

# Long-term prospects for flavor physics at HL hadron colliders

Giovanni Punzi

Universita' di Pisa and INFN

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# Current landscape at hadron colliders

- LHC and HL-LHC are an immense source of Heavy Quarks
- Current/foreseen experiments only exploit a fraction of this enormous production
  - ATLAS/CMS:
    - Full LHC lum: 3000 fb<sup>-1</sup>
    - But limited efficiency: lepton / hi-pt requirements
  - LHCb:
    - High efficiency also on hadronic/charm events
    - But limited luminosity: projected 50fb<sup>-1</sup> vs 3000 fb<sup>-1</sup>
- *“Europe’s top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine” [EU strategy document]*
- What if we could fully exploit the production of  $\sim 10^{14}$  b-quarks and  $\sim 10^{15}$  c-quarks per year ?

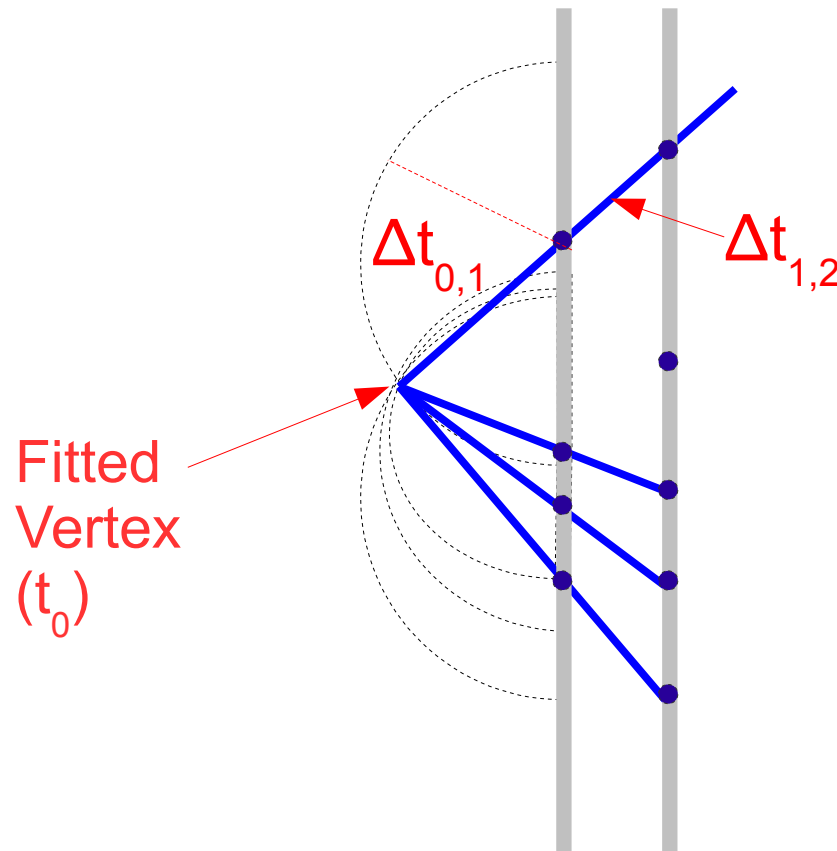
# What physics from samples of $\sim 10^{14}$ b-quarks and $\sim 10^{15}$ c-quarks per year ?

- Comparing to V. Vagnoni talk:  $L \sim 10^{33} \rightarrow L \sim 10^{35}$ 
  - $O(100x)$  limits,  $O(10x)$  resolutions
  - Nominally: UT angles  $0.1^\circ$ , charm CPV  $10^{-5}$ ,  $B_d/B_s \rightarrow \mu\mu \sim 3\%$
- Discussion on the impact to search of new physics could be long, and will not touch it here.  
(See L. Silvestrini's talk for initial comments)
- Not easy to predict the impact of a wide set of precision measurements (also on the ability of theory to describe it).  
Some trust the principle *“The great advances in science usually result from new tools rather than from new doctrines.”* (F. Dyson)
- For the moment let's just consider what it takes to make a High-Luminosity Flavor experiment

