Working at 5 ns bunch spacing?

Trying to put some order into initial brainstorming…

More questions than answers -> hoping to trigger some discussion

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Baseline beam conditions

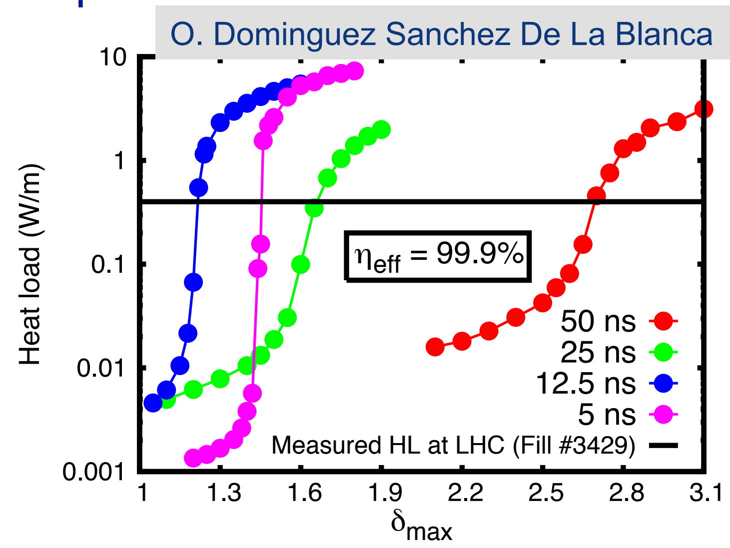
D. Schulte - FCC kick-off meeting

	LHC	HL-LHC	HE-LHC	FCC-hh
Cms energy [TeV]	14		33	100
Luminosity [$10^{34}cm^{-2}s^{-1}$]	1	5	5	5
Bunch distance [ns]	25			25 (5)
Background events/bx	27	135	147	170 (34)
Bunch length [cm]	7.5	7.5	7.5	8

- ☐ Pileup of ~170 with 25 ns bunch spacing

Bunch spacing options

- Can we get better conditions with smaller bunch spacing?
- Trade off between operational parameters and experimental conditions
- From operational point of view 5 ns separation is the lowest limit
- Intermediate values between 5 ns and 25 ns may be disfavoured for e-cloud buildup
  - Lowest multipacting threshold at ~12.5 ns separation
  - 5 ns situation similar to 25 ns
- Considering 5 ns as only option for the following



5ns spacing

- Different approaches
  - Machine's view: keep total current constant
  - Experiment's wish: increase current to get higher luminosity for same pileup
  - Realistic view: Something in between?

5ns, constant L/lower pileup

- Same peak luminosity, 5 times smaller pileup
- Beware:

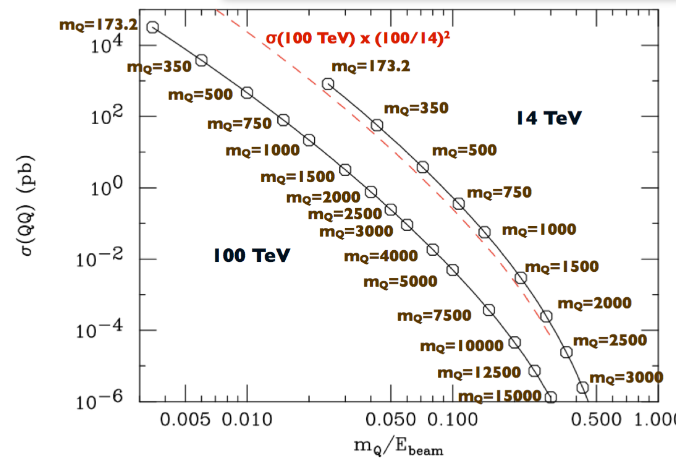
$$L \propto \frac{N^2 \times n_b}{\varepsilon \beta}$$

