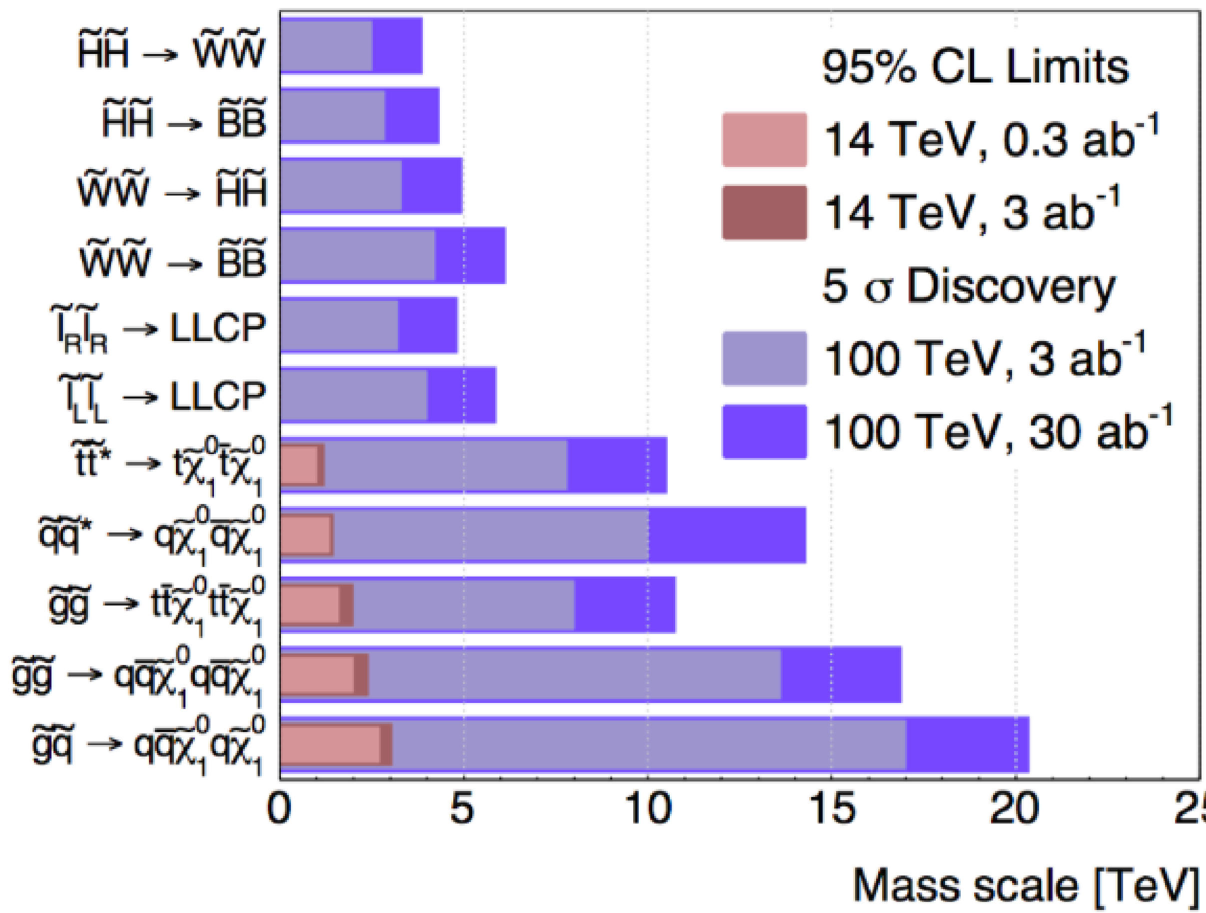
- gg→HH (most promising?) , qq→HHqq (via VBF)
- Reference benchmark process: HH→bb γγ
- Goal: 5% (or better) precision for SM selfcoupling

$HH \to b\bar{b}\gamma\gamma$	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

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

Summary

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

- Detectors will need to be more capable on all fronts
  - Faster
  - Larger dynamic range
  - Much higher resolution
  - Much higher granularity
  - Much more forward-detection capability
  - Much higher bandwidth, smarter triggers
- HL-LHC upgrade will provide experience and insights, but need to look beyond

