Selected Snowmass 2013 CSS studies for a 100 TeV pp collider

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Snowmass CSS Experiences

- LPC@FNAL contribution to Snowmass 2013 CSS Energy Frontier effort
  - LPC is a remote analysis center for US physicists
  - (enjoy co-operation with PKU, many students resident at LPC over the years)

- Defining the tools for simulation (Delphes updates and tuning)
- Generate background MC for future hadron colliders in partnership with the Open Science Grid (established snowmass VO, develop tools etc)
- Snowmass whitepapers
  - Snowmass detector and simulation
    - partnership with some ATLAS members
  - Novel methods for Standard Model event generation
    - partnership with some ATLAS members and SLAC theory group
  - Use of OSG for event generation for snowmass
- Snowmass studies relevant to 100 TeV (SUSY, Heavy Top, 2HDM, dijets…)
- On Jan 31st – regrouped to asses how to contribute to the global FCC effort.
- Organization of a workshop in the works

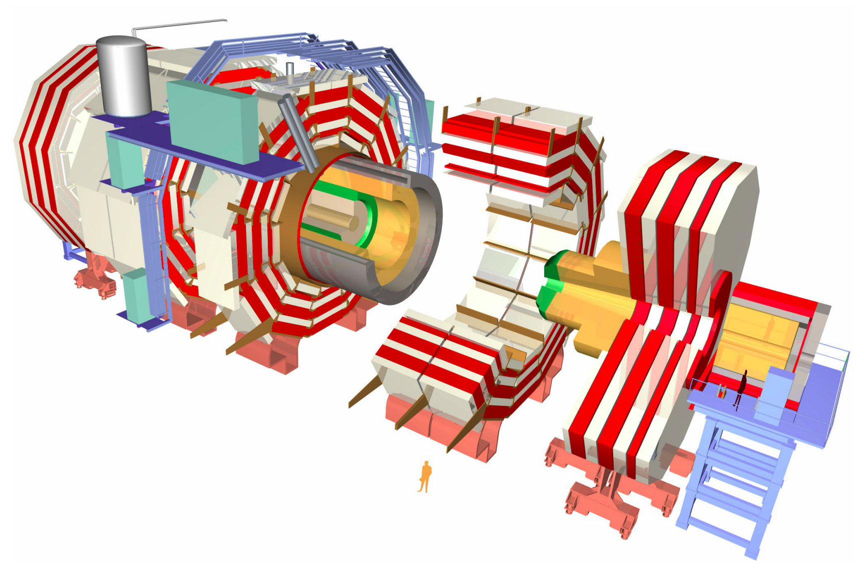
hadron collider facilities

facility	$\sqrt{s}$	L	$\int L dt$	time scale
LHC	14 TeV	10^{34}	300/fb	2015-2021
HL-LHC	14 TeV	$5x10^{34}$.	3000/fb	2023-2030
HE-LHC	26-33 TeV	$2x10^{34}$	300/fb/year	>2035
VHE-LHC	42-100 TeV			>2035

European Strategy for Particle Physics Preparatory Group:
Physics Briefing Book, CERN-ESG-005

Defining tools for simulation

- arXiv:1309.1057, arXiv:1307.6346
- Simulate generic LHC-like detector with Delphes3 for 14, 33 and 100 TeV pp studies
  - 0, 50, 140 pileup interactions per bunch crossing
  - tuned to reproduce full simulation at 8 TeV.



- For 100 TeV, used the combined snowmass detector for 14/33 TeV
- not an optimal choice, but a reasonable start to understand the limitations of the current detectors and provide a base for future designs.

SM Samples at 100 TeV

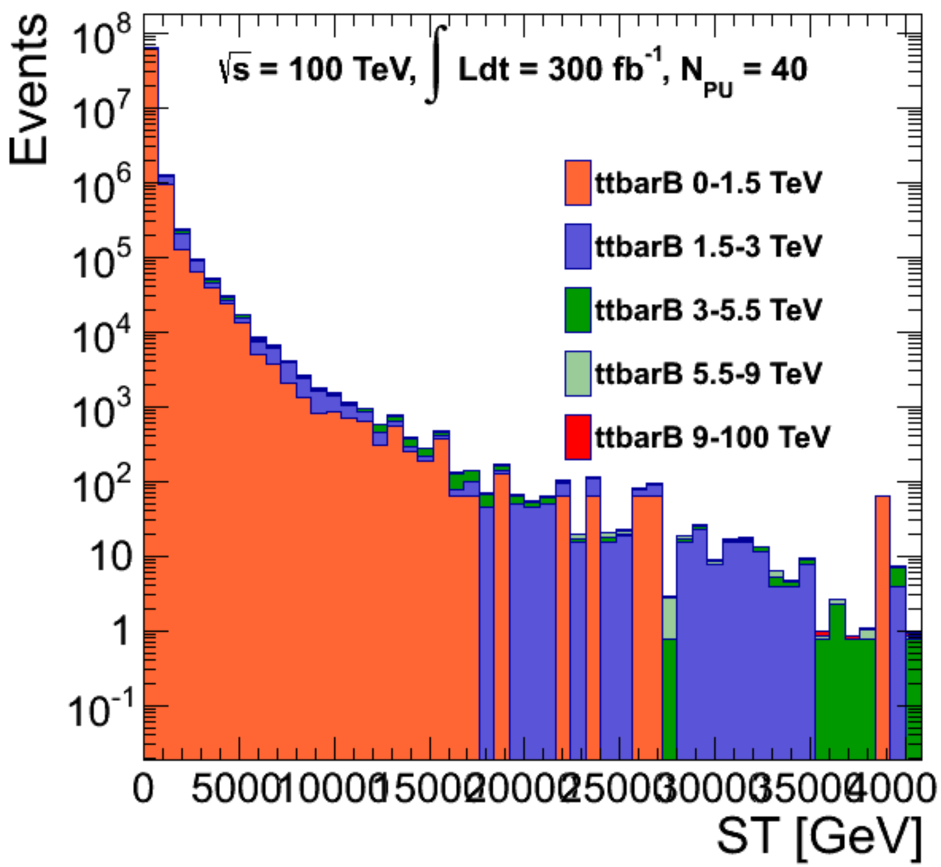
- SM background categories generated (arXiv:1308.1636)

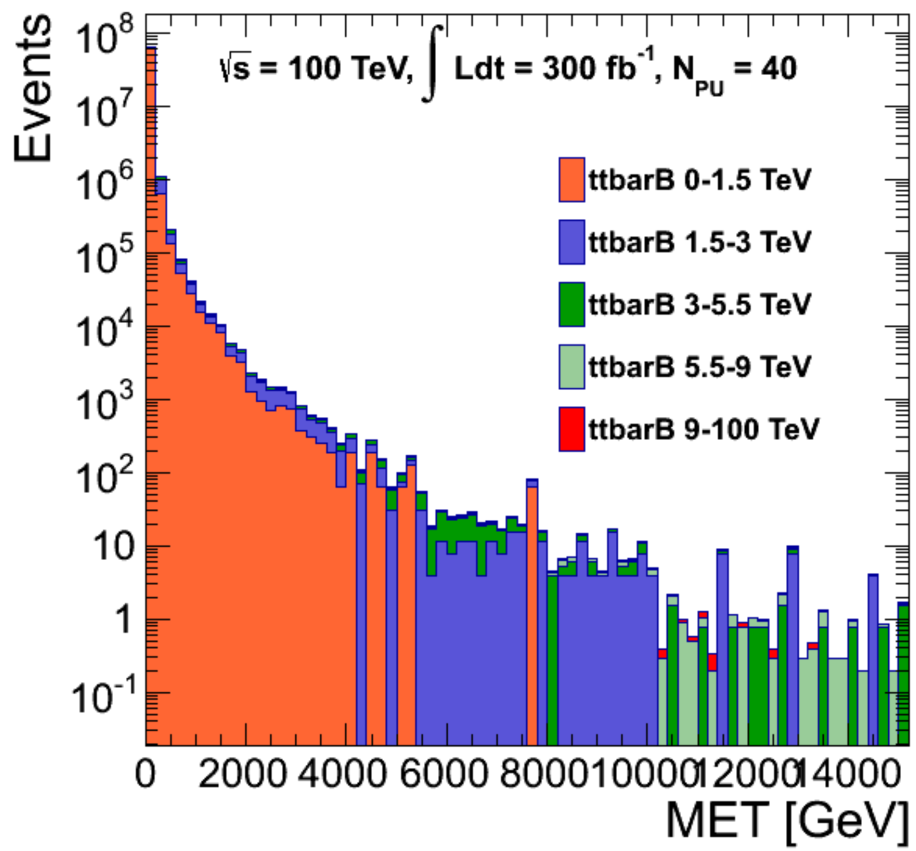
Aram Avetisyan,[1] John M. Campbell,[3] Timothy Cohen,[2] Nitish Dhingra,[4] James Hirschauer,[3] Kiel Howe,[5] Sudhir Malik,[6] Meenakshi Narain,[7] Sanjay Padhi,[8] Michael E. Peskin,[2] John Stupak III,[9] and Jay G. Wacker[2]