- One needs to compensate with smaller emittance
  - Beam-beam limit: $\varepsilon \propto N$ $\Rightarrow$ in principle OK
- Few operational advantages. e.g. smaller beam -> smaller impedance -> possibly small crossing angle
- Clearly preferred scenario for machine operations

5ns: higher L

- Theoretically we could gain up to a factor 5 in peak luminosity keeping 170 interactions per crossing
  - Higher lumi desirable for optimal mass reach as production rate drop as ~$1/M^2$

M. Mangano - FCC kick off meeting

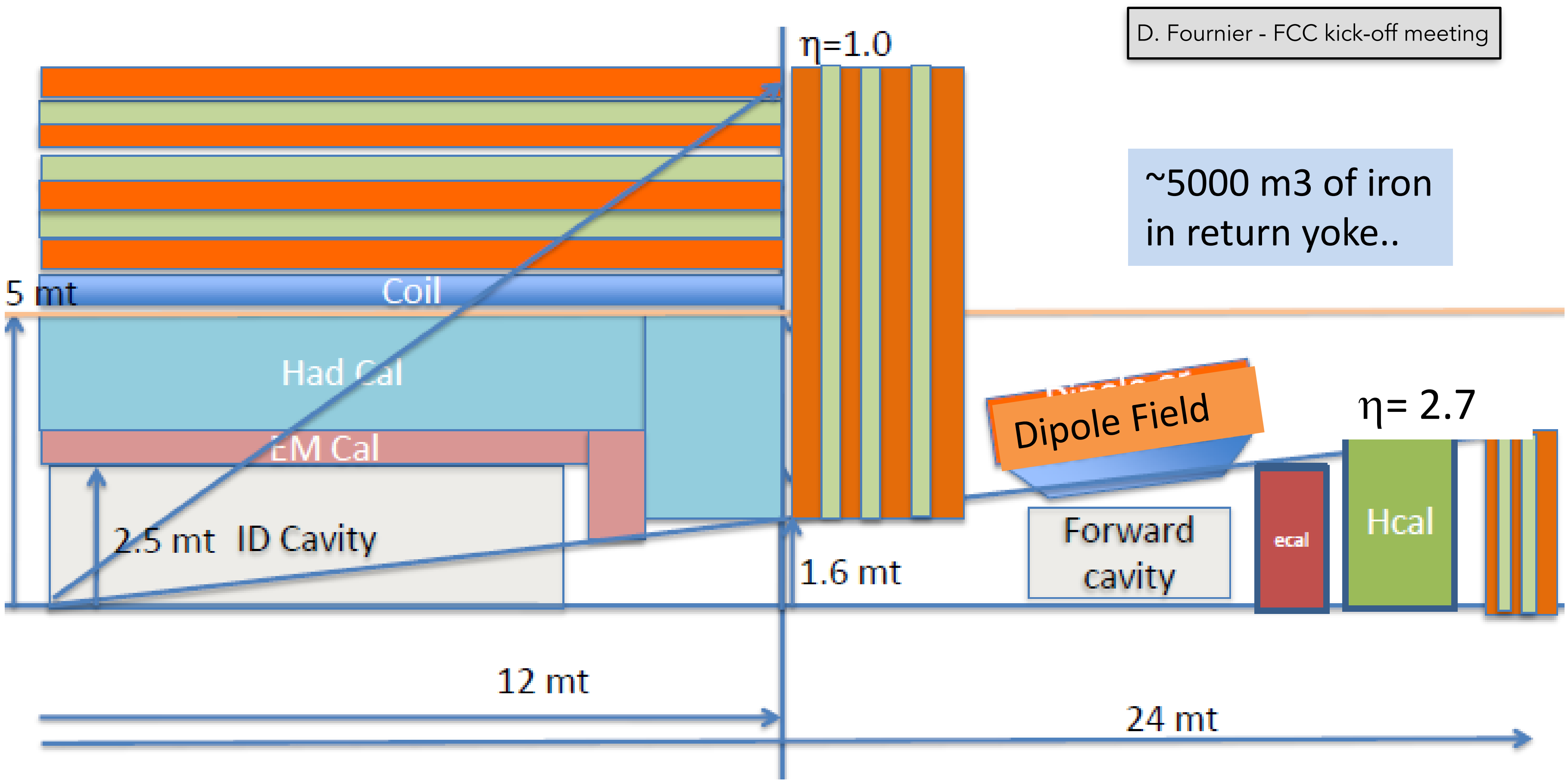


- But 5x increase in beam current:
  - How many dumps/abort gaps would we need?
  - Can we build injection protection devices?
  - Can we stand synchrotron radiation?
- A pragmatic view:
  - Considering:
    - operational drawbacks
    - charge limit in the injection chain: ~2.5e11 per 25 ns interval (after upgrades)
    - possible increase in crossing angle
    - …
  - It looks unrealistic today to assume more than a 2x more luminosity from 5ns
  - But surprises are welcome…

Global perspective

