Physics & Detectors at the LHC and the SLHC

2005 ILC Physics & Detector Workshop

Snowmass, CO, August 17, 2005

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Outline:

ATLAS, CMS & LHC

Startup Discovery Physics examples

SLHC Upgrade

Mature LHC → SLHC Discovery Physics examples

Detector Upgrades

This talk is available on:

http://cmsdoc.cern.ch/cms/TRIDAS/tr/0508/Smith_ILC_SLHC_Aug05.pdf

(Thanks to S. Dasu, D. Denegri, A. De Roeck, G. Hall, B. Mellado, A. Nikitenko, M. Spiropulu)

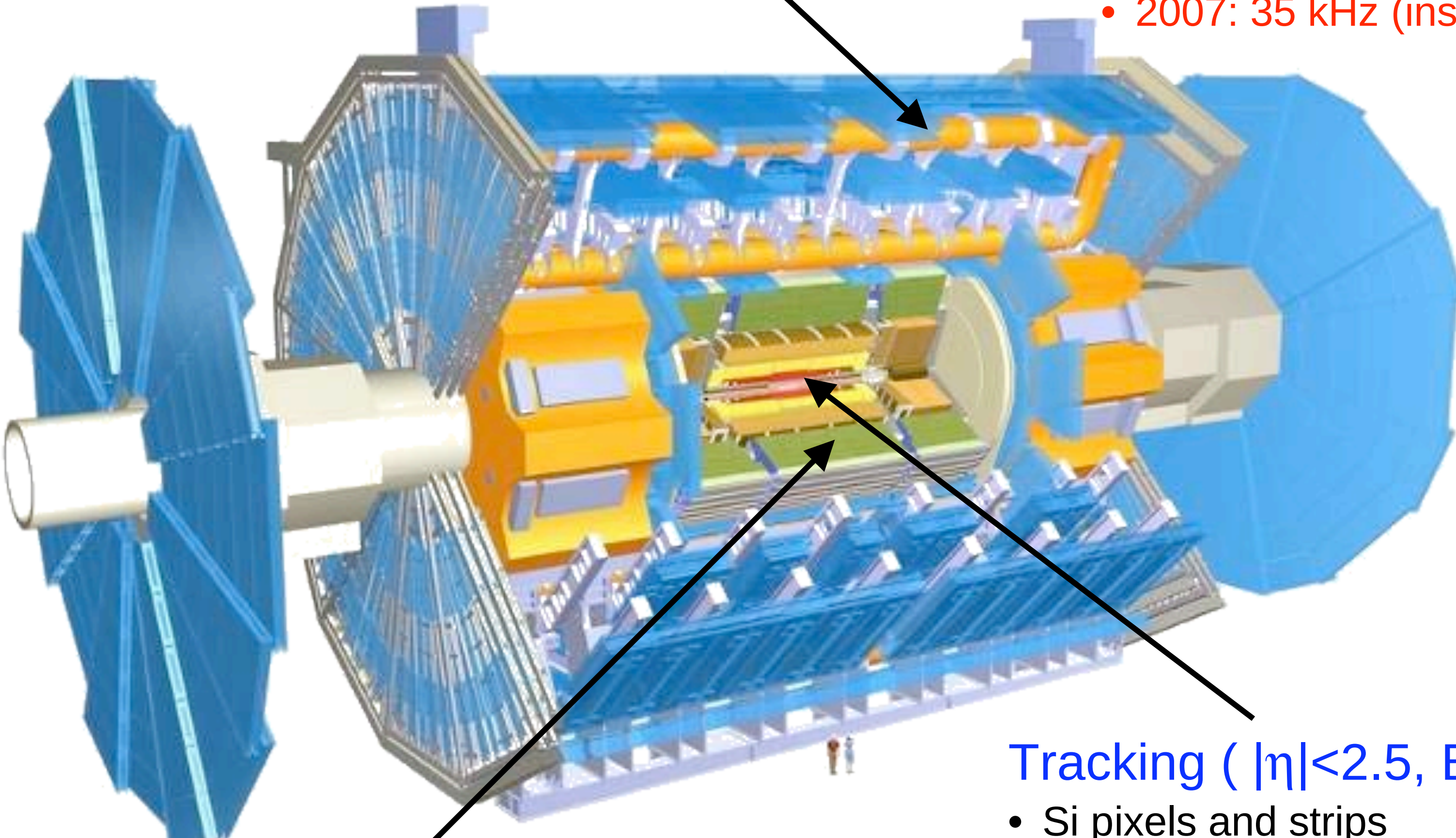
ATLAS in 2007

Muon Spectrometer (|η|<2.7)

- air-core toroids with muon chambers

Level-1 Trigger Output

- 2007: 35 kHz (instead of 75)



Tracking (|η|<2.5, B=2T)

- Si pixels and strips
- TRD (e/π separation)
- 2007: TRT |η| < 2 (instead of 2.4) & 2 pixel layers/disks instead of 3

Calorimetry (|η|<5)

- EM : Pb-LAr
- HAD : Fe/scintillator (central), Cu/W-Lar (fwd)

ATLAS in 2005

Assembly of 8th barrel toroid by end of this month,
In Sept: Start to install Barrel & Endcap Calorimeters, Inner Detector Services

CMS in 2007

Superconducting Coil, 4 Tesla

CALORIMETERS

ECAL

76k scintillating PbWO4 crystals

HCAL

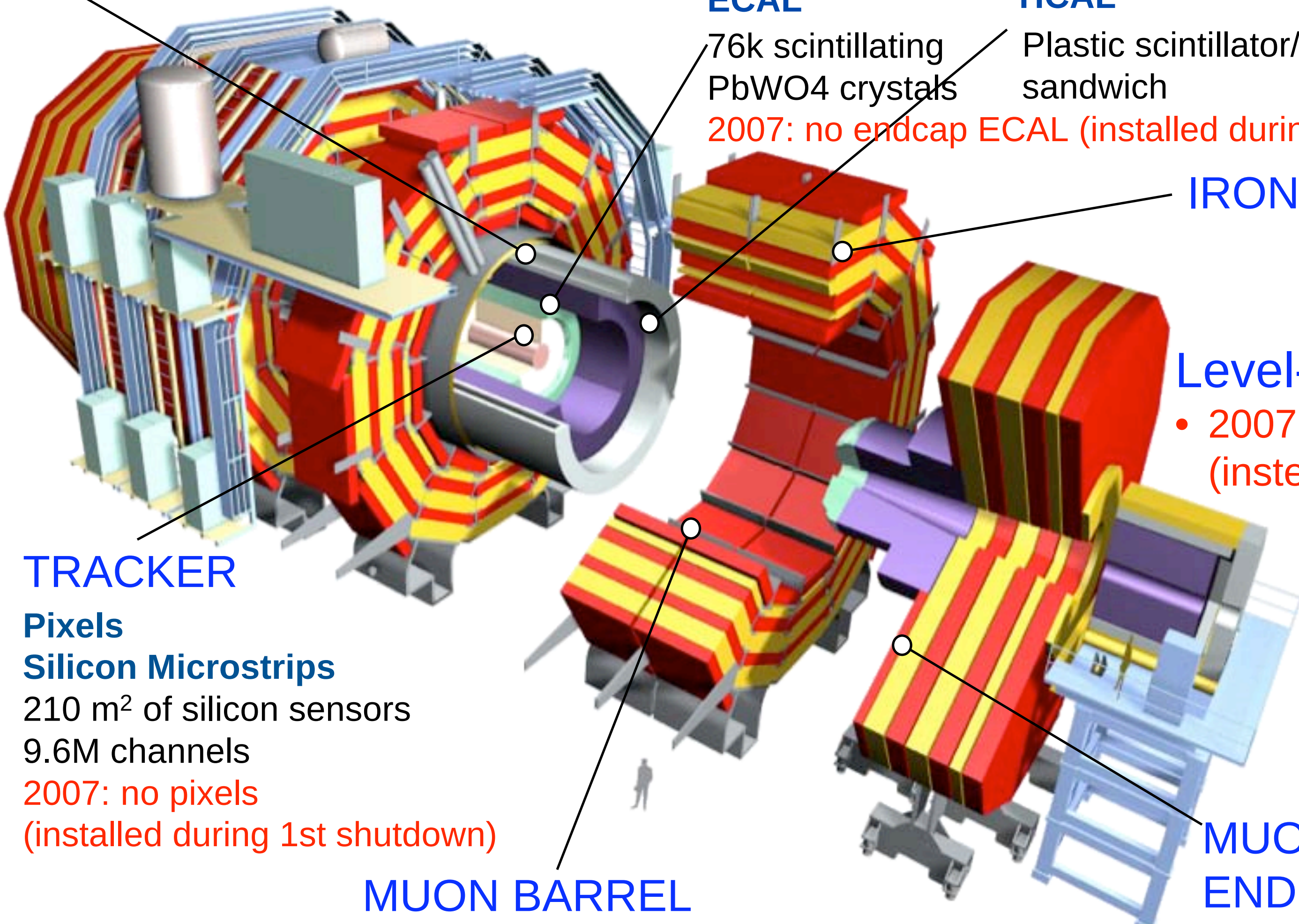
Plastic scintillator/brass sandwich

2007: no endcap ECAL (installed during 1st shutdown)

IRON YOKE

Level-1 Trigger Output

- 2007: 50 kHz (instead of 100)



TRACKER

Pixels

Silicon Microstrips

210 m^2 of silicon sensors

9.6M channels

2007: no pixels (installed during 1st shutdown)

2007:
RPC $|\eta| < 1.6$ instead of 2.1
& 4th endcap layer missing

MUON BARREL

Drift Tube Chambers (DT)

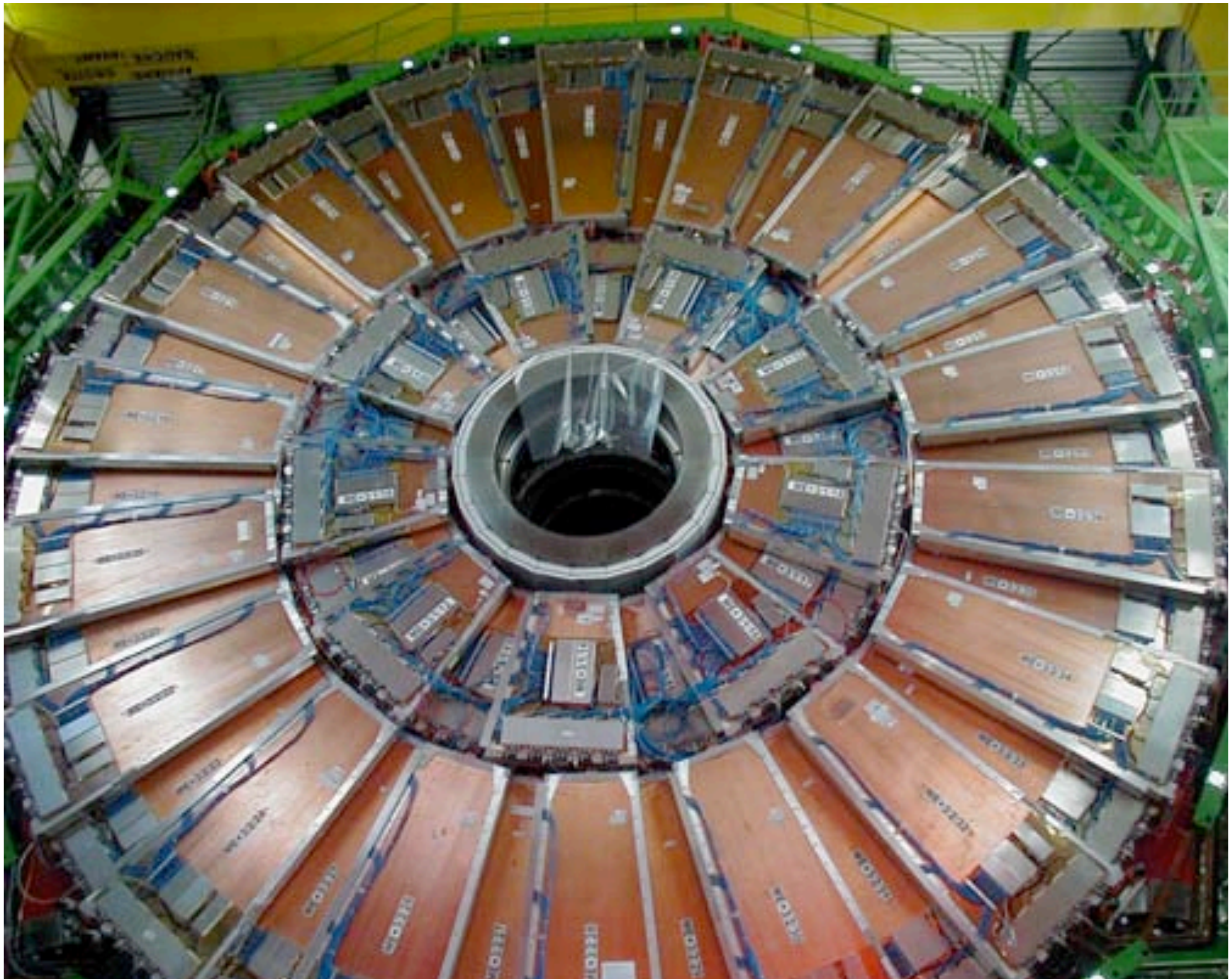
Resistive Plate Chambers (RPC)

MUON ENDCAPS

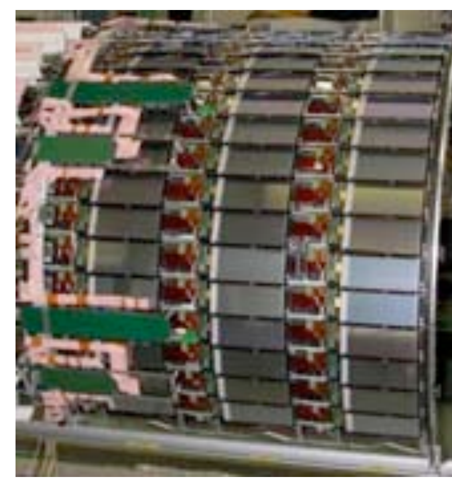
Cathode Strip Chambers (CSC)

Resistive Plate Chambers (RPC)

CMS in 2005



Tracker Modules



Cathode Strip Chambers on Endcap Muon Disks (in service bldg.)

LHC Startup

Stage 1
Initial commissioning
43x43→156x156, 3×10^{10}/bunch
$L = 3 \times 10^{28} - 2 \times 10^{31}$

Starts in 2007

Shutdown

Stage 2
75 ns operation
936x936, $3\text{-}4 \times 10^{10}$/bunch
$L = 10^{32} - 4 \times 10^{32}$

Stage 3
25 ns operation
2808x2808, $3\text{-}5 \times 10^{10}$/bunch
$L = 7 \times 10^{32} - 2 \times 10^{33}$

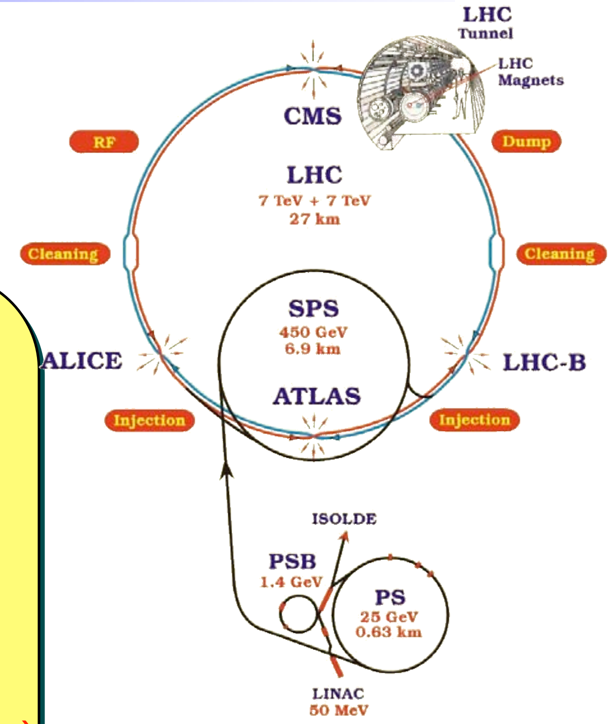
Year one (+) operation
Lower intensity/luminosity:
- Event pileup
- Electron cloud effects
- Phase 1 collimators
- Equipment restrictions
- Partial Beam Dump

75 ns. bunch spacing (pileup)
Relaxed squeeze

Long Shutdown

Stage 4
25 ns operation
Push to nominal per bunch
$L = 10^{34}$

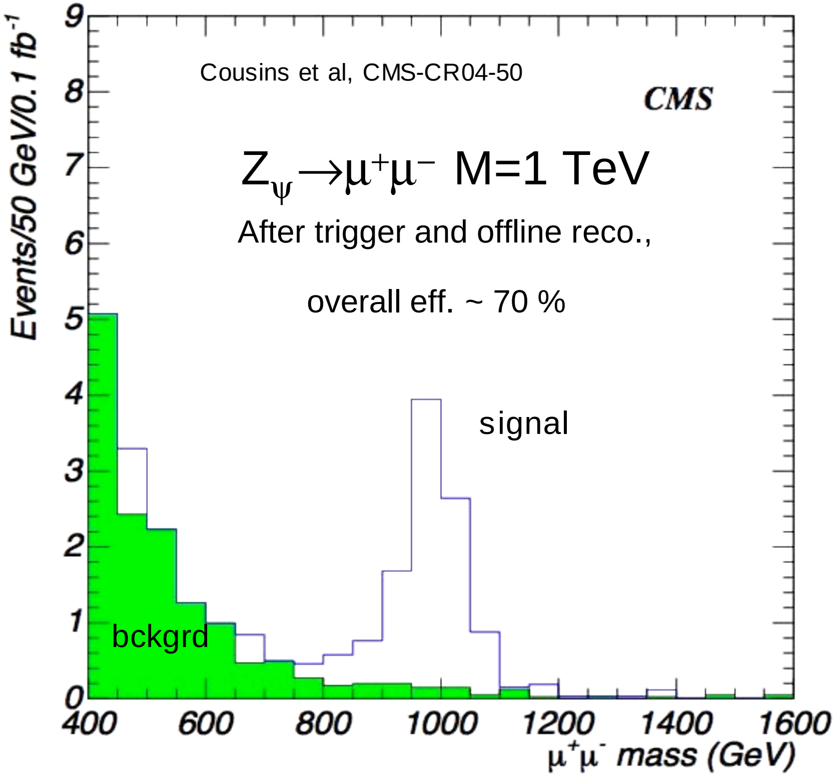
Phase 2 collimation
Full Beam Dump
Scrubbed
Full Squeeze



LHC start: New resonance → leptons (with 10 fb^{-1})

Z' : e.g. any new heavy gauge boson

- GUT, dynamical EWSB, little Higgs, ...
- Clear signature, low background

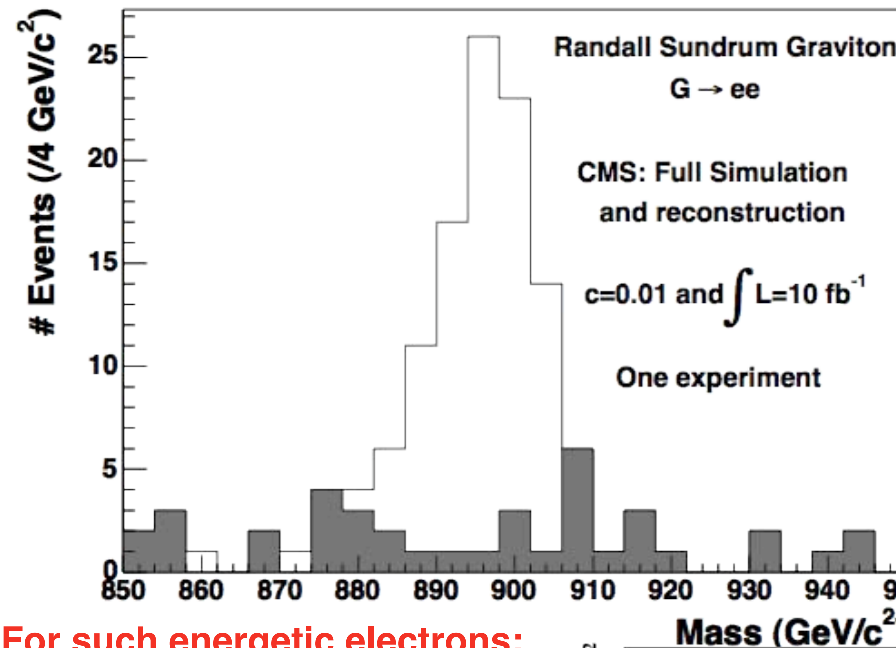


Similar ATLAS study for Z' → e$^+$e$^-$

- In SSM, SM-like couplings
- ~1.5 fb^{-1} needed for discovery up to 2 TeV
- Z → $\ell\ell$ +jet and DY needed to get energy calibration & understand lepton efficiency

Models with compact extra dimensions

- Randall-Sundrum model
- Massive Kaluza-Klein excitations eg. Gravitons

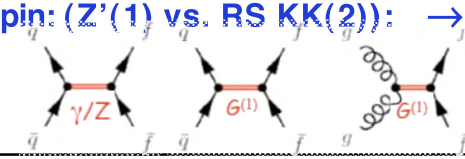


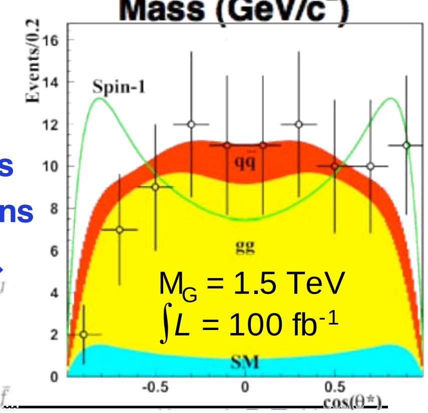
For such energetic electrons:

- Correct for ECAL saturation

Later: distinguish btw. models

- Forward-backward asymmetries
- Other hints for ED: E_{miss}, photons
- Spin: (Z'(1) vs. RS KK(2)): →

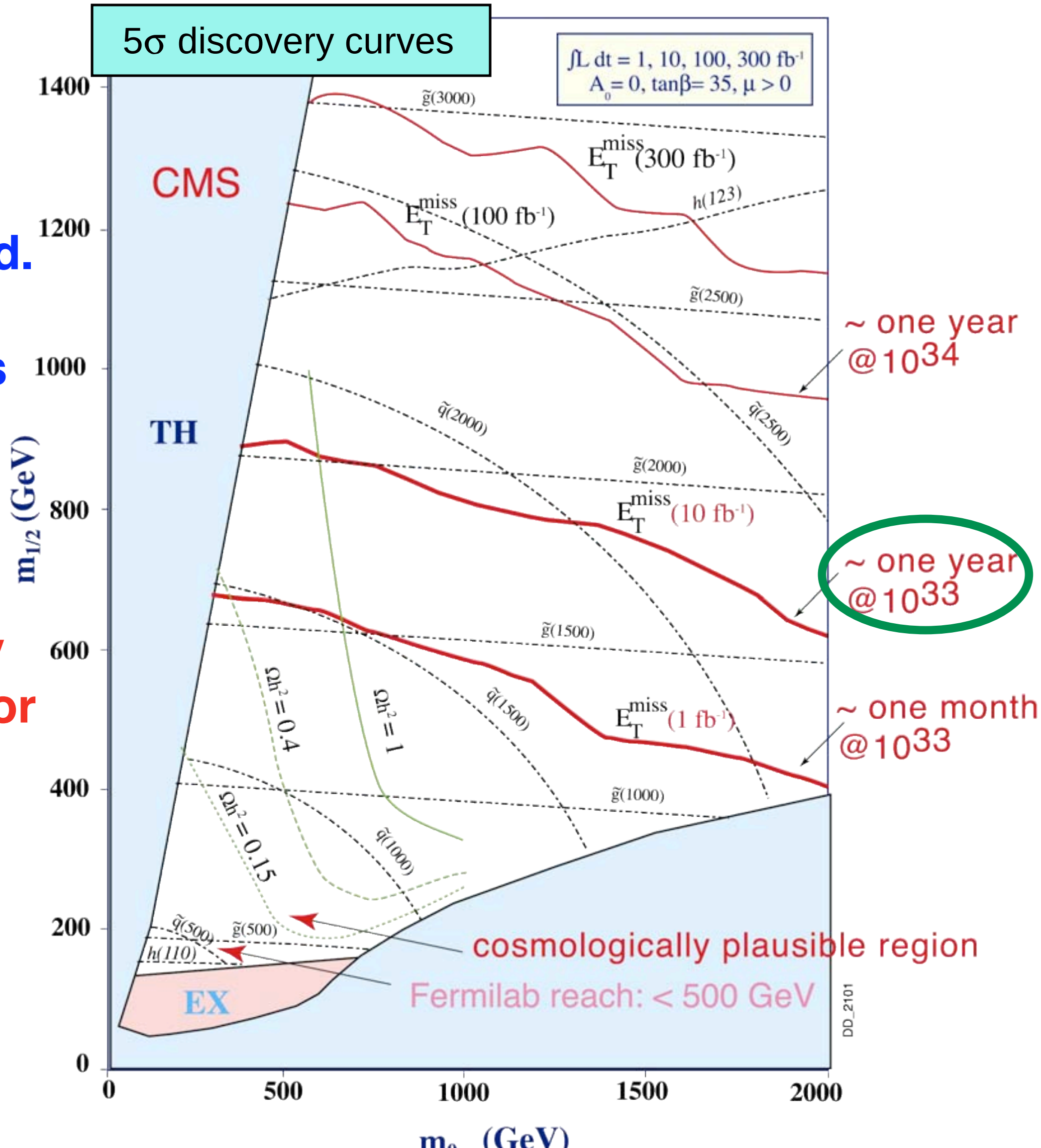




LHC Start: Search for SUSY

Large squark/ gluino pair prod. cross sections

~100 evts/day at 10^{33} for squark, gluino masses ~1 TeV.

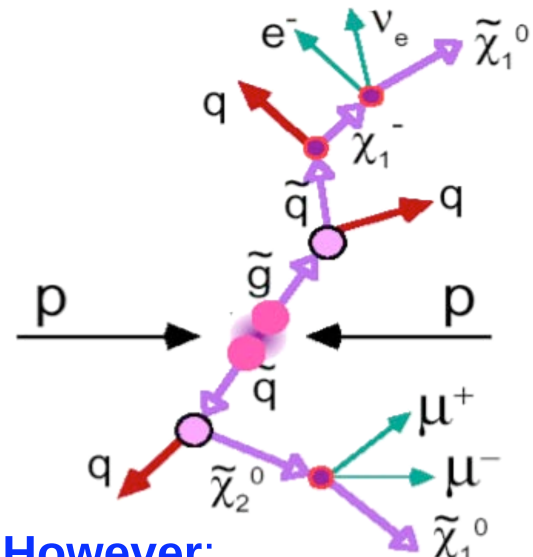


Spectacular signatures

Use multi-jet, multi-leptons & E_t^{miss} for discrimination.

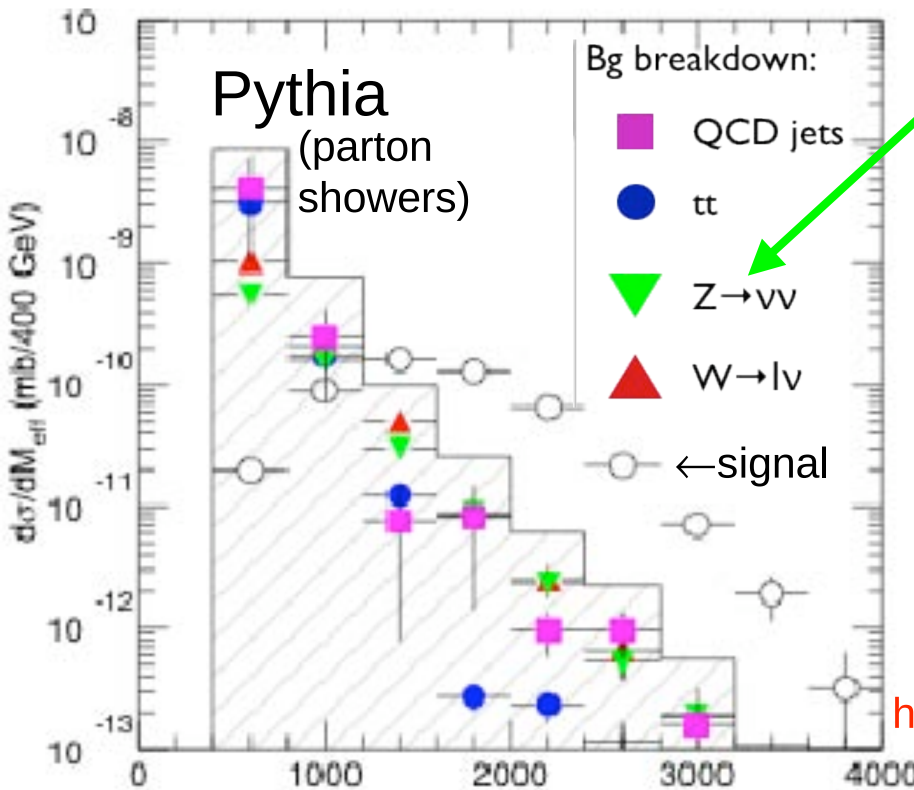
eg. $M_{\mathrm{eff}} = E_{\mathrm{T}}^{\mathrm{miss}} + \sum_{\mathrm{jets}} p_{\mathrm{T}}(\mathrm{j})$

peak in Meff correlated with $M_{SUSY} = \min(m_{squark}, m_{gluino})$

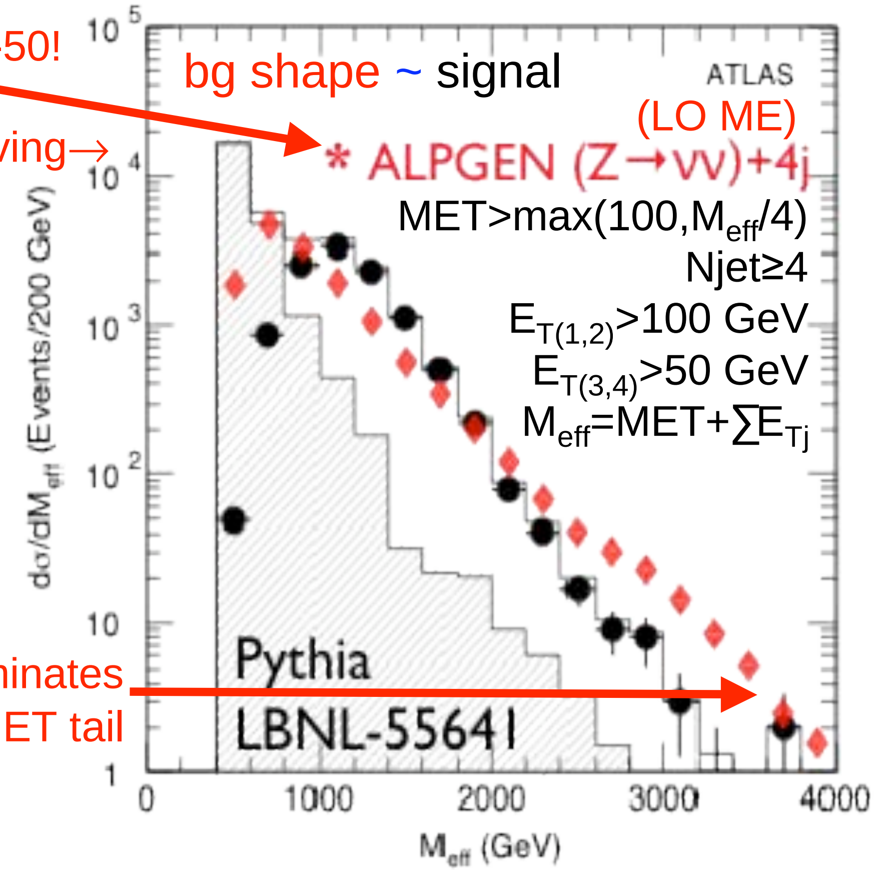


However:
Detector & Physics backgrounds are a major problem ⇒

SUSY Bkgd. Uncertainties



x 10-50!
evolving→
*dominates high MET tail



Calculations are improving/evolving but not at end of story (LO: scales)

Will need to use data control samples & matching MC to estimate backgrounds:

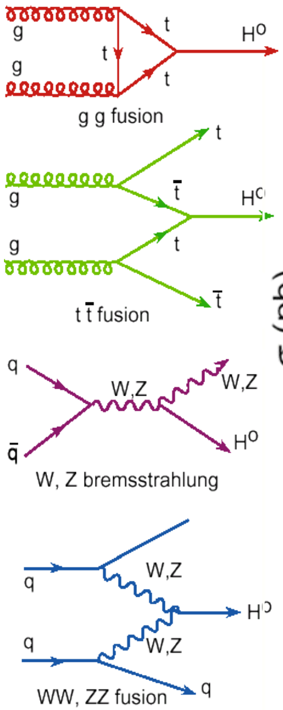
(optimize cuts to remove fake MET)

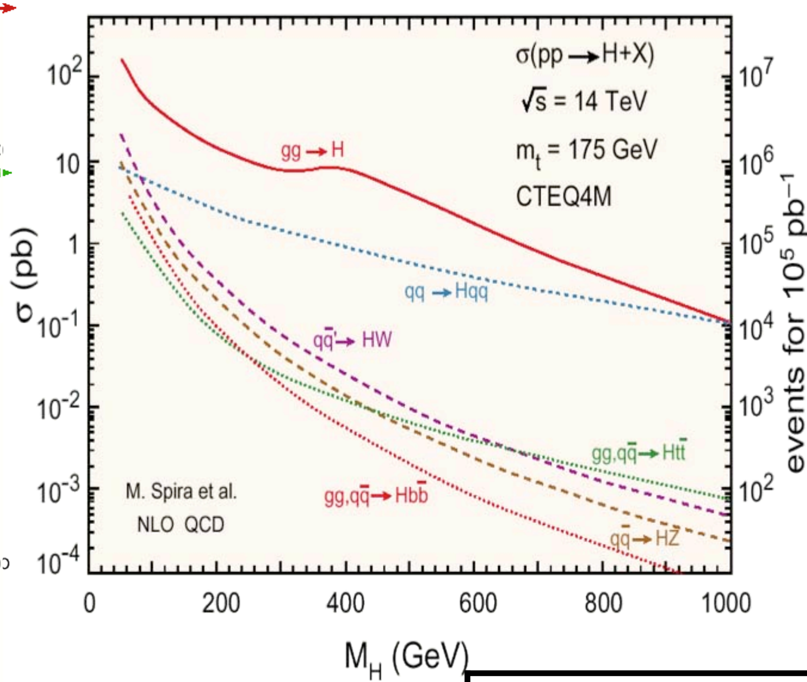
Then there are the classic detector MET problems…much work involved!

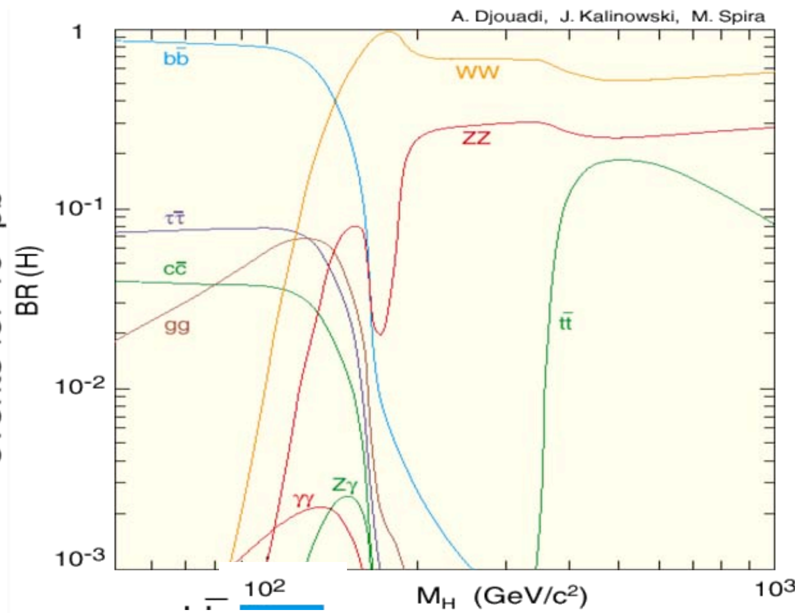
Background process	Control samples
Z (→ νν) + jets	Z (→ ee, μμ) + jets
W (→ τν) + jets	W (→ eν, μν) + jets
tt→ blνbjj	tt→ blν blν
QCD multijets	lower E_T sample →

match MC at low MET, use for bkgd. at high MET

LHC Start: Higgs Production/Decay







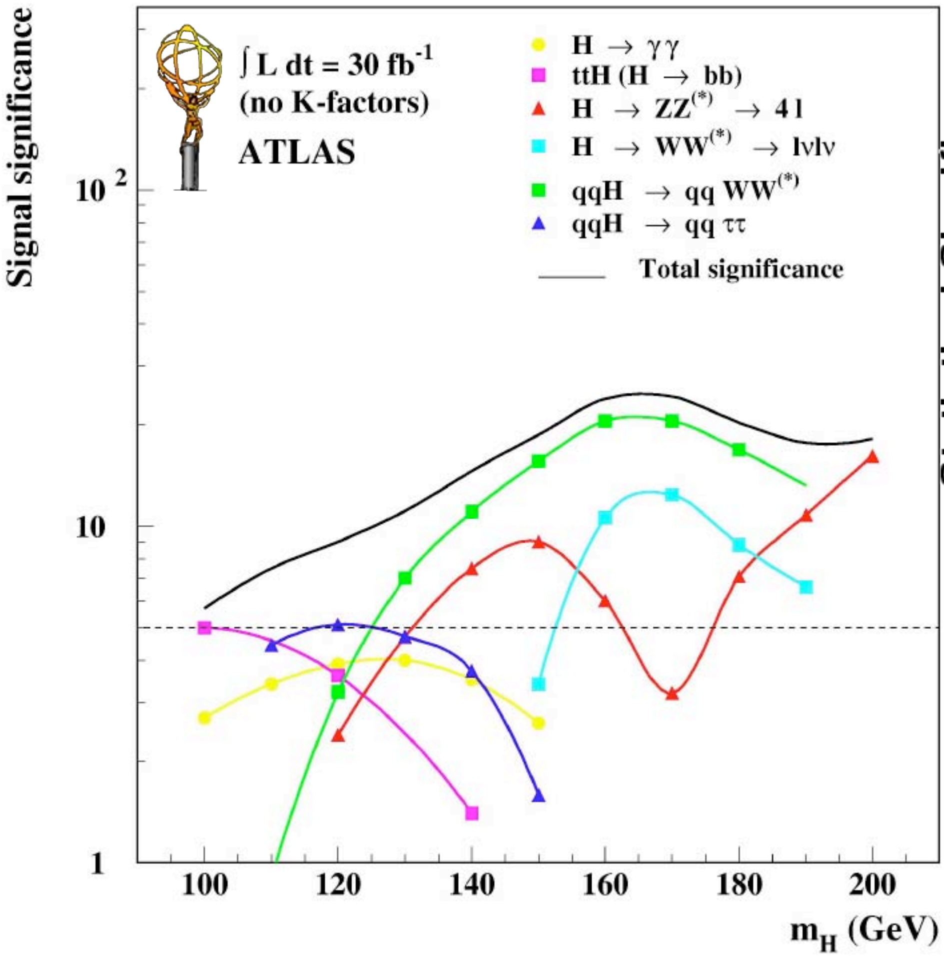
Low-mass search :

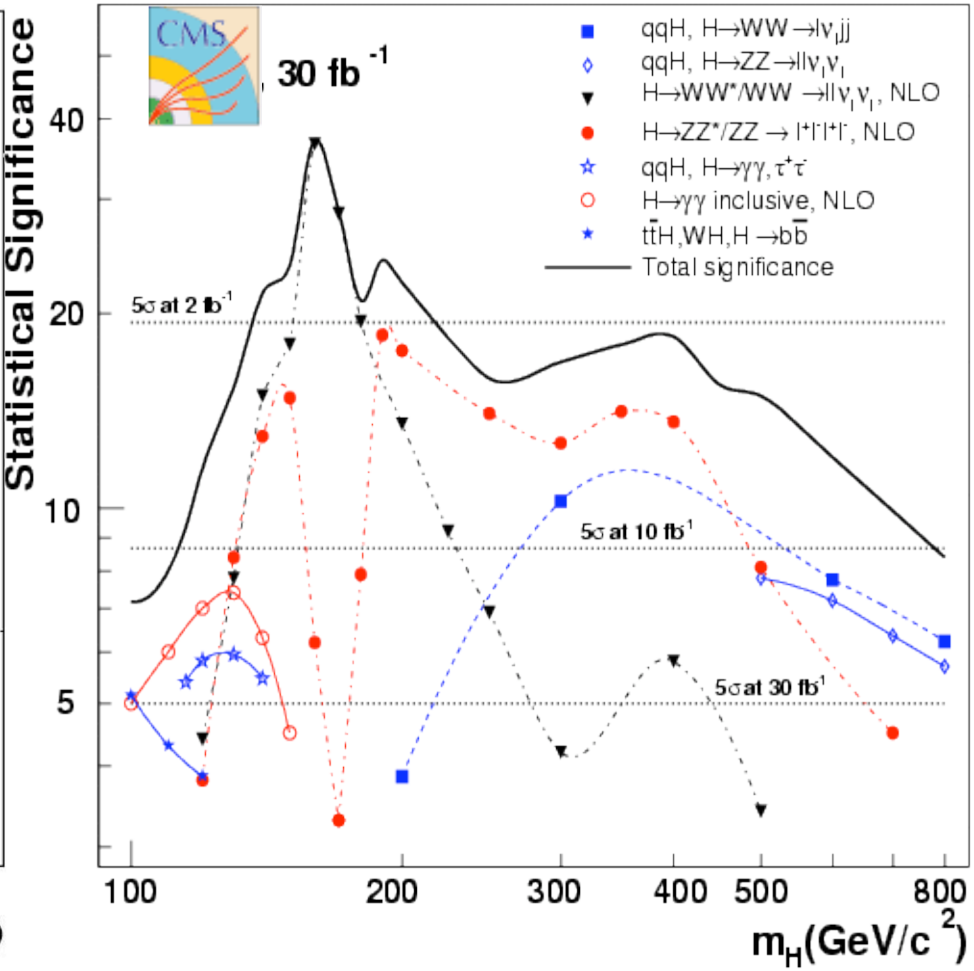
H → γγ and H → ZZ* → 4ℓ only channels with a mass peak, very good mass resol. ~1%.