Dataset Name	Main Processes	Final States	Order
Dominant Backgrounds			
B-4p, Bj-4p[a]	vector boson + jets	$V + nJ$	$\mathcal{O}(\alpha_s^n \alpha_w)$
BB-4p	divector + jets	$VV + nJ$	$\mathcal{O}(\alpha_s^n \alpha_w^2)$
TT-4p	top pair + jets	$TT + nJ$	$\mathcal{O}(\alpha_s^{2+n})$
TB-4p	top pair off-shell $T^* \to Wj$ + jets	$TV + nJ$	$\mathcal{O}(\alpha_s^{n+1} \alpha_w)$
TJ-4p	single top (s and t-channel) + jets	$T + nJ$	$\mathcal{O}(\alpha_s^{n-1} \alpha_w^2)$
LL-4p	off-shell $V^* \to LL$ + jets	$LL + nJ$ $[m_{ll} > 20$ GeV$]$	$\mathcal{O}(\alpha_s^n \alpha_w^2)$
Subdominant Backgrounds			
TTB-4p	top pair + boson	$(TTV + nJ), (TTH + nJ)$	$\mathcal{O}(\alpha_s^{2+n} \alpha_w)$
BLL-4p	off-shell divector $V^* \to LL$ + jets	$VLL + nJ$ $[m_{ll} > 20$ GeV$]$	$\mathcal{O}(\alpha_s^n \alpha_w^3)$
BBB-4p	tri-vector + jets, Higgs associated + jets	$(VVV + nJ), (VH + nj)$	$\mathcal{O}(\alpha_s^n \alpha_w^3)$
H-4p	gluon fusion + jets	$H + nJ$	$\mathcal{O}(\alpha_s^n \alpha_h)$
BJJ-vbf-4p	vector boson fusion + jets	$(V + nJ), (H + nJ)$ $[n \geq 2]$	$\mathcal{O}(\alpha_s^{n-2} \alpha_w^3)$

SM Samples at 100 TeV

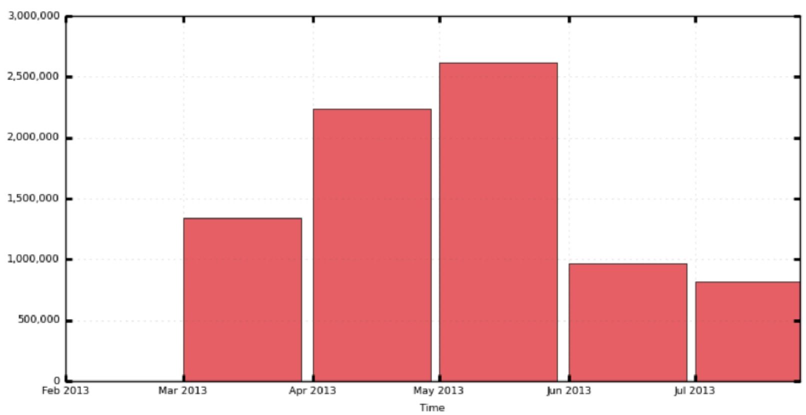
- SM background – distributions.

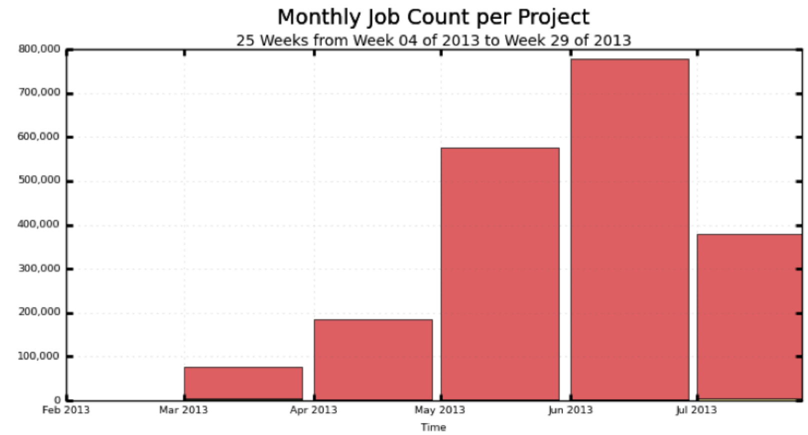




SM MC Production

- A challenging task - intensive computing resources are needed. Harness the resources via OSG
  - about 8M CPU hours and 900M events simulated with 0, 50, 140 pileup.





Many thanks to:
John Stupak, Sanjay Padhi, Nitish Dhingra, Marko Sylz,
Jim Hirschauer, Aram Avetisyan

A few Physics Studies:

- sensitivity studies for snowmass @ 100 TeV

LPC meeting on future 100 TeV proton collider

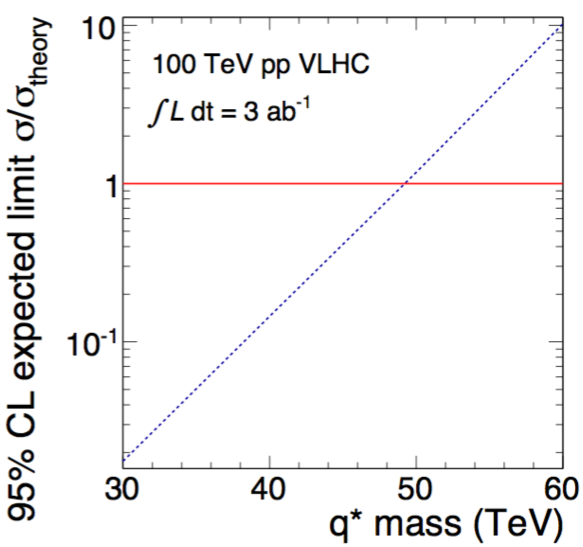
chaired by Sanjay Padhi (Univ. of California San Diego (US))

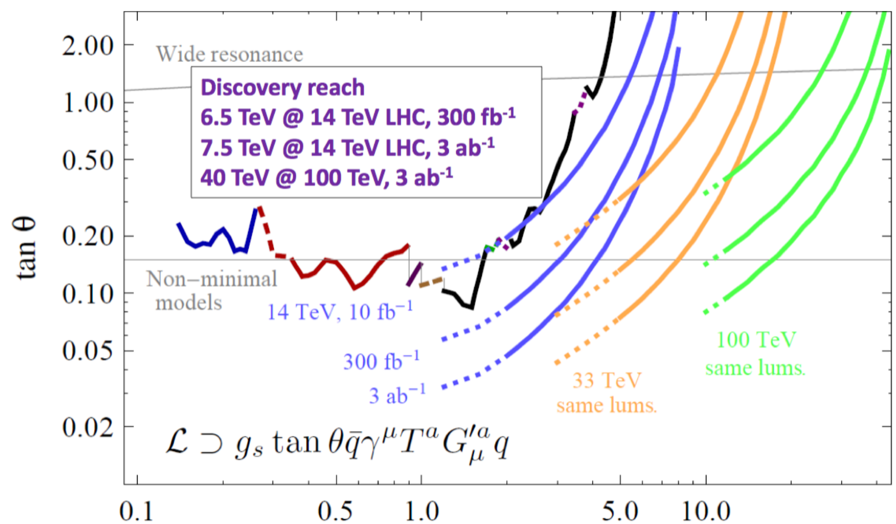
Friday, 31 January 2014 from **08:30** to **15:20** (America/Chicago)
at **Fermilab (Sunrise)**