Summary

- Entering new regime on detector design and technology
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  - We must prepare for a broader range of possible new physics
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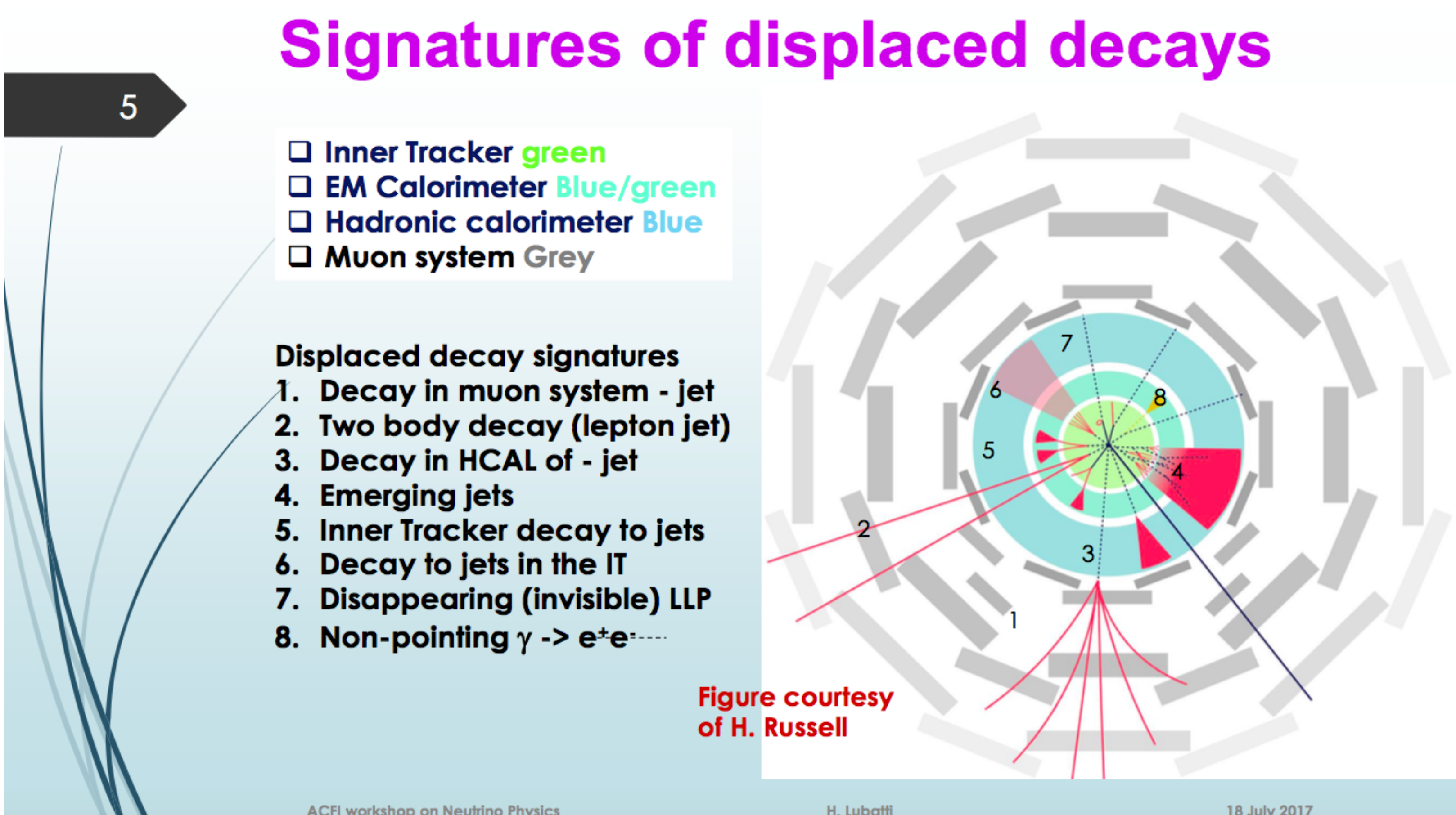
  - Prudent to continue CDF & D0 (Run 2), ATLAS & CMS general-purpose detector philosophy

- 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 → high-granularity EMCAL
  - Boosted H/W/Z/top substructure → 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