H → WW* → 2ℓ 2ν (140 – 180 GeV) high rate, no mass peak, good understanding of SM bkg. needed

↓ Decay / Production →	Inclusive	VBF	WH/ZH	ttH
$H \rightarrow \gamma\gamma$	YES	YES	YES	YES
$H \rightarrow bb$			YES	YES
$H \rightarrow \tau\tau$		YES		
$H \rightarrow WW^*$	YES	YES	YES	YES
$H \rightarrow ZZ^*$, $Z \rightarrow \ell^+\ell^-$, ℓ=e,μ	YES			

LHC start: Higgs Search





Almost all allowed mass range explored with 10 fb^{-1} for ATLAS-CMS

With 30 fb^{-1}, more than 7 σ for the whole range

Mature LHC Program

If Higgs observed:

- Measure parameters (mass, couplings), need up to 300 fb^{-1}
- Self-coupling not accessible with LHC alone*

If we think we observe SUSY:

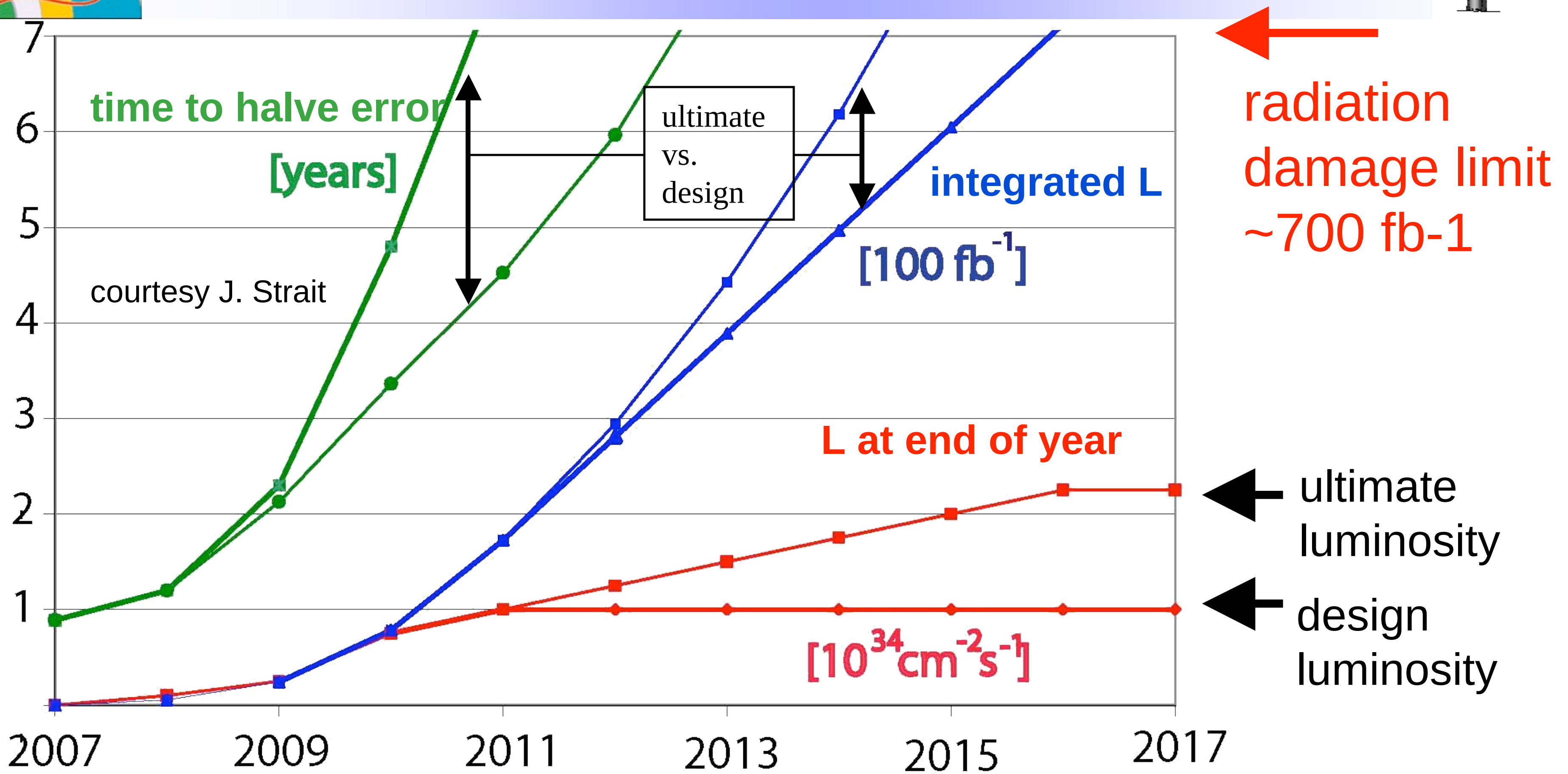
- Try to measure mass (study cascades, end-points, …)
- Try to determine the model: MSSM, NMSSM, …
- Establish connection to cosmology (dark matter candidate?)
- Understand impact on Higgs phenomenology
- Try to determine the SUSY breaking mechanism
- Difficult/impossible with LHC alone*:
  - sleptons > 350 GeV, full gaugino mass spectrum, sparticle spin-parity & all couplings, disentangle squarks of first two generations

If neither or something else:

- Strong $W_L W_L$ scattering? Other EWSB mechanisms?
- Extra dimensions, Little Higgs, Technicolor ?
- Do we have to accept fine-tuning (*e.g.* Split Supersymmetry) ?

What's next to follow up on this*: LHC upgrade & ILC

Time Scale of LHC Upgrade



(1) ***LHC IR quads life expectancy*** estimated <10 years from radiation dose

(2) the ***statistical error halving time*** will exceed 5 years by 2011-2012

(3) therefore, it is reasonable to plan a ***machine luminosity upgrade based on new low-β IR magnets before ~2014***

LHC performance limitations

— Ruggeriero & Zimmerman, CERN

Beam dumping system limits total current; upgrade may be necessary

- Compatible with ultimate intensity of 1.7×10^{11}/bunch, increases to 2.0×10^{11}/bunch could be tolerated with reduced safety margin or after moderate upgrade

Detector architecture

- Limits luminosity; detector upgrade in parallel with accelerator upgrade, which could allow moving low-β quads closer to the IP
- In their present configurations, the CMS and ATLAS detectors can accept a maximum luminosity of 3–5×10^{34} $cm^{-2}s^{-1}$

Collimation & machine protection: limits total current & β^*

- Machine protection is challenging: beam transverse energy density is 1000 times that of the Tevatron; simple graphite collimators may limit maximum transverse energy density to half the nominal value in order to prevent collimator damage; closing collimators to 6σ yields an impedance at the edge of instability; a local fast loss of 2.2×10^{-6} of the beam intensity quenches nearby arc magnets

Electron cloud: may constrain minimum bunch spacing

- Additional heat load on beam screen; its value depends on beam & surface parameters; at 75-ns spacing no problem anticipated; initial bunch populations at 25-ns spacing will be limited to half nominal value

Beam-beam: limits N_b/ε & crossing angle; compensation schemes may help

LHC Upgrade Scenarios – I

LHC phase 0: maximum performance w/o hardware changes

LHC phase 1: maximum performance with arcs unchanged

LHC phase 2: maximum performance with 'major' changes

Nominal LHC: 7 TeV w/ L=10^{34} $cm^{-2}s^{-1}$ in IP1 & IP5 (ATLAS & CMS)

Phase 0:

1. collide beams only in IP1&5 with alternating H-V crossing
2. increase N_b up to beam-beam limit → L=2.3x10^{34} $cm^{-2}s^{-1}$
3. increase dipole field to 9T (ultimate field) → E_{max}=7.54 TeV

Phase1: changes only in LHC insertions and/or injector complex include:

1. modify insertion quadrupoles and/or layout → β^*=0.25 m
2. increase crossing angle by ~1.4
3. increase N_b up to ultimate intensity → L=3.3x10^{34} $cm^{-2}s^{-1}$
4. halve σ_z with high harmonic system → L=4.6x10^{34} $cm^{-2}s^{-1}$
5. double number of bunches (and increase θ_c!)
   → L=9.2x10^{34} $cm^{-2}s^{-1}$ (excluded by e-cloud?)

LHC Upgrade Scenarios – II

phase 2: luminosity & energy upgrade:

- modify injectors to significantly increase beam intensity and brilliance beyond ultimate value (possibly together with beam-beam compensation schemes)
- equip SPS with s.c. magnets, upgrade transfer lines, and inject at 1 TeV into LHC
- install new dipoles with 15-T field and a safety margin of 2 T, which are considered a reasonable target for 2015 and could be operated by 2020

→ beam energy around 12.5 TeV

For the rest of this talk, just consider phase 1 (SLHC)

Baseline (S)LHC Parameters

parameter	symbol	nominal LHC	ultimate LHC	shorter bunches	
#bunches	n_b	2808	2808	5616	
protons/bunch	N_b [10^{11}]	1.15	1.7	1.7	
bunch spacing	Δt_{sep} [ns]	25	25	12.5	←25 ns → 12.5 ns
average current	I [A]	0.58	0.86	1.72	
norm. transv. emittance	ε_n [μm]	3.75	3.75	3.75	
longit. profile		Gaussian	Gaussian	Gaussian	
rms b. length	σ_z [cm]	7.55	7.55	3.78	
beta at IP1&IP5	β^* [m]	0.55	0.5	0.25	
crossing angle	θ_c [μrad]	285	315	445	
Piwinski parameter	$\theta_c\sigma_z/(\sigma^*$ 2)	0.64	0.75	0.75	
luminosity	L [10^{34} cm^{-2}s^{-1}]	1.0	2.3	9.2	←10^{34} → 10^{35}
events/ crossing		19	44	88	← pileup x 5
length luminous region (rms)	σ_{lum} [mm]	44.9	42.8	21.8	

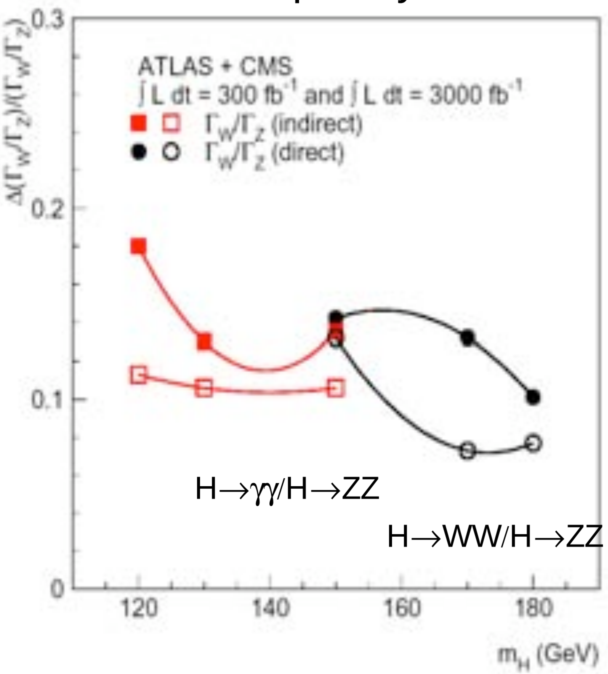
←SLHC

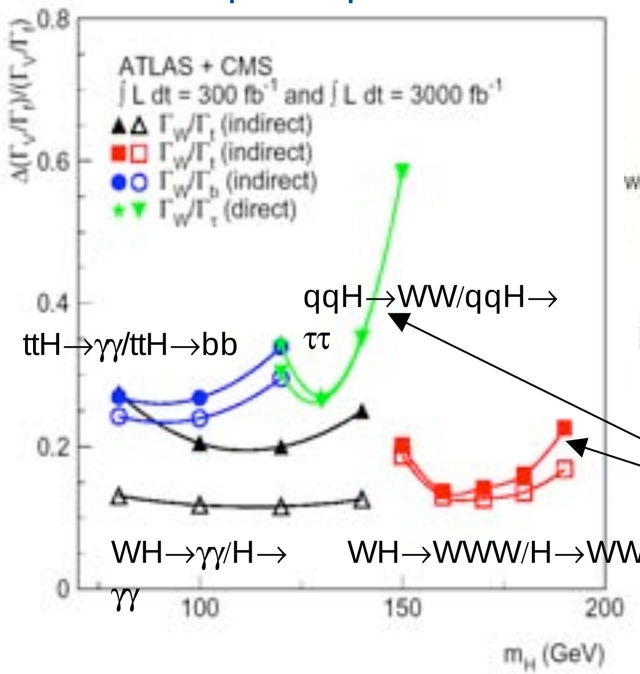
LHC,SLHC: SM Higgs Couplings

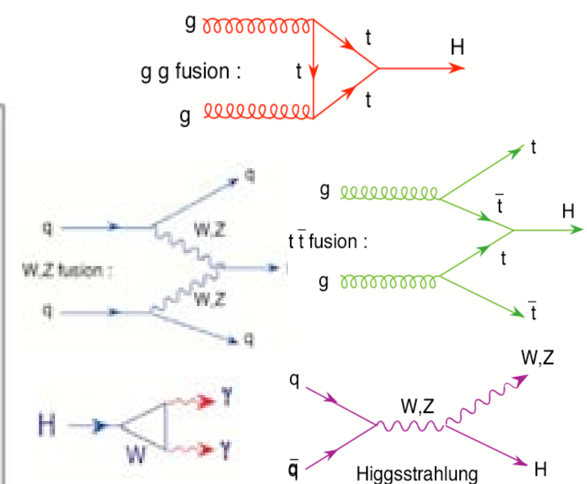
Combine different production & decay modes
$\rightarrow$ ratios of Higgs couplings to bosons & fermions

- Independent of uncertainties on σ^{tot}_{Higgs}, Γ_{H}, $\int L dt$ $\rightarrow$ stat. limited
- Benefit from LHC $\rightarrow$ SLHC (assuming similar detector capabilities)

full symbols: LHC, 300 fb^{-1} per experiment
open symbols: SLHC, 3000 fb^{-1} per experiment





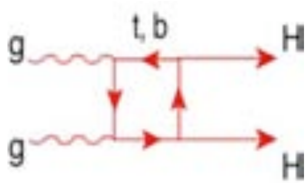


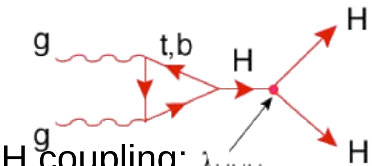
syst.- limited at LHC (σ_{th}), ~ no improvement at SLHC

➡ SLHC ratios of Higgs couplings should be measurable with a ~ 10% precision

Higgs pair prod. & self coupling

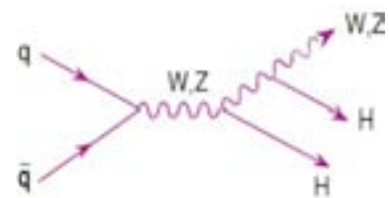
Higgs pair production through two Higgs bosons radiated independently (from VB, top) & from trilinear self-coupling terms proportional to λ_{HHH}^{SM}

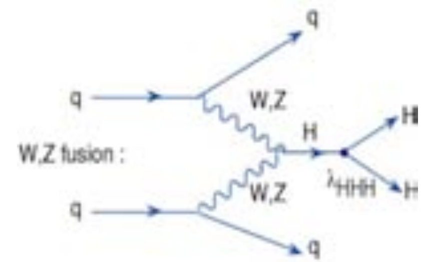




triple H coupling: λ_{HHH}

$\lambda_{HHH}^{SM} = 3m_H^2/v$





+…

.

$\sigma(pp \rightarrow HH)$ < 40 fb, M_H >110 GeV

Small BR for clean final states →no sensitivity at LHC (10^{34}),

but some hope at SLHC:

channel investigated:

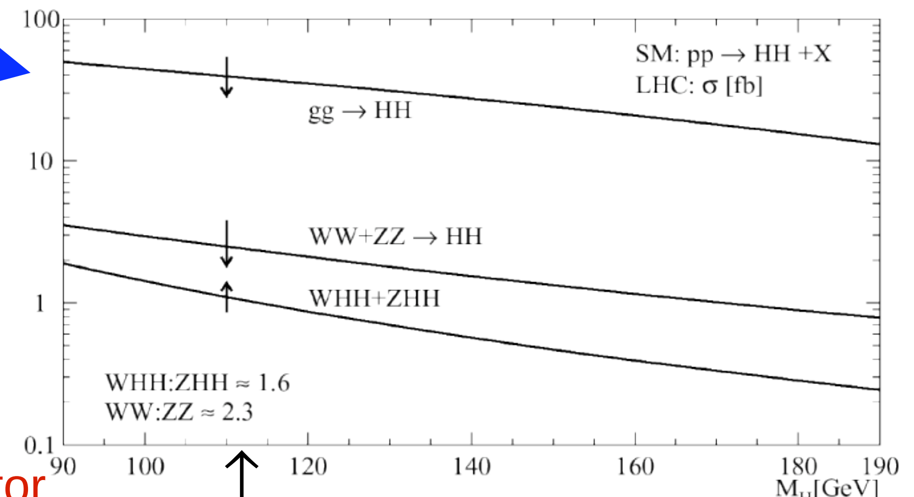
170 < m_H < 200 GeV (ATLAS):

$gg \rightarrow HH \rightarrow W^+ W^- W^+ W^- \rightarrow l^\pm \nu jj \; l^\pm \nu jj$

with same-sign dileptons - difficult!

May be possible to determine total cross section & λ_{HHH} with ~ 25% statistical error for 6000 fb^{-1} (optimistic?) for similar detector performance as present LHC detectors.

cross sections for Higgs boson pair production in various production mechanisms and sensitivity to λ_{HHH} variations



arrows correspond to variations of λ_{HHH} from 1/2 to 3/2 of its SM value

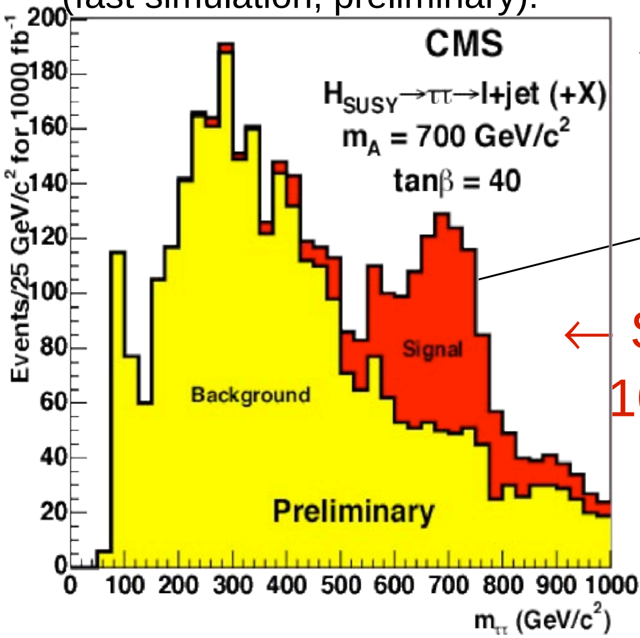
SLHC: improved reach for heavy MSSM Higgs bosons

Order of magnitude increase in statistics with SLHC should allow

Extension of discovery domain for massive MSSM Higgs bosons A,H,$H^{\pm}$

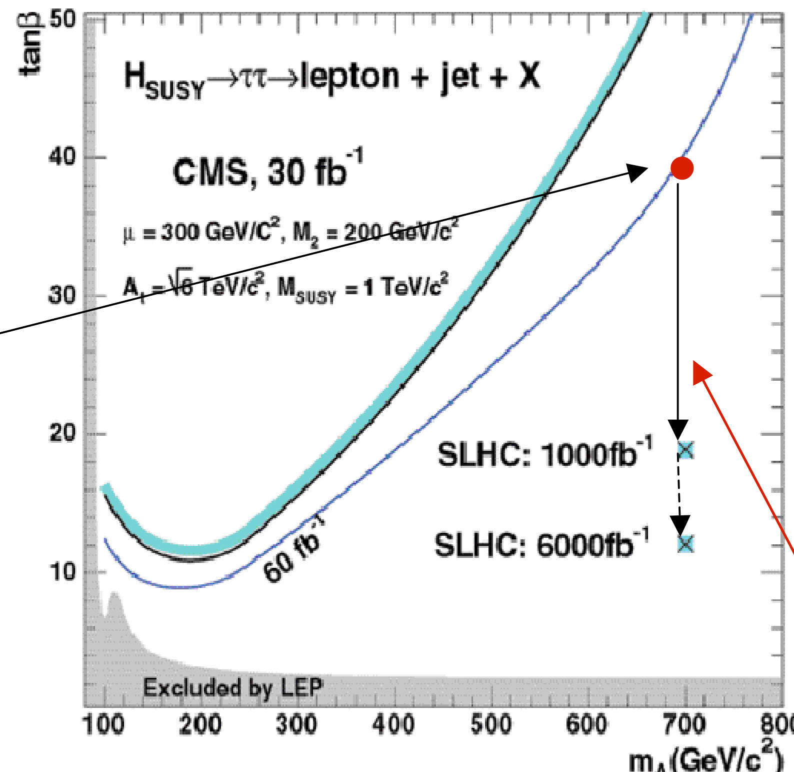
e.g.: A/H $\rightarrow \tau\tau \rightarrow$ lepton + τ-jet, produced in bbA/H

Peak at 5σ limit of observability at LHC greatly improves at SLHC, (fast simulation, preliminary):