Dijet Studies

Felix Yu, Jake Anderson (FNAL)

- Quark Compositeness, Excited Quark, Dijet Resonances:
- At a hadron collider the strongly produced dijet resonance is among the first particle searches published.
- Probing quark compositeness is a natural model.
  $1\ \mathrm{eV}^{-1} \approx 0.2\ \mu\mathrm{m}$ so $1\ \mathrm{TeV}^{-1} \rightarrow 0.2 \times 10^{-18}$
- At 95% CL, one could exclude q* masses up to almost 50 TeV.
  - This is probing the structure of quarks down to 4×10^{-21}m.
- 5sigma discovery reach for resonances upto 40 TeV



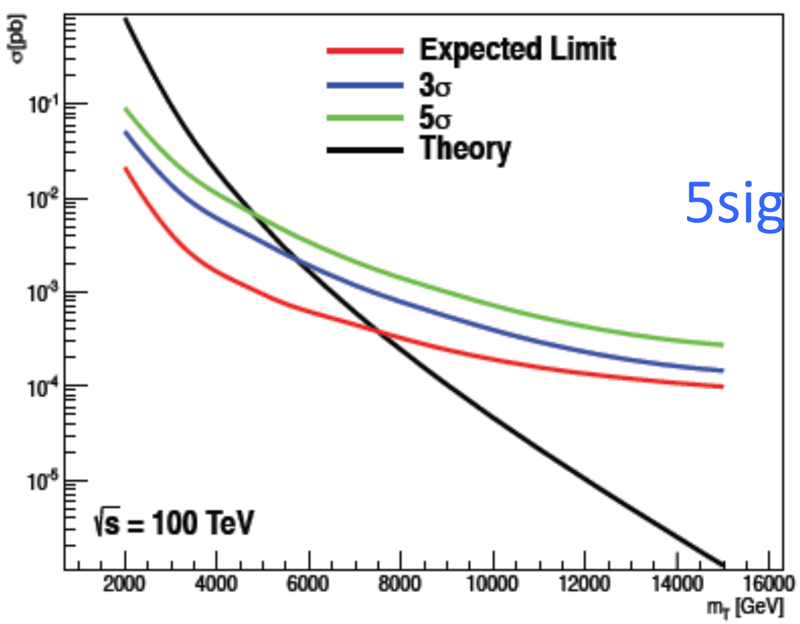


Could discover resonances with tan θ as small as 0.03 to 0.08

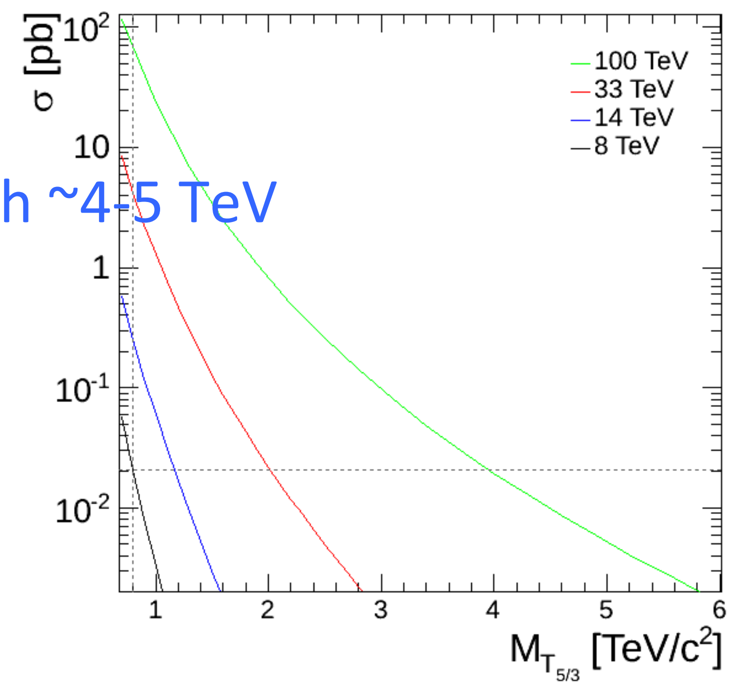
Heavy Top Partners

- T w/charge 2/3 T w/charge 5/3

optimization necessary to identify boosted top quark jets.



5sig reach ~4-5 TeV



Ahuja, Choudhary, Narain, Stupak, Black, et al.

A. Avestisyan

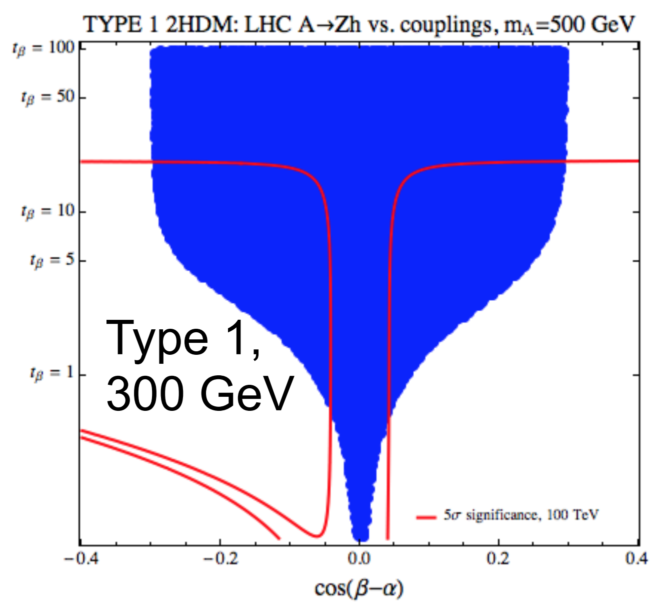
Heavy Higgs: 2HDM Models

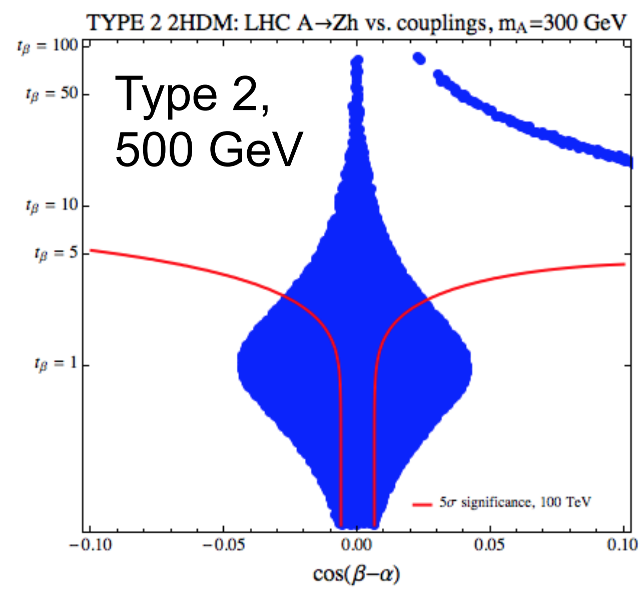
Craig, Dhingra, Narain, Stupak

- Important to fully explore the Higgs sector
- Precision measurement of h(125) couplings can constrain parameter space of the 2HDM
  - Little (no) sensitivity near (at) alignment limit
- Direct search offers unique potential to probe regions of parameter space near the alignment limit
- Important to pursue both coupling measurements and direct search
- Study H ZZ 4l and A Zh ll+bb/tautau

