Experiments at the high energy frontier: achievements and future challenges

- Recent past – solid foundation
    - LEP, HERA, Tevatron
- Present day – pointing the way
    - Tevatron, LHC
- Next steps
    - Detector upgrades for HL-LHC
    - Linear collider ILC/CLIC

Joint ECFA-EPS Session, Grenoble, 23 July 2011

Pippa Wells, CERN

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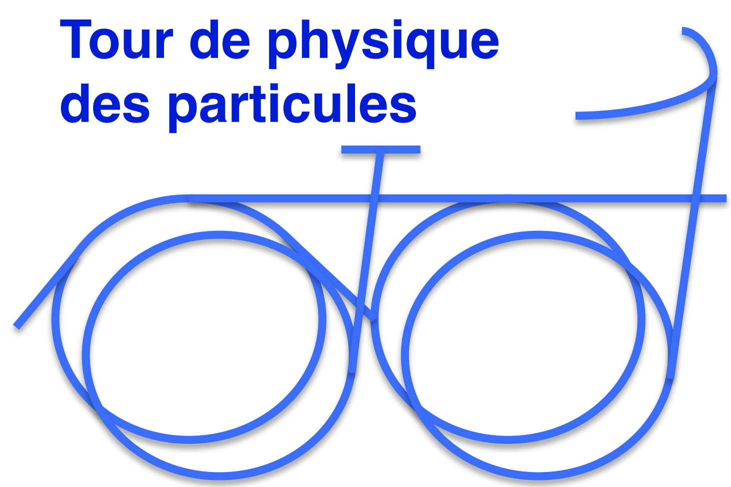
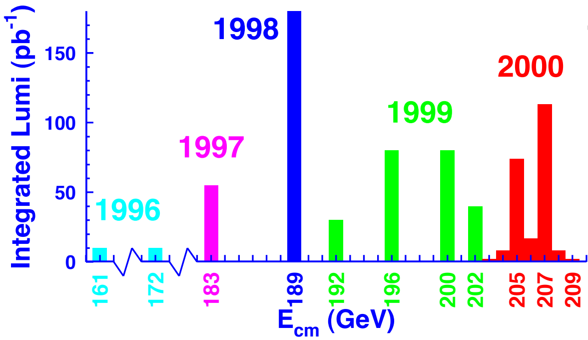
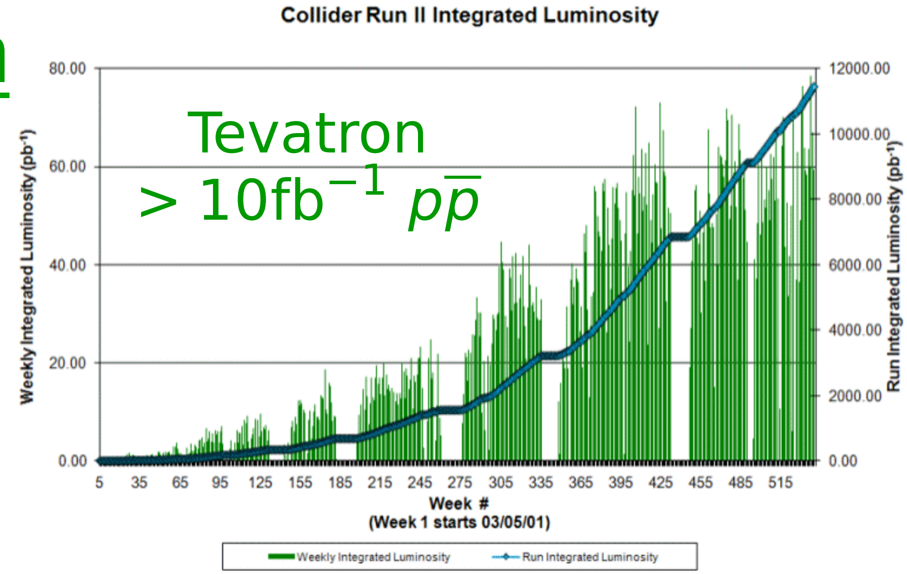


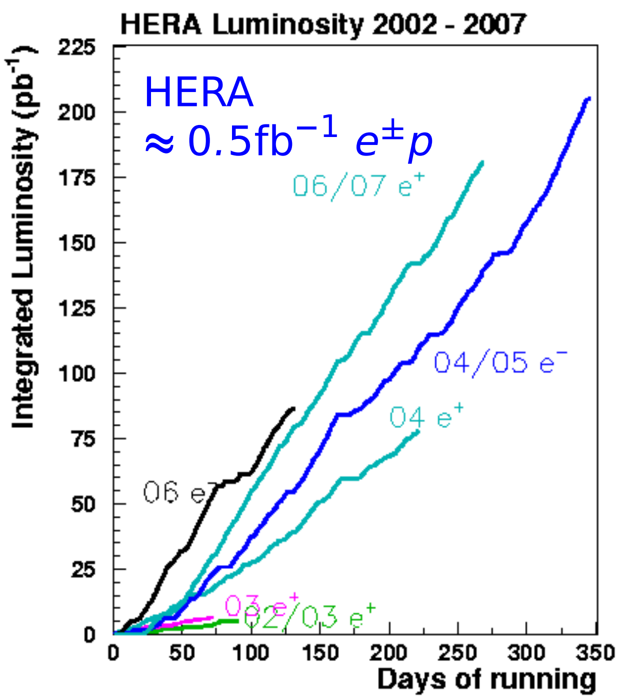
High-energy terrain

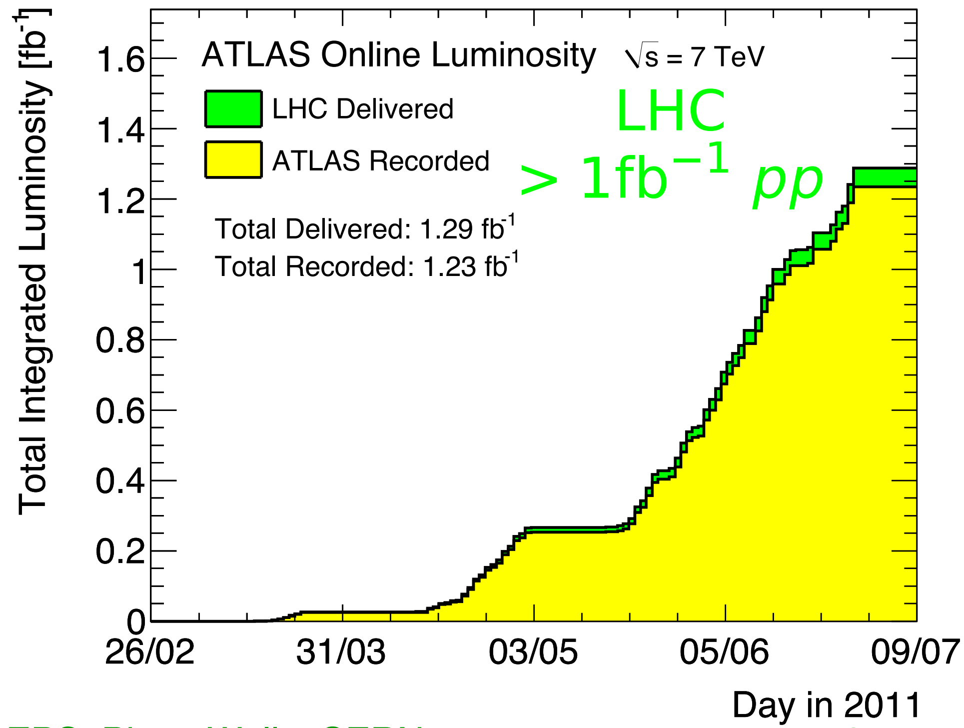
LEP: 4.5M Z, 10k W^+W^- x 4 expts

+SLC

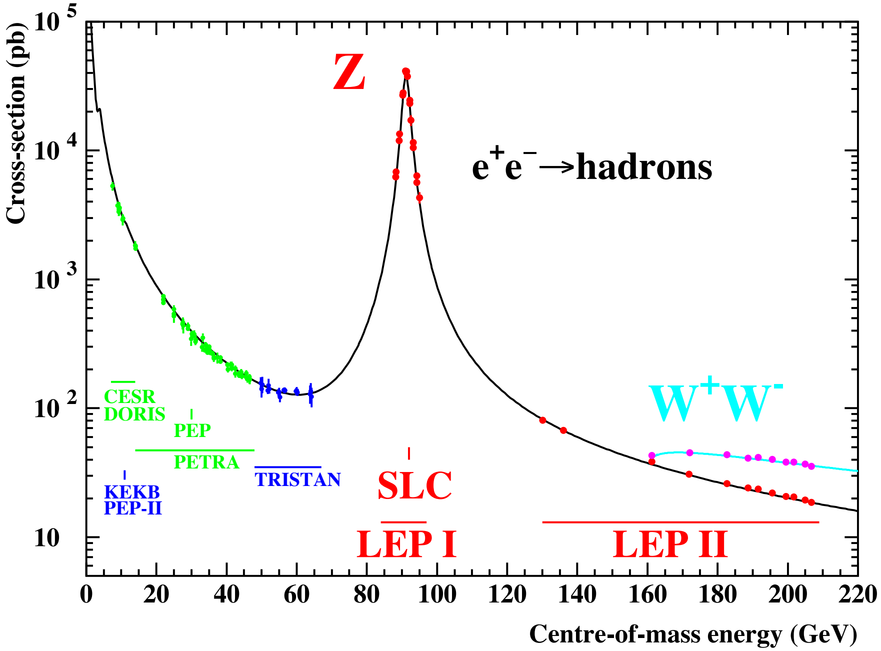




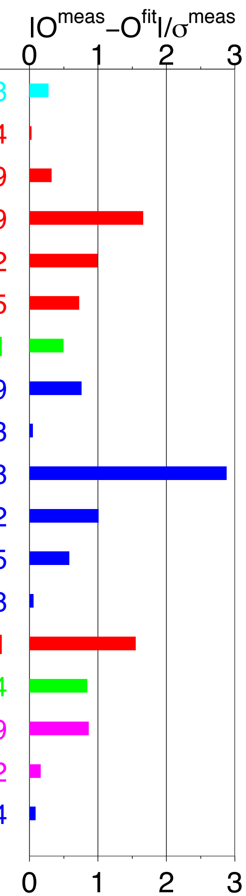




LEP + SLC legacy



	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.479
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.3 ± 1.1	173.4



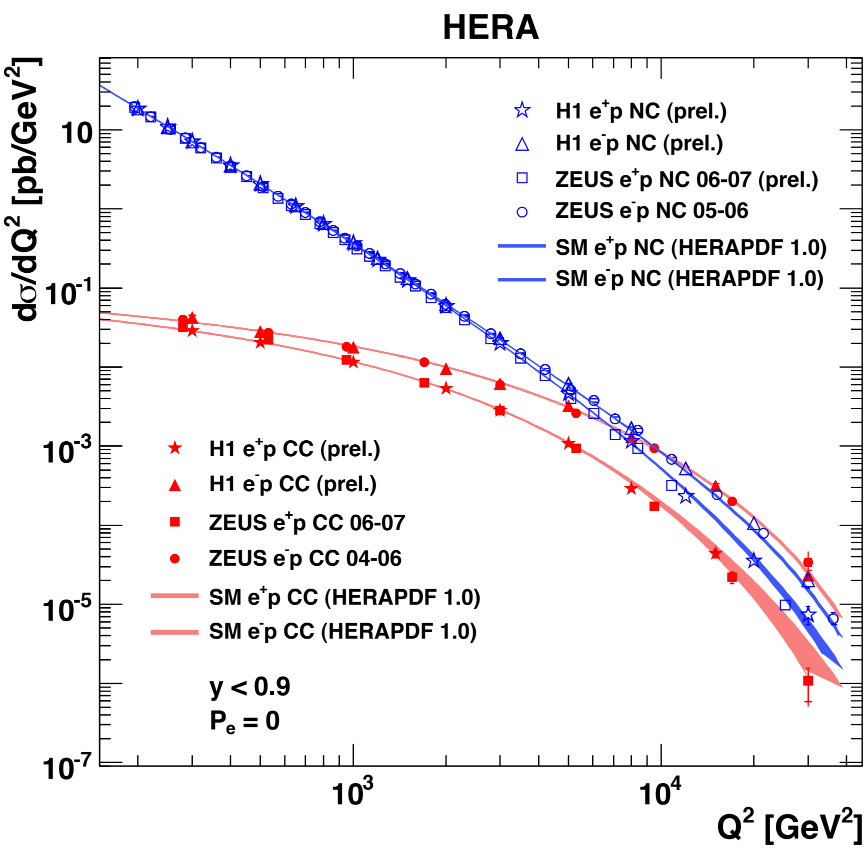
July 2010

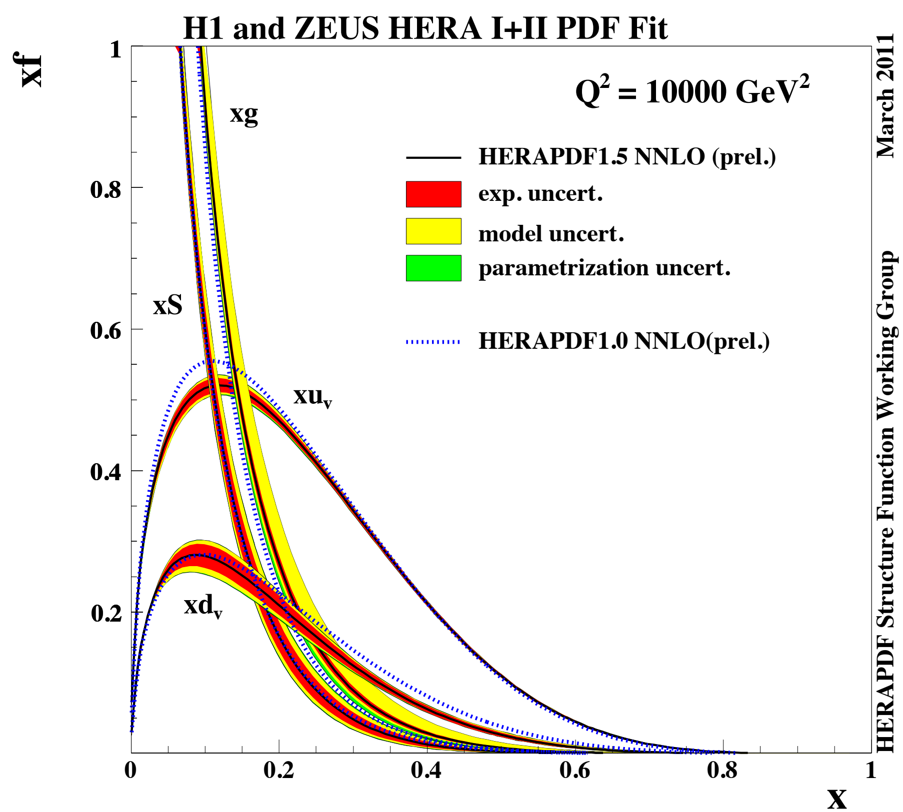
- Z and W mass, width and couplings
  - m_Z precision 2.1 MeV, (of which 1.7 MeV from beam energy)
  - Some intriguing discrepancies eg. asymmetries
- QCD, B physics
- Constraints on Higgs mass from direct searches and electroweak fits
- Constraints on SUSY and other physics beyond the Standard Model

HERA

- Neutral and charged current cross sections vs Q^2
- Searches for new particles

- H1 and ZEUS combined results being finalised
- Proton structure: PDF fits improve predictions for LHC