S. Lehti

← SLHC $1000\ fb^{-1}$



←LHC $60\ fb^{-1}$

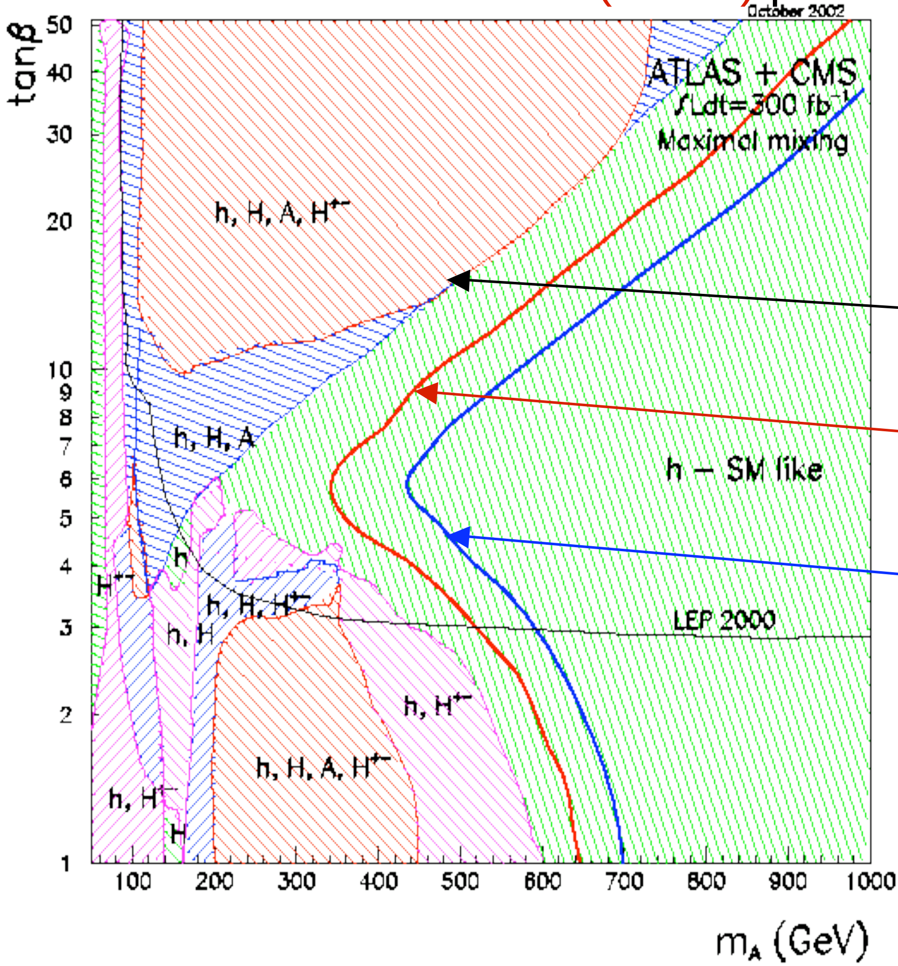
←SLHC $1000\ fb^{-1}$

gain in reach

b-tagging performance comparable to present LHC detectors required

SLHC: improved reach for MSSM Higgs bosons

MSSM parameter space regions for > 5σ discovery for the various Higgs bosons, 300 fb^{-1} (LHC), and expected improvement - at least two discoverable Higgs bosons - with 3000 fb^{-1} (SLHC) per experiment, ATLAS & CMS combined.



green area: region where only one (the h, ~ SM-like) among the 5 MSSM Higgs bosons can be found (assuming only SM decay modes)

LHC contour, 300 fb^{-1}/exp

SLHC contour, 3000 fb^{-1}/exp at least one heavy Higgs <u>discoverable</u> up to here

SLHC contour, 3000 fb^{-1}/exp at least one heavy Higgs <u>Excludable</u> (95% CL) up to here

Heavy Higgs observable region increased by ~ 100 GeV

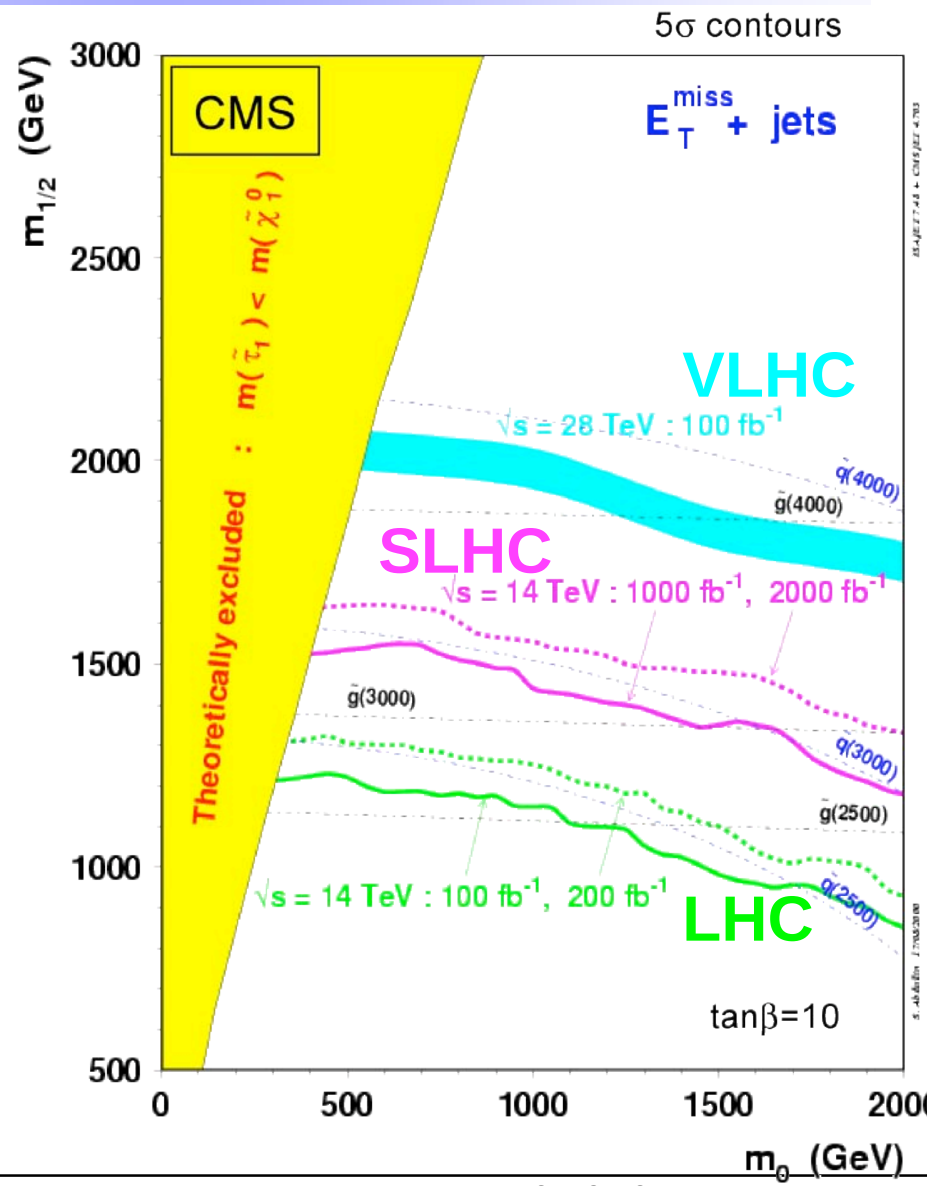
Supersymmetry at SLHC

Use high E_T jets, leptons & missing E_T

- Not hurt by increased pile-up at SLHC

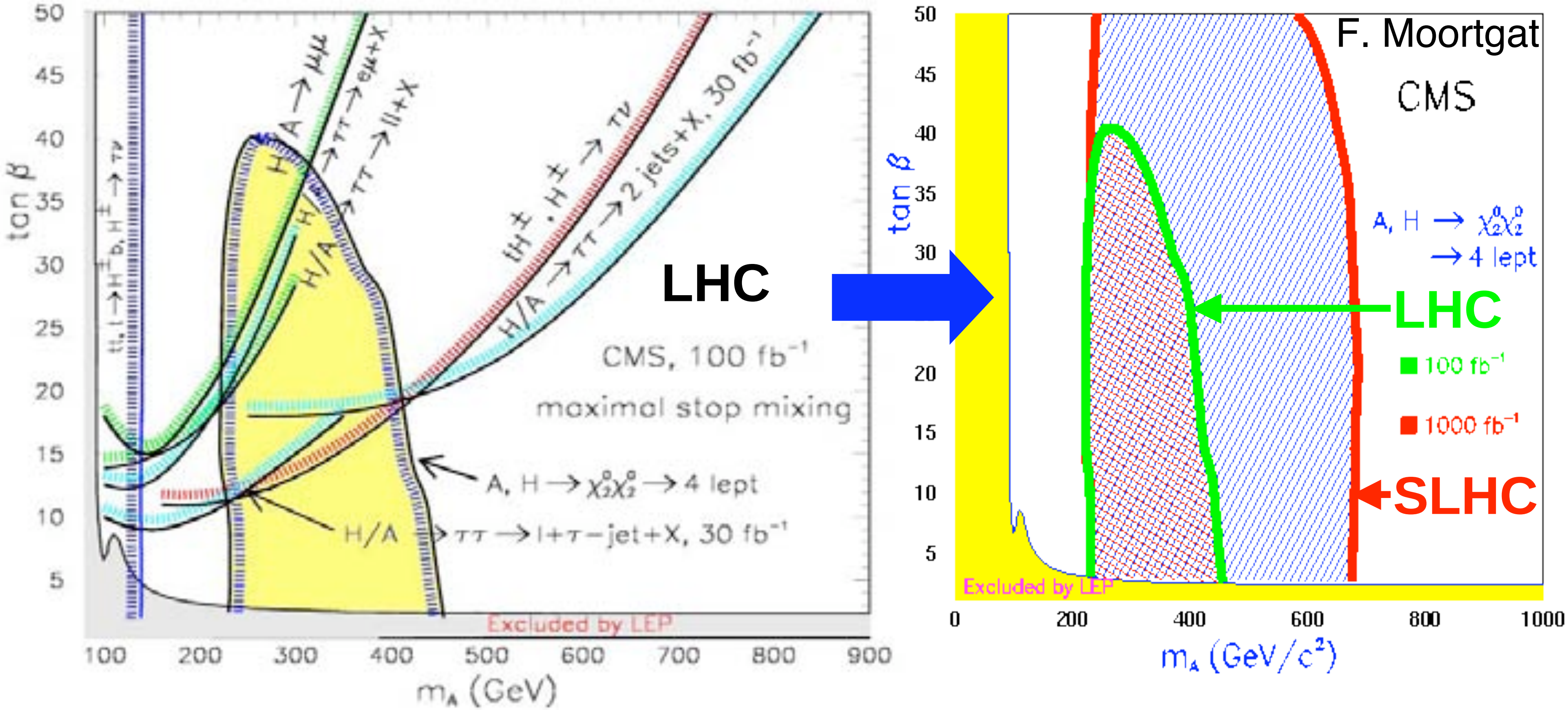
Extends discovery region by ~ 0.5 TeV

- ~ 2.5 TeV → 3 TeV
- (4 TeV for VLHC)
- Discovery means > 5σ excess of events over known (SM) backgrounds



Improved coverage of A/H decays to neutralinos, 4 isolated leptons

Use decays of H,A into SUSY particles, where kinematically allowed



$A/H \to \chi\chi \to 4$ iso. leptons

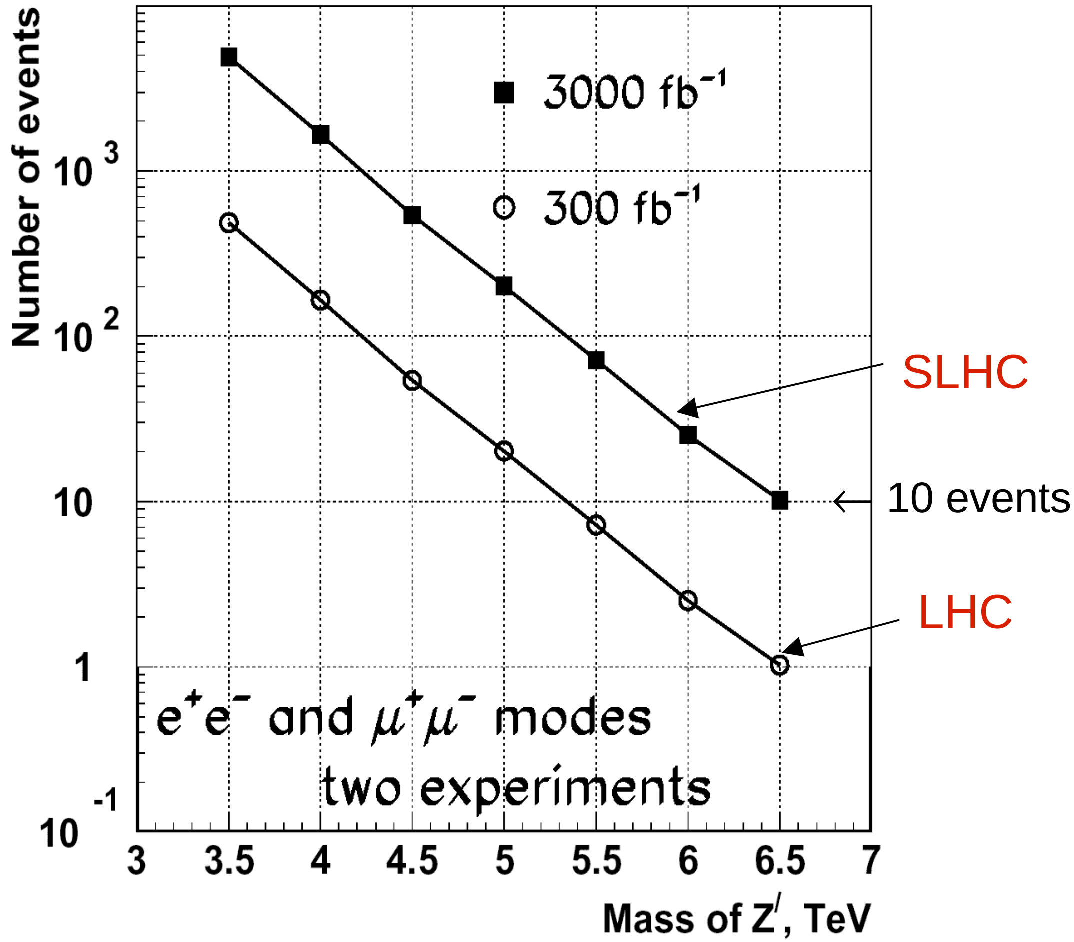
Strongly model/MSSM parameter dependent:
M_2 = 120 GeV, μ= -500 GeV,
$M_{sleptons}$ = 2500 GeV, $M_{squark,\ gluino}$ = 1TeV

New gauge bosons: LHC & SLHC

sequential Z' model, Z' production (assuming same BR as for SM Z) and Z' width:

Z' mass (TeV)	1	2	3	4	5	6
$\sigma(Z' \to e^+e^-)(fb)$	512	23.9	2.5	0.38	0.08	0.026
$\Gamma_{Z'}$ (GeV)	30.6	62.4	94.2	126.1	158.0	190.0

Acceptance, e/μ reconstruction eff., resolution, effects of pile-up noise at 10^{35}, ECAL saturation included. (CMS study)



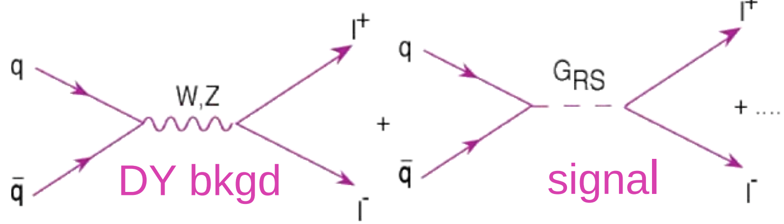
Assuming 10 events to claim discovery, reach at:

LHC (600 fb^{-1}) ≈ 5.3 TeV

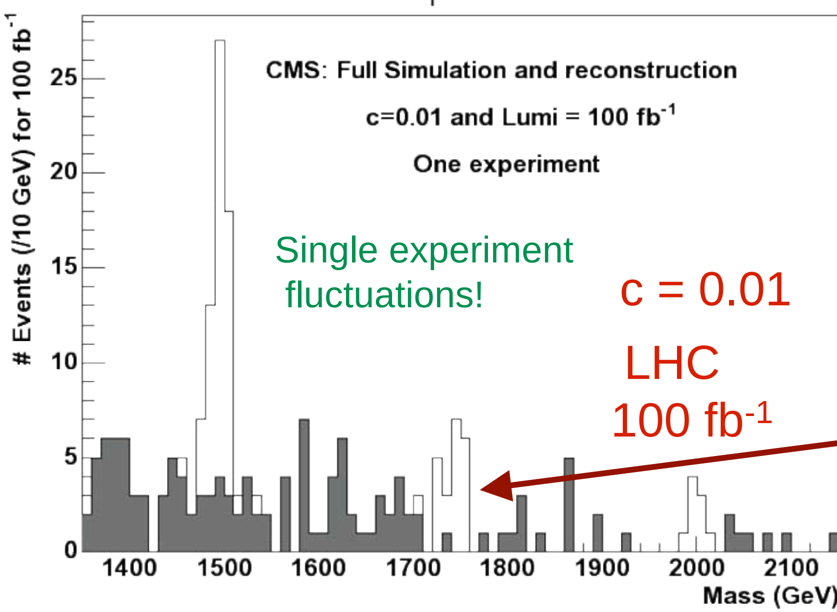
SLHC (6000 fb^{-1}) ≈ 6.5 TeV

LHC Extra Dimensions: Randall-Sundrum model

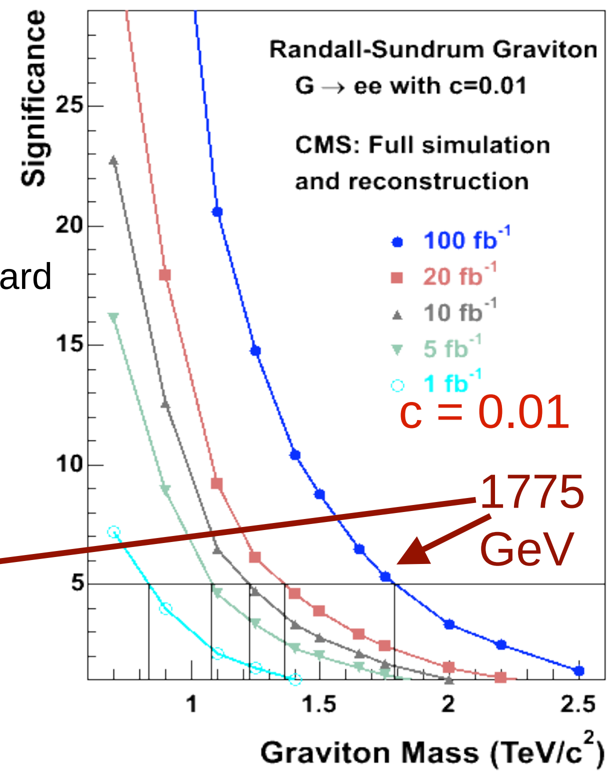
pp $\rightarrow$ G_{RS} $\rightarrow$ ee full simulation and reconstruction chain in CMS,
2 electron clusters, p_t > 100 GeV, $|\eta|$ < 1.44 and 1.56 < $|\eta|$ < 2.5, el. isolation, H/E < 0.1, corrected for saturation from ECAL electronics (big effect on high mass resonances!)



$$S = 2(\sqrt{N_S + N_B} - \sqrt{N_B}).$$



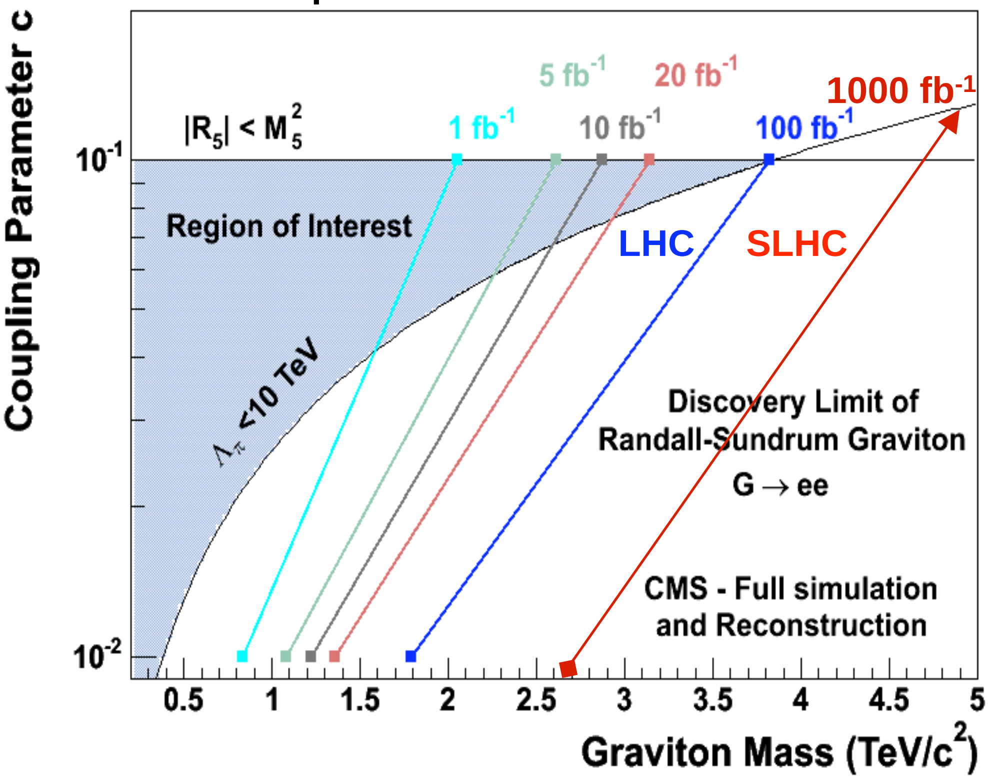
C. Collard



LHC: statistics limited. SLHC: ~ 10 increase in luminosity$\rightarrow$ mass reach - increased by 30% - & differentiate a Z' (spin = 1) from G_{RS} (spin = 2)