Blue region:
allowed by HL-LHC (in absence of observed deviations from SM)

Red – 5sig sensitivity

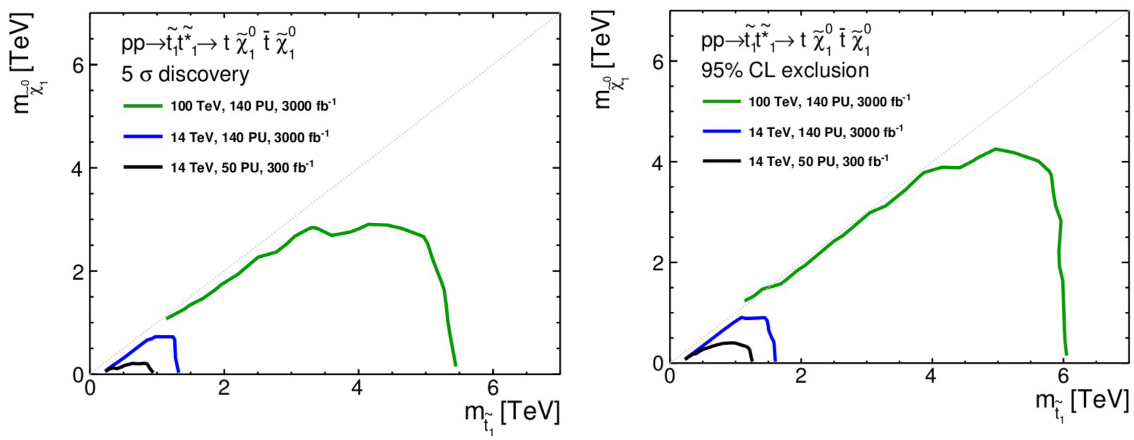




SUSY

- Direct Stop Production – can probe upto 6 TeV

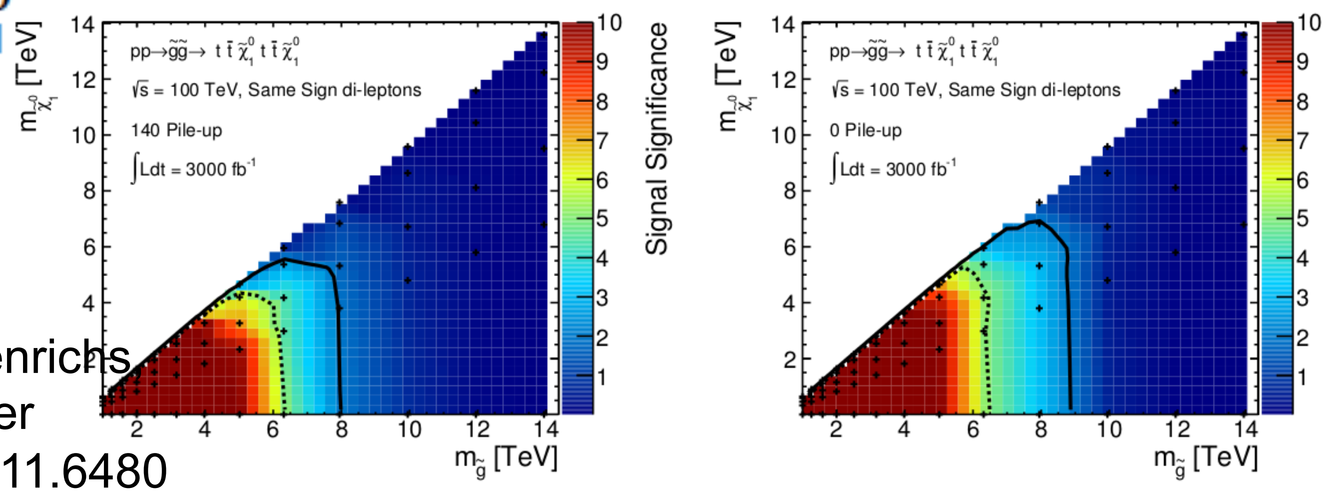
S. Padhi (UCSD)



- Studies using 3rd generation squarks

$$\tilde{g}\tilde{g} \to t\bar{t}\tilde{\chi}^0_1 t\bar{t}\tilde{\chi}^0_1$$

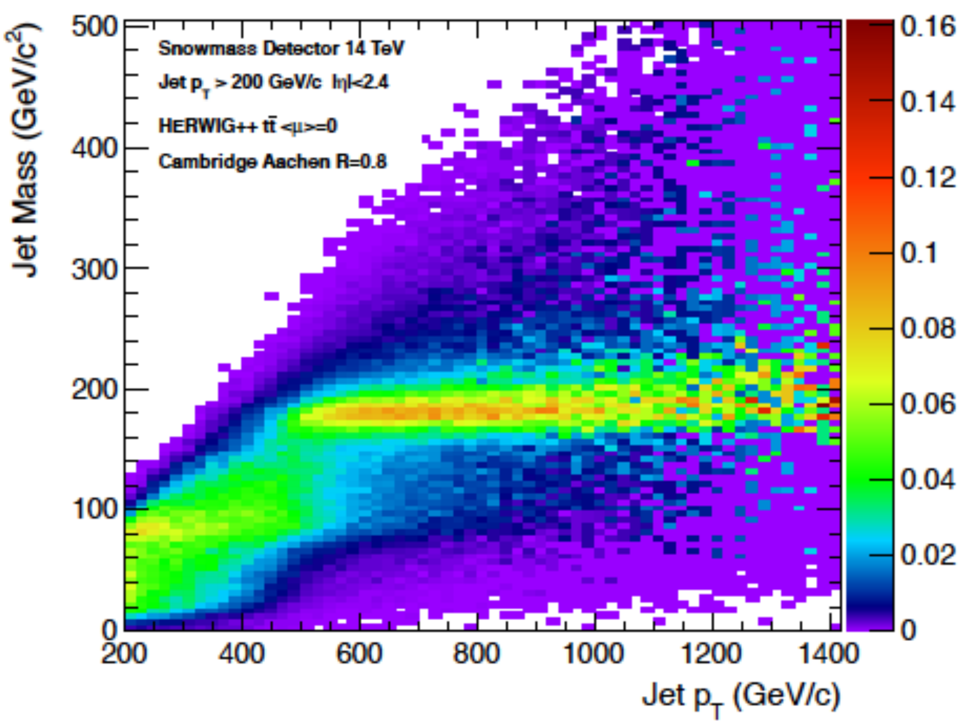
Sensitive to gluino mass of 8 TeV



Cohen, Golling, Hance, Henrichs
Howe, Loyal, Padhi, Wacker
arXiv:1310.0077, arXiv:1311.6480

Top reconstruction:

- highly boosted jets, constituents of top quark not resolved. Need to revisit the top-tagging and jet substructure algorithms,