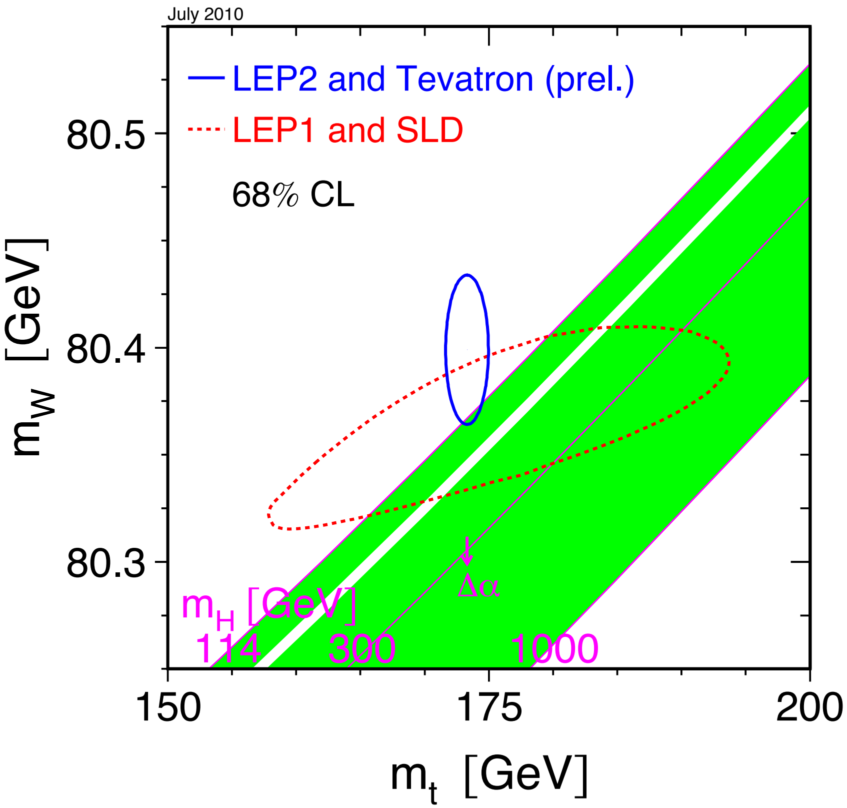


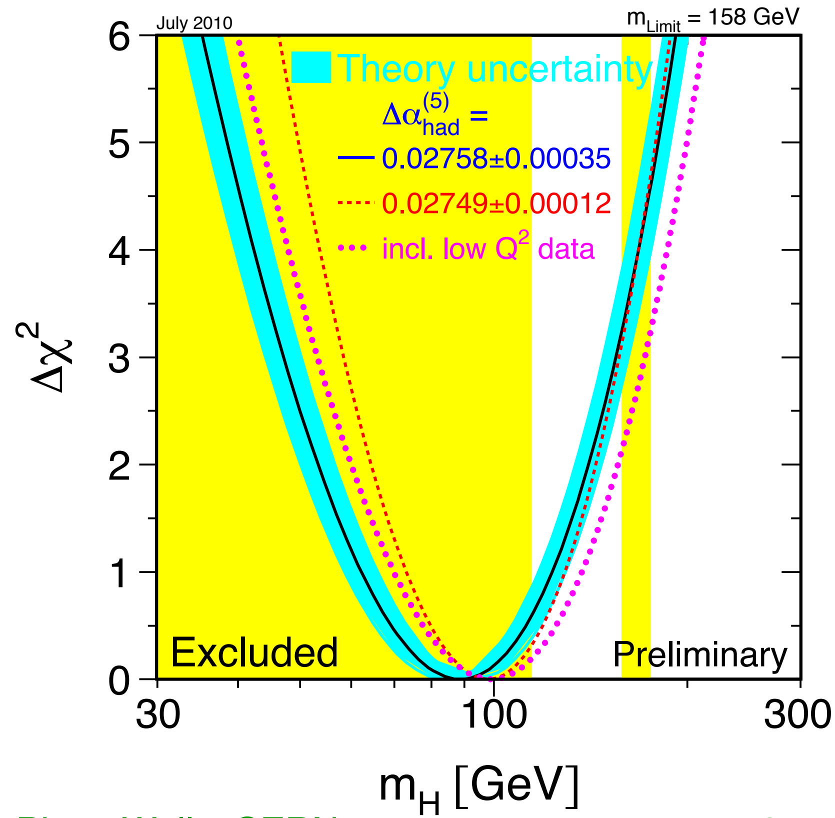


http://tevewwg.fnal.gov/

Tevatron – CDF and D0

- Top mass precision of 1.1 GeV (Summer 2010)
  - Will be below stated LHC goal of 1 GeV with latest updates
- Tevatron W Mass uncertainty 31 MeV
  - Combining with LEP, world average precision 23 MeV
  - Ultimate precision may be ~15 MeV

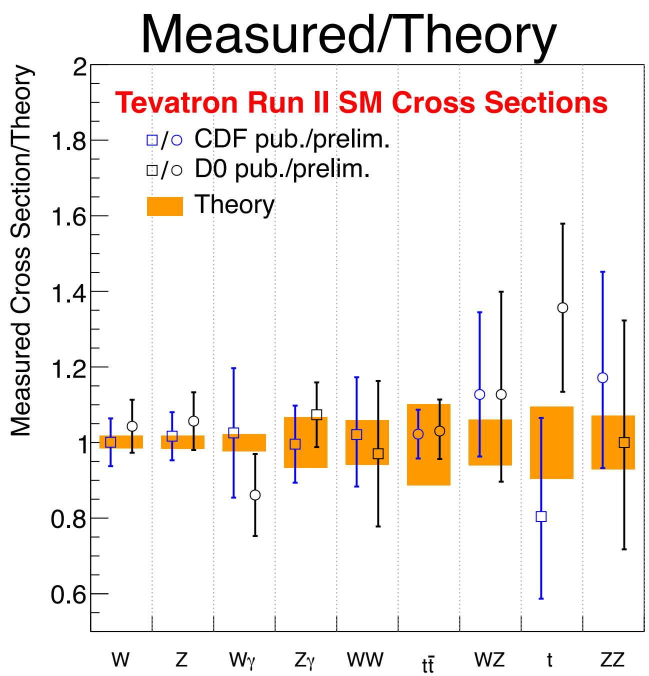


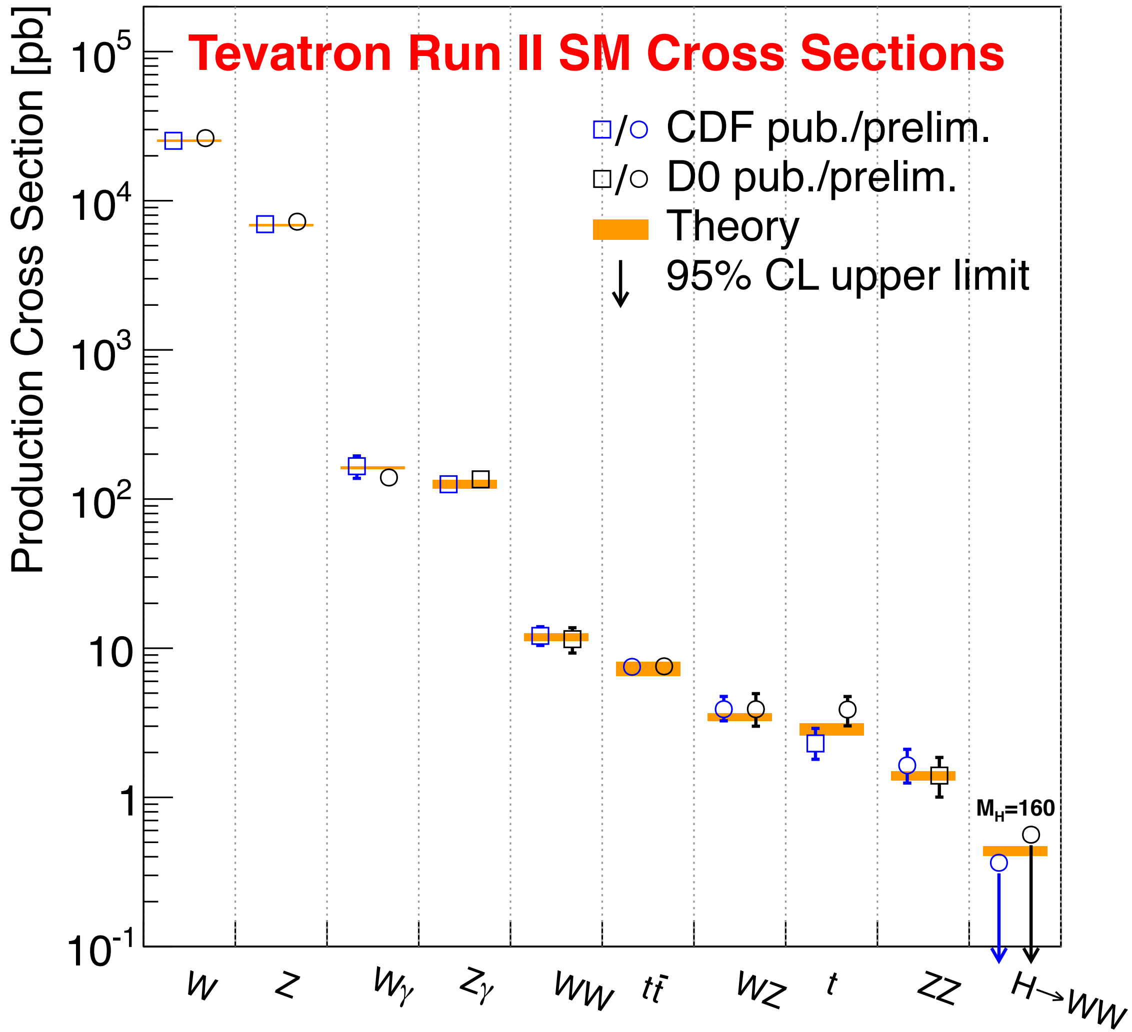


Electroweak and top cross-sections

σ(tt) measurement is more precise than the theoretical prediction

Higgs search – see later



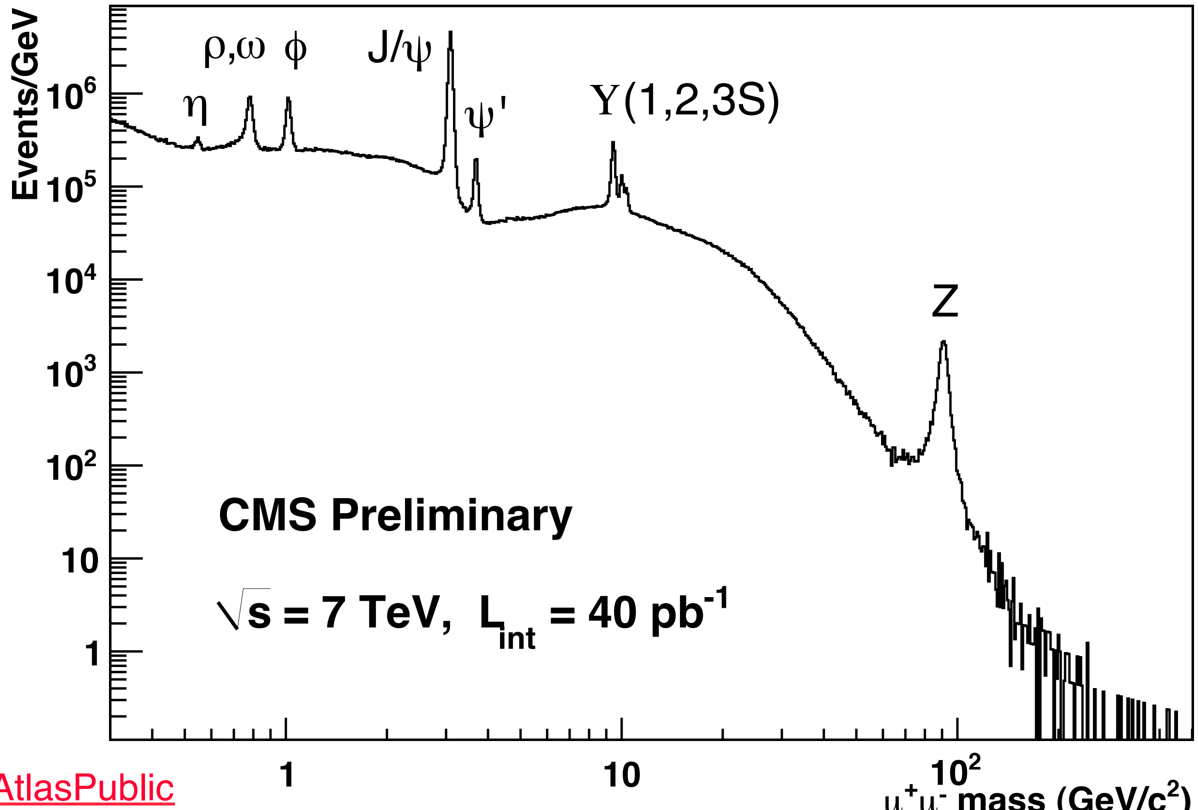


LHC with $1fb^{-1}$ at 7 TeV

- Experiments and collider are operating very well
- 20^{th} century discoveries firmly re-established at the LHC
- Sensitivity to physics beyond the Standard Model and beyond the Tevatron reach

Muon pair mass spectrum with known resonances

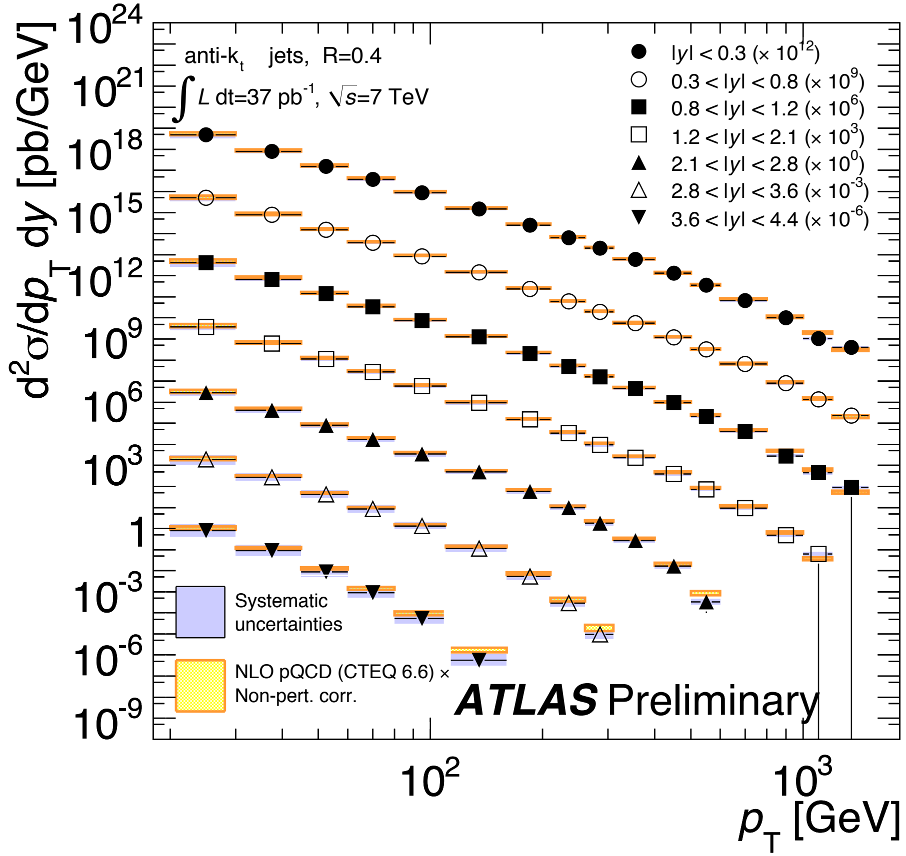
Verify calibration and look for new resonances, eg. Z'



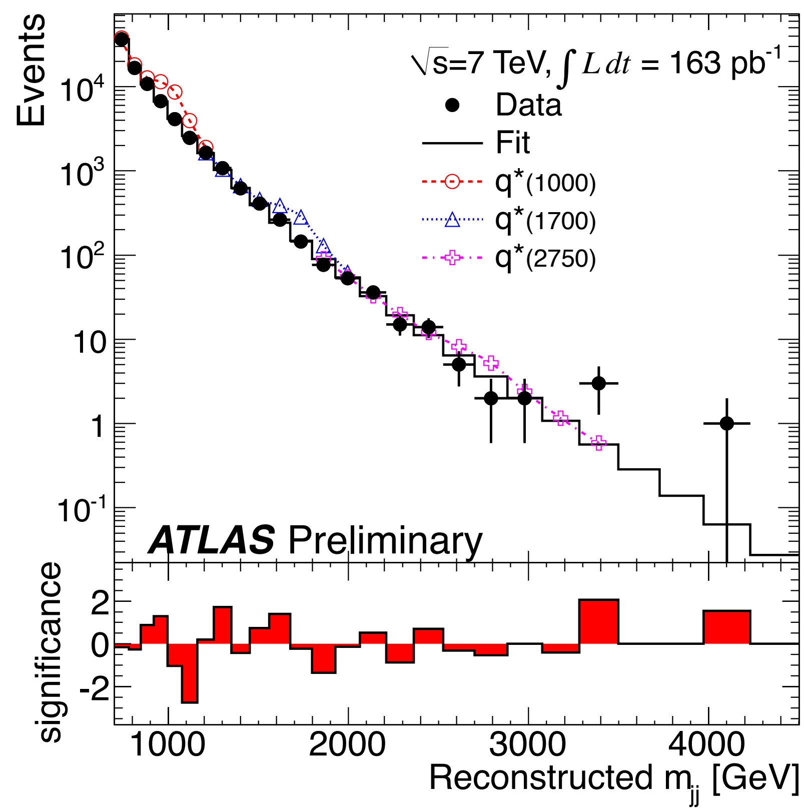
https://twiki.cern.ch/twiki/bin/view/AtlasPublic
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