- Smaller bunch spacing are useful only if we are able to distinguish them (applies to all luminosity scenarios)
- Few constraints identified so far
  - Detector
    - Fast detectors technology needed at least for tracking, calorimeters and L1 trigger chambers (if we decide to trigger)
    - Higher power consumption for same detector granularity
  - DAQ/Trigger
    - Different issues according to trigger scenario
      - L1 trigger based scenario
        - Needed <5ns online trigger resolution
      - No (or reduced) L1 trigger selection
        - Probably significantly more data throughput from analog calorimeters
        - Hence more readout links, larger HLT network
      - Option to run DAQ at 40 MHz with time-stamping could be investigated
        - Some increase in throughput and in FE complexity (3 extra bits per channel to identify crossing)

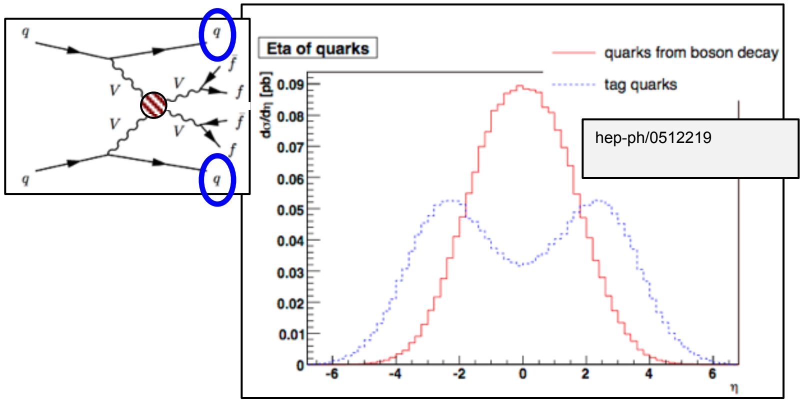
Initial detector ideas

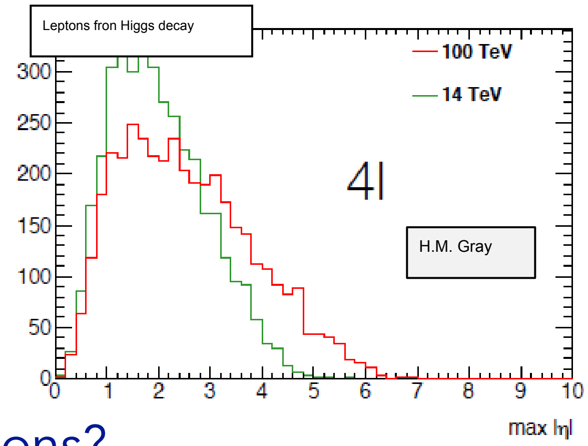


- Assuming this scheme for the following discussion

L1 Trigger approach

- Do we need to trigger at L1 on forward tag jets for VBF?