(b) Cambridge/Aachen R=0.8

R.Calkins et al
arxiv:1308.0963

EF Detector Challenges

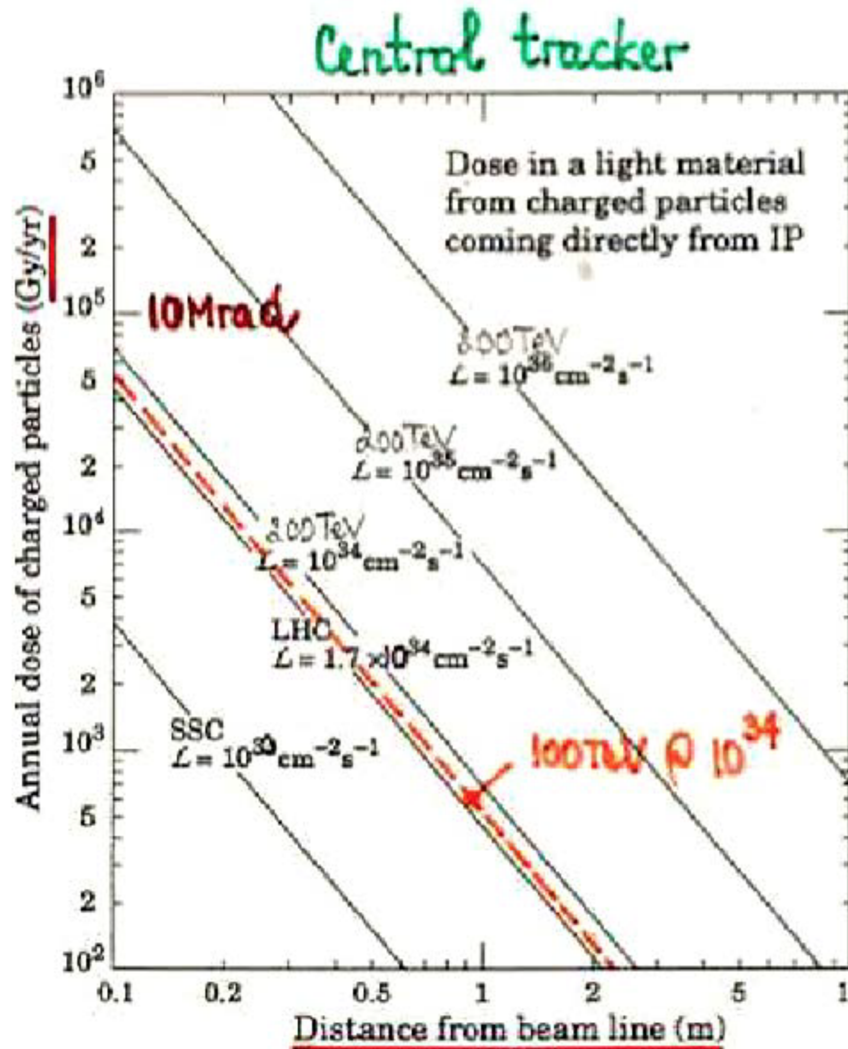
- As beam energy increases, we are still looking at ewk scale phenomena involving W and Z bosons and their decay products
- We would like to detect all "well known" stable particles including products of short lived objects decays: pions, kaons, muons, etc.
  - Need 4π detector with layers of tracking, calorimeter and muon system
- maintain acceptance to relatively soft particles
- maintain large angular acceptance to minimize theoretical uncertainties and retain sensitivity to distinguish between different models should we find something new
- superior spatial and time resolution for pattern recognition in high occupancy environment

EF Detector Challenges

- Central tracker
  - Most challenging need to preserve momentum resolution for ~10 times higher momentum tracks
- Calorimetry
  - Getting better with energy: hadronic energy resolution ~50%/√E, 2% at 1TeV
  - Length of shower increase has log(E) dependence –not major issue
- Muon system
  - Main challenge is momentum resolution and showering of muons as they are becoming “electrons” due to large γ factor

Radiation Doses

- Radiation in the center region scales with luminosity, not energy
- Occupancies and radiation doses
  - For 10^{35} $cm^{-2}sec^{-1}$, challenging for both due to pileup and radiation aging
- Detectors for 100 TeV collider are challenging



D. Denisov (VLHC study)

challenges

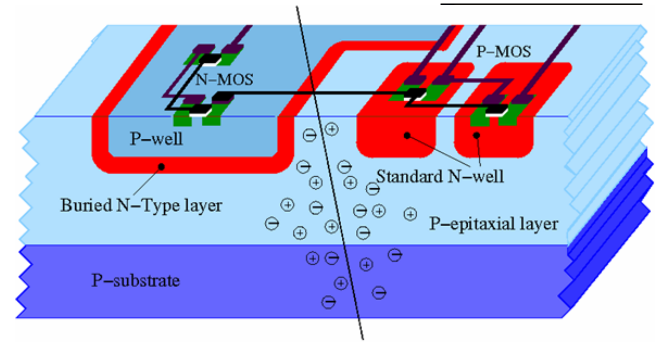
- interaction rate
  - increase rejection power of trigger system
  - low power, high bandwidth data links
- pileup
  - pixelization
  - precision timing
- radiation damage
  - radiation hard detector technologies
  - operate at low temperatures

features: next generation tracker

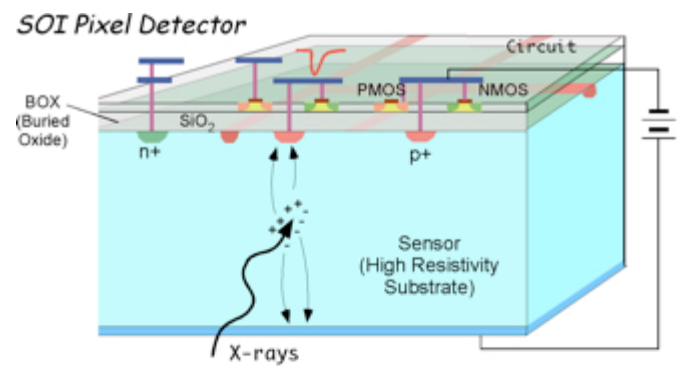
- high resolution in high rate environment
  - thin, highly pixelated sensors
- time measurement (for pileup reduction)
  - thin, low capacitance sensors
- radiation hard (LHC fluence 2×10^{16} cm^{-2})
  - operate at low temperature
  - small depletion depth
  - materials other than silicon
- low mass
  - thin sensors
- power for increased channel count and speed
  - multipurpose support structure
  - more efficient cooling

monolithic pixels

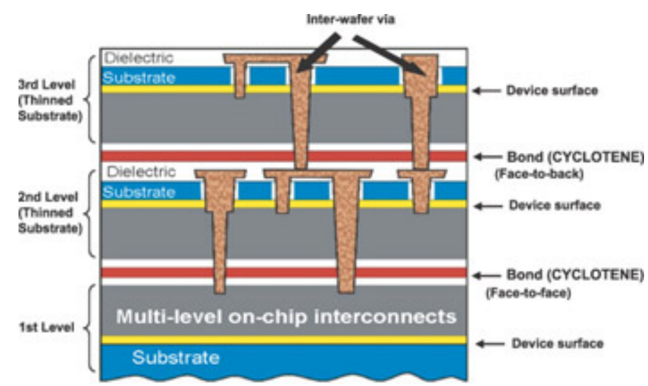
- MAPS (monolithic active pixel sensors)
  – sensor and readout circuitry implanted in same Si wafer
  ☑ thin, low mass, high granularity, low capacitance
  ☒ radiation hardness, slow, coupling of digital electronics and sensor
- SOI (silicon on insulator sensors)
  – thin CMOS layer, oxide bonded to a thick silicon handle wafer used as sensor and connected to electronics by vias through oxide
  ☑ large, fast signal, high granularity, low capacitance
  ☒ radiation hardness, thinning of handle wafer, coupling of digital electronics and sensor
- 3D integration
  – vertical stacking of wafers by vias, bonding, thinning, interconnection
  ☑ similar advantages as SOI and MAPS, separate optimization of sensor and electronics
  ☒ availability of technology, how to fabricate large devices at low cost