LHC jets

- Inclusive jet distribution:
  - Individual jets with p_T greater than 1 TeV

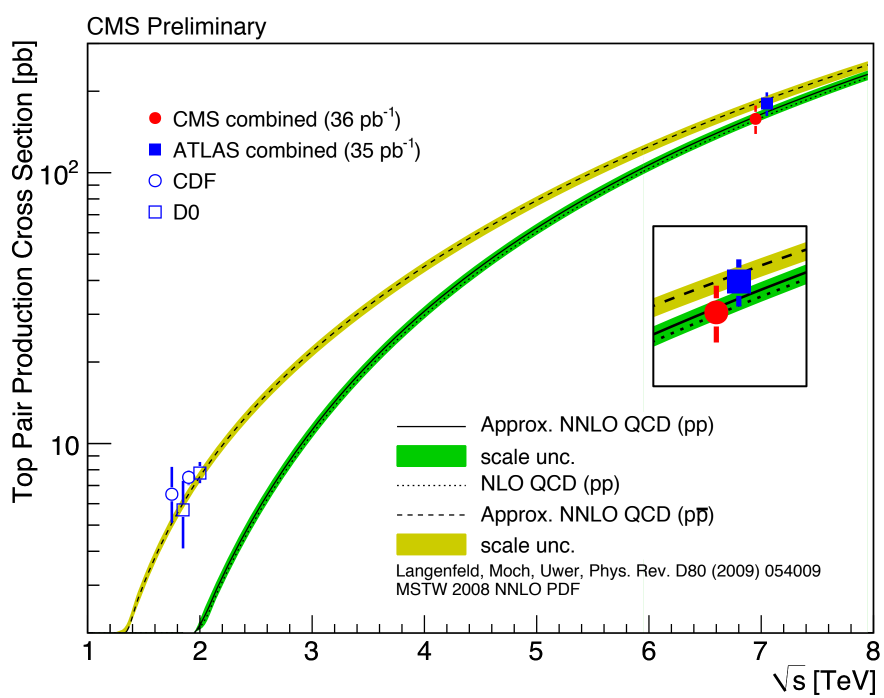


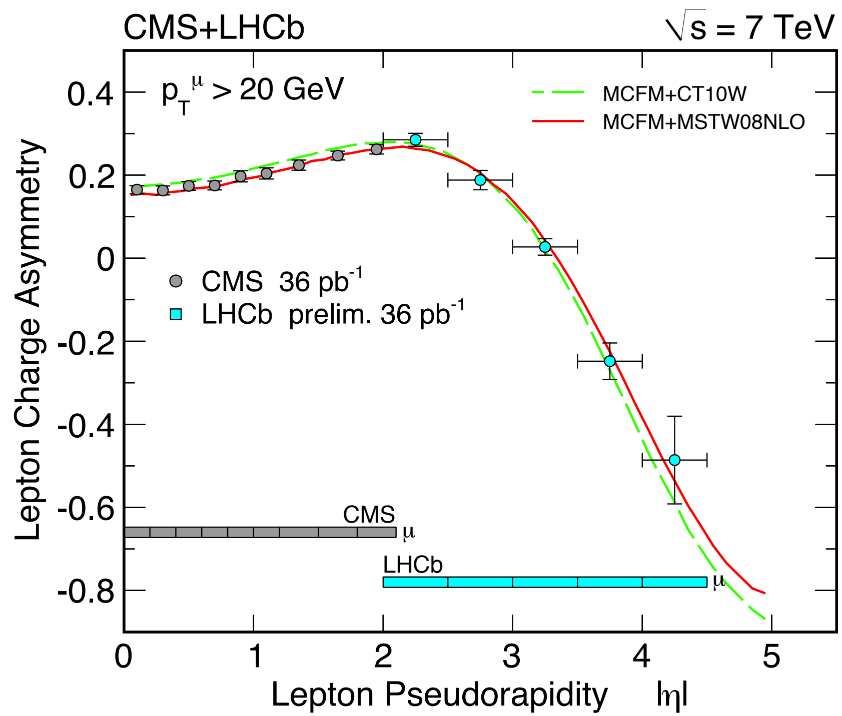
- Dijet mass spectrum
  - Extends to 4 TeV, exclude eg. q* with m<2.49 TeV



LHC analysis chain in full swing

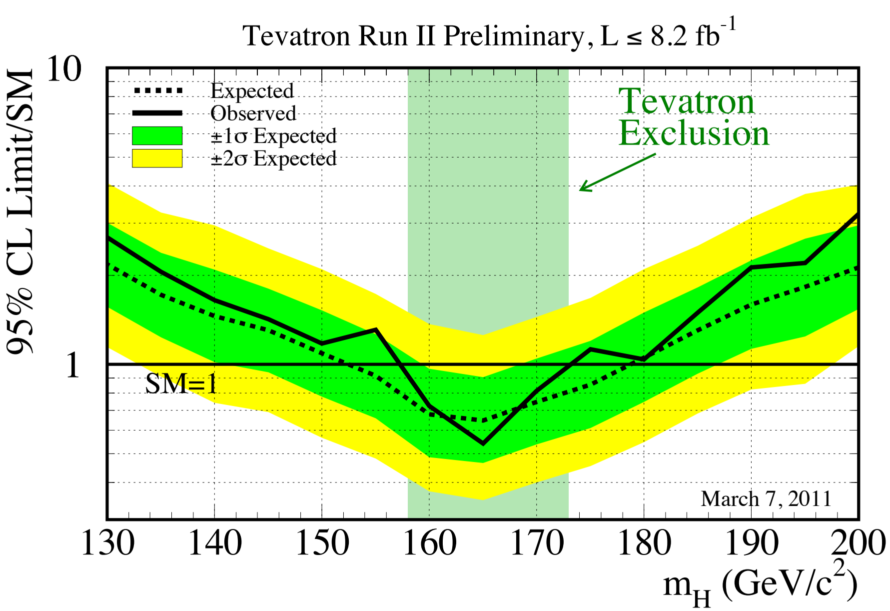
- Headline physics results depend on detailed technical studies
  - Operation, trigger, calibration, grid computing
  - Identifying leptons, jets, missing energy
  - Understanding beam and instrumental backgrounds, and effects of pile-up
  - Luminosity uncertainty 3.5 to 4% level.
- Examples: Top pair production, W charge asymmetry

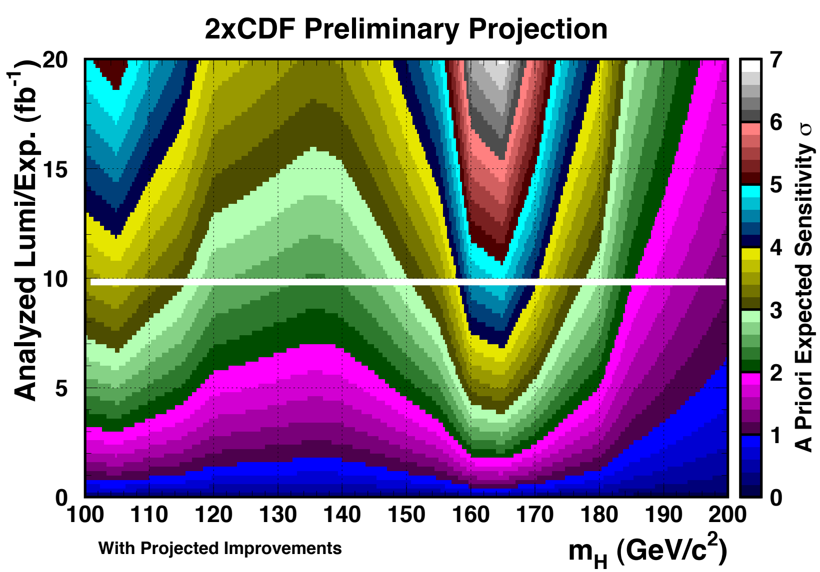




Tevatron Higgs search

- From March 2011, exclude at 95% C.L.: $158 < m_H < 173$ GeV
- New Tevatron combination will be shown in next week's plenary talk
  - "No channel left behind"; "Stay tuned…."
- Expect about 10 fb^{-1} for analysis per experiment by end of Sept 2011



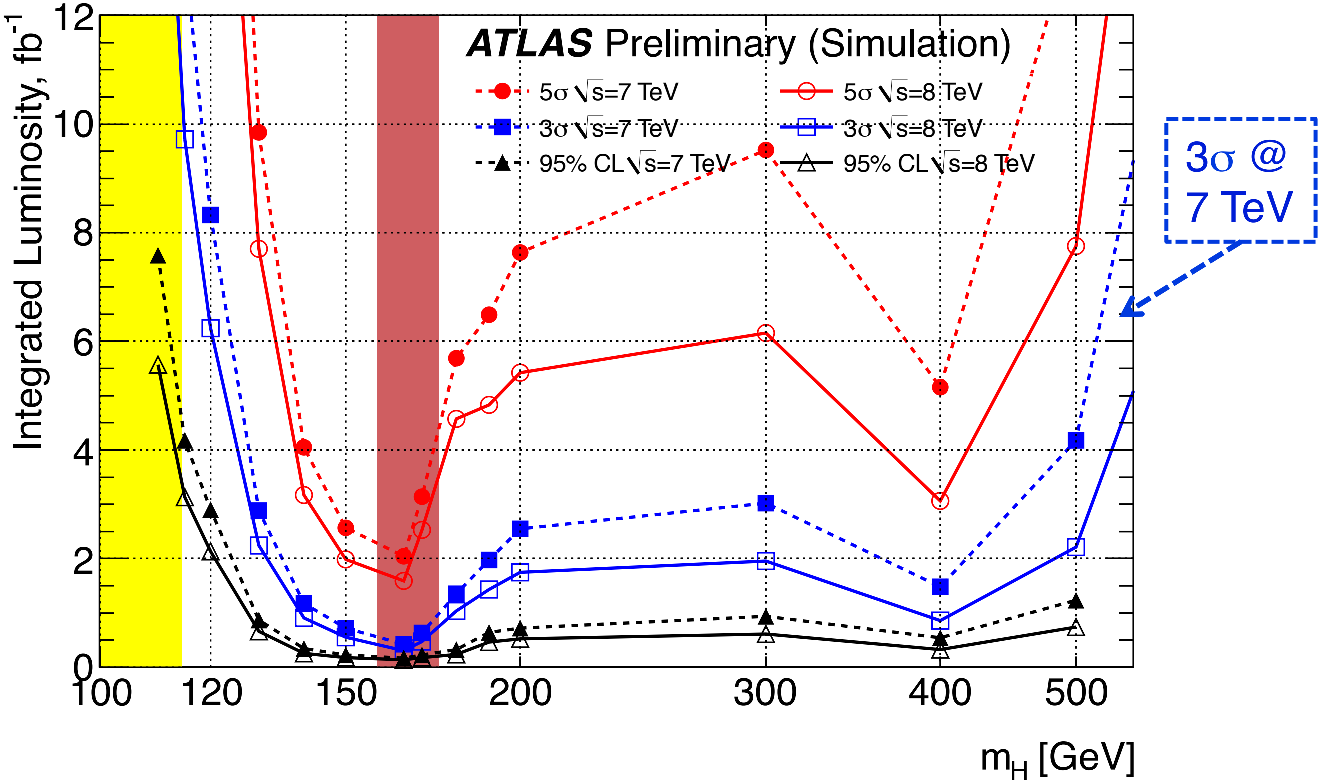


regions with ~3σ sensitivity
in optimistic projection, 2 expts

LHC Higgs

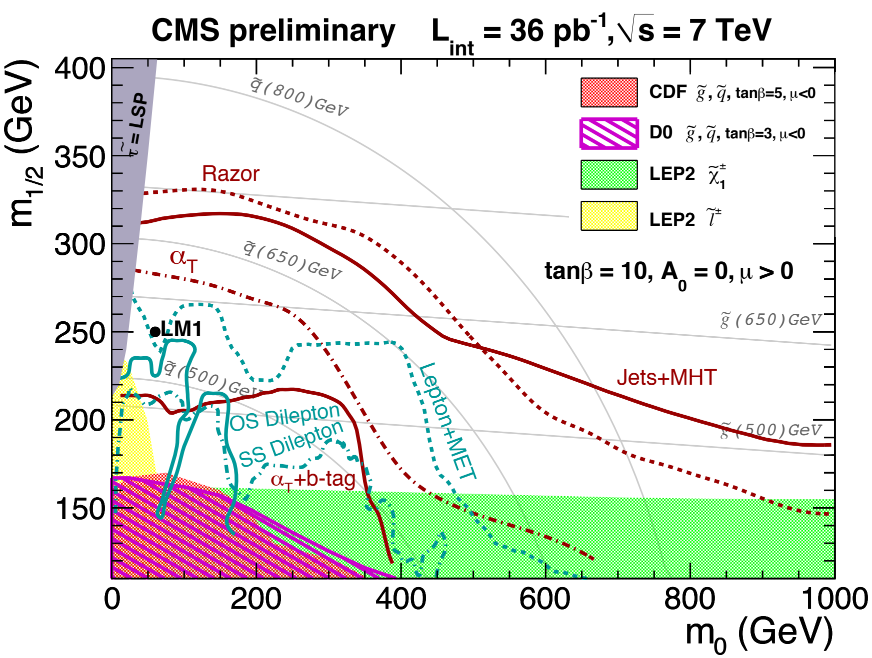
- Expect to close the book on the existence or otherwise of a Standard Model-like Higgs with the 2011-2012 data sample (10 fb^{-1})
- Very exciting new results at this conference with 1fb^{-1}
- First LHC combinations are underway

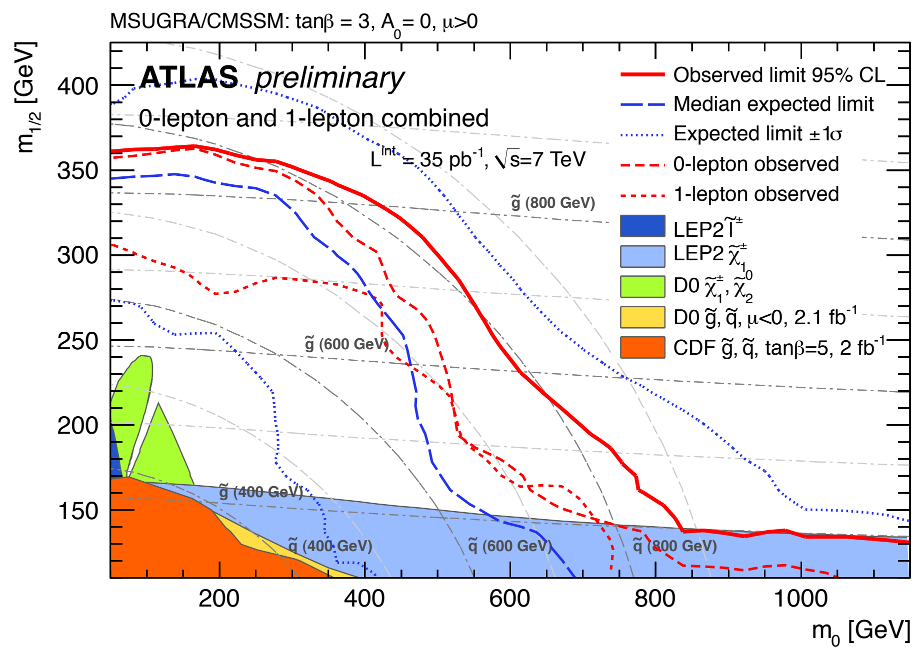
ATLAS and CMS have similar expectations, so can approximately scale the lumi needed by factor 2



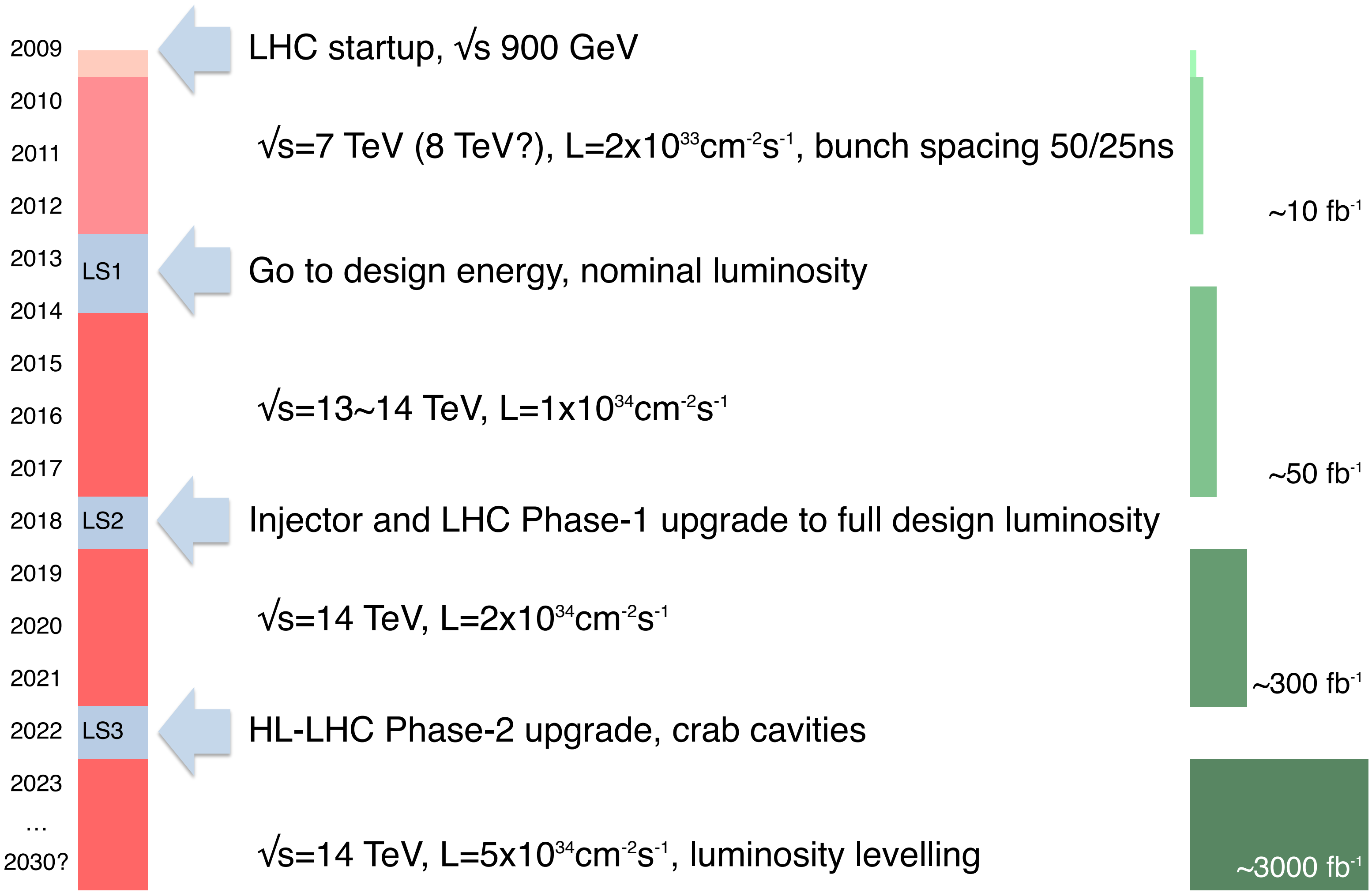
LHC SUSY and exotica

- Many new results with improved sensitivity
  - Unfortunately no sign of physics beyond the Standard Model
  - Still a long way to go with more luminosity and higher energy
- Examples: SUSY exclusions in with 2010 data