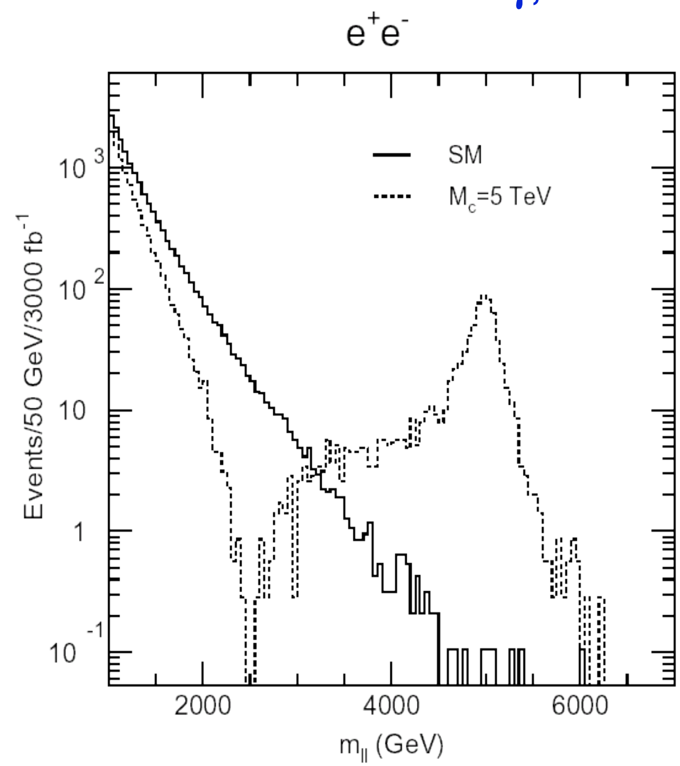
LHC, SLHC Gravitons

whole plane theoretically allowed,
shaded part favored:



TeV scale Extra Dimensions

- KK excitations of the γ,Z



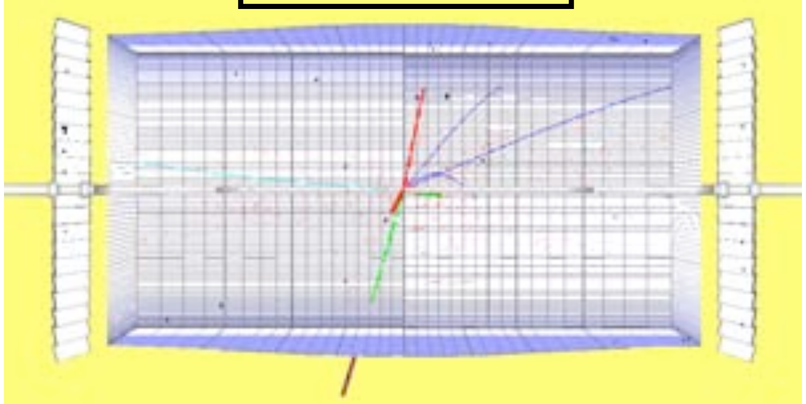
LHC→ SLHC: (100→1000 fb^{-1}):
Increase in reach by ~ 1 TeV

Direct:	LHC/600 fb^{-1}	6 TeV
	SLHC/6000 fb^{-1}	7.7 TeV
Interf:	SLHC/6000 fb^{-1}	20 TeV

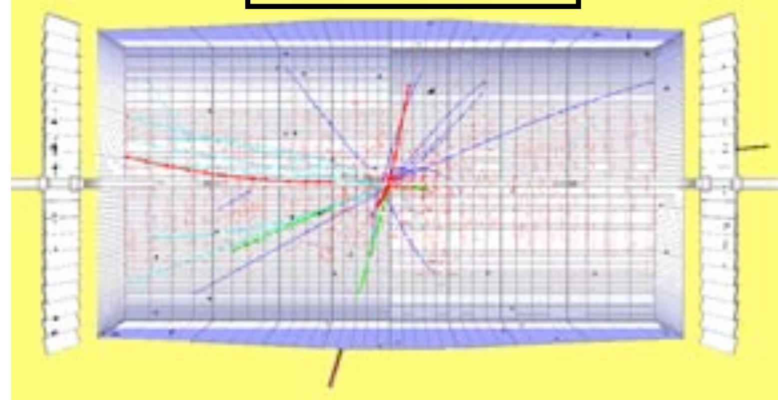
Detector Luminosity Effects

H→ZZ → μμee, M_H= 300 GeV for different luminosities in CMS

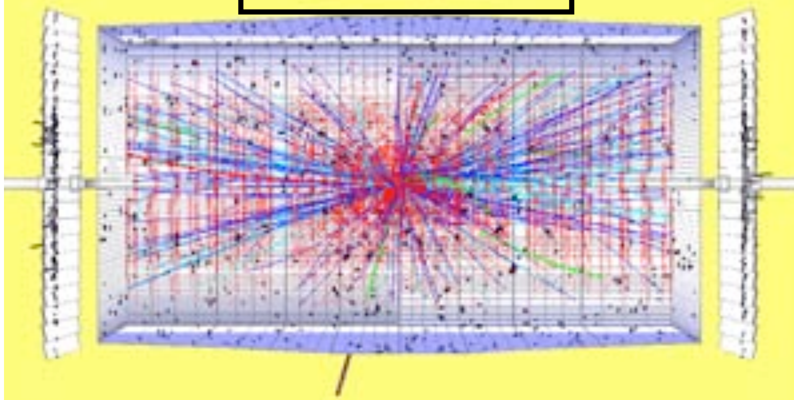
10^{32} cm^{-2}s^{-1}



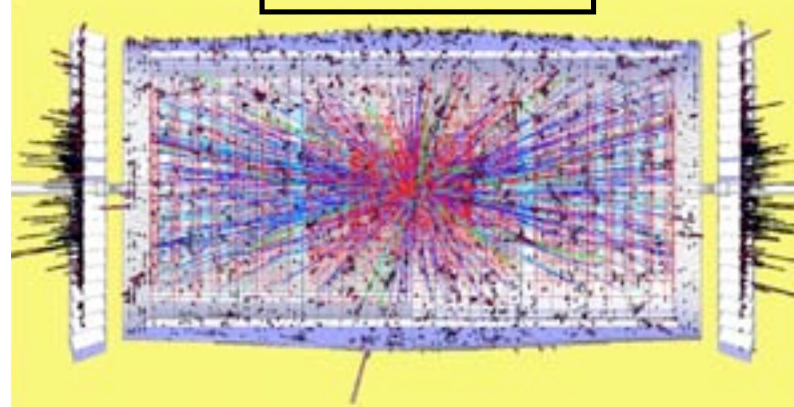
10^{33} cm^{-2}s^{-1}



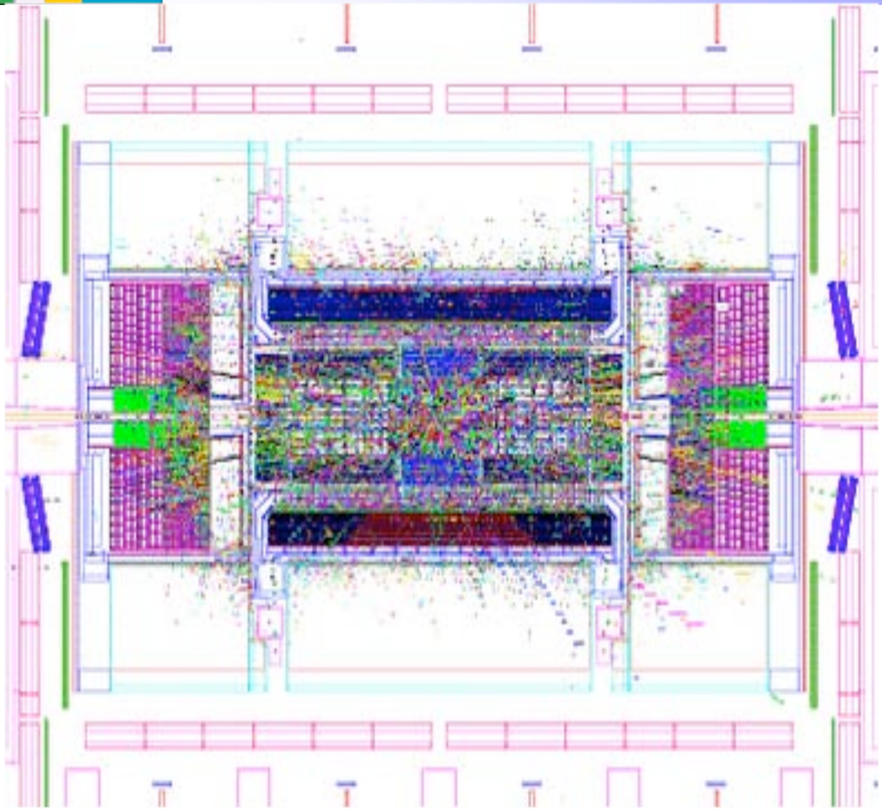
10^{34} cm^{-2}s^{-1}

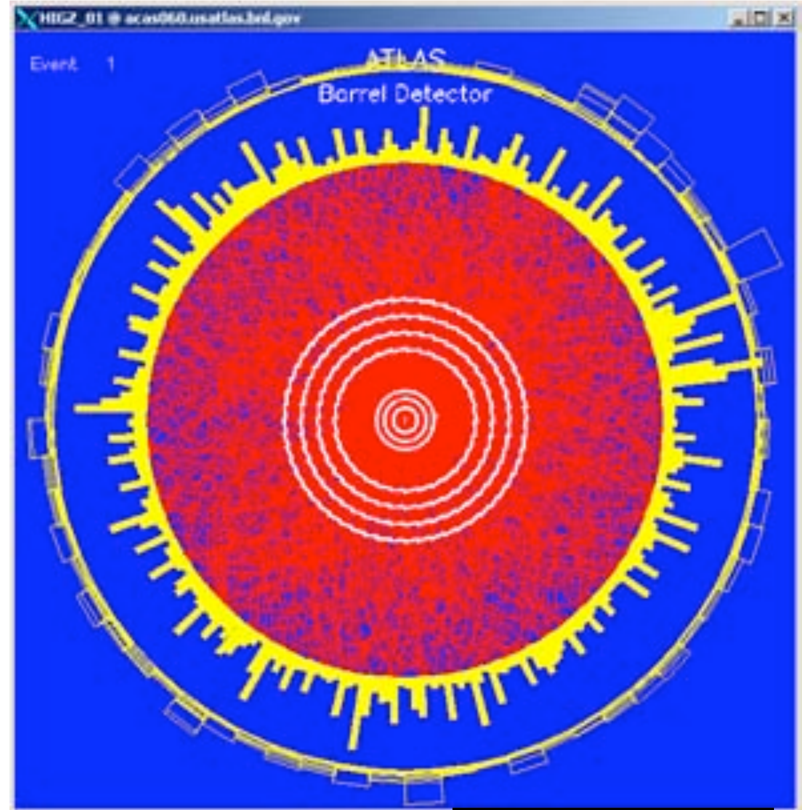


10^{35} cm^{-2}s^{-1}



Expected Pile-up at Super LHC
in ATLAS at 10^{35}





$N_{ch}(|y| \leq 0.5)$

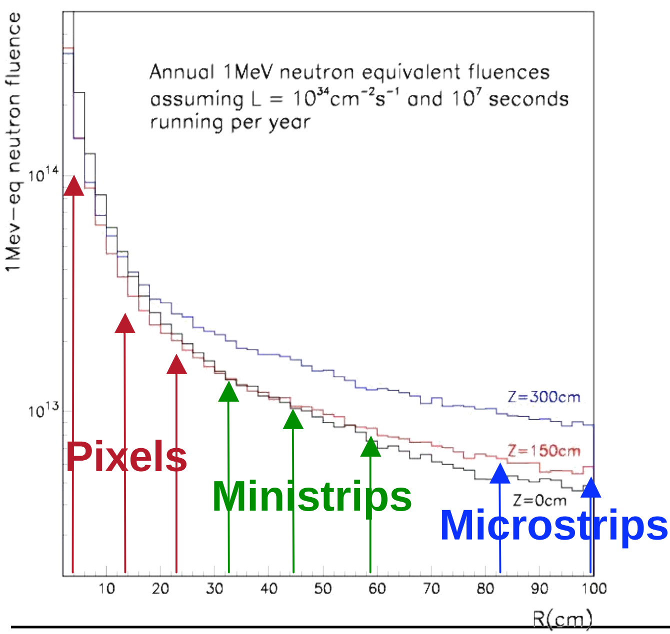
- 230 min.bias collisions per 25 ns. crossing
- ~ 10000 particles in $|\eta| \leq 3.2$
- mostly low p_T tracks
- requires upgrades to detectors

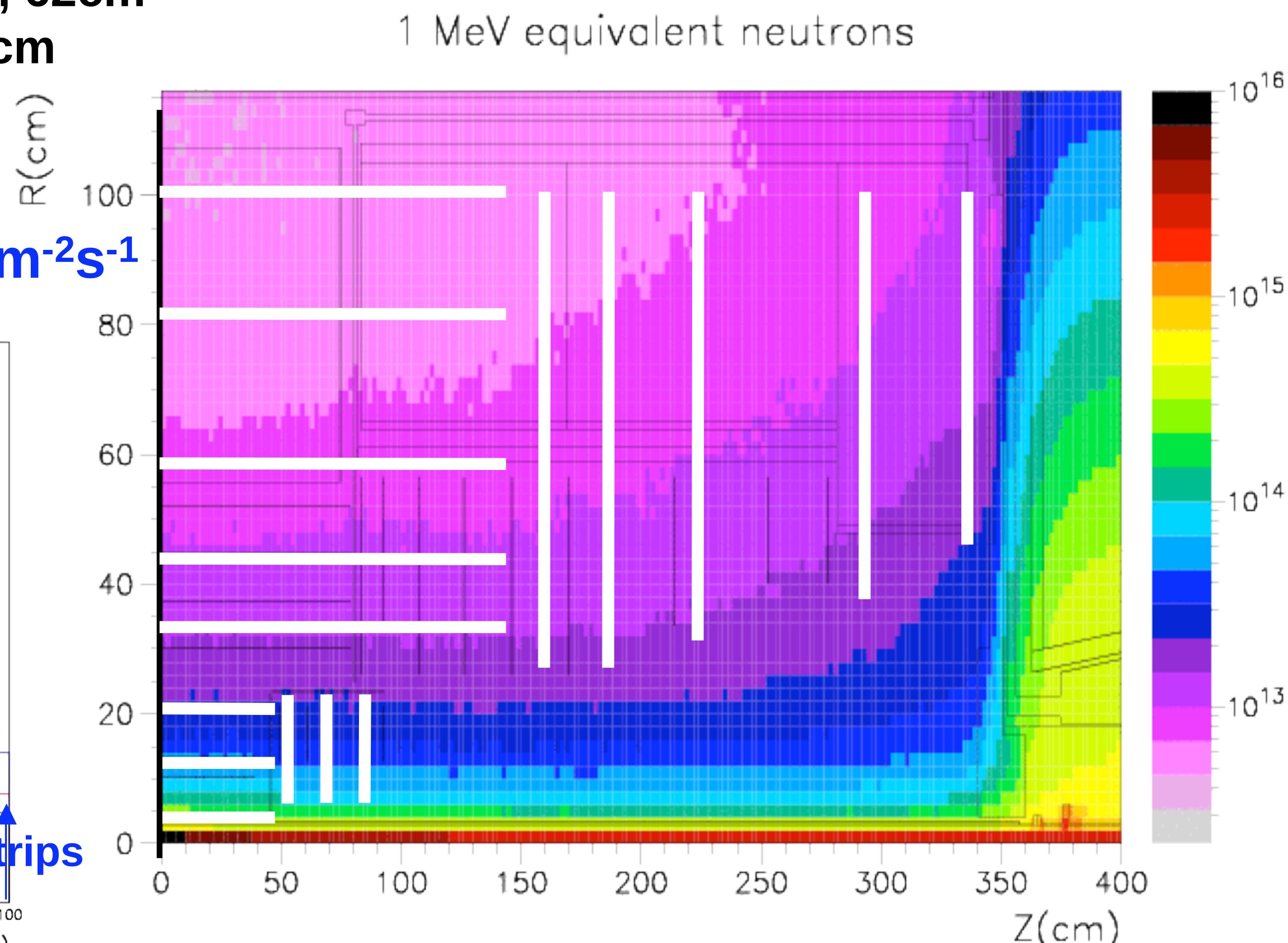
ATLAS Tracker Region Charged Hadron Irradiation

Possible radii of new tracker:
Pixels: r=6cm, 15cm, 24cm
Ministrips: r=35cm, 48cm, 62cm
Microstrips: r=84cm, 105cm

Need to multiply by 10 then number of years of SLHC operation (10 assumed here)

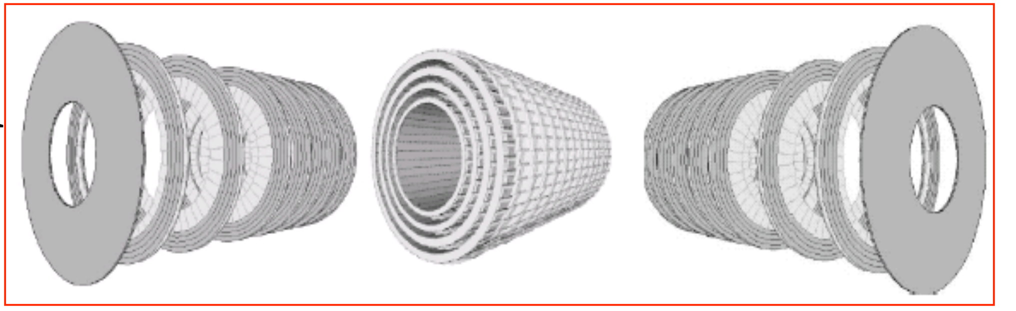
Annual Doses at $10^{34}cm^{-2}s^{-1}$



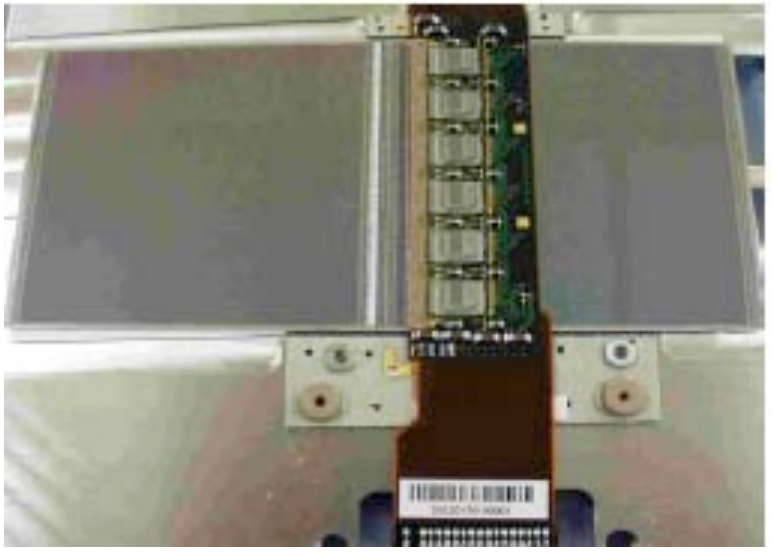


Possible ATLAS Super-LHC Module Design

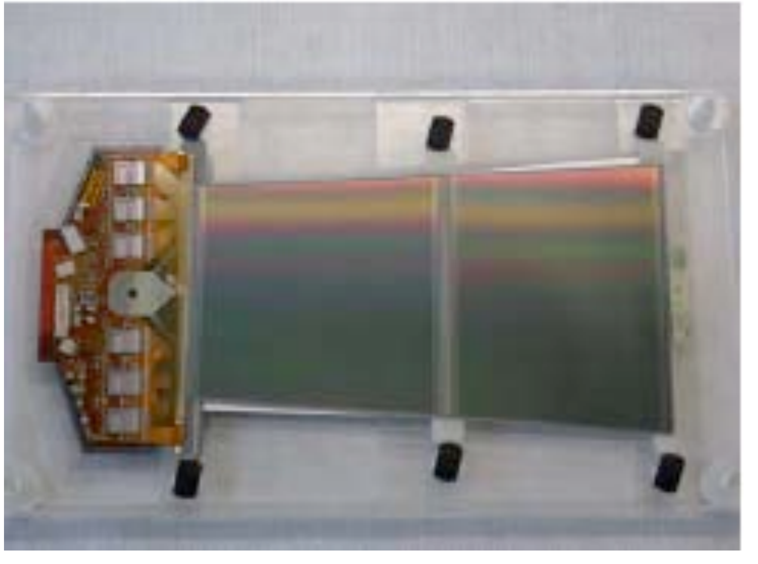
ATLAS Tracker Based on Barrel and Disc Supports