MAPS, U Pavia



Silicon-on-insulator pixel, KEK

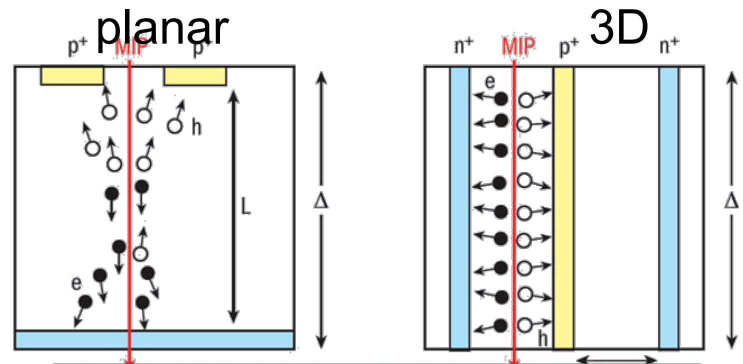


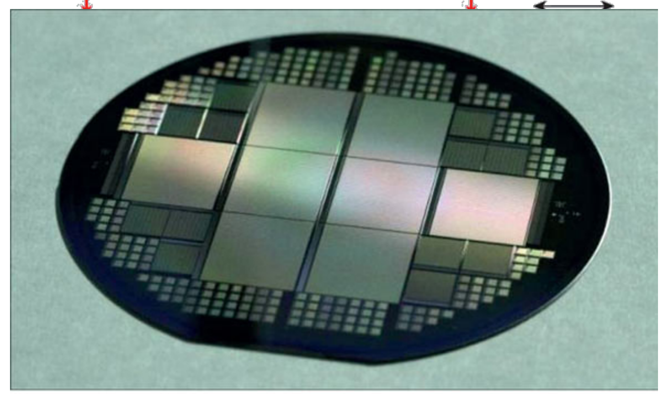
3-D Integration, RPI

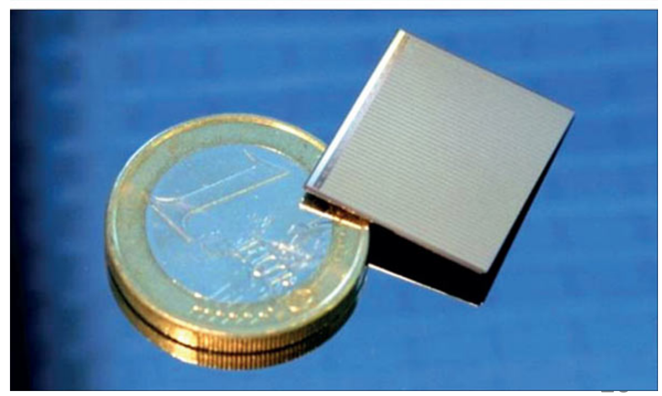
U. Heintz (snowmass IF summary)

3D pixel sensors

- planar sensors collect charge with implant pixels on sensor surface
- 3D sensors collect charge with implant columns in bulk
  - smaller depletion depth
  - faster charge collection
  - lower leakage current
  - lower depletion voltage
  - lower power dissipation
  - radiation tolerant ($V_{dep} \propto d^2$)







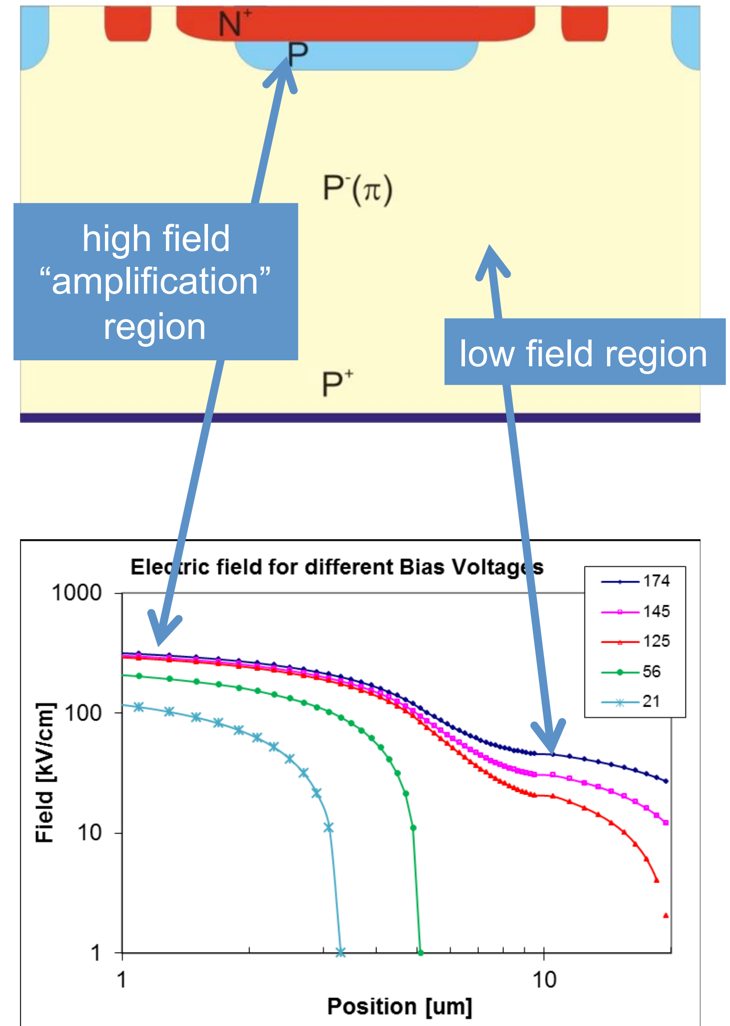
ATLAS IBL sensors - CERN

diamond sensors

- chemical vapor deposition (CVD) diamond
  - band gap 5.5 eV (silicon: 1.1 eV)
  - displacement energy 42 eV/atom (silicon: 15 eV)
  - only 60% as many charge carriers as silicon
  - intrinsically radiation tolerant
  - low Z
  - do not require extensive cooling
- issues
  - availability
    - currently two viable industrial suppliers
  - small signal
  - reduced charge collection after irradiation

4D ultra-fast silicon detectors

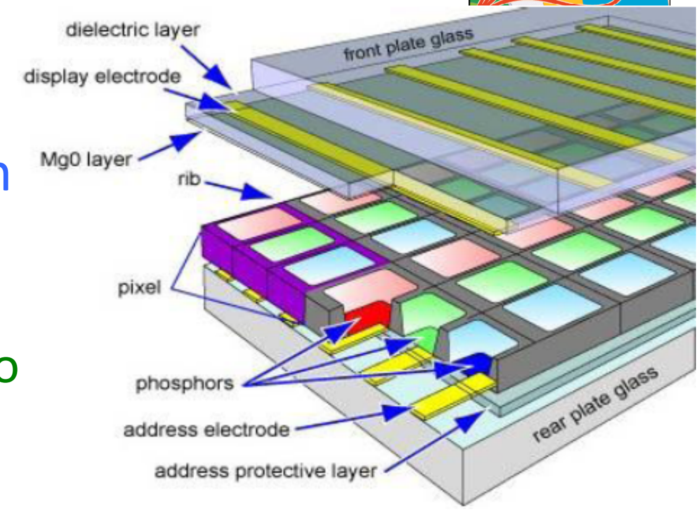
- combine precise spatial resolution with ps time resolution
  - thinned silicon (≈5 µm)
  - charge multiplication in bulk
- R&D required
  - wafer processing options
    - n-bulk vs p-bulk,
    - planar vs 3D sensors
    - epitaxial vs float zone
    - depth and lateral doping profile

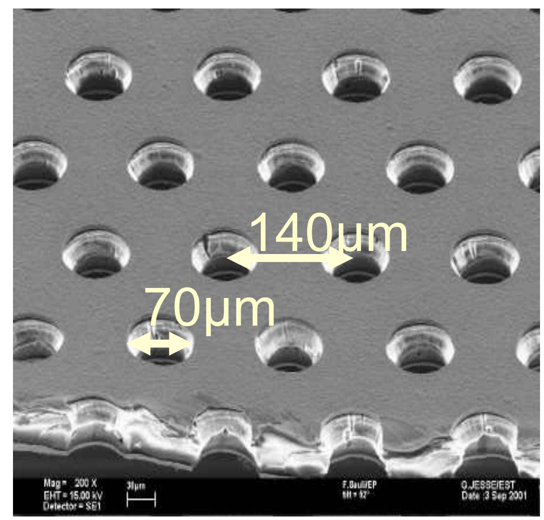


MPGD (micropattern gas detectors)