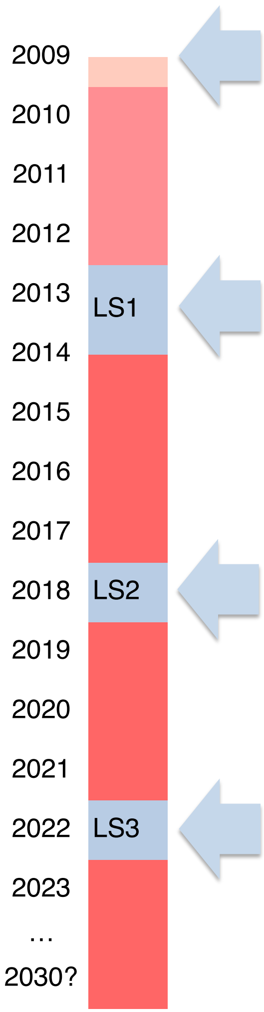




LHC *draft* plan



Tracker related upgrades



Startup

Phase-0

ATLAS: new inner pixel layer (IBL) with new Be beampipe,
refurbish present pixel, new evaporative cooling

CMS: reduced radius beampipe in preparation for new pixels

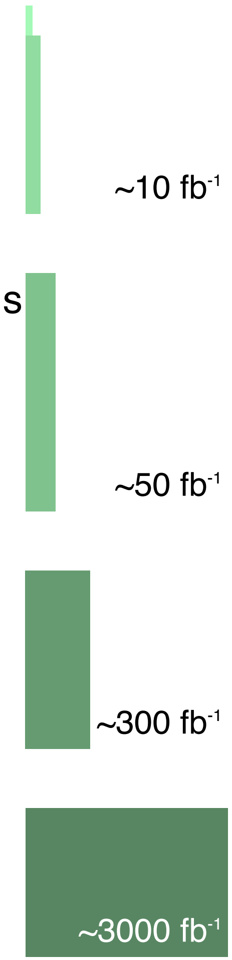
Phase-1

ATLAS: fast track trigger input to high level trigger (FTK)
new pixel if proven necesssary in 2013-14

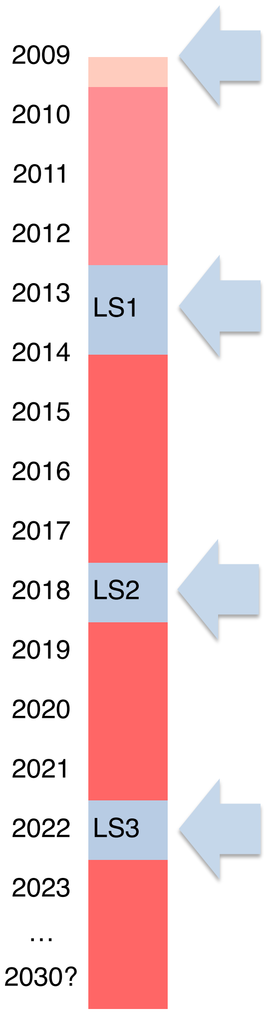
CMS: new 4-layer pixel system (to be ready end 2015)

Phase-2

ATLAS & CMS: Phase-2 trackers. Higher granularity for higher occupancy, improved radiation hardness, maybe with layers giving level 1 trigger.



Detector upgrades timeline



Startup

Phase-0

ATLAS: Replace minimum bias scintillators; cryo, magnet and muon consolidation; new shielding; Al beam pipes

CMS: Endcap muon 4th layer, shielding,1st layer granularity; replace photodetectors of forward and outer HCAL; replace beam scintillation counters; cryo, UPS, movement system & barrel muon consolidation; ALARA shielding test

Phase-1

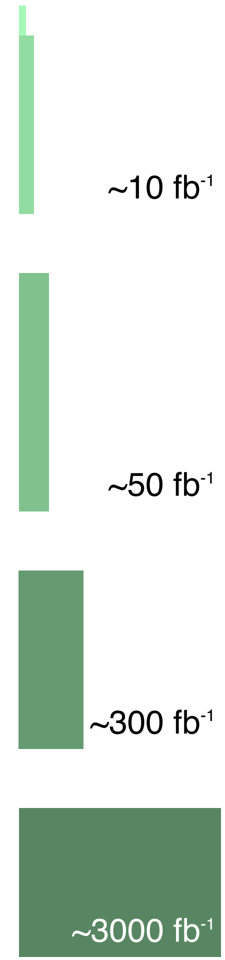
ATLAS: New muon small wheels; topological trigger; higher granularity L1 trigger; warm mini FCAL if needed

CMS: Replace barrel and endcap HCAL photodetectors & revise readout for depth granularity; major trigger revision

Phase-2 possibilities

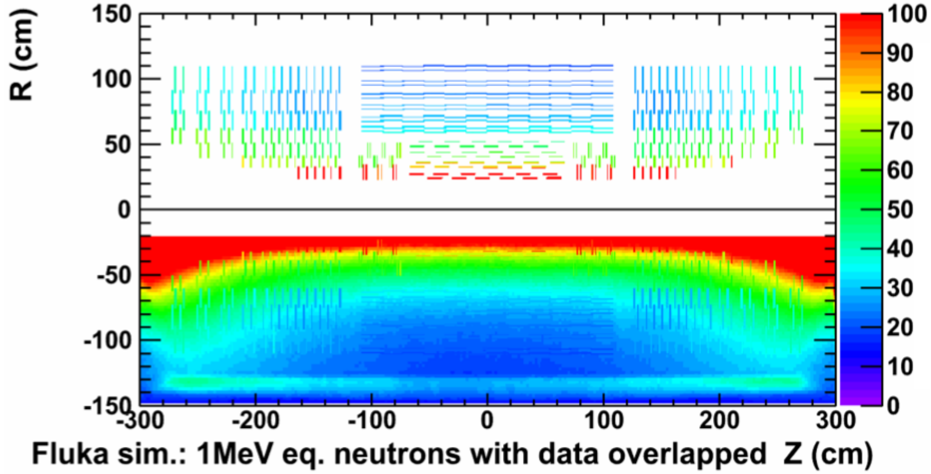
ATLAS: new FCAL; additional muon chambers; shielding; LAr cold electronics if needed; new calo front-end

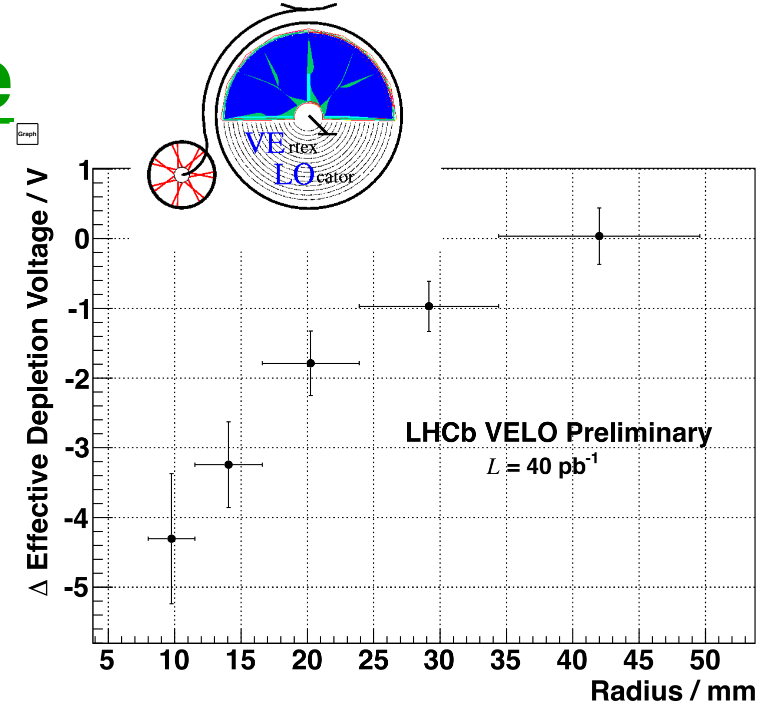
CMS: major electronics consolidation/replacement; new ECAL endcaps?; DAQ upgrade; fwd region revision



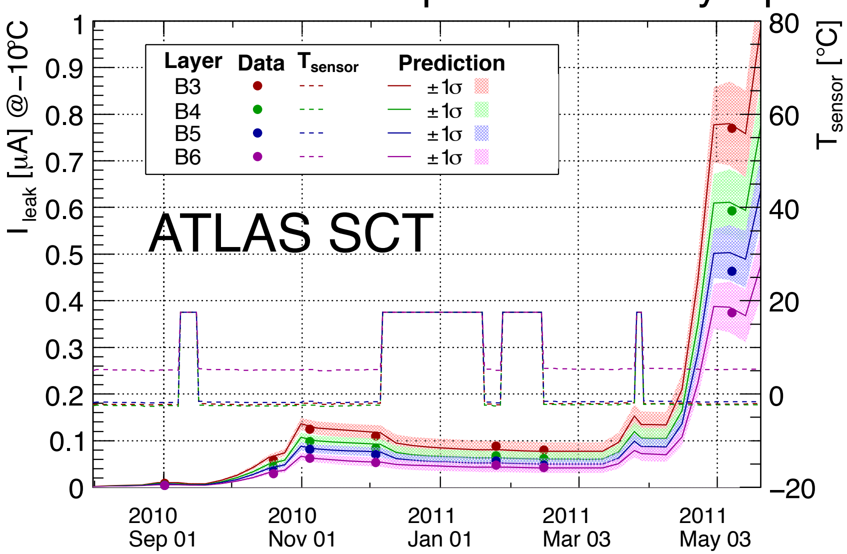
LHC radiation damage

CMS leakage currents proportional to FLUKA dose





Model with lumi and temperature history input

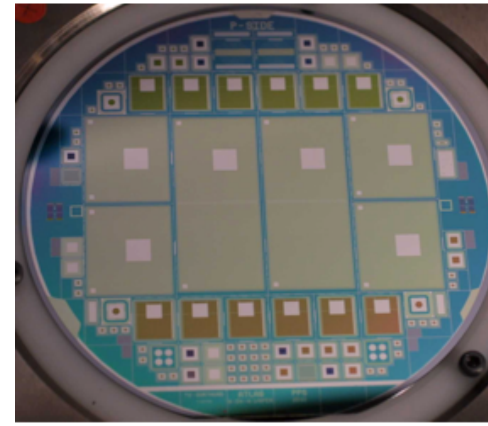


- Direct measurements of radiation and cavern fluences can be made and compared with simulation
- Also compare silicon detector evolution with expectation
  - Leakage current
  - Depletion voltage
- Important for long term survival

ATLAS new pixel layer

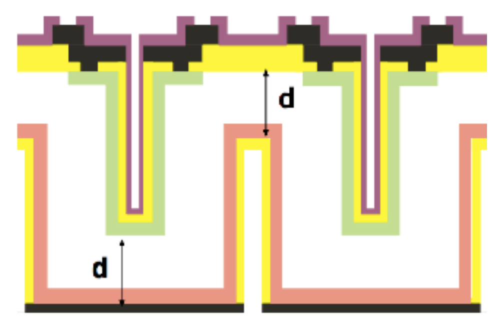
- Insertable b-layer (IBL) to be installed together with lower radius beam pipe.
  - Smaller pixels (50x400 μm → 50x250 μm)
  - New readout chip
- Fast track for installation in 2013
  - Full production of planar sensors. Also manufacture 3d sensors for possible use in forward part, taking advantage of geometry

Planar pixel sensors



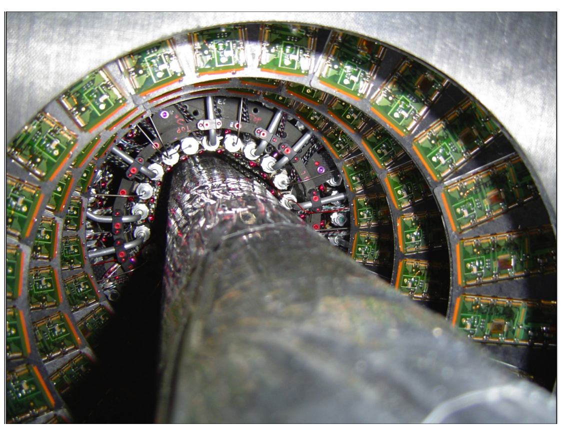
3d sensors – shorter path length for charge flow

n+ etched and filled from top

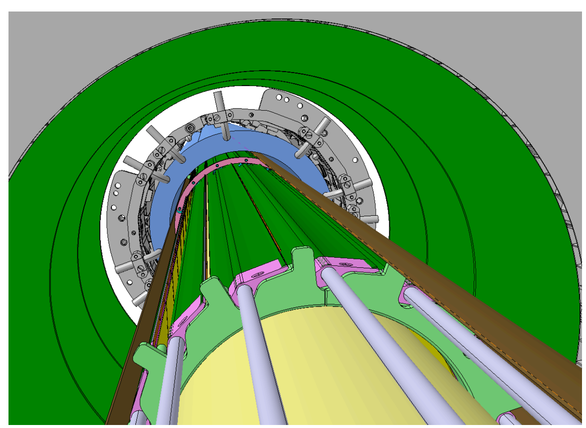


p+ etched and filled from bottom

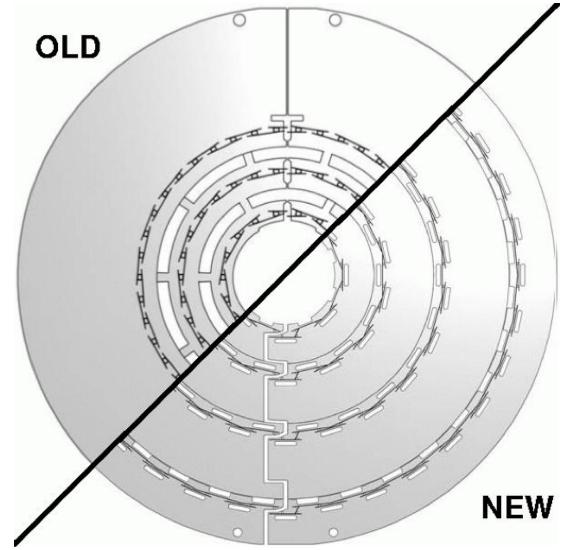
Present pixels



IBL on new beam pipe

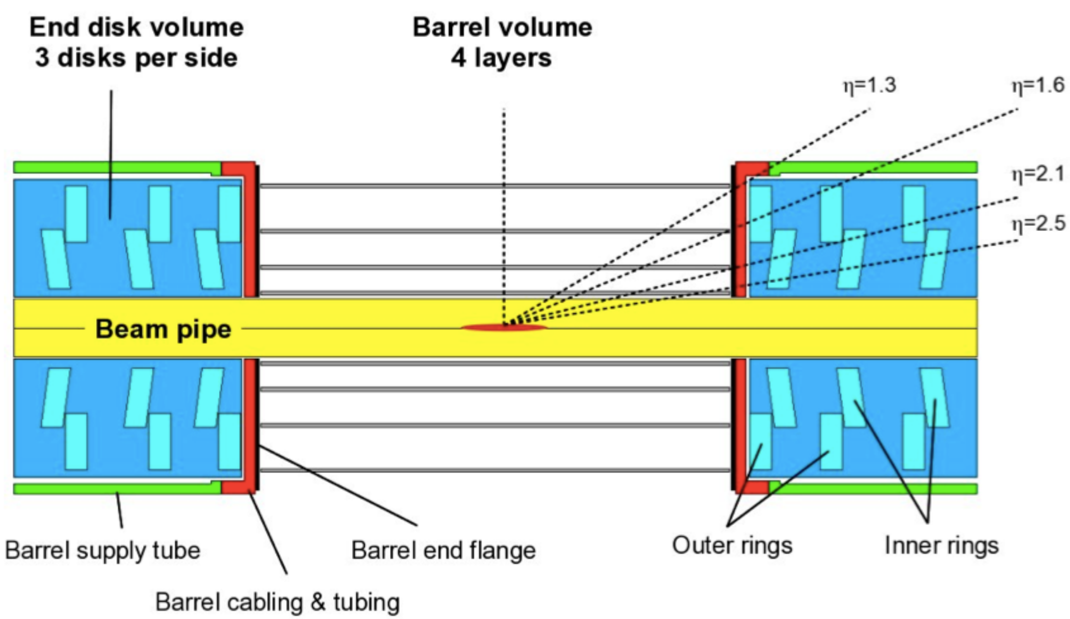


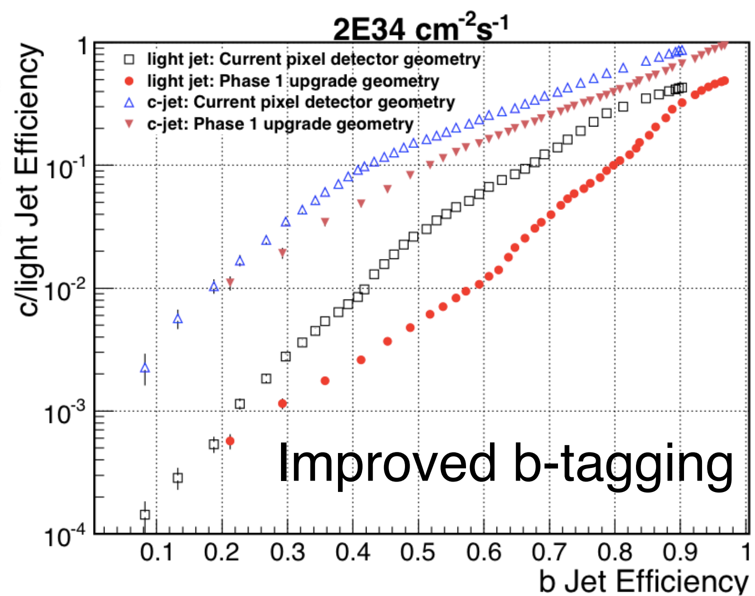
CMS phase-1 pixel upgrade



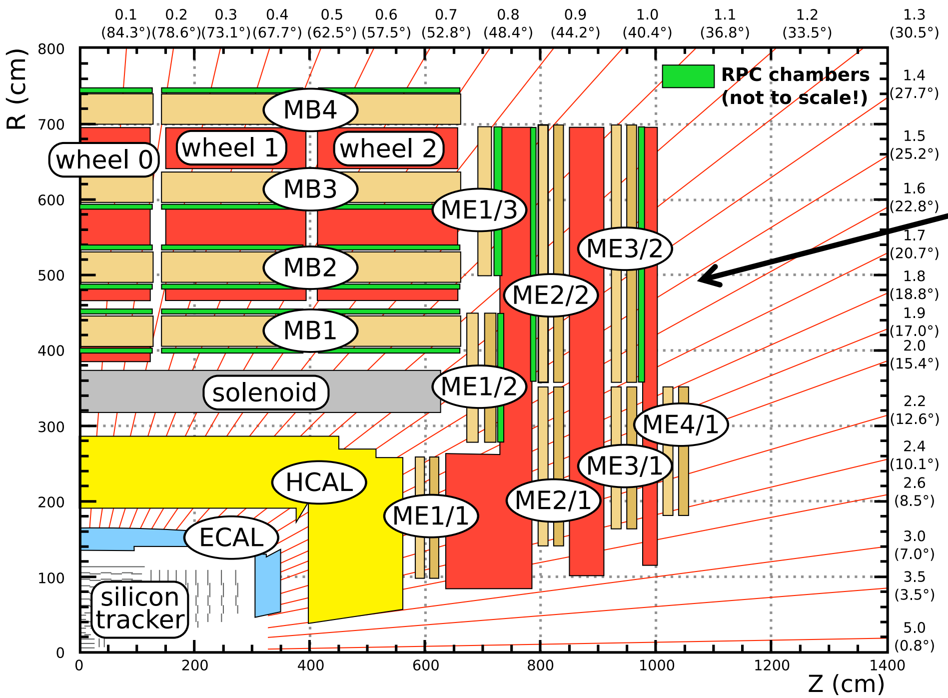
Upgrade for design lumi. Aim to be ready end 2015