Effectively two styles of modules (with 12cm long strips)



Barrel Modules



Forward Modules

SLHC Upgrade: CMS Tracker

- G. Hall

Higher granularity & more pixels required

Material budget is limited

Power is limited

- Increase in channels, power in cables
- Hope for partial relief from smaller feature size technology

Level-1 Trigger capability

- More about this later…

Digital readout with sophisticated processing

Radiation Tolerance

- Qualification is time consuming
- SEU: Error detection & correction

Large system size & large number of channels

- Automated testing & diagnostics
- Design for production

CMS Pixel Upgrade Ideas

- Propose 3 Pixel Systems that are adapted to fluence/rate and cost levels *- R. Horisberger*

- Pixel #1 max. fluence system ~400 SFr/cm^2

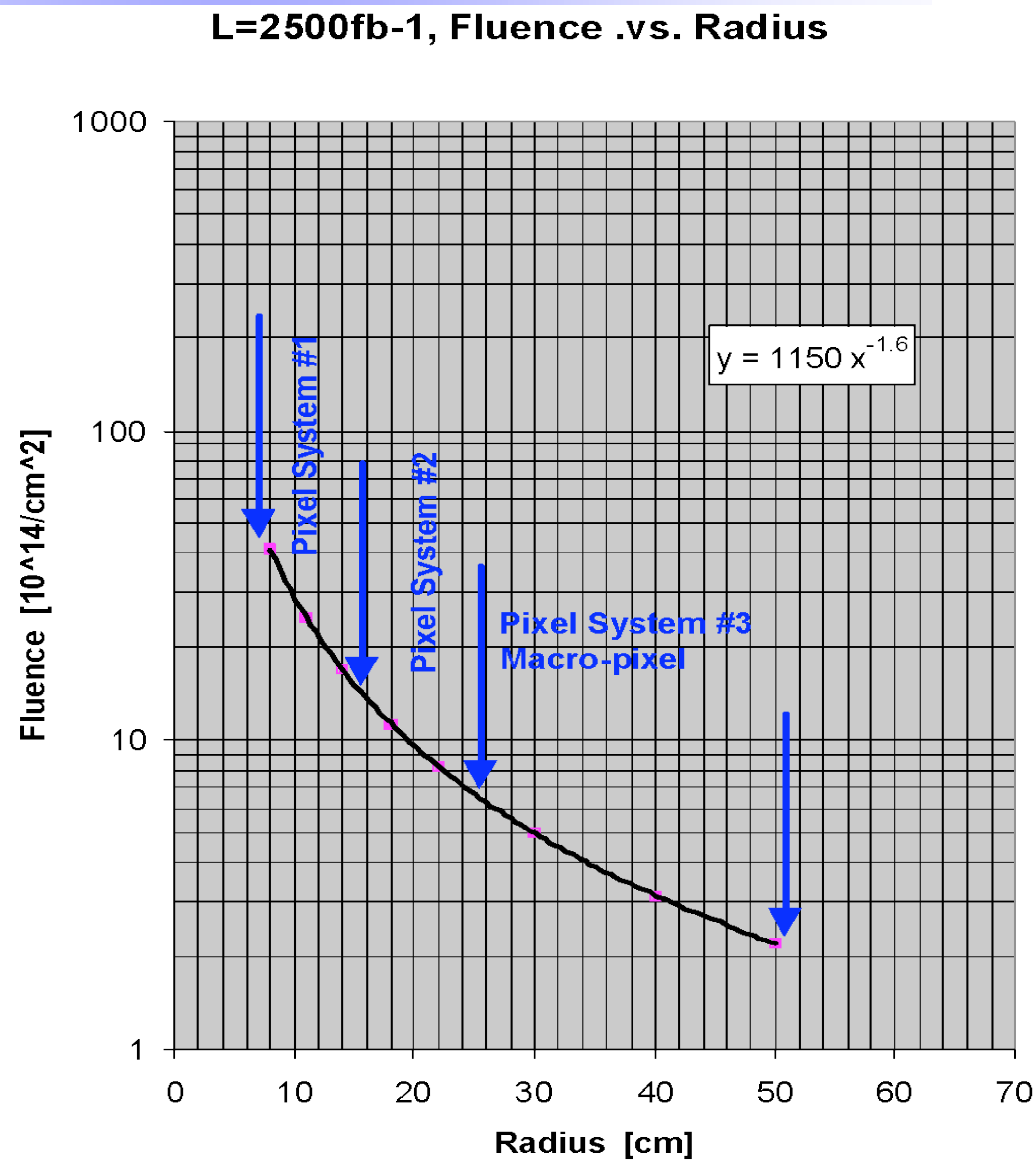
- Pixel #2 large pixel system ~100 SFr/cm^2

- Pixel #3 large area system Macro-pixel ~40 SFr/cm^2

- 8 Layer pixel system can eventually deal with 1200 tracks per unit η

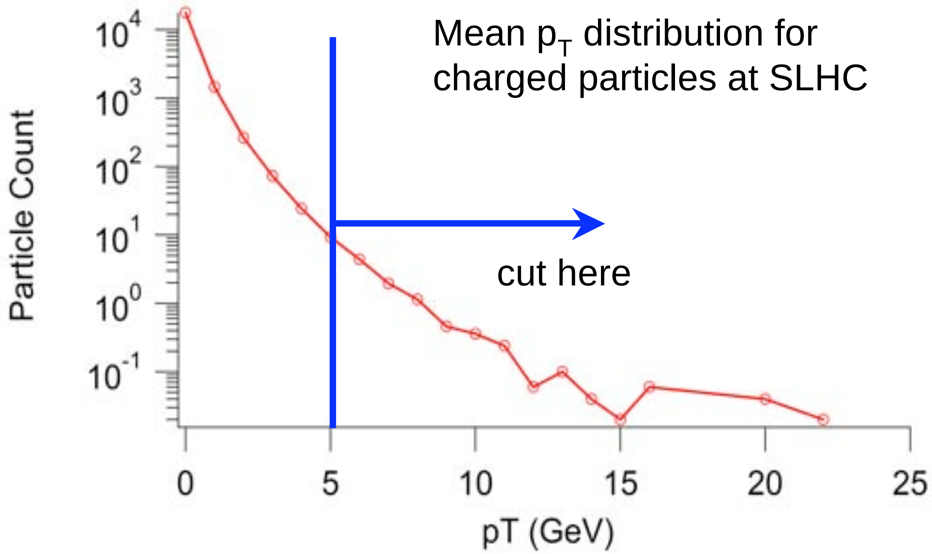
- Use cost control and cheap design considerations from very beginning.

- Question is timescale ????



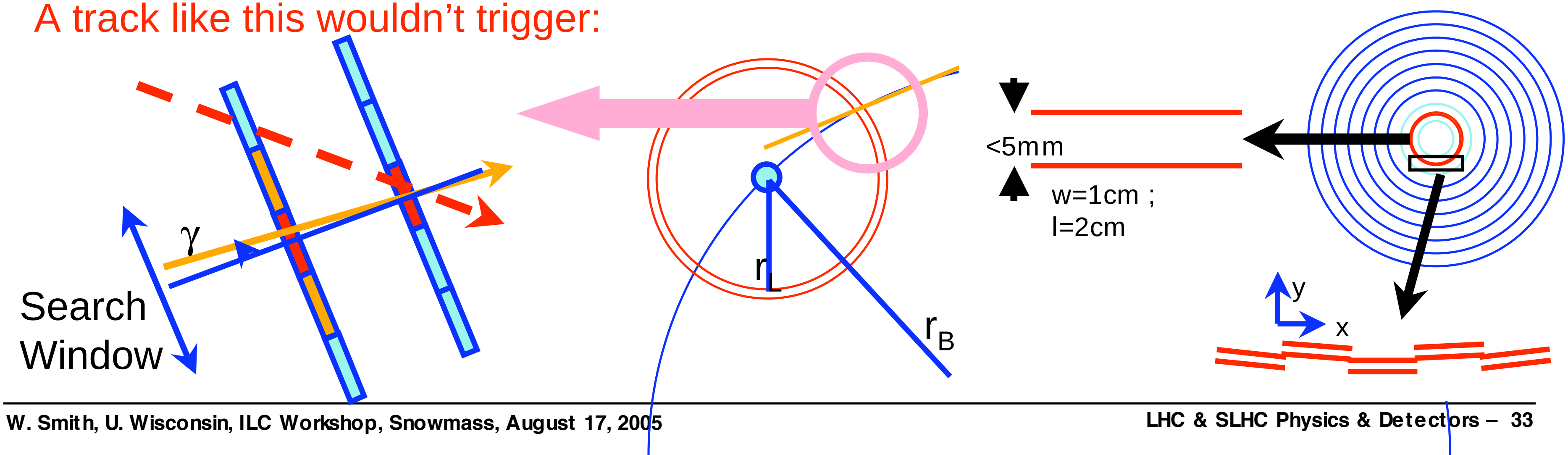
CMS ideas for trigger-capable tracker modules – very preliminary

- Use close spaced stacked pixel layers
- Geometrical p_T cut on data (e.g. 5 GeV):
- Angle (γ) of track bisecting sensor layers defines p_T ($\Rightarrow$ window)
- For a stacked system (sepn. ~1mm), this is ~1 pixel
- Use simple coincidence in stacked sensor pair to find tracklets
- More on implementation later



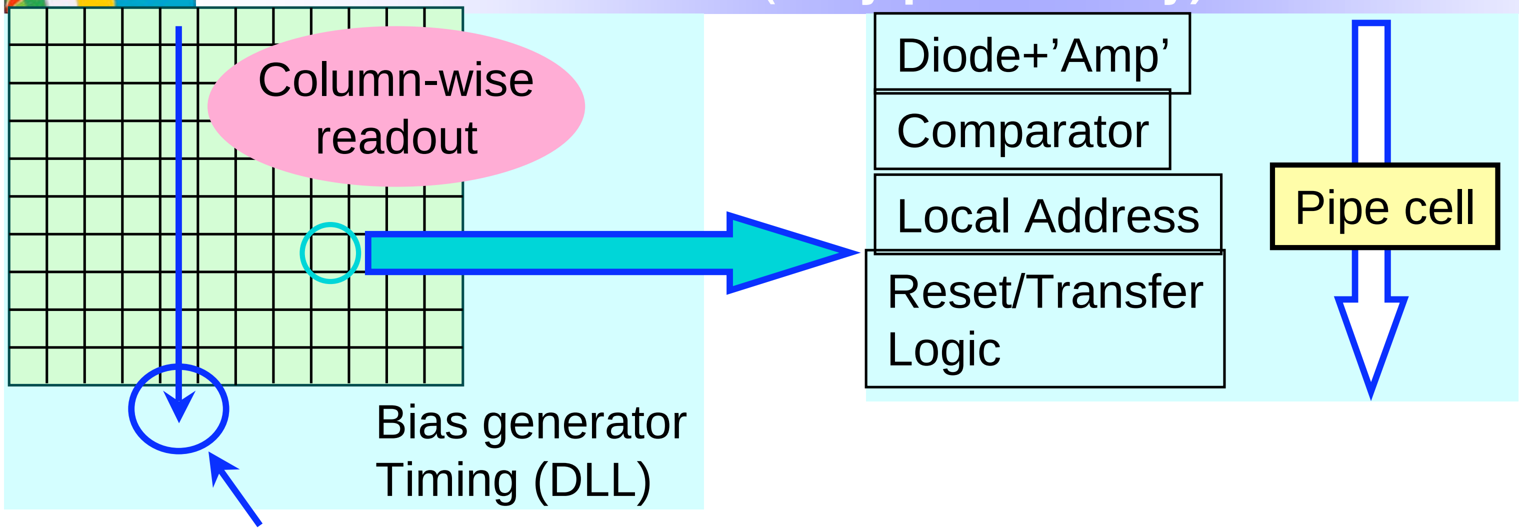
-- C. Foudas & J. Jones

A track like this wouldn't trigger:

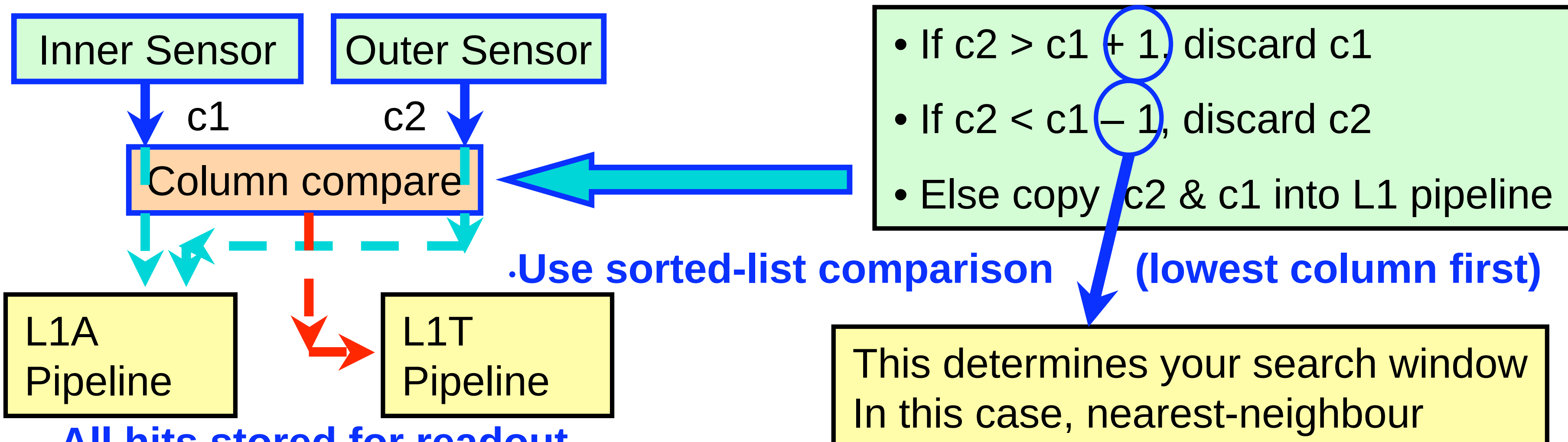


CMS Tracker Readout/Trig. Ideas

(very preliminary)



- At end of column, column address is added to each data element
- Data concatenated into column-ordered list, time-stamp attached at front



- Use sorted-list comparison (lowest column first)
- All hits stored for readout

SLHC: CMS Calorimeter

HF:Quartz Fiber: Possibly replaced

- Very fast – gives good BX ID
- Modify logic to provide finer-grain information
  - Improves forward jet-tagging

HCAL:Scintillator/Brass: Barrel stays but endcap replaced

- Has sufficient time resolution to provide energy in correct 12.5 ns BX with 40 MHz sampling. Readout may be able to produce 80 MHz already.

ECAL: $PBWO_4$ Crystal: Stays

- Also has sufficient time resolution to provide energy in correct 12.5 ns BX with 40 MHz sampling, may be able to produce 80 MHz output already.
- Exclude on-detector electronics modifications for now — difficult:
  - Regroup crystals to reduce $\Delta\eta$ tower size — minor improvement
  - Additional fine-grain analysis of individual crystal data — minor improvement

Conclusions:

- Front end logic same except where detector changes
- Need new TPG logic to produce 80 MHz information
- Need higher speed links for inputs to Cal Regional Trigger

SLHC: ATLAS Calorimeter

- F.E. Taylor

LAr: Pileup will be ~ 3.2 X higher @ 10^{35}

- Electronics shaping time may need change to optimize noise response

Space charge effects present for $|\eta|>2$ in EM LAr calorimeter

- Some intervention will be necessary

BC ID may be problematical with sampling @ 25 ns

- May have to change pulse shape sampling to 12.5 ns

Tilecal will suffer some radiation damage $\Delta LY < 20\%$

- Calibration & correction – may be difficult to see Min-I signal amidst pileup

SLHC: ATLAS Muons

- F.E. Taylor

Muon Detector issues:

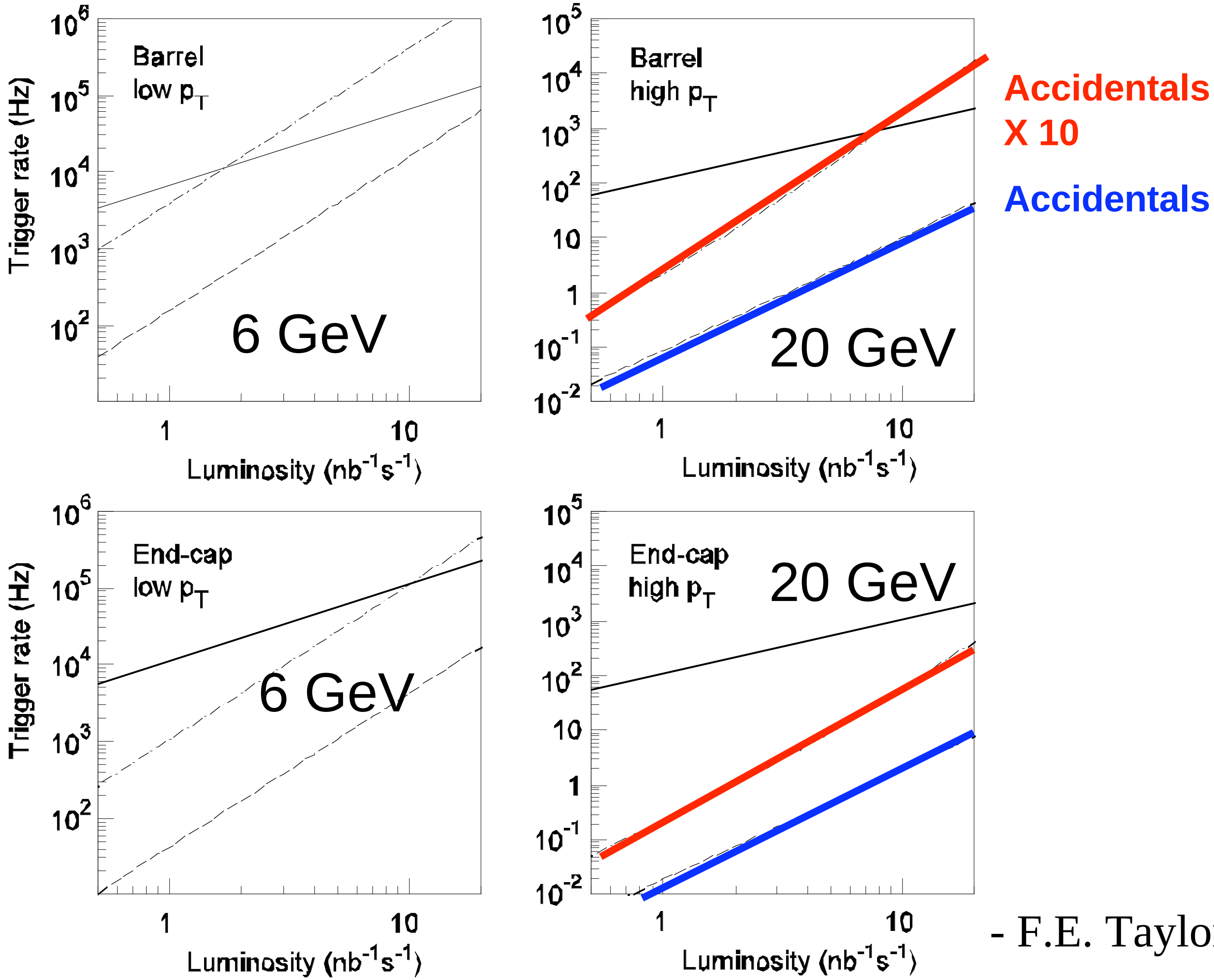
- **Faster & More Rad-Hard trigger technology needed**
  - RPCs (present design) will not survive @ 10^{35}
    - **Intrinsically fast response ~ 3 ns, but resistivity increases at high rate**
  - TGCs need to be faster for 12.5 BX ID…perhaps possible
- **Gaseous detectors only practical way to cover large area of muon system (MDT & CSC) Area ~ 10^4 m^2**
  - Better test data needed on resol'n vs. rate
  - Bkg. γ and neutron efficiencies
  - Search for faster gas $\Rightarrow$ smaller drift time
  - Drive technologies to 10^{35} conditions

Technologies:

- **MDT & CSC & TGC will be stressed – especially high $|\eta|$ ends of deployment, RPCs will have to be replaced**

ATLAS μ Trig. Resolution & Rate

@ 10^{35} ($100\ nb^{-1}\ s^{-1}$) Trig Rate ~ 10^4 Hz & mostly 'real' if accidental rate nominal – higher thresholds ~ larger fraction of accidentals



- F.E. Taylor

CMS Endcap Muon

4 stations of CSCs: Bunch Crossing ID at 12.5 ns:

- **Use second arriving segment to define track BX**
  - Use a 3 BX window
- **Improve BX ID efficiency to 95% with centered peak, taking 2nd Local Charged Track, requiring 3 or more stations**
  - Requires 4 stations so can require 3 stations at L1
- **Investigate improving CSC performance: HV, Gas, …**
  - If 5 ns resolution $\Rightarrow$ 4 ns, BX ID efficiency might climb to 98%

Occupancy at 80 MHz: Local Charged Tracks found in each station

- **Entire system: 4.5 LCTs /BX**
- **Worst case: inner station: 0.125/BX (others 3X smaller)**
- **P(≥ 2) = 0.7% (spoils di-μ measurement in single station)**
- **Conclude: not huge, but neglected neutrons and ghosts may be under-estimated$\Rightarrow$ need to upgrade trigger front end to transmit LCT @ 80 MHz**