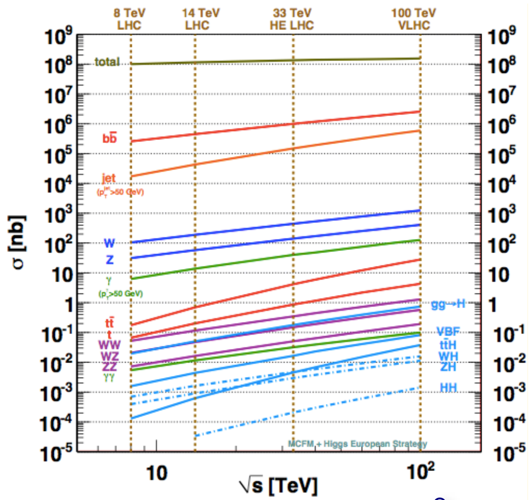


- Up to which η do we need to trigger on leptons?
  - ~40 MHz of muons from B decays at η>3 and L=5x10^{34}

    170 interactions 40 MHz * σ_{in}/σ_{bb} * BR(to muons) * 4 * 2/5*

    (assuming flat distribution in η up to 5)
  - And p_t resolution in dipole worsen exponentially with η

    $dp/p \propto p_{\parallel} = p_t \sinh \eta$
    - Endcap toroid is not an option for very high η



"Triggerless" approach

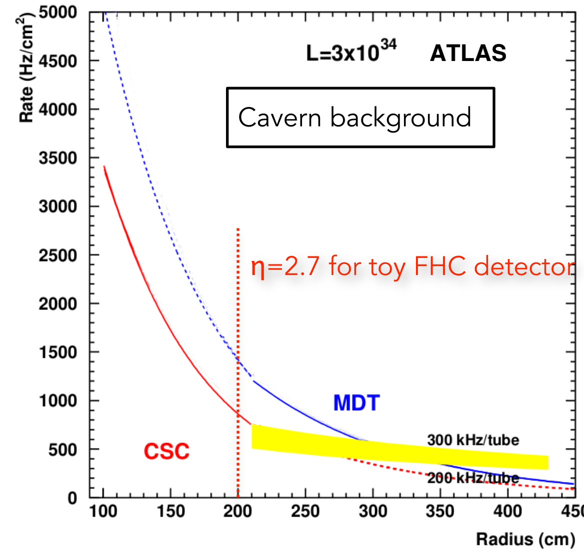
- All data is readout from the detector at each crossing
  - Reduction in HLT farm ⇒ not really *triggerless*
- Large data volume to be read from detector already at 25ns
  - ~750 TB/s from tracker (W.Riegler, FHC meeting)
  - ~150 - 600 TB/s from calorimeters?
    - ATLAS LAr assumes 150 TB/s for HL LHC
    - Analog calorimeter data does not scale with occupancy
    - Possible increase in channel count for a non projective geometry
    - Would we need more transverse / longitudinal granularity if we want particle flow?
  - **We need serious R&D on high-speed/ low-power/ rad-hard links**
    - Assuming that power dissipation scales with B/W we need rad-hard on chip photonics within the next 20 years…
    - <u>No drive for rad hard from commercial world at the moment</u>
      ⇒ we need to take the lead
- At 5 ns, data volume for an analog calorimeter would increase by 5x
  - We need to study zero-suppression approach on front-end ASICS
  - Alternative of digital calorimeter imply much higher granularity
- Could we consider a hybrid approach with simple 10x L1 reduction?

Trigger & DAQ

- "Triggerless" scenario at 40 MHz (~ Pb/s data throughput) is very challenging but not evidently unrealistic
  - Huge but probably feasible HLT network
    - Assuming availability of commercial 1Tb/s links/switches
  - HLT computing needs to be properly addressed
    - How much do we believe Moore's law to be fundamental?
  - Even a simple 10x reduction at L1 would be very useful though
  - For a 5ns scenario at constant luminosity we would certainly need to extend to all detectors zero suppression in FE
- L1 Trigger scenario
  - Trigger processing OK even at 5 ns
    - Modern FPGAs can already be clocked at 400 kHz
    - Smaller pileup per crossing (for constant Lumi) would reduce combinatorial
      - Provided that we have good online time resolution
  - Deadtime depends on size of de-randomisers buffers vs occupancy
    - Main dependency is on luminosity rather than bunch crossing frequency
- Clock distribution should be OK even at 200 MHz
  - Today's TTC clock has ~50 ps precision
  - Sub ns synchronisation over large distances is being studied already
    - See: http://www.ohwr.org/projects/white-rabbit
- No immediate showstopper at sight but a lot of studies needed for Readout and HLT