- Additional layer (→ 4 barrels, 3 disks). Smaller radius beam pipe
- Improved read out chip (buffer, link speed) to prevent data loss
- CO_2 evaporative cooling, displaced optical transmitters and revised service routing result in less total material than present pixel





CMS phase-1 endcap muon and HCAL



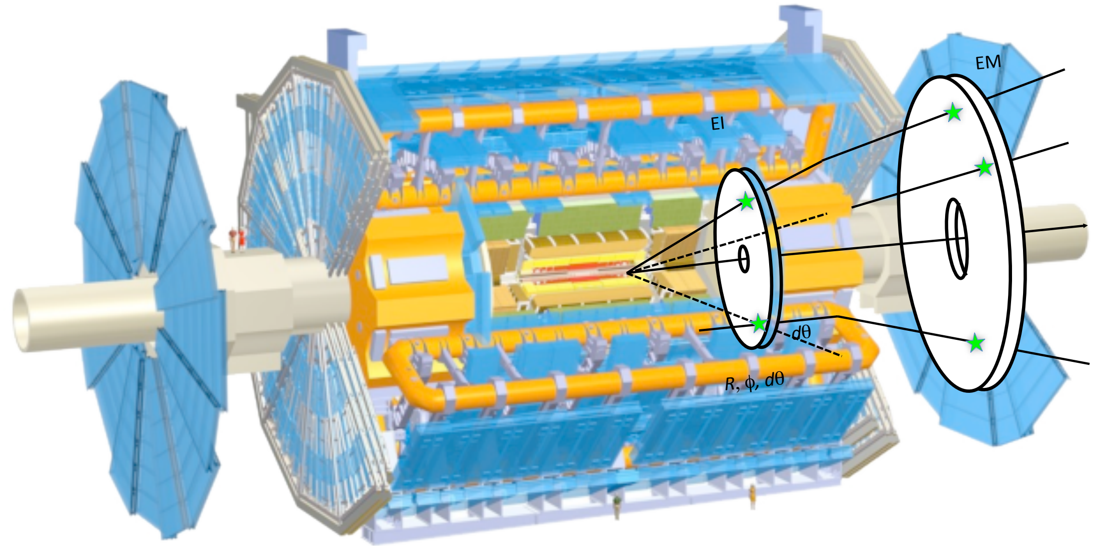
- ME4/2 CSC chambers & ME4/1+2 RPC chambers to be added, completing original design
- ME1 readout granularity increased
- New shielding wall

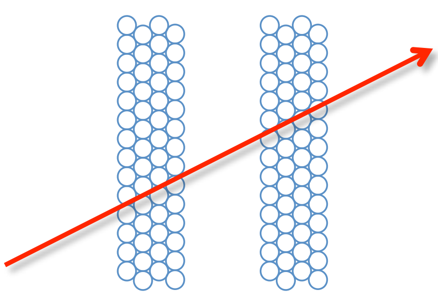
- Hybrid Photodiodes (HPD) of HCAL have discharge problems in low B-field.
  - Work OK at full field
- Silicon Photomultipliers (SiPM) now available as alternative
  - Commercial SiPMs already OK for outer HCAL
  - R&D in progress for fully satisfactory version for barrel and endcap

ATLAS muon small wheel

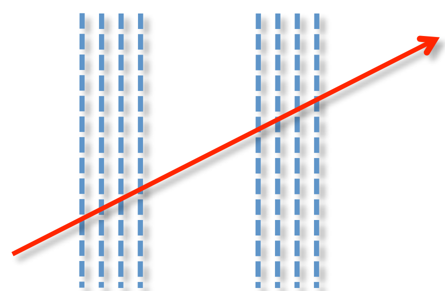
small & big wheels

- Reduce forward muon fake rate
- New small wheel with high rate tracking and fast segment finding for L1 trigger input
- Also space for extra neutron shielding

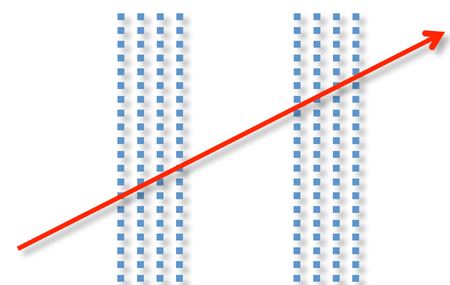




Small Tube MDTs



Large area micromegas



High rate TGCs

ATLAS muon small wheel

small & big wheels

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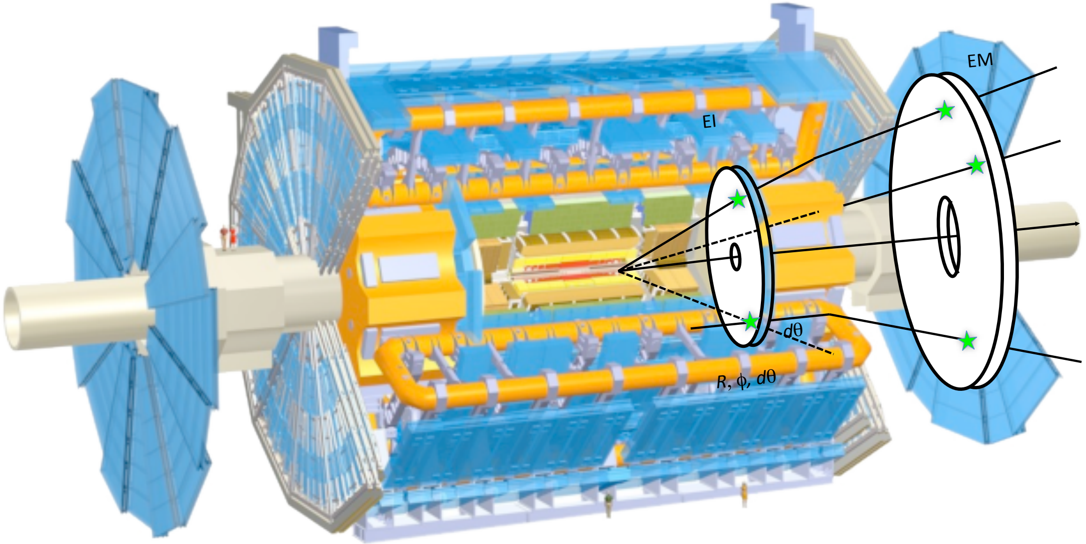

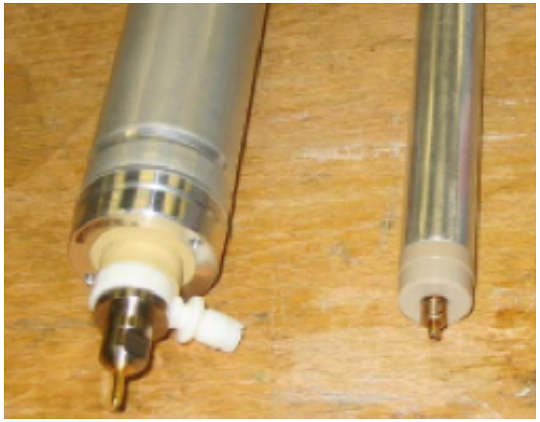

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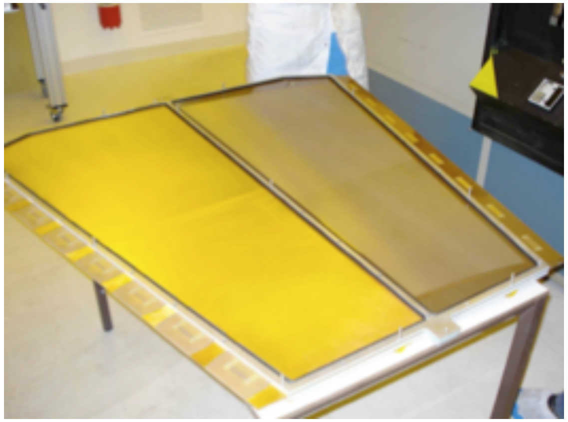
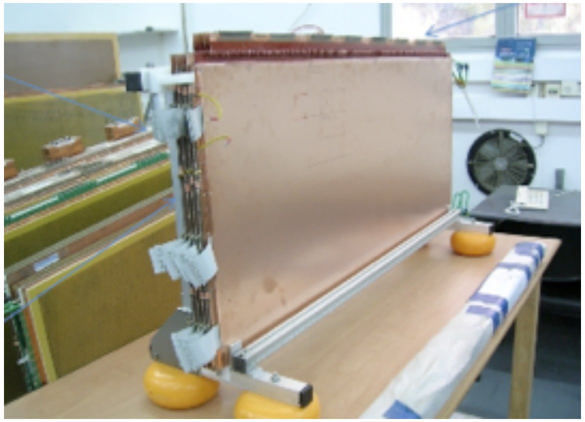


Large area micromegas



High rate TGCs

LHC detector upgrades - summary

- ATLAS Letter of Intent for the Phase1 Upgrade
  - In preparation for end 2011
- CMS Technical Proposal for the Upgrade of the CMS Detector Through 2020
  - [CERN-LHCC-2011-006 ; CMS-UG-TP-1 ; LHCC-P-004]
  - Includes discussion of Phase-2 R&D in the appendix
- The upgrade path is clear for the next ~10 years
  - Clear does not mean “simple”
  - R&D ongoing in parallel with simulation studies
  - Must be flexible in case of surprises from the data analysis
  - Understand cavern backgrounds, radiation doses and radiation damage with present detectors
  - Shutdown planning must include time-consuming consolidation work vital to maintain performance
  - Phase 2 detectors for HL-LHC to be designed in detail

LC design requirements

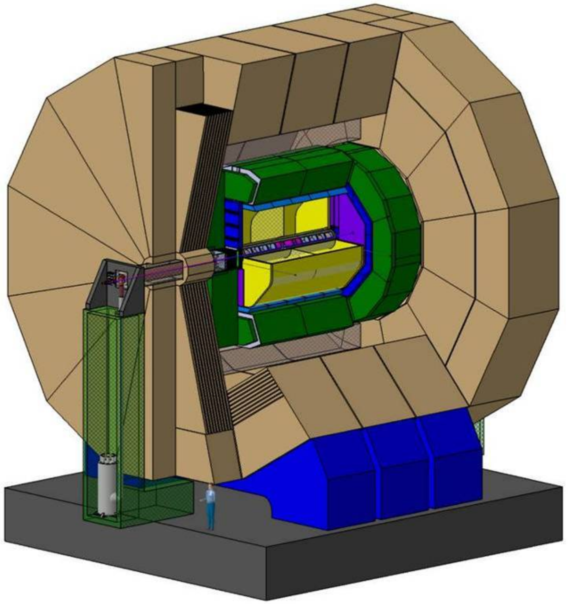
Areas requiring significantly improved precision compared to LHC detectors to achieve the physics goals of ILC/CLIC:

- Jet energy resolution to $\sigma(E)/E_{jet} \sim 3\%$ [LHC: ~10% at 100 GeV]
  - distinguish hadronic decays of W, Z, H, top, χ
  - high granularity calorimeters and particle flow algorithms
- Momentum resolution $\sigma(1/p_T) = 5 \times 10^{-5}$ (GeV^{-1})
  [LHC: $\sigma(1/p_T) = \sim 2 \times 10^{-4}$ (GeV^{-1})]
  - Higgs recoil mass (HZ events) and SUSY decay end-points
- Impact parameter resolution $\sigma = 5 \oplus 10/(p \sin^{3/2}\theta)$ μm
  [LHC: $\sigma = 20 \oplus 100/(p \sin^{3/2}\theta)$ μm]
  - Identify Z and H heavy quark (b, c) decays
- Implications for tracker:
  - Minimise material in trackers to reduce multiple scattering
  - Sensor precision must be matched by stable structures and precise alignment

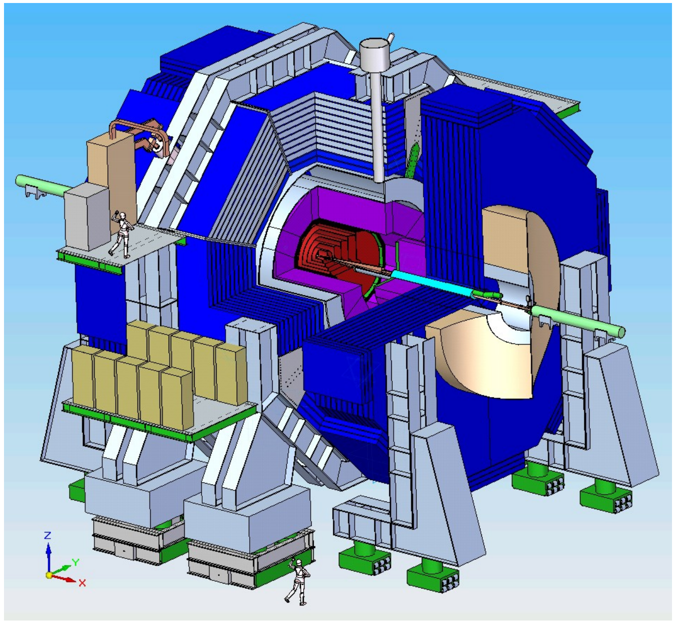
LC vs LHC environment

- Detectors need different aspect ratio to match distribution of interesting physics events
  - Also final focus quadrupoles as close as possible to the interaction point at LC
- Beam backgrounds
  - Most difficult background from $\gamma\gamma \rightarrow$ hadrons
  - However, no issue of radiation damage [10^{-4} times LHC]
- Beam time structure – bunch trains with typically one interesting event per train
  - Can read out all events without a hardware trigger, compared to LHC reduction from 40 MHz to <100 kHz at level 1

ILC detectors



- ILD: International Large Detector
  - "Large" - tracker radius 1.8m, silicon and TPC
  - High granularity calorimetry for particle flow analysis
  - Both in large solenoid with 3.5 T field