Occupancy in Track-Finder at 80 MHz:

- **Using 4 BX window, find 0.5/50 ns in inner station (every other BX at 25 ns!)**
  - ME2–4 3X smaller, possibly only need 3 BX
- **Need studies to see if these tracks generate triggers**

SLHC: CMS Drift Tubes & RPCs

DT:

- Operates at 40 MHz in barrel
- Could produce results for 80 MHz with loss of efficiency…or…
- Could produce large rate of lower quality hits for 80 MHz for combination with a tracking trigger with no loss of efficiency

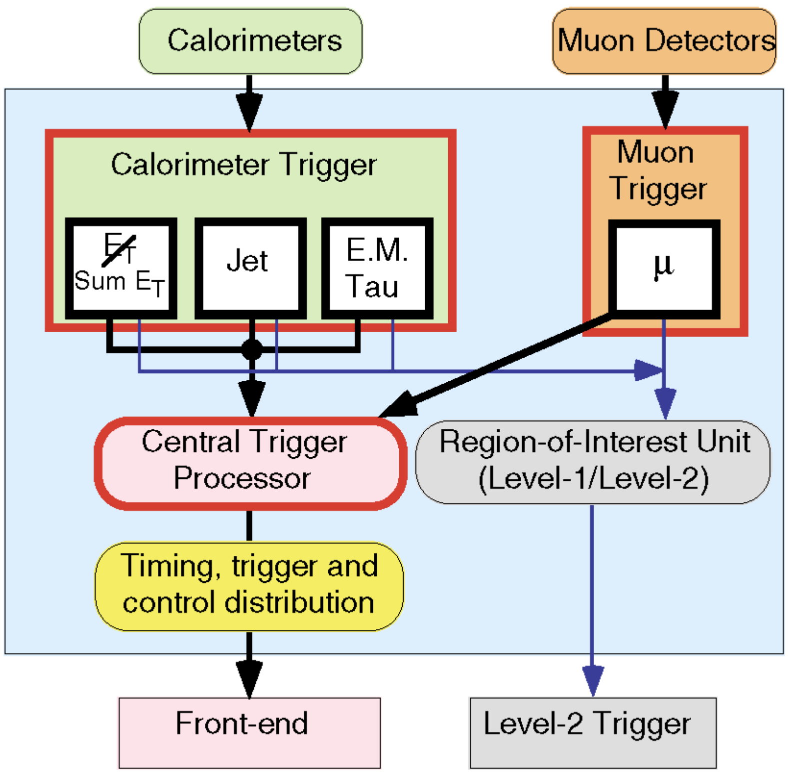
RPC:

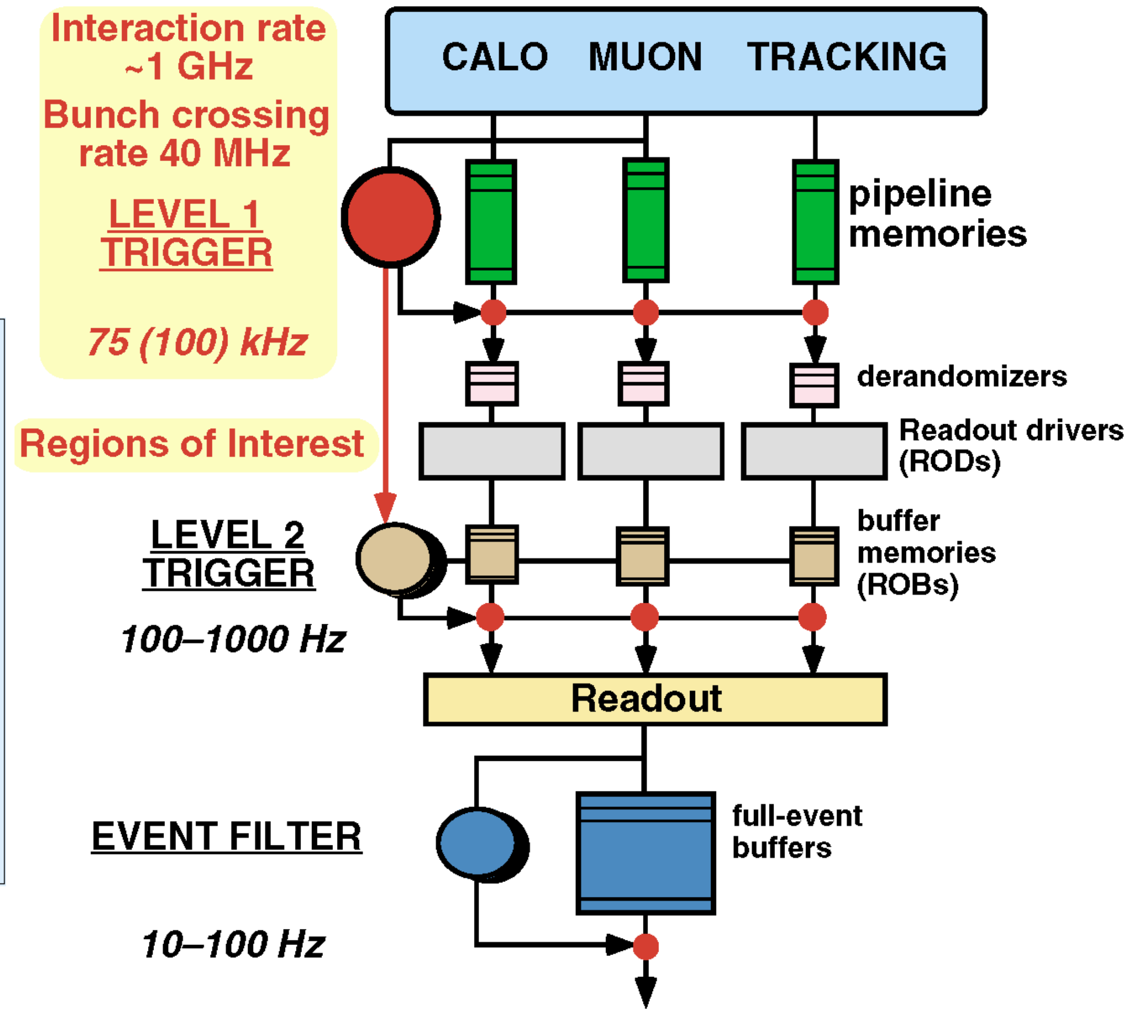
- Operates at 40 MHz
- Could produce results with 12.5 ns window with some minor external changes.
- Uncertain if RPC can operate at SLHC rates, particularly in the endcap

ATLAS Trig & DAQ for LHC

Overall Trigger & DAQ Architecture: 3 Levels:

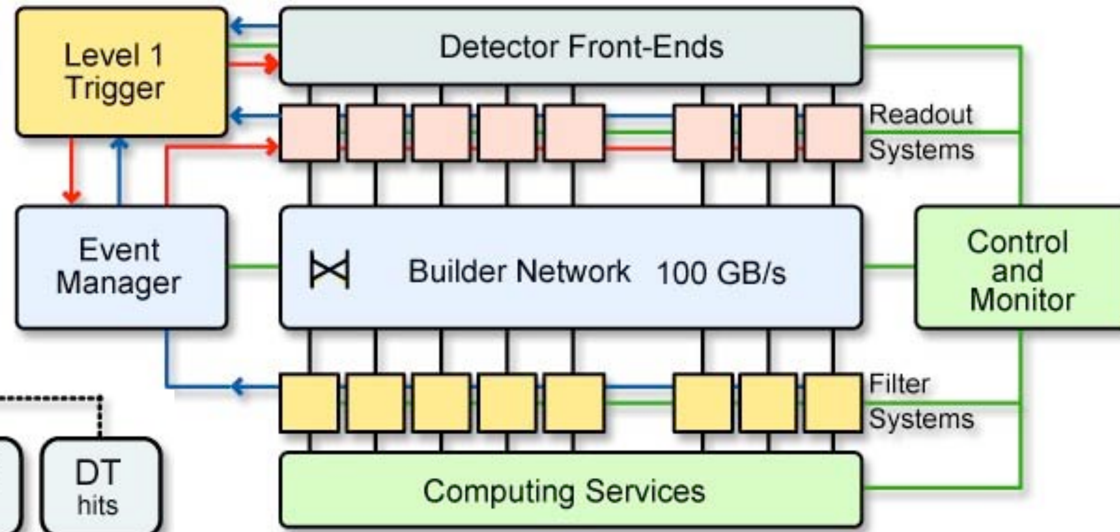
Level-1 Trigger:



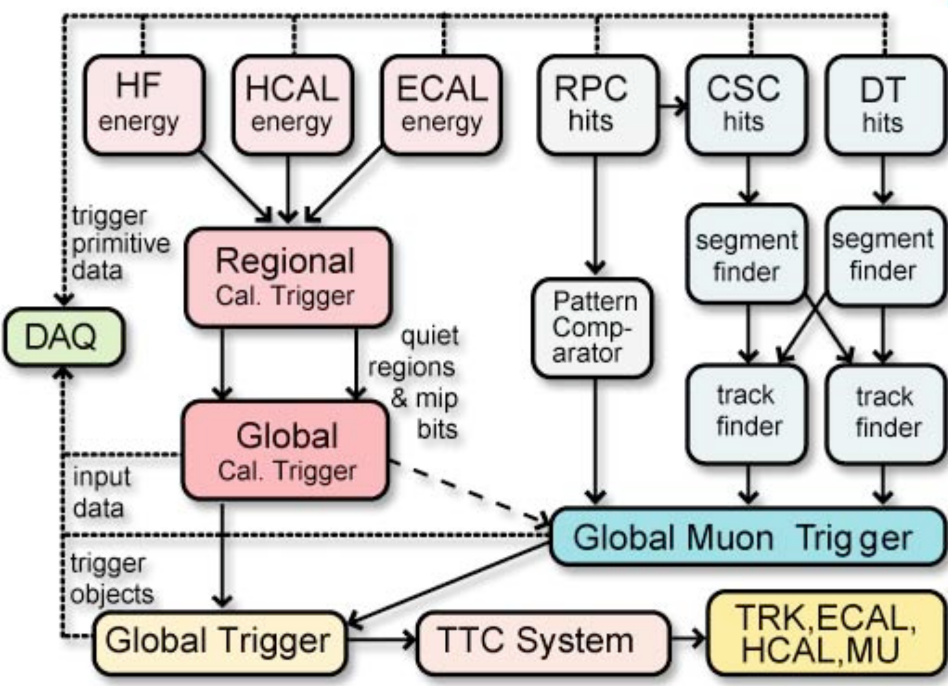


CMS Trig & DAQ for LHC

Overall Trigger & DAQ Architecture: 2 Levels:



Level-1 Trigger:



Interaction rate: 1 GHz

Bunch Crossing rate: 40 MHz

Level 1 Output: 100 kHz (50 initial)

Output to Storage: 100 Hz

Average Event Size: 1 MB

Data production 1 TB/day

SLHC Level-1 Trigger @ 10^{35}

Occupancy

- **Degraded performance of algorithms**
  - Electrons: reduced rejection at fixed efficiency from isolation
  - Muons: increased background rates from accidental coincidences
- **Larger event size to be read out**
  - New Tracker: higher channel count & occupancy → large factor
  - Reduces the max level-1 rate for fixed bandwidth readout.

Trigger Rates

- **Try to hold max L1 rate at 100 kHz by increasing readout bandwidth**
  - Avoid rebuilding front end electronics/readouts where possible
    - **Limits: ⟨readout time⟩ ($< 10\ \mu s$) and data size (total now 1 MB)**
  - Use buffers for increased latency for processing, not post-L1A
  - May need to increase L1 rate even with all improvements
    - **Greater burden on DAQ**
- **Implies raising E_T thresholds on electrons, photons, muons, jets and use of less inclusive triggers**
  - Need to compensate for larger interaction rate & degradation in algorithm performance due to occupancy

Radiation damage — Increases for part of level-1 trigger located on detector

SLHC Trigger @ 12.5 ns

Choice of 80 MHz

- Reduce pile-up, improve algorithm performance, less data volume for detectors that identify 12.5 ns BX data
- Be prepared for LHC Machine group electron-cloud solution
- Retain ability to time-in experiment
  - Beam structure vital to time alignment
- Higher frequencies ~ continuous beam

Rebuild level-1 processors to use data "sampled" at 80 MHz

- Already ATLAS & CMS have internal processing up to 160 MHz and higher in a few cases
- Use 40 MHz sampled front-end data to produce trigger primitives with 12.5 ns resolution
  - e.g. cal. time res. < 25 ns, pulse time already from multiple samples
- Save some latency by running all trigger systems at 80 MHz I/O
- Technology exists to handle increased bandwidth

SLHC Trigger Requirements

High-P_T discovery physics

- Not a big rate problem since high thresholds

Completion of LHC physics program

- Example: precise measurements of Higgs sector
- Require low thresholds on leptons/photons/jets
  - Use more exclusive triggers since final states will be known

Control & Calibration triggers

- W, Z, Top events
- Low threshold but prescaled

SLHC Level-1 Trigger Menu

ATLAS/CMS Studies in hep-ph/0204087:

- inclusive single muon p_T > 30 GeV (rate ~ 25 kHz)
- inclusive isolated e/γ E_T > 55 GeV (rate ~ 20 kHz)
- isolated e/γ pair E_T > 30 GeV (rate ~ 5 kHz)
  - or 2 different thresholds (i.e. 45 & 25 GeV)
- muon pair p_T > 20 GeV (rate ~ few kHz?)
- jet E_T > 150 GeV.AND.E_T(miss) > 80 GeV (rate ~ 1–2 kHz)
- inclusive jet trigger E_T > 350 GeV (rate ~ 1 kHz)
- inclusive E_T(miss) > 150 GeV (rate ~1 kHz);
- multi-jet trigger with thresholds determined by the affordable rate

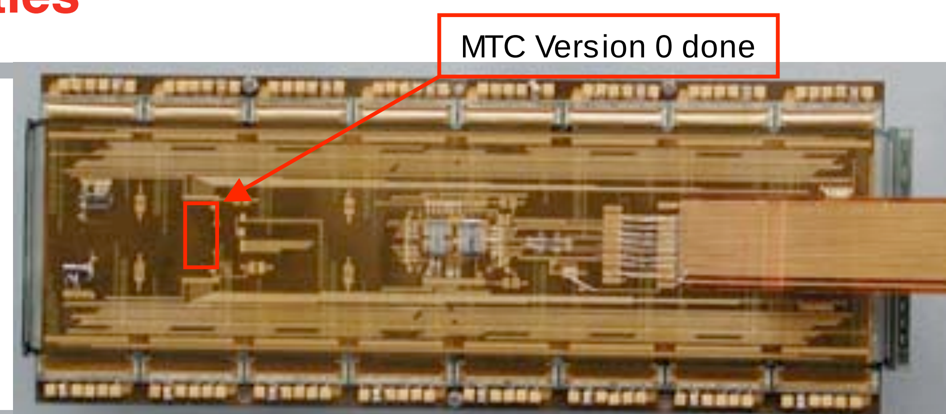
CMS SLHC L-1 Tracking Trigger
Ideas & Implications for L-1

Additional Component at Level-1

- **Actually, CMS already has rudimentary L-1 Tracking Trigger**
  - Pixel z-vertex in $\Delta\eta \times \Delta\phi$ bins can reject jets from pile-up
- **SLHC Track Trigger could provide outer stub and inner track**
  - Combine with cal at L-1 to reject π^0 electron candidates
  - Reject jets from other crossings by z-vertex
  - Reduce accidentals and wrong crossings in muon system
  - Provide sharp P_T threshold in muon trigger at high P_T
- **Cal & Muon L-1 output needs granularity & info. to combine w/ tracking trig. Also need to produce hardware to make combinations**

Move some HLT algorithms into L-1 or design new algorithms reflecting tracking trigger capabilities

- Local track clusters from jets used for 1st level trigger signal → jet trigger with σ_z = 6mm!
- Program in Readout Chip track cluster multiplicity for trigger output signal
- Combine in Module Trigger Chip (MTC) 16 trig. signals & decide on module trigger output



Use of CMS L1 Tracking Trigger

- D. Acosta

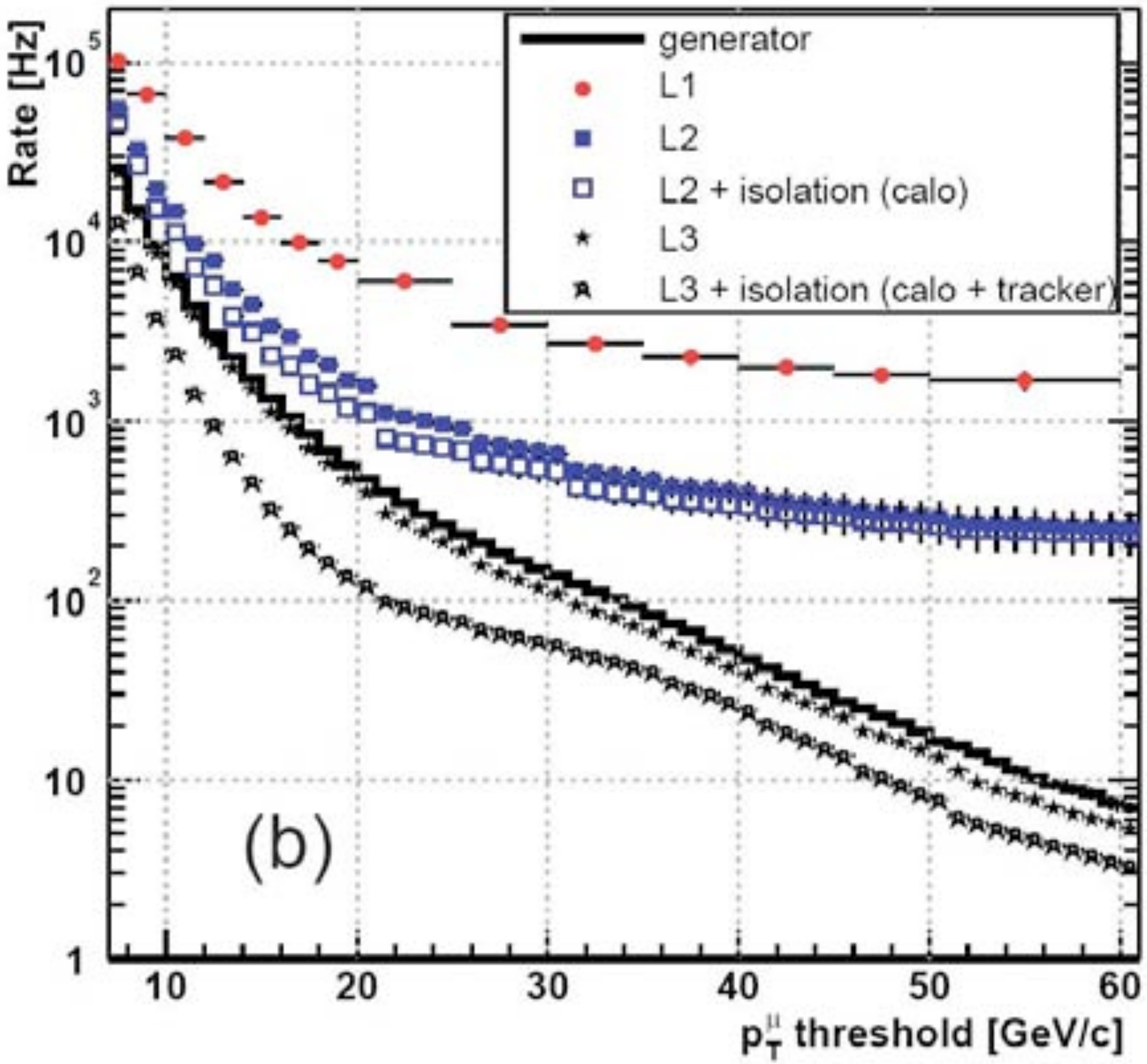
Combine with L1 CSC as is now done at HLT:

- Attach tracker hits to improve P_T assignment precision from 15% standalone muon measurement to 1.5% with the tracker
  - Improves sign determination & provides vertex constraints
- Find pixel tracks within cone around muon track and compute sum P_T as an isolation criterion
  - Less sensitive to pile-up than calorimetric information *if* primary vertex of hard-scattering can be determined (~100 vertices total at SLHC!)