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

http://cepc.ihep.ac.cn/preCDR/volume.html

http://tlep.web.cern.ch

http://lhec.web.cern.ch

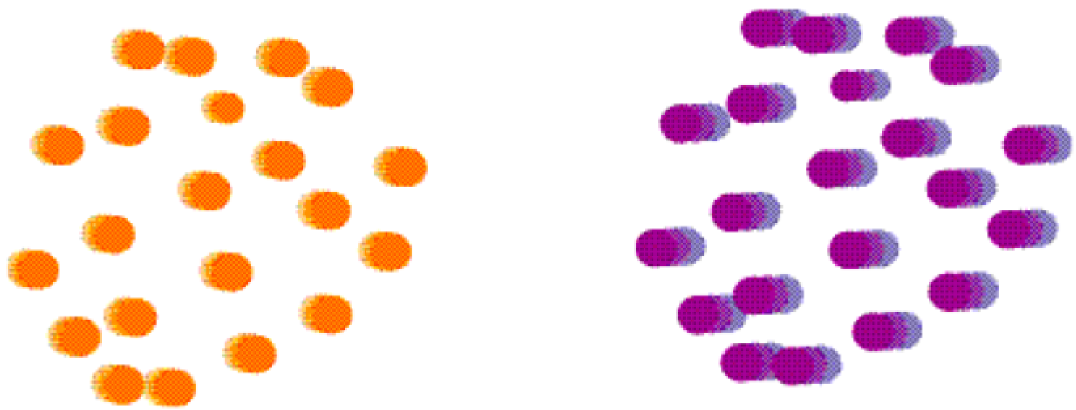
backup

Timing

Collider Luminosity and Sensor Timing

Luminosity is a measure of how often protons get close enough to interact

$$L = f\,\frac{n_1 n_2}{4\pi\, s_x s_y}$$



50 ns → 25 ns at LHC

f= beam crossing frequency

n= protons/bunch

s = transverse beam size

L ~ 10^{34} crossings/cm^2/sec

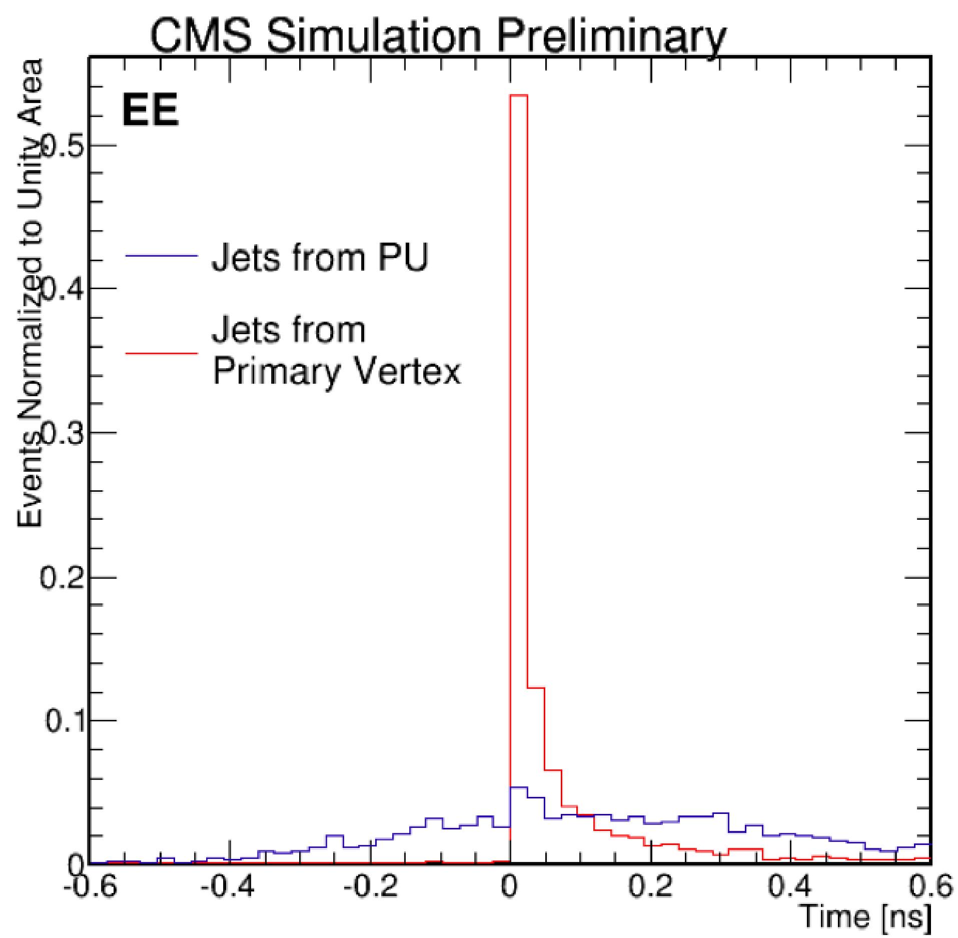
Reducing pileup by reducing *n* requires increasing *f* => faster detectors

5 ns option to be considered

Beam power increases in inverse proportion to crossing time (unless *s* reduced)

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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