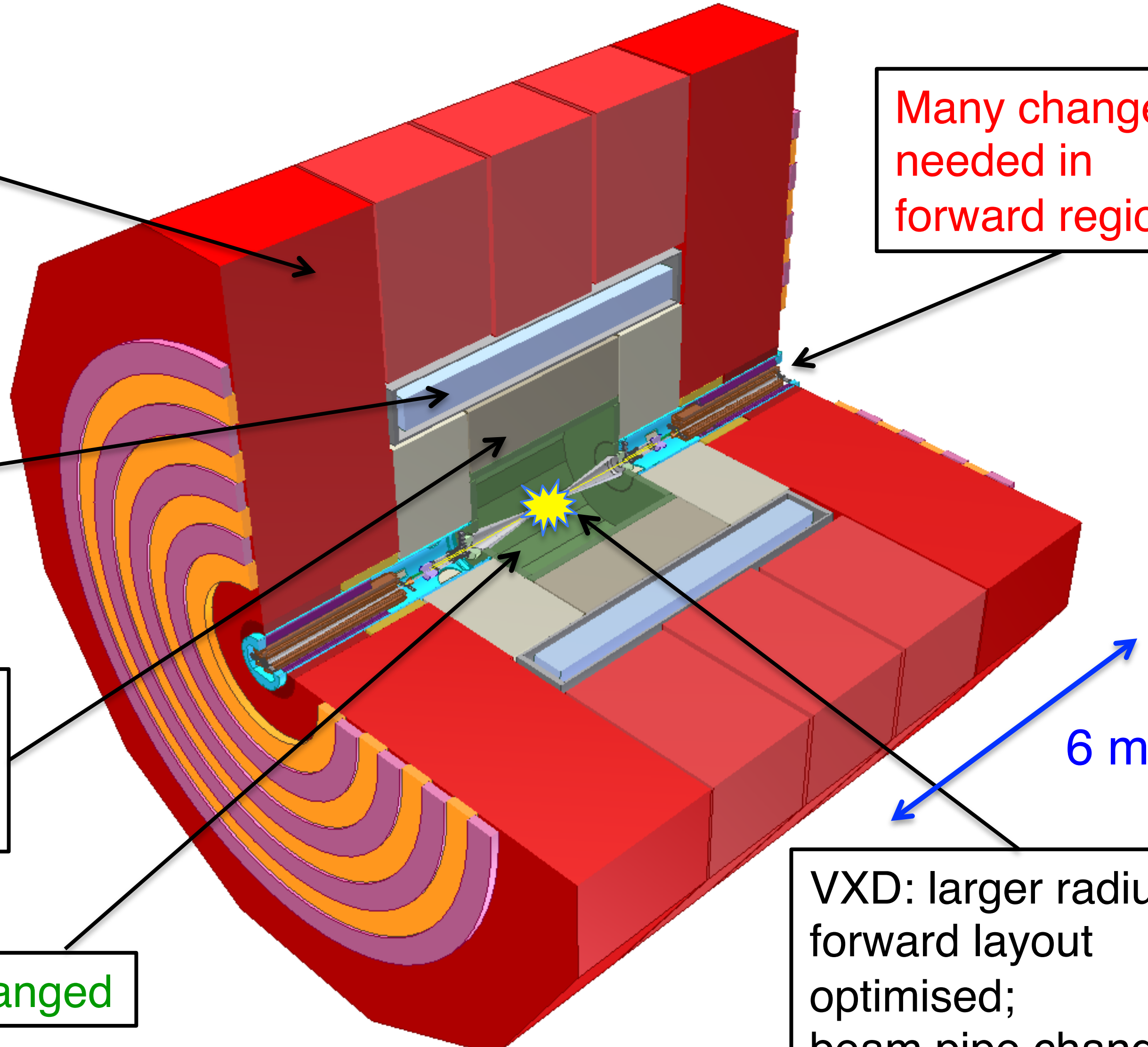
- SiD: Silicon Detector
  - Tracker radius 1.2m, all silicon
  - High granularity calorimetry for particle flow analysis
  - Both in large solenoid with 5 T field – pushing magnet technology

ILD changes for CLIC

Yoke dimensions and Yoke muon instrumentation layout changed

Many changes needed in forward region

Solenoid at 4T, dimensions ~unchanged

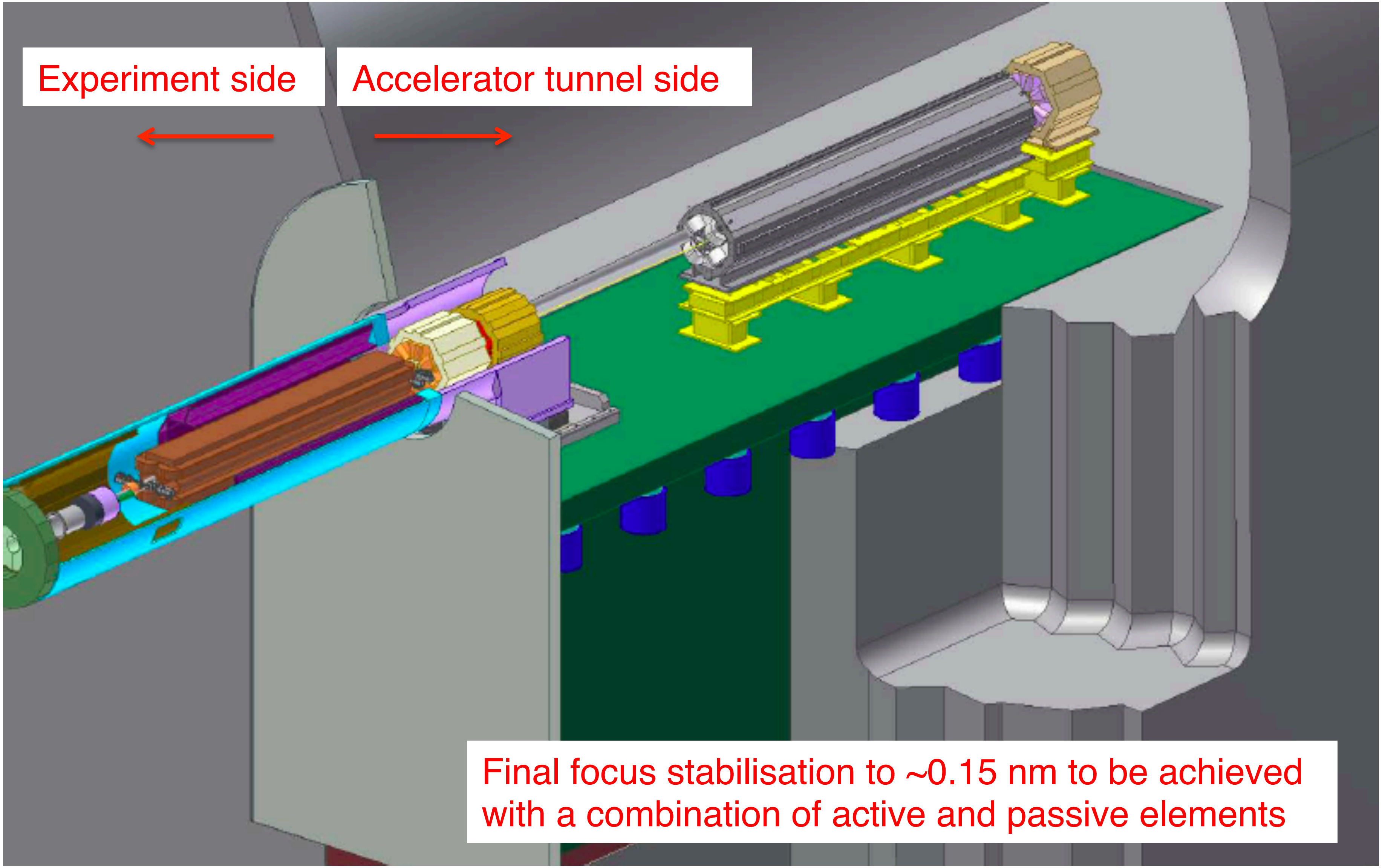


Calorimetry 7.5Λ, tungsten barrel, steel end-cap

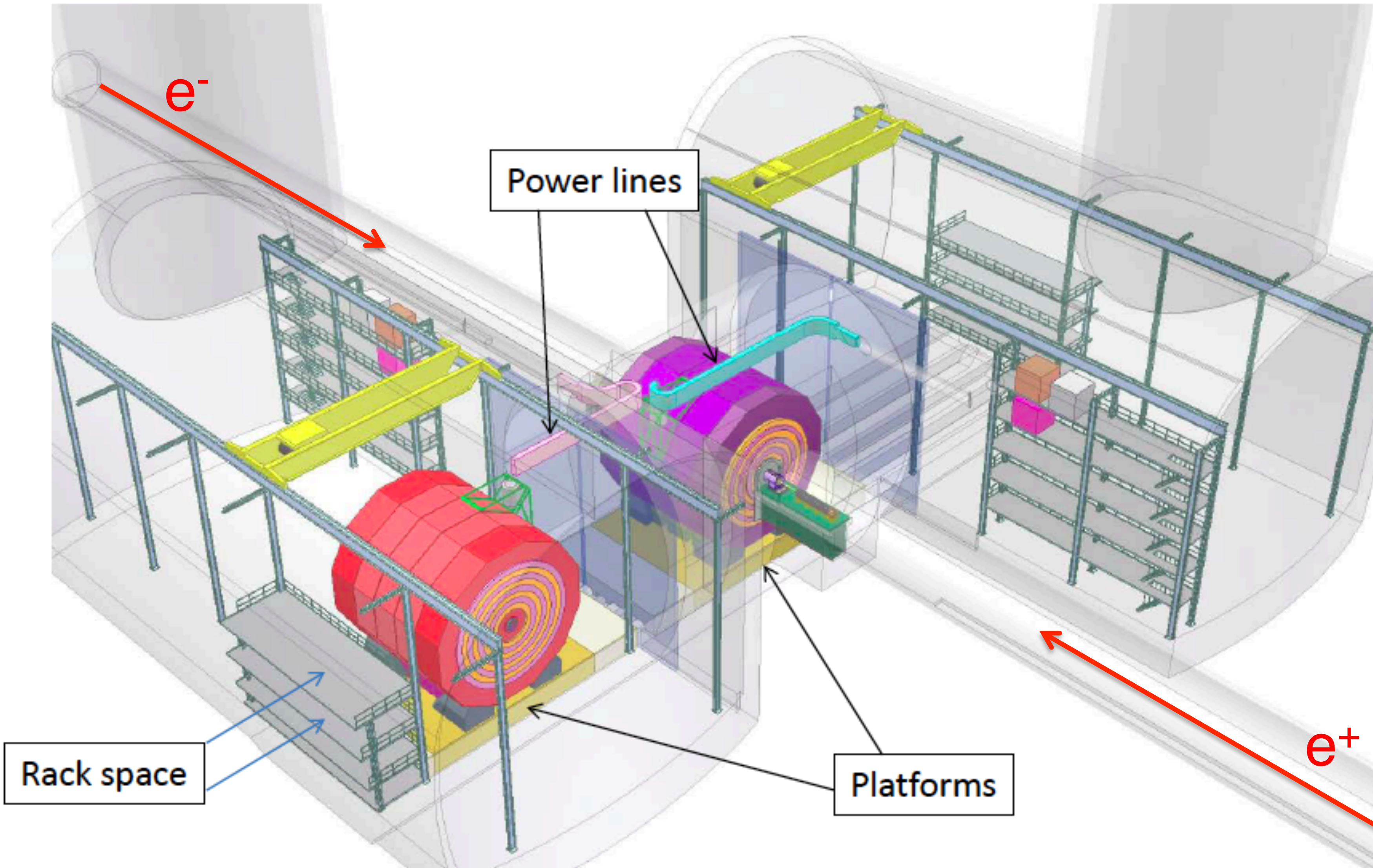
Main tracker unchanged

VXD: larger radius; forward layout optimised; beam pipe changed.

Final focus stabilisation at CLIC



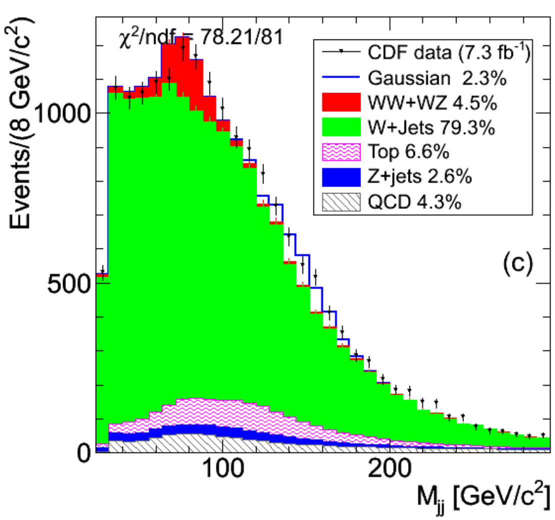
Two LC experiments in push-pull

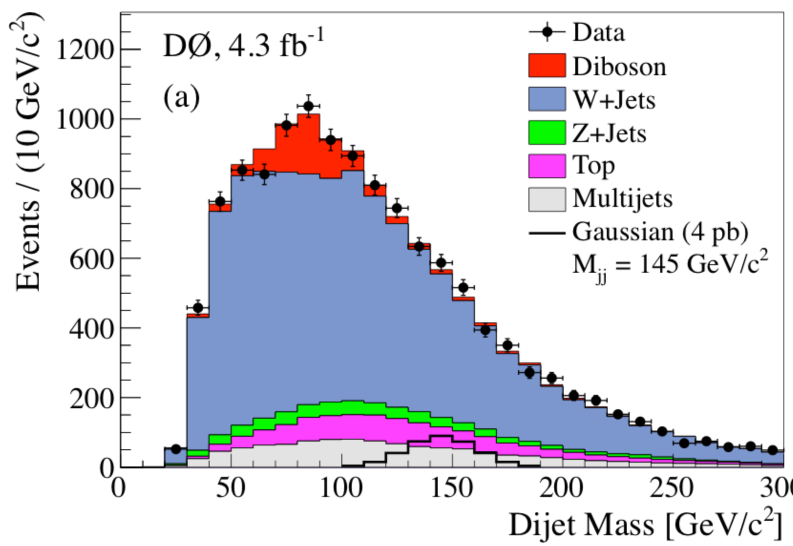


Push-pull

- Benefits
  - Complementary detectors with different technologies
  - Independent analyses
- Disadvantages
  - Additional cost and complexity of mechanics and services
  - Alignment reproducibility for machine and experiment
  - Loss of accelerator efficiency after interruption to smooth running
- Example of a famous recent cross check from CDF and D0

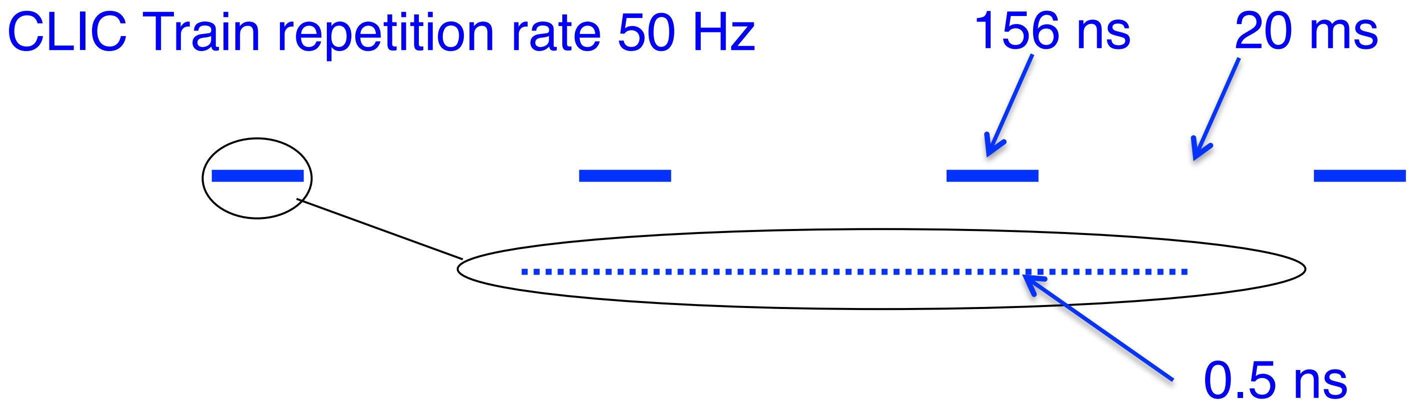
Dijet mass in e/μ ν j j events



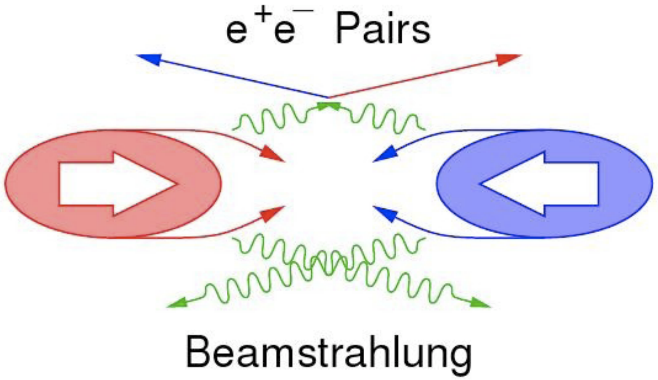


Beam time structure

- LHC design 25 ns bunch spacing, ~continuous
  - Precise time measurements to reject non-collision background
- ILC 5 Hz trains of 1312 bunches, 738 ns apart
  - (spacing depends on final choice of RF scheme)
- CLIC 50 Hz trains of 312 bunches, 0.5 ns apart
- ILC/CLIC: Read out full train with no hardware trigger
  - Expect one interesting event per train
  - Time stamping of hits to reject background offline
  - Allows "pulse powering" of tracker at 5 Hz or 50 Hz