Muon chambers

- Detector
  - Mostly tagging of tracks extrapolated from tracker
    - No need of a very fast detector if enough granularity
- Trigger
  - Fast detector seems to be available for barrel
    - e.g. RPC with improved radiation hardness and rate capability (ongoing R&D)
  - Rate of cavern background in forward region up to $\eta = 2.7$ needs to be studied and optimised to be able to use RPCs
    - Simple extrapolation from ATLAS to 10^{35} $cm^{-2}s^{-1}$ and 100 TeV give ~10 kHz/cm^2
      - Expected to be OK for future RPCs
    - But **strong dependence on shielding and location of forward tracker** : needs to be seriously studied as soon as we have a stable detector layout
  - For η>2.7 trigger chambers are only available for tagging (no field)
    - Only option is track trigger
      - Is it feasible?
      - How do we tag muon tracks online (otherwise basically triggering on every crossing)?
      - Here fast muon chambers would be needed despite high rate…



Tracker technologies

- Several fast technologies available (< 5 ns time resolution)
  - But time to collect over 300 μm of standard high resistivity silicon for standard fields is already few ns (depending on carrier)
  - HVCMOS with ~100 μm thickness? Other options?
- Need to study **power consumption**
  - With triggerless scenario power consumption from readout optics scales dramatically w.r.t. HL LHC for same detector occupancy
    - Rad hard on silicon photonics…
  - Increases with higher pipeline clock if going to smaller bunch separation
    - Difficult to estimate: relative dependence on occupancy vs clock
- Propagation time over readout lines would need to be minimised
  - Higher readout granularity ⇒ higher material, higher power
- What about effect of low momentum loopers (hanging around for several BCs)?

Calorimeters technologies

- Crystal calorimeters
  - Concerns on radiation hardness for the endcap region
  - Difficult to have longitudinal segmentation
- Liquid noble gas calorimeters
  - Influence on measured energy fluctuations from all crossings occurring within typical peaking time (~40 ns)
    - Limited effective pileup reduction with smaller bunch spacing
    - Possible mitigation:
      - Reduced shaping time = higher noise
        - Possible impact on low p_T objects
      - Thinner gaps?
      - With higher Z liquid (Kr,Xe) to compensate for sampling ratio?
- Silicon sampling calorimeters? Can we afford cost?
  - Look at linear collider silicon based sampling calorimeters R&D for ECAL
- We could be thinking of an heterogeneous approach vs η

Conclusions

- So far we haven't identified a showstopper against running with short bunch spacing
- But the detector technologies to fully benefit from the small spacing need to be studied
  - R&D needed
    - Rad-hard, high-speed, low-power readout links
    - Fast calorimetry (Sampling Silicon based calorimeter?)
    - Fast and rate capable muon trigger chambers (upgraded RPCs?)
    - …
- And we need physics studies to evaluate effect of shorter bunch spacing for different total luminosities
  - Would we benefit enough to justify extra detector complexity even without luminosity increase?
    - e.g. in back-to-back jet tagging for VBF?
  - Study trigger approach
    - Traditional L1 for reduction to ~1MHz vs "triggerless"
      - Something in between?
        -> simple 10x reduction to keep throughput to HLT under control

Next steps

- Complete list of questions to address
  - Any input is welcome
- Produce some reasonable occupancy simulations
- Study in detail more demanding high-lumi scenario
  - Take 5x higher Lumi as benchmark despite "unreasonable" machine requirements
- Address physics case for lower pileup at constant luminosity
  - Decide if we are still interested if that's really everything the machine can offer