BROWN

- applicable for calorimeters and trackers
- potentially low cost, low mass, large area, high granularity, fast, radiation hard
- plasma panel sensors (PPS)
  - resemble plasma-TV display panels, modified to detect gas ionization in the individual cells
- resistive plate chambers (RPC)
  - improve rate capabilities, granularity
- flat panel microchannels
- gas electron multipliers (GEMs)
- micromegas
- R&D needed
  - reduce readout cost by developing highly integrated, radiation-hard front-end electronics
  - materials with resistance to aging
  - cost-effective construction techniques





U. Heintz (snowmass IF summary)

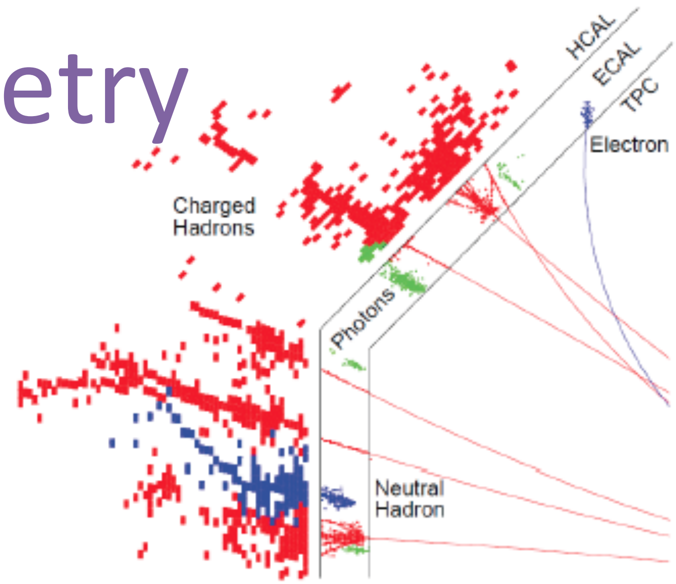
dream calorimeter features

- radiation hard
- high rate capability
- detect and accurately measure e/ γ and jets in the presence of large background/pileup
  - need $\sigma/E \leq 30\%/\sqrt{E}$ to separate W→qq and Z→qq
  - jet resolution limited by fluctuations in hadronic showers
  - compensating calorimeters
    - same response for EM and hadronic component
    - neutrons liberated in hadronic interactions → slow
  - new calorimeter techniques

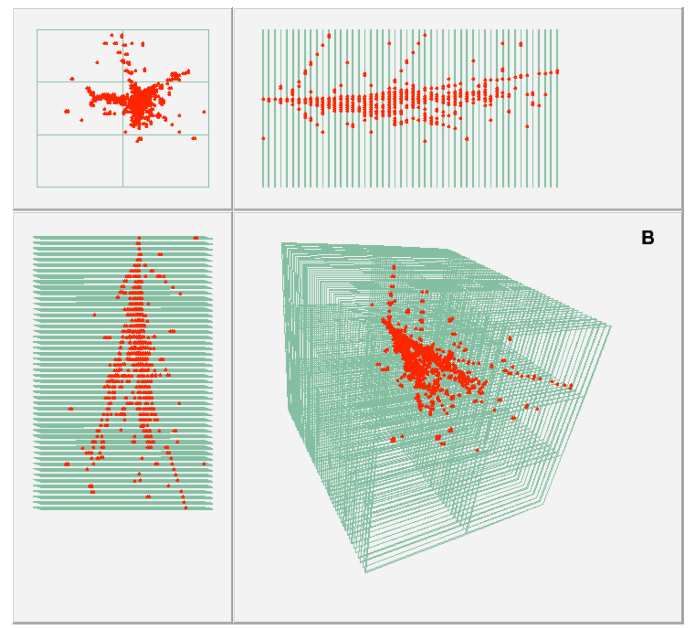
U. Heintz (snowmass IF summary)

particle flow calorimetry

- reconstruct individual particles in shower
- apply particle specific corrections
  - measure charged particles in tracker
  - measure photons in em calorimeter
  - measure neutral hadrons in hadron calorimeter
- imaging calorimeters
  - particle flow requires detailed image of shower
  - requires high granularity detectors
  - micro-pattern gas detectors
- planned for e+e- collider detectors
- can it be made to work at high rate, high background hadron colliders?



Typical topology of a simulated 250GeV jet in CLIC ILD

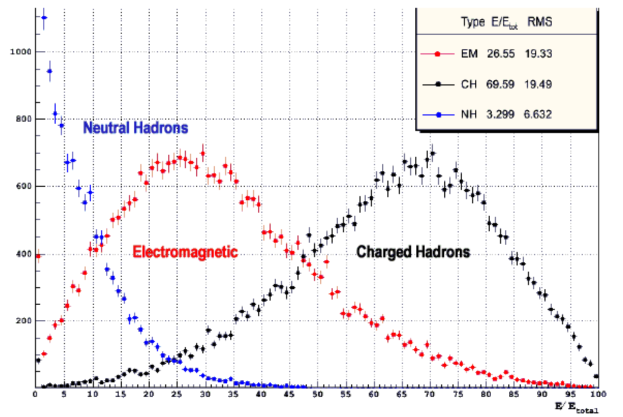


U. Heintz (snowmass IF summary)

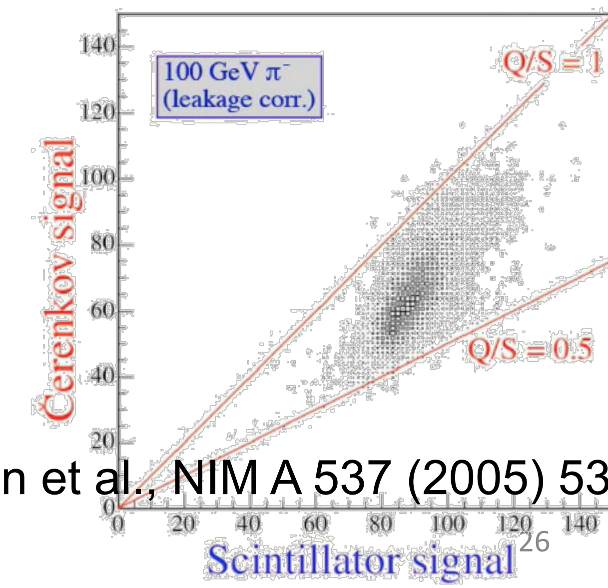
dual readout calorimetry

- measure EM/had ratio using Cerenkov light (EM) and scintillation light (EM +had)
- resolution limit $\sigma/E \leq 15\%/\sqrt{E}$
- sampling calorimeter
  - e.g. Pb/Cu + scintillating fibers
- homogeneous calorimeter
  - need dense and low cost material
- photodetectors
  - sensitive over large frequency range

Fraction Energy of Particles in Jets



11/24/2003 DHCal Study at UTA-A Report Venkatesh Kaushik 18



Akchurin et al., NIM A 537 (2005) 537

U. Heintz (snowmass IF summary)

emerging technologies

- graphene
  - high e mobility at room temperature
  - high thermal conductivity
  - strength and rigidity at low mass
  - applications: integrated circuits, switching optical devices (modulators)
- silicene
  - similar to graphene – based on silicon
- amorphous nanocrystalline thin-film silicon
  - radiation hard
  - low cost
  - incorporate nanocrystalls of crystalline silicon to achieve detector grade properties

U. Heintz (snowmass IF summary)

conclusion

- Simulation tools exist
  - evolve detector description, object performances
- MC generation is resource intensive
  - continue to use the OSG infrastructure for snowmass
  - update SM samples with the modified simulation and detector responses.