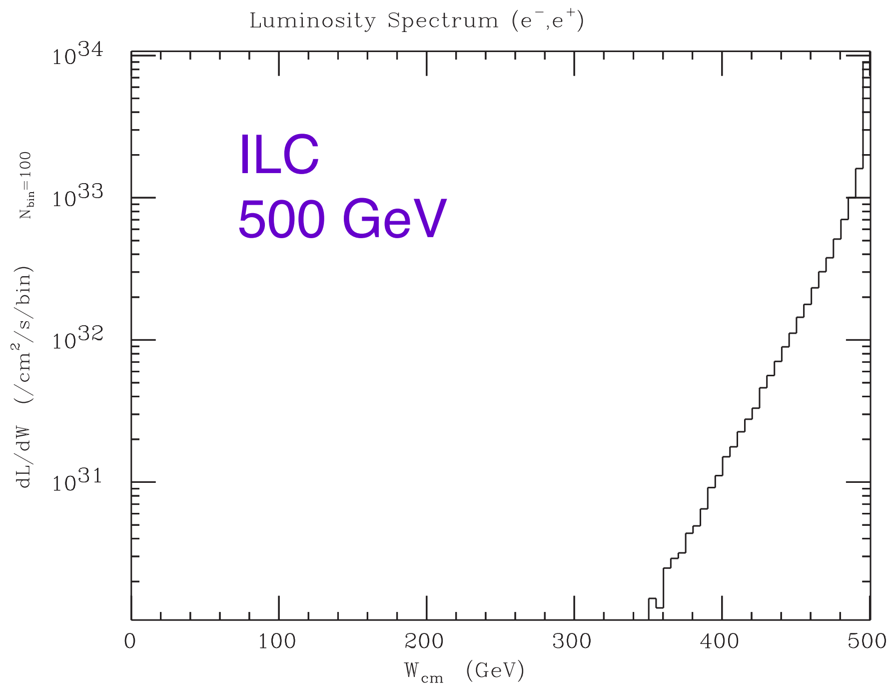


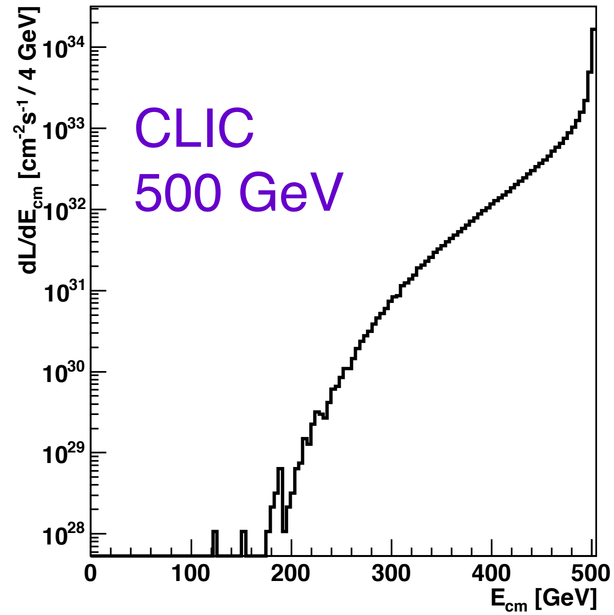
Beam backgrounds

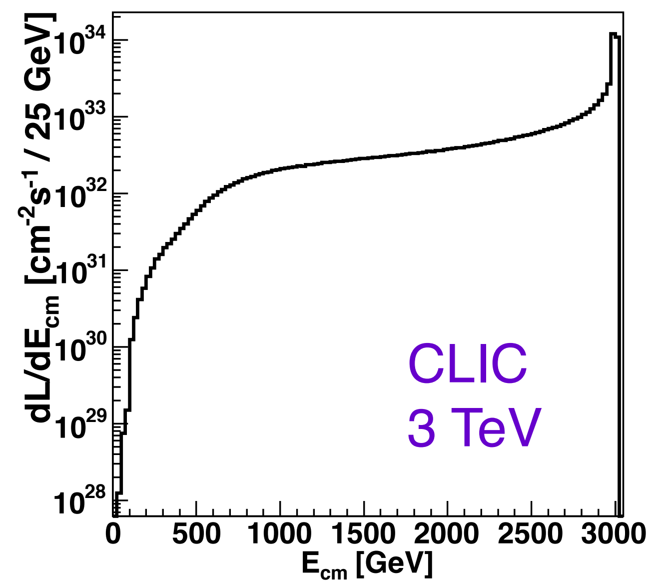


- CLIC situation more extreme than ILC due to smaller beam size.
- CLIC at 3 TeV:
  - Coherent pairs – 3.8 x 10^8 per bunch crossing
    - Disappear down beam pipe
  - Incoherent pairs – 3.0 x 10^5 per bunch crossing
    - Suppressed by solenoid
  - $\gamma\gamma \rightarrow$ hadrons – 3.2 events per BC
    - 28 particles, 50 GeV per BC, 15 TeV per train!
  - Halo muons from beam delivery system
    - Maybe up to 5 muons per train, spread over detector surface
- Compare to LHC at design luminosity:
  - ~25 minimum bias pile-up events per bunch crossing, spread in z but not in time. (Bunch length o(100) μm at LC, few cm at LHC)

LC centre of mass energy







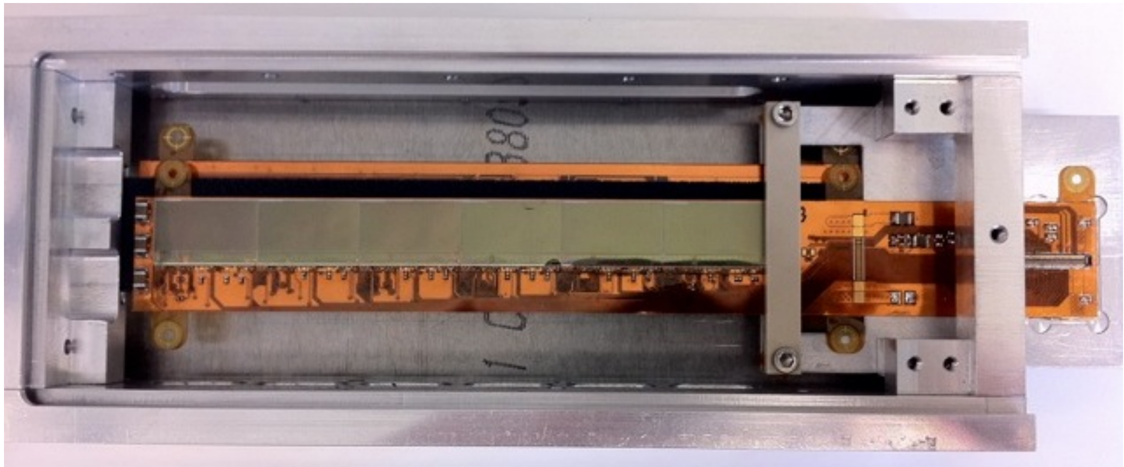
Want to know E_{cm} distribution as additional energy scale input to physics analyses

- CLIC at 3TeV – 30% of events are within 1% of the highest energy
- In ILC and CLIC, plan spectrometers before and after interaction point to measure beam energy distribution

LC Tracker feasibility

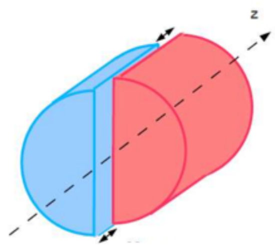
- Aim for air cooling, to reduce material from pipes and fluid
  - Low radiation dose, so no need to keep silicon sub-zero
  - Read out in bursts with pulse powering → lower heat load
- Possible challenges – studies are starting
  - Vibrations from air flow
  - Damage from repeated ramping of voltages in B-field
  - Thermal expansion/contraction
- For all stability issues, plans to use laser alignment systems: infra-red laser alignment (SiD) and frequency scanning interferometry (ILD)

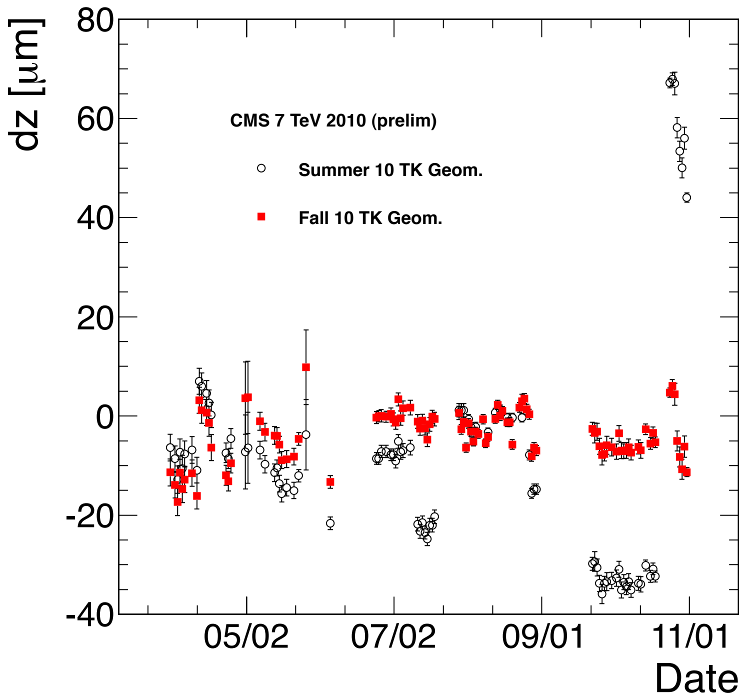
PLUME: Design, fabricate and test a Pixel Ladder with Ultra-low Material budgEt based on CMOS sensors.

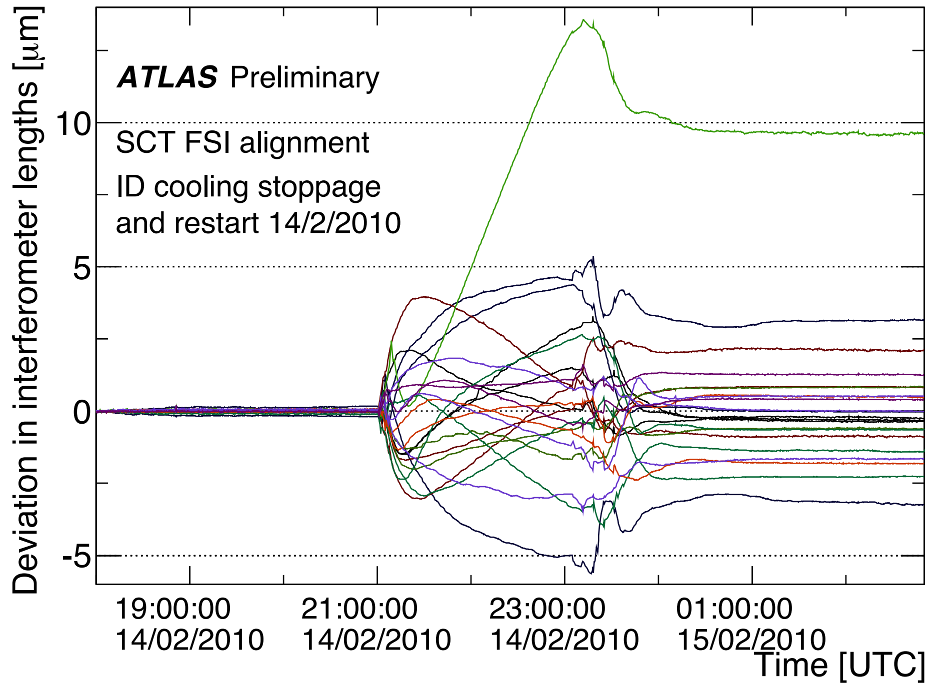


LHC alignment

- Alignment stability?
- CMS BPIX half barrel drifts along beam line corrected by calibration





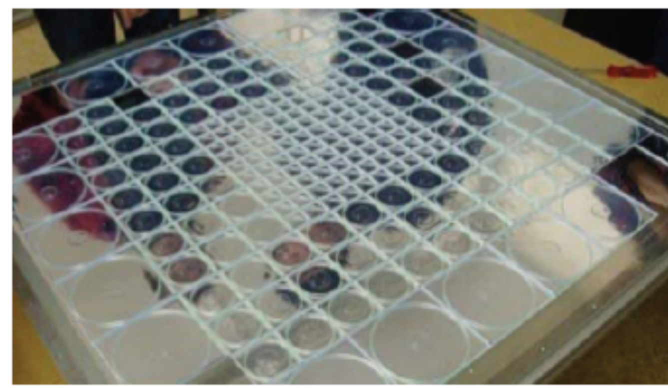


- ATLAS Frequency Scanning Interferometry internal to SCT barrel and end caps shows sub-micron movements outside cooling or B-field changes.
- CMS silicon strips tracker Laser Alignment System (LAS) shows modules stable to 1-2 μm (rms)

LC Calorimeter R&D

- CALICE collaboration have made several prototypes and carried out beam tests, including
  - Silicon tungsten ECAL
  - Scintillator ECAL and HCAL
  - Gaseous HCAL
  - Scintillator tungsten HCAL for CLIC
- Input to:
  - Geant-4 comparisons
  - Particle flow algorithms

Scintillator tungsten HCAL prototype



Scintillator tiles, 3*3 cm (at centre)

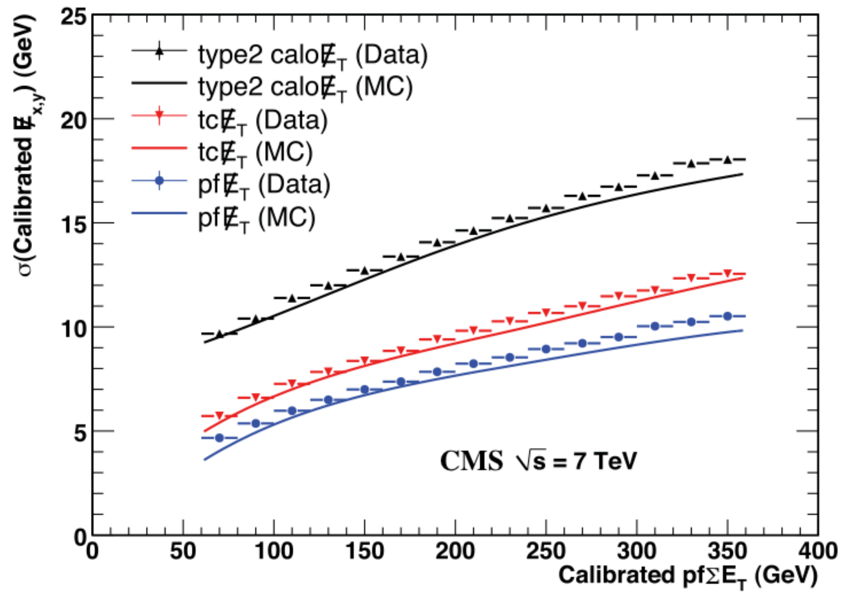
Read out by SiPM (and wave-length shifting fibre)

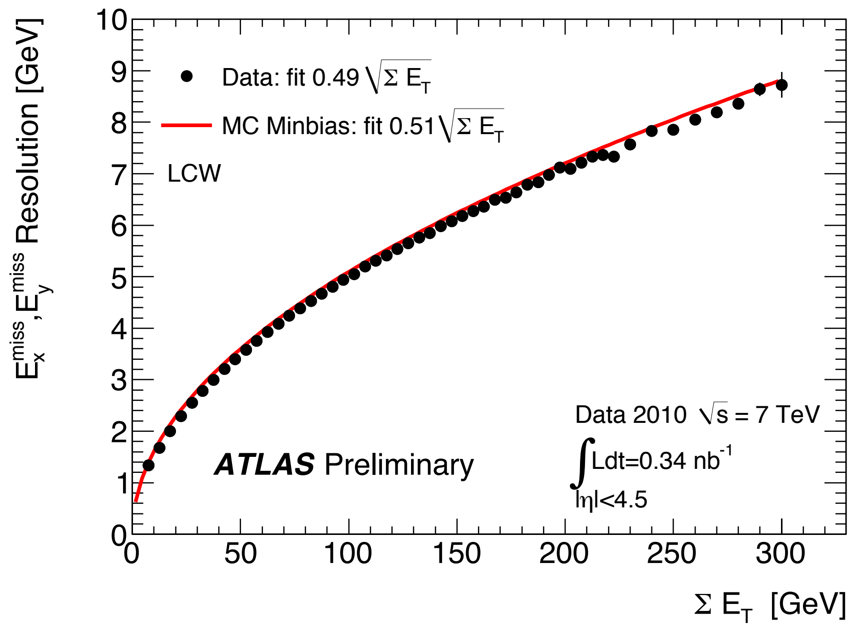
Particle Flow at CMS

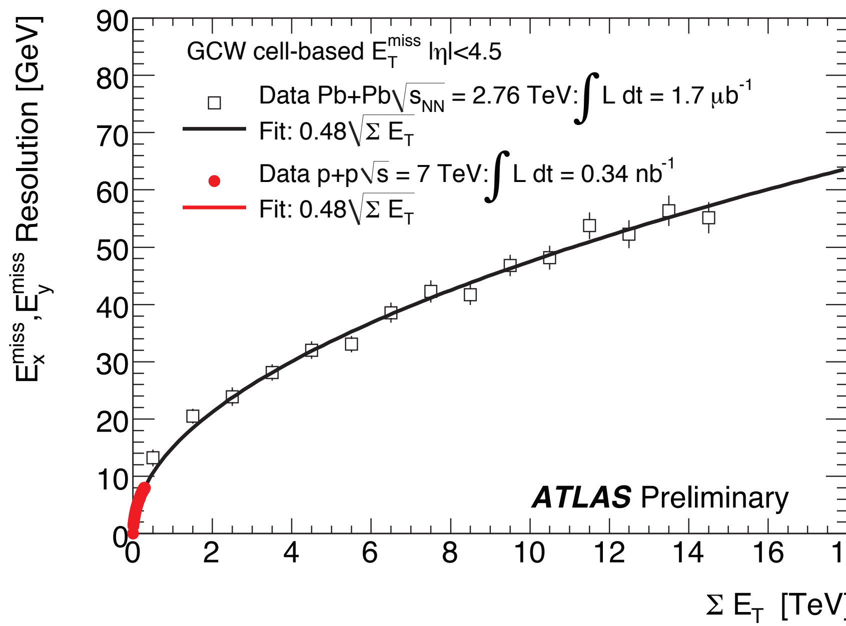
PF has many applications in CMS.

Example: E_T^{miss} resolution, improved with tracks, and further improved with particle flow algorithm.