To do this requires η–ϕ information on muons finer than the current 0.05–2.5°

- No problem, since both are already available at 0.0125 and 0.015°

CMS Muon Rate at $L = 10^{34}$



From CMS DAQ TDR

Note limited rejection power (slope) without tracker information

CMS SLHC Calorimeter Trigger

- S. Dasu

Electrons/Photons:

- Report on finer scale to match to tracks

τ-jets:

- Cluster in 2x2 trigger towers with 2x2 window sliding by 1x1 with additional isolation logic

Jets:

- Provide options for 6x6, 8x8, 10x10, 12x12 trigger tower jets, sliding in 1x1 or 2x2

Missing Energy:

- Finer grain geometric lookup & improved resolution in sums

Output:

- On finer-grain scale to match tracking trigger
  - Particularly helpful for electron trigger

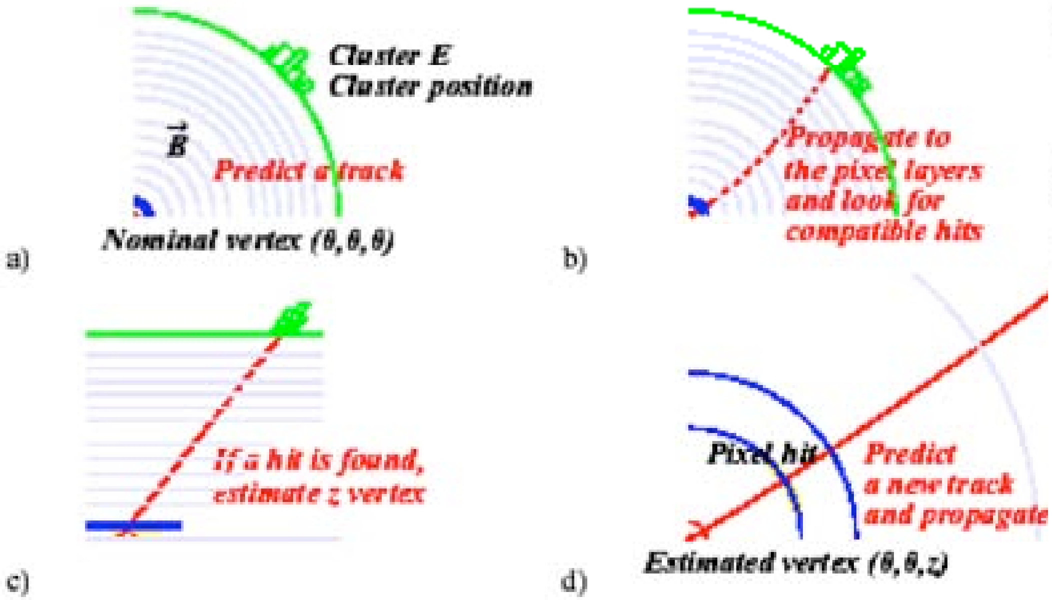
Reasonable extension of existing system

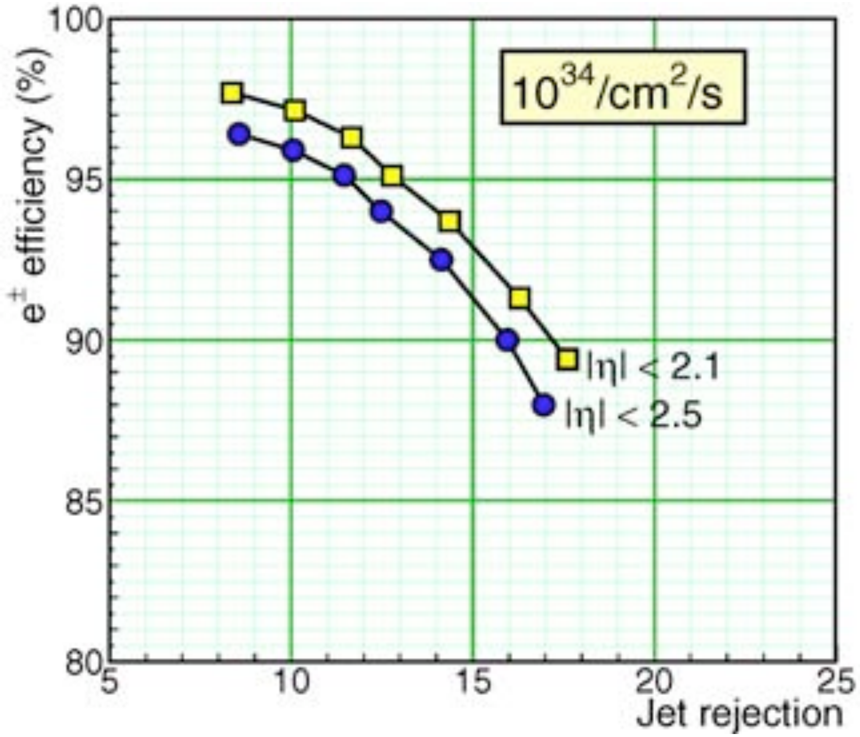
- Assuming R&D program starts soon

CMS tracking for electron trigger

Present CMS electron HLT

- C. Foudas & C. Seez

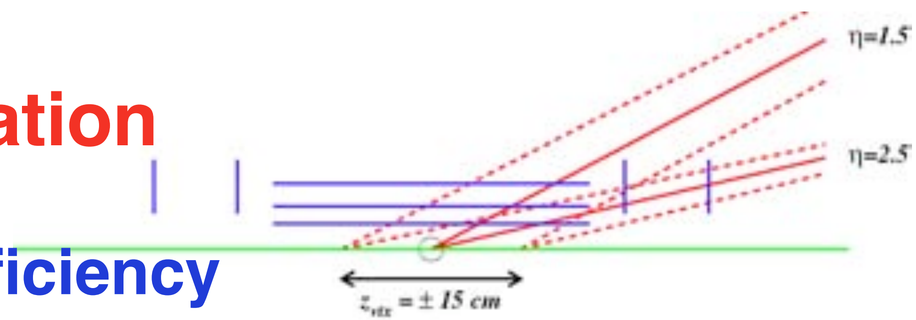




Factor of 10 rate reduction

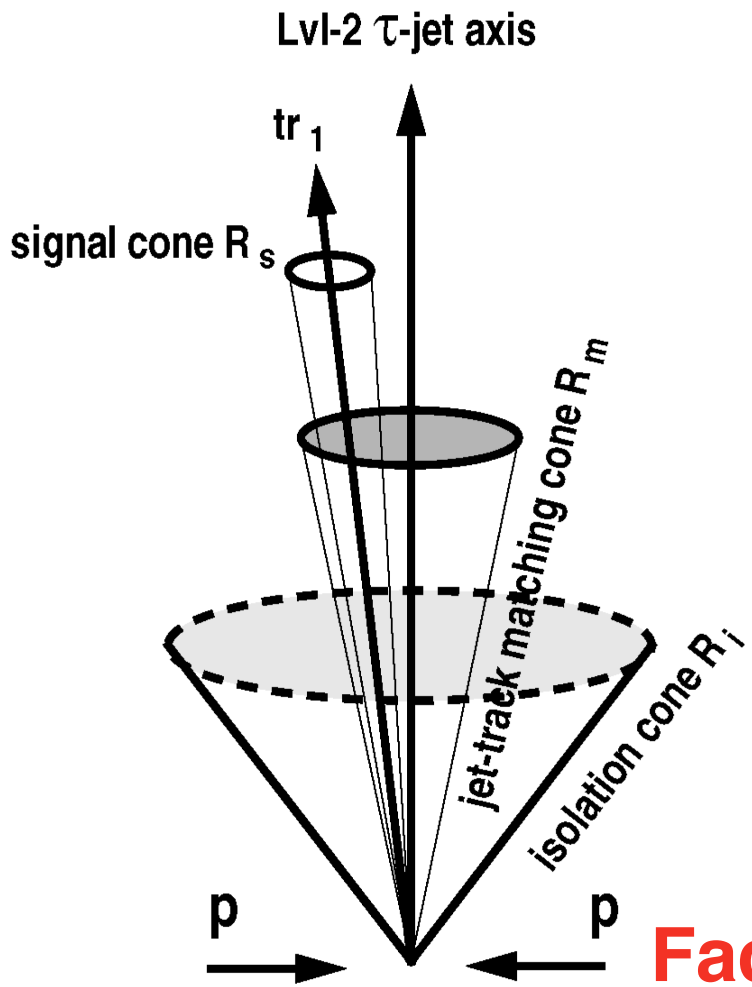
γ: only tracker handle: isolation

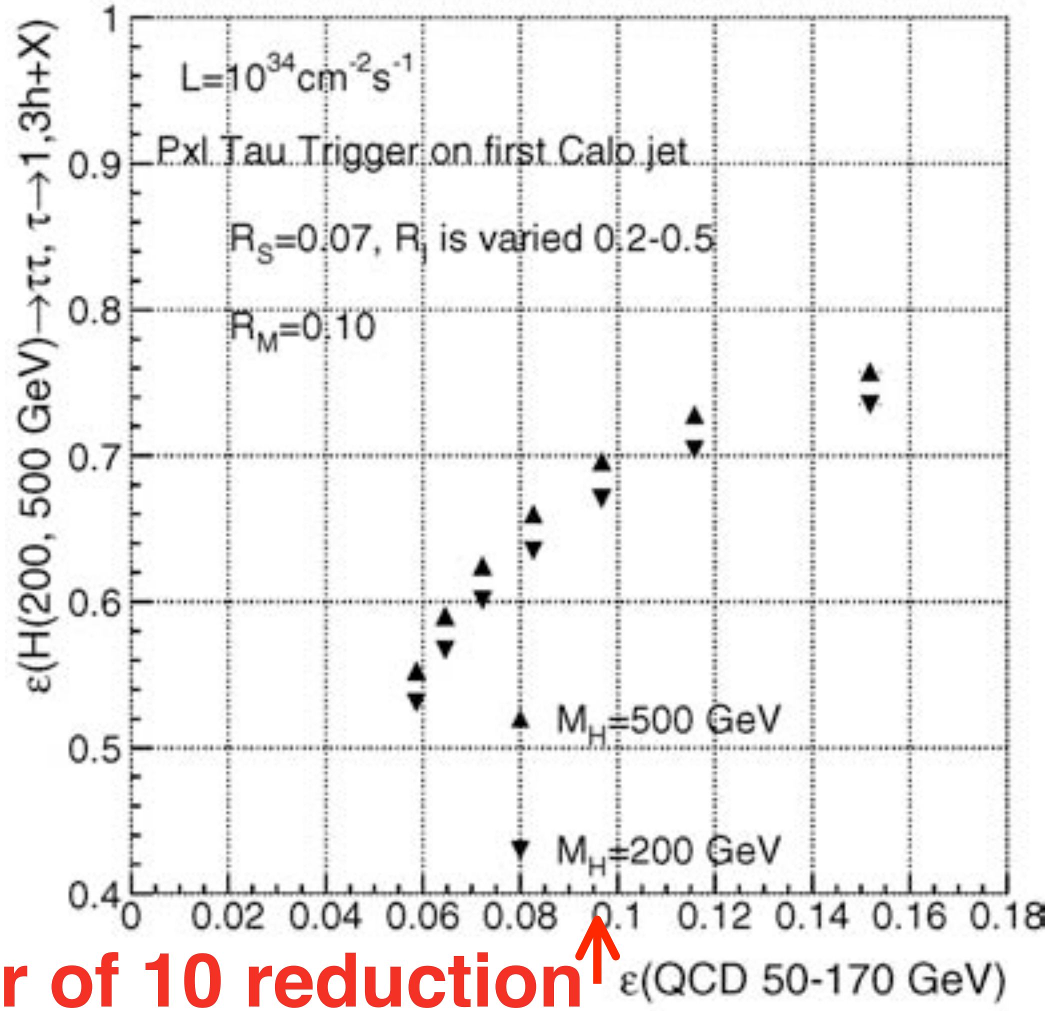
- Need knowledge of vertex location to avoid loss of efficiency



CMS tracking for τ-jet isolation

τ-lepton trigger: isolation from pixel tracks outside signal cone & inside isolation cone





Factor of 10 reduction

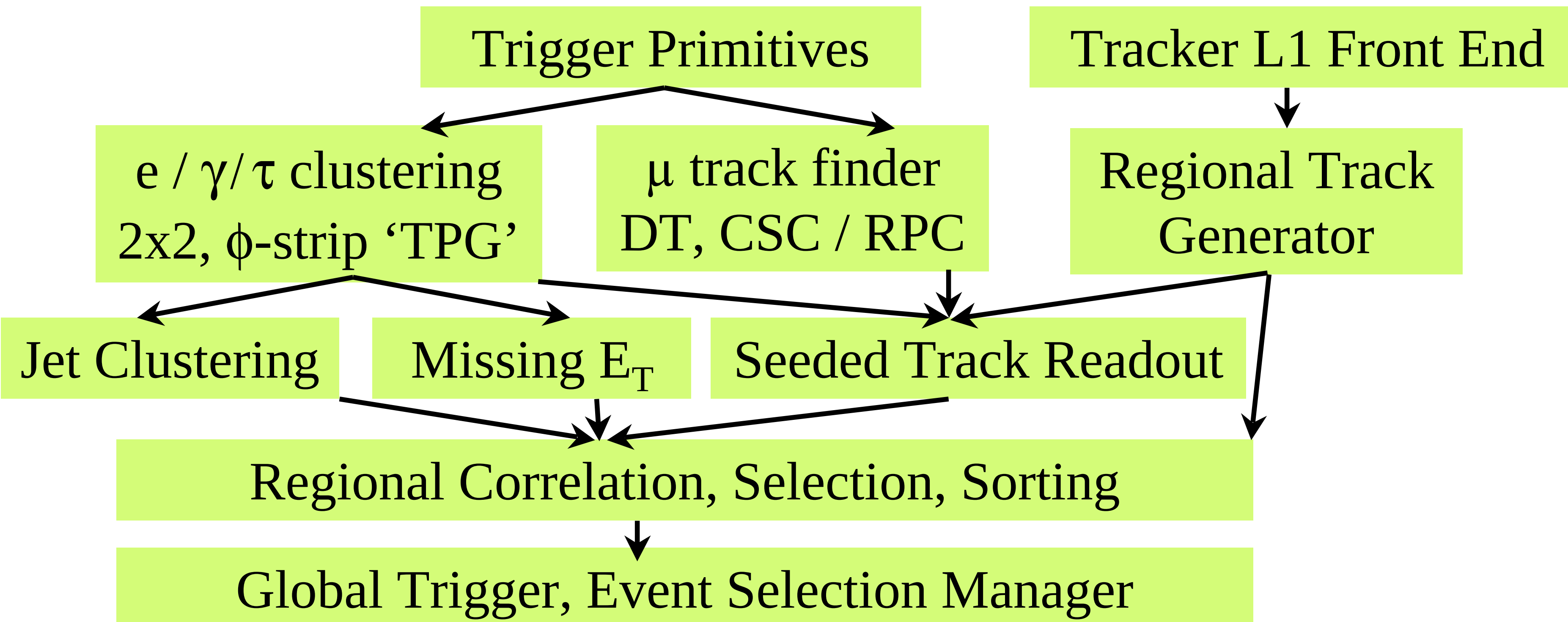
CMS L1 Algorithm Stages

Current for LHC:

TPG ⇒ RCT ⇒ GCT ⇒ GT

Proposed for SLHC (with tracking added):

TPG ⇒ Clustering ⇒ Correlator ⇒ Selector



CMS SLHC Trigger Architecture

LHC:

- **Level 1: Regional to Global Component to Global**

SLHC Proposal:

- **Combine Level-1 Trigger data between tracking, calorimeter & muon at Regional Level at finer granularity**
- **Transmit physics objects made from tracking, calorimeter & muon regional trigger data to global trigger**
- **Implication: perform some of tracking, isolation & other regional trigger functions in combinations between regional triggers**
  - New “Regional” cross-detector trigger crates
- **Leave present L1+ HLT structure intact (except latency)**
  - No added levels —minimize impact on CMS readout

CMS Level-1 Latency

CMS Latency of 3.2 μsec becomes 256 crossings @ 80 MHz

- Assuming rebuild of tracking & preshower electronics will store this many samples

Do we need more?

- Yield of crossings for processing only increases from ~70 to ~140
  - It's the cables!
- Parts of trigger already using higher frequency

How much more? Justification?

- Combination with tracking logic
- Increased algorithm complexity
- Asynchronous links or FPGA-integrated deserialization require more latency
- Finer result granularity may require more processing time
- ECAL digital pipeline memory is 256 40 MHz samples = 6.4 μsec
  - Propose this as CMS SLHC Level-1 Latency baseline

CMS SLHC L-1 Trigger Summary

Attempt to restrict upgrade to post-TPG electronics as much as possible where detectors are retained

- **Only change where required — evolutionary — some possible pre-SLHC?**
  - Inner pixel layer replacement is just one opportunity.

New Features:

- **80 MHz I/O Operation**
- **Level-1 Tracking Trigger**
  - Inner pixel track & outer tracker stub
  - Reports "crude" P_T & multiplicity in $\sim 0.1 \text{x}\ 0.1\ \Delta\eta \times \Delta\phi$
- **Regional Muon & Cal Triggers report in ~ 0.1 x 0.1 $\Delta\eta \times \Delta\phi$**
- **Regional Level-1 Tracking correlator**
  - Separate systems for Muon & Cal Triggers
  - Separate crates covering $\Delta\eta \times \Delta\phi$ regions
  - Sits between regional triggers & global trigger
- **Latency of 6.4 μsec**

SLHC DAQ

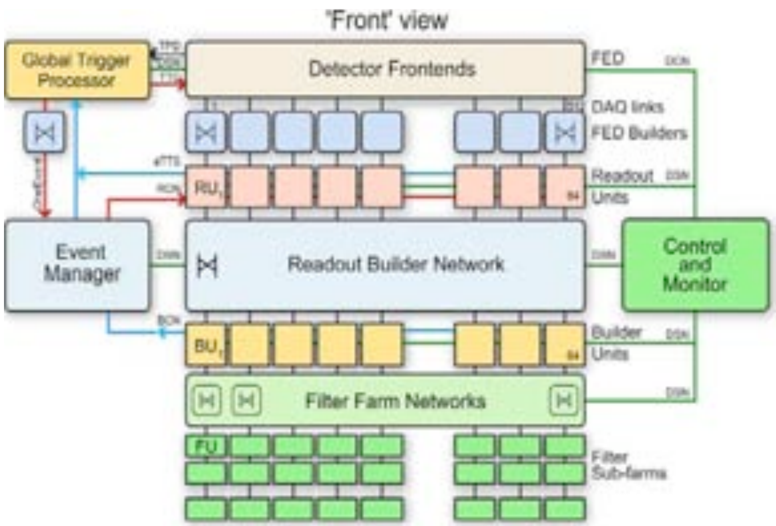
SLHC Network bandwidth at least 5–10 times LHC

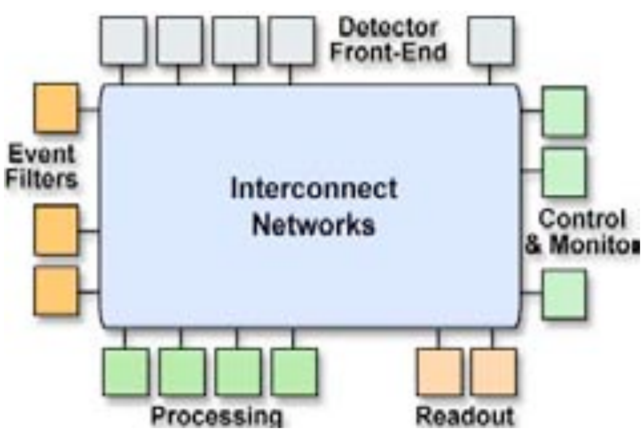
- Assuming L1 trigger rate same as LHC
- Increased Occupancy
- Decreased channel granularity (esp. tracker)

Upgrade paths for ATLAS & CMS can depend on present architecture

- ATLAS: Region of Interest based Level-2 trigger in order to reduce bandwidth to processor farm
  - Opportunity to put tracking information into level-2 hardware
  - Possible to create multiple slices of ATLAS present RoI readout to handle higher rate
- CMS: scalable single hardware level event building
  - If architecture is kept, requires level-1 tracking trigger

SLHC: CMS DAQ: Possible structure upgrade





- S. Cittolin

LHC DAQ design:

A network with Terabit/s aggregate bandwidth is achieved by two stages of switches and a layer of intermediate data concentrators used to optimize the Event Builder traffic load.
Event buffers ~100GByte memory cover a **real-time interval of seconds**

SLHC DAQ design:

A **multi-Terabit/s network** congestion free and scalable (as expected from communication industry).
In addition to the Level-1 Accept, the Trigger has to transmit to the front ends additional information: event type & event destination address of the processing system (CPU, Cluster, TIER..) where the event has to be built and analyzed.
The event fragment delivery and therefore the **event building will be controlled by the network protocols** and (commercial) network internal resources (buffers, multi-path, network processors, etc.)
Real time buffers of Pbytes temporary storage disks could permit a **real-time interval of days**, allowing event selection tasks to better exploit the available distributed processing power (even over the GRID!).

New SLHC Fast Controls, Clocking & Timing System (TTC)

80 MHz:

- **Provide this capability "just in case" SLHC can operate at 80 MHz**
  - Present system operates at 40 MHz
- **Provide output frequencies close to that of logic**

Drive High-Speed Links

- **Design to drive next generation of links**
  - Build in very good peak-to-peak jitter performance

Fast Controls (trigger/readout signal loop):

- **Provides Clock, L1A, Reset, BC0 in real time for each crossing**
- **Transmits and receives fast control information**
- **Provides interface with Event Manager (EVM), Trigger Throttle System**
  - For each L1A (@ 100 kHz), each front end buffer gets IP address of node to transmit event fragment to
  - EVM sends event building information in real time at crossing frequency using TTC system
    - **EVM updates 'list' of avail. event filter services (CPU-IP, etc.) where to send data**
    - **This info.is embedded in data sent into DAQ net which builds events at destination**
  - Event Manager & Global Trigger must have a tight interface
- **This control logic must process new events at 100 kHz → R&D**

Conclusions

The LHC will initiate a new era in colliders, detectors & physics.

- **Searches for Higgs, SUSY, ED, Z' will commence**
  - Exploring the TeV scale
- **Serious challenges for the machine, experiments & theorists will commence**

The SLHC will extend the program of the LHC

- **Extend the discovery mass/scale range by 25–30%**
- **Could provide first measurement of Higgs self-coupling**
- **Reasonable upgrade of LHC IR optics**
- **Rebuilding of experiment tracking & trigger systems**
- **Need to start now on R&D to prepare**