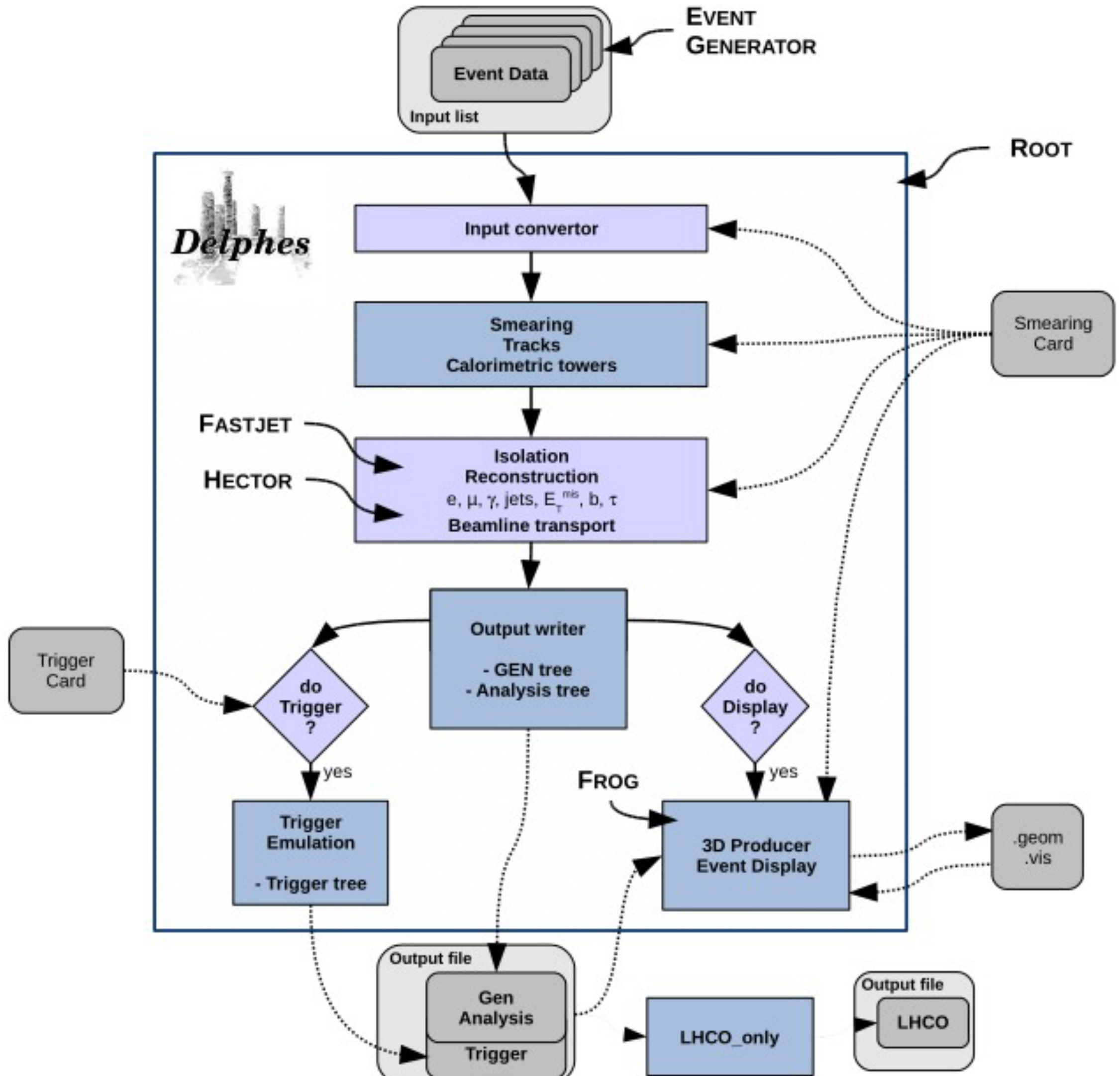
- the challenges at energy frontier facilities will be substantial
  - there are many ideas for instrumentation that can address these challenges
- in order to realize our physics goals, we need to invest in technology R&D
  - need a funding structure that enables detector R&D

Delphes 3

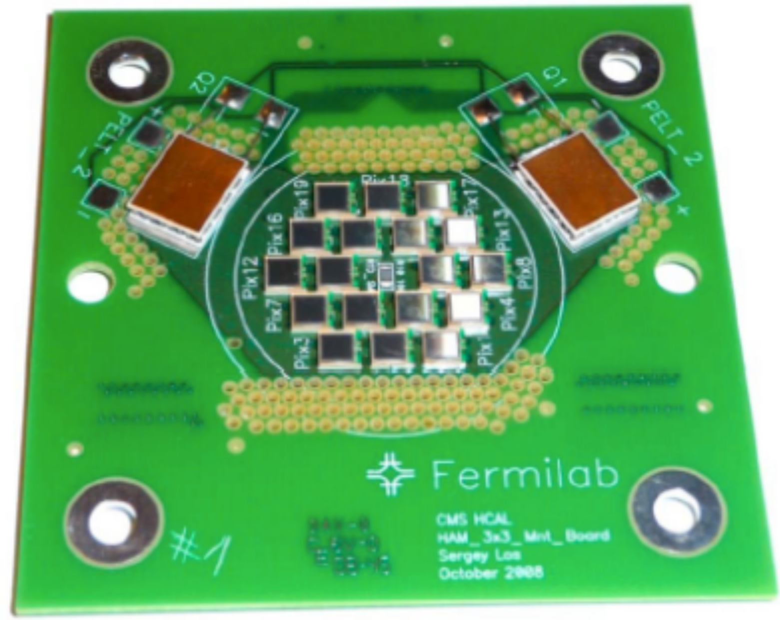
(https://cp3.irmp.ucl.ac.be/projects/delphes)

- Delphes3 supports addition of PU events
- Many improvements were motivated based on current studies

- For Snowmass studies, plan to use Delphes3 framework
  - use best expected performance
- pileup subtraction will be the key



solid state photo detectors



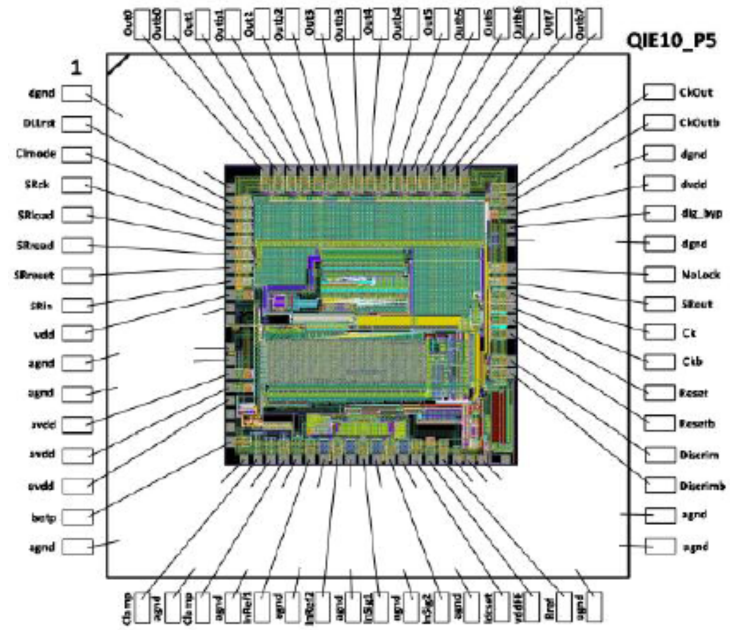
SiPM mounting card - CMS

- Silicon Photomultipliers (SiPM)
  - Geiger-mode APDs
  - low power
  - low voltage
  - low noise (compared to APDs)
  - compact
  - excellent timing resolution
  - insensitive to magnetic fields
- R&D directions
  - Si is sensitive to radiation
    - need to cool devices to keep leakage current down
    - GaAs or InGaAs
  - Si has small attenuation length for UV light
    - needed to detect Cerenkov light
    - SiC (bandgap = 3.2 eV)

U. Heintz (snowmass IF summary)

ASICs
(application specific integrated circuits)

- ASICs
  - small size
  - lower power dissipation
  - radiation tolerant
- R&D to develop
  - high-speed waveform sampling
  - pico-second timing
  - low-noise high-dynamic-range amplification and shaping
  - digitization and digital data processing
  - high-rate data transmission
  - low temperature operation



U. Heintz (snowmass IF summary)