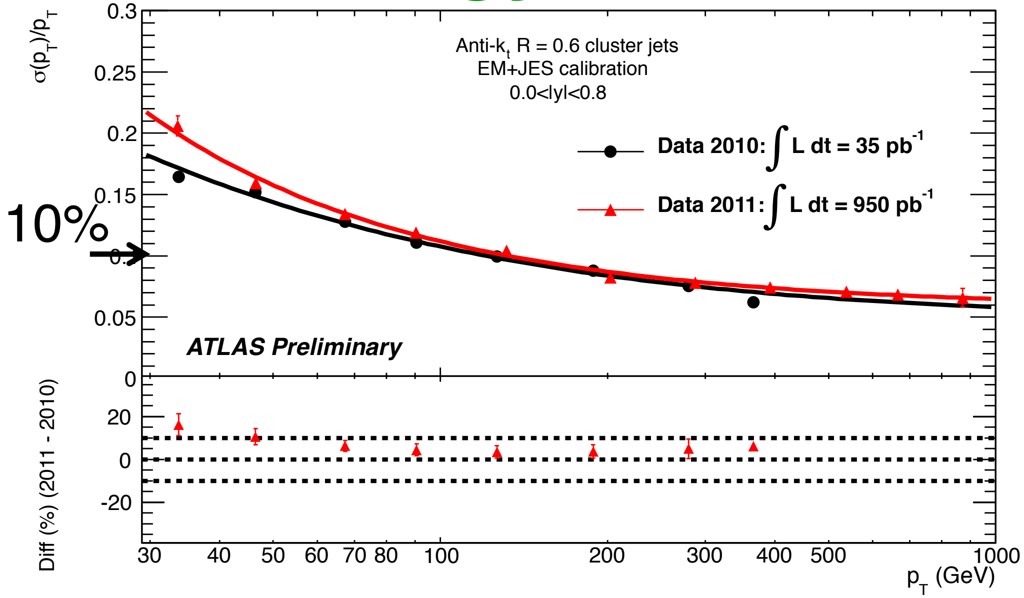
Comparison: ATLAS E_T^{miss} resolution for min bias events, and extended to ΣE_T=14 TeV with PbPb heavy ion sample, using calo only.







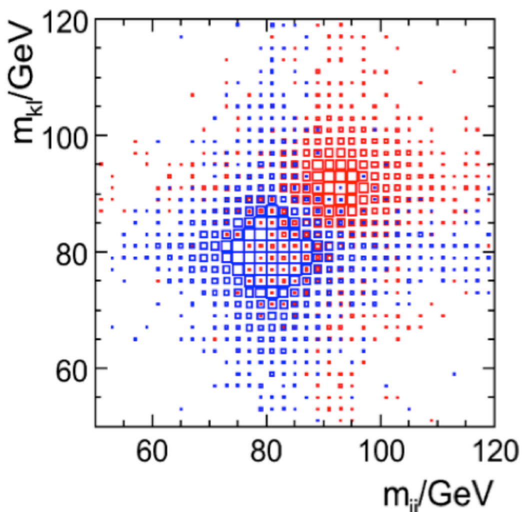
Jet energy resolution

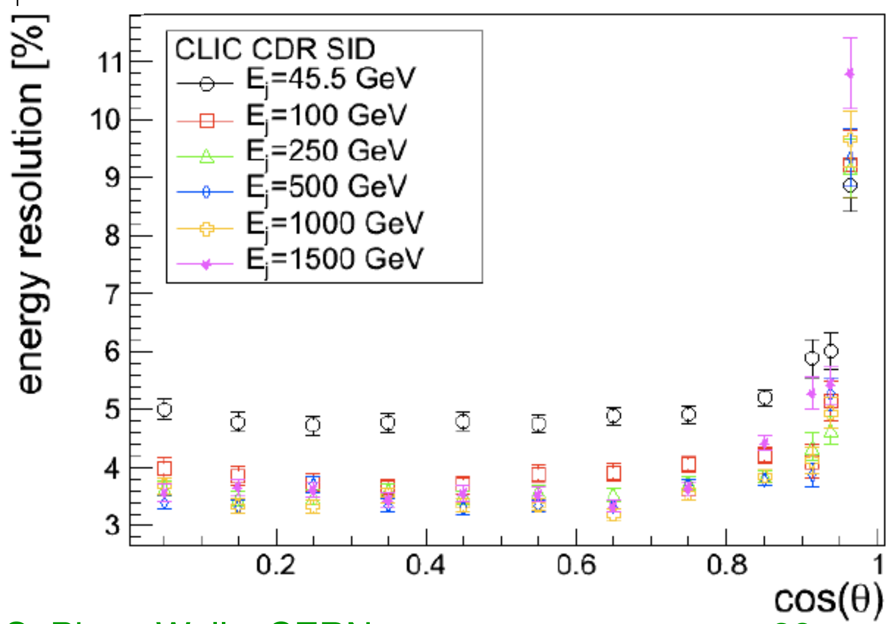


ATLAS jet energy resolution comparing 2010 with 2011 (more pile-up)

Using PFA, jet energy resolution of 3-4% can be achieved, even for high-energy jets at CLIC

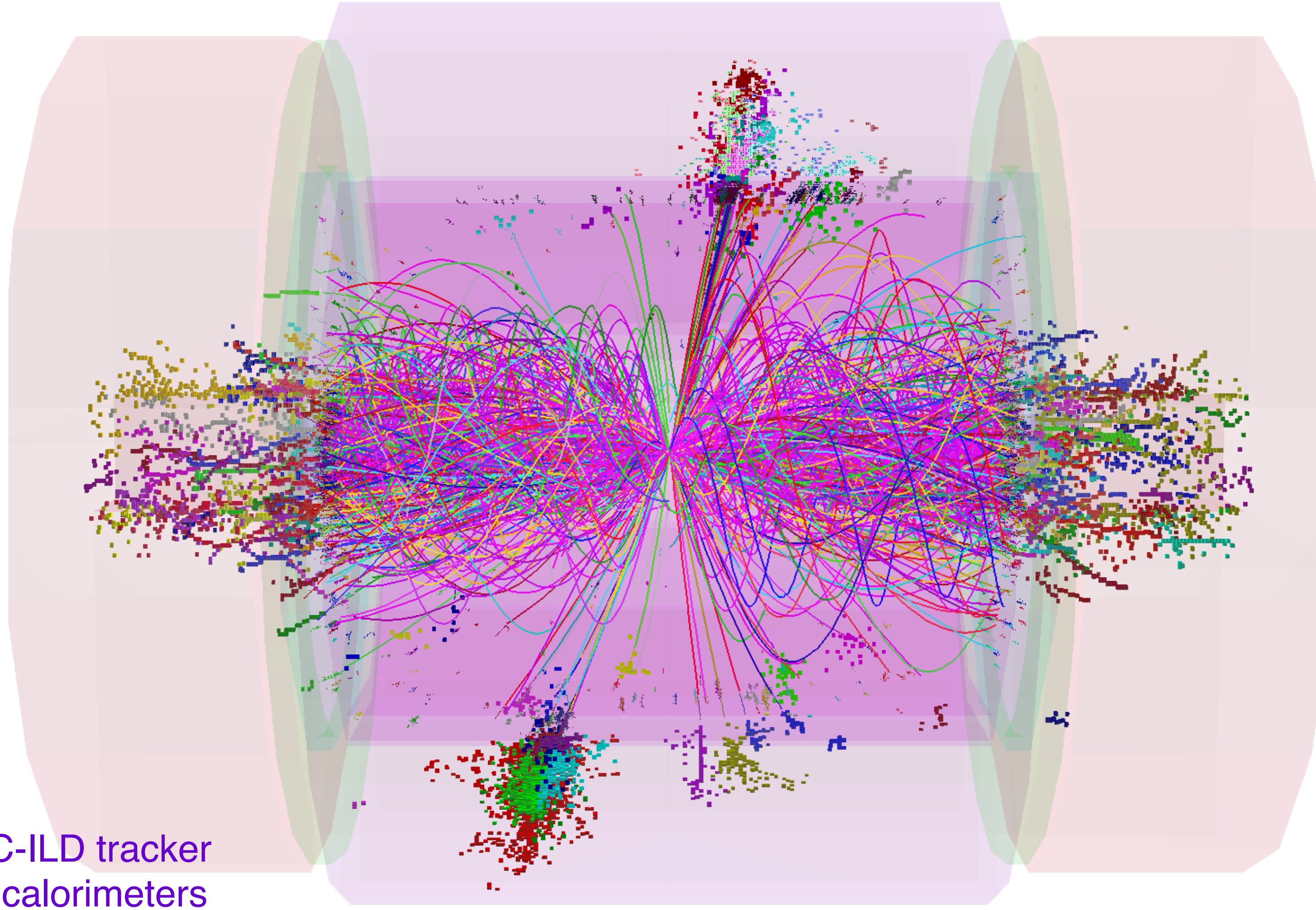
W, Z pair separation in the ILD detector in multijet final states





Particle Flow Algorithm for CLIC

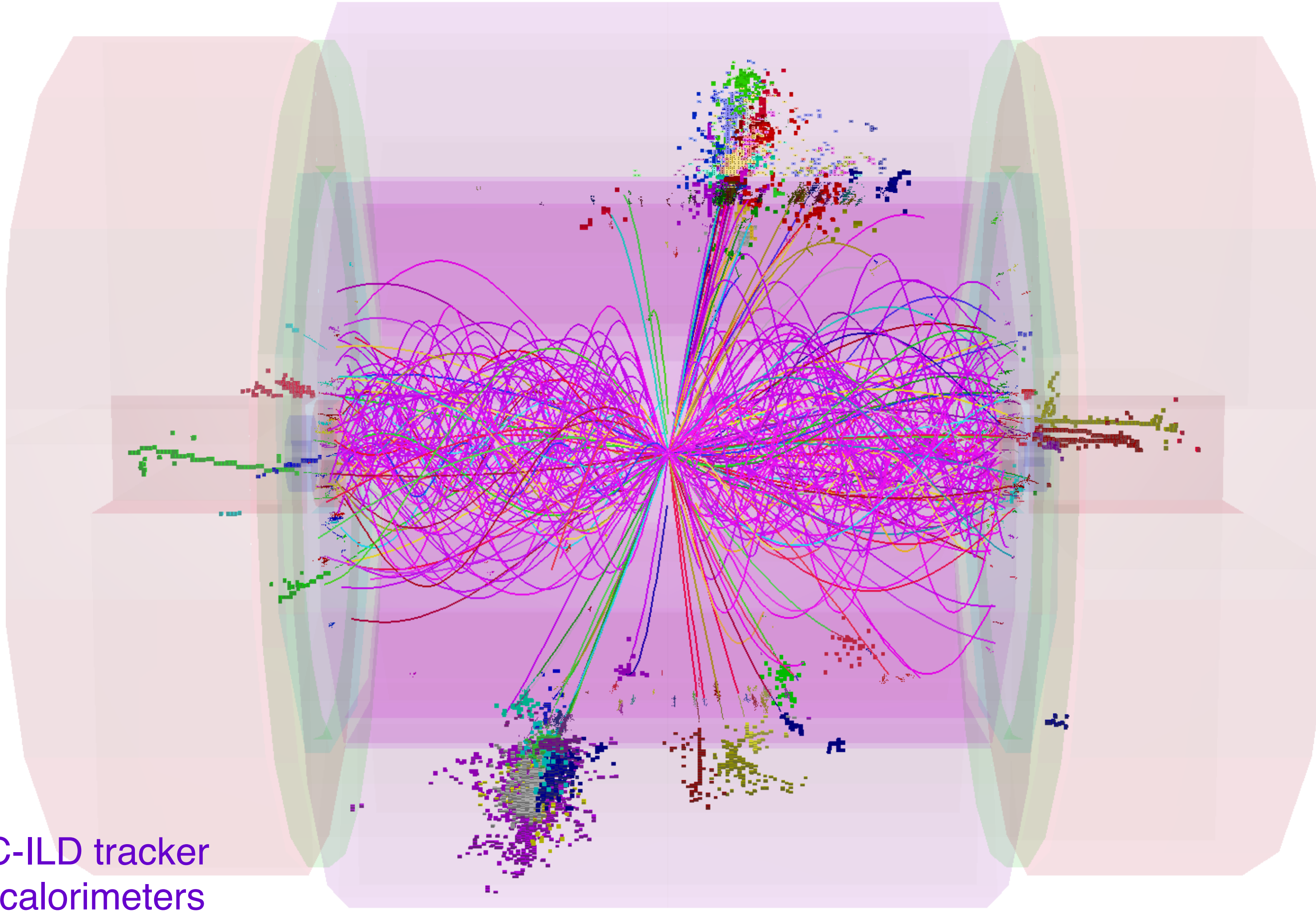
1 TeV Z→qq, with 60 BC overlaid → 1.4 TeV of background



CLIC-ILD tracker
and calorimeters

PFA with time stamping

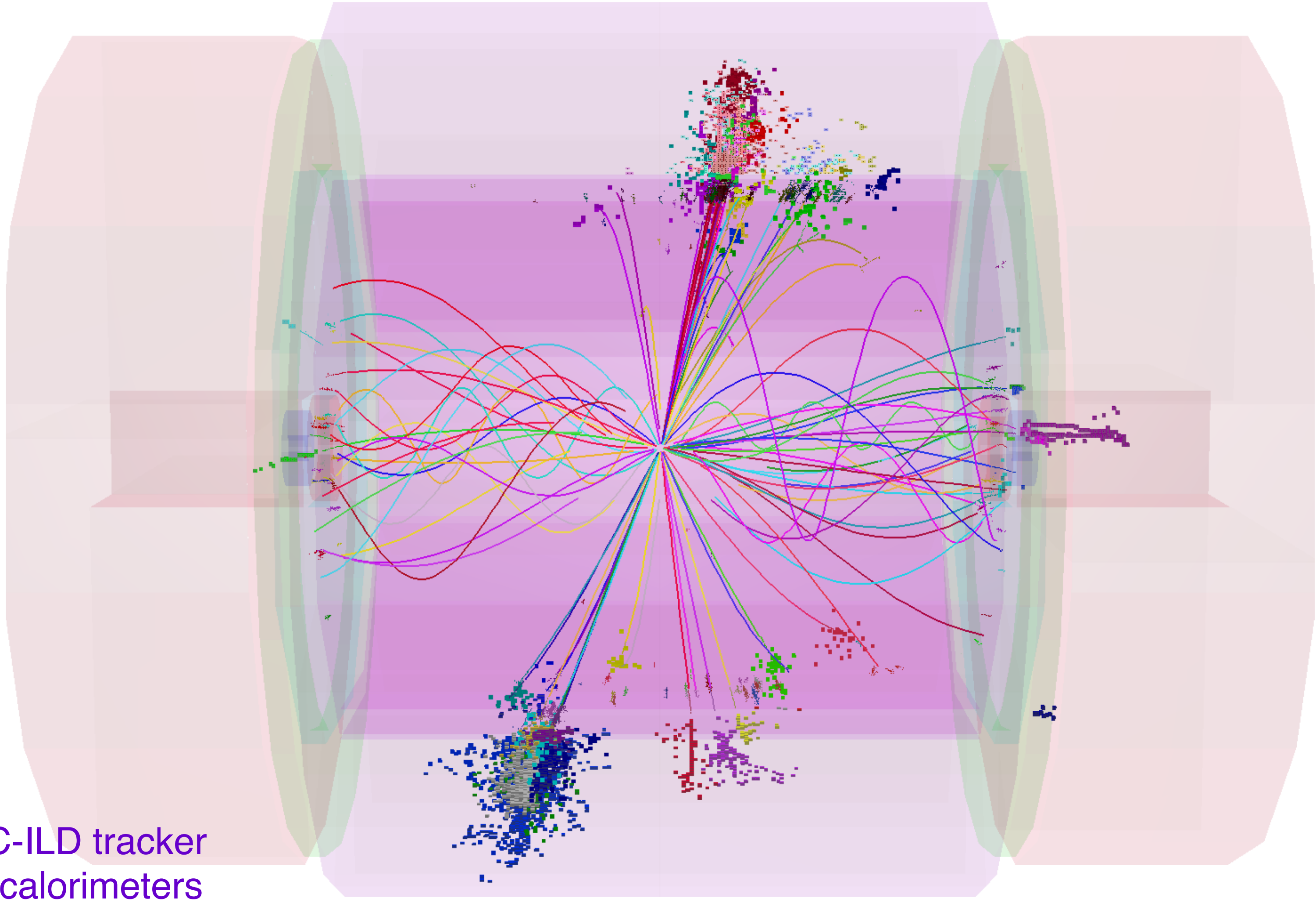
Loose Selection of objects → 0.3 TeV of background



CLIC-ILD tracker
and calorimeters

PFA with time stamping

Tight selection → 0.1 TeV of background



CLIC-ILD tracker
and calorimeters

ILC and CLIC detectors timeline

- ILC reference design report (4 volumes) August 2007
  - Volume 2: Physics, Volume 4: Detectors
- Letters of Intent 2009
  - IDAG (International Detector Advisory Group) validated two detector concepts, ILD and SiD
- Collaborations working towards Detailed Baseline Design Report (DBD) in 2012
  - R&D in progress. Will also account for accelerator changes SB2009 (Strawman Baseline) eg. reducing number of bunches by factor 2
- CLIC detector designs based on ILD and SiD
  - Modifications for higher beam energy and beam structure
- Working towards conceptual design report (CDR) in the second half of this year (2011).
  - Volume 2: physics and detector
- Issues of reduced funding for linear collider in some countries

Conclusions and outlook

- Firm bedrock of Standard Model
  - Will need time to complete HERA and Tevatron analyses
- LHC machine and experiments – great performance at 7 TeV
  - New discoveries and non-discoveries (Higgs and beyond the SM) will point the way for future machines
- LHC detector upgrades
  - The path is rather well defined, and very challenging
  - May need to adapt in the light of experience and (non)-discoveries
- ILC and CLIC
  - Wise strategy of designing CLIC detectors with ILC starting point
  - Clear R&D areas identified, with collaborations for common efforts
  - Challenge of making definite designs for several possible futures

- We are enjoying the chance to live in interesting times!