# 1) A Detector with strong tracking capability

- Other detectors do play a role - but good Tracking is mandatory
- Don't think many people doubt that an adequate tracker is within feasibility
  - Lots of ongoing work for the Phase-2 CMS and ATLAS
  - Lots of other R&D (see F. Forti presentation)
- Pattern recognition challenging, but can be helped in various ways
  - Double-layer detectors (a la CMS) → Local measurement of track angle
  - Time-tagged silicon pixel detectors
    - e.g. UFSD project in CSN-5 (See N.Cartiglia at WhatNext meeting)
      - Projected 10ps resolution on pixel hits
  - Combining both methods promising to handle 100 vertex crossings
- May have to give up finding individual event vertexes
  - May have to work with the beamline as a linear source of tracks
  - Not a problem to measure decay lengths if tracking resolution is good
  - Ability to separate individual collisions not as important as in HI-PT.

# Tracking in a time-tagged detector



- Timing constraint allow vertex reconstruction from a single layer !
- Also strict constraints to hit association between layers (on top of bi-layer)
- Would not say indispensable, but definitely a great help if it can be made.

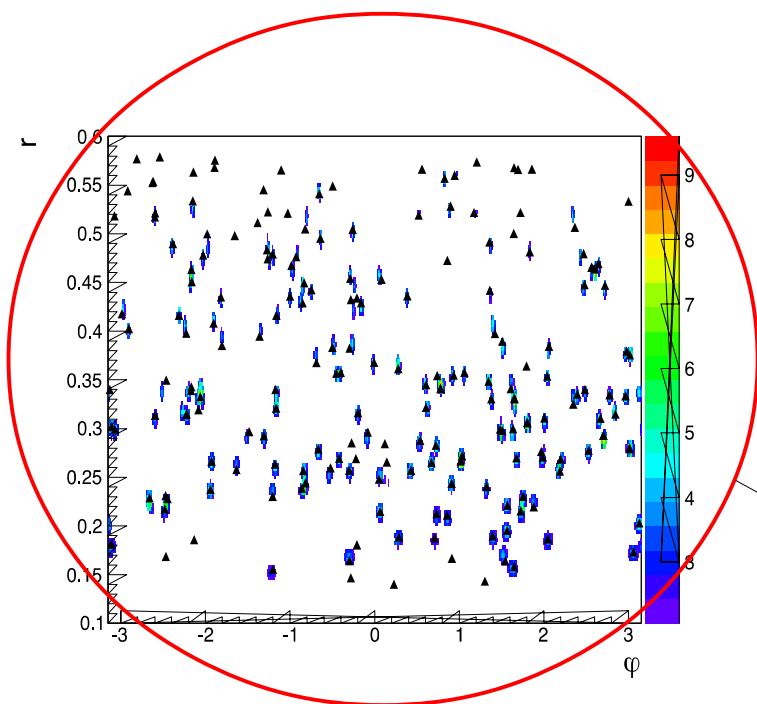
## 2) Reading out the whole detector at *each* crossing

- Unlike the case in Hi-Pt physics, there is no easily-extracted subsample of the event data that can be used to select events
- Muons can partly help, but with many events/crossing there are limitations
  - Except for the 'easiest' modes, ALL events will have to be “processed” - this means a substantial part of the data.
  - Detector readout must happen at 40MHz – at least most of the tracking
- Progress of telecom technology makes this not a dream anymore
  - LHCb upgrade readout plans to read pixels at 40MHz
  - 10-50 Tb/s @  $2 \times 10^{33}$  → thousands of optical links (3.5Gb/s payload)
  - Current optical links do 40Gb/s, and keep improving.
  - Other possibilities studied: wireless 60GHz links, infrared links...
    - (look at WIT-2014, last week in Philadelphia)
  - Target of reading full events at  $5 \times 10^{34}$  does not seem crazy.  $\sim 1\text{Pb/s}$  ?
    - Reduction may come from design tricks of previous slide
    - “forward geometry” may be easier to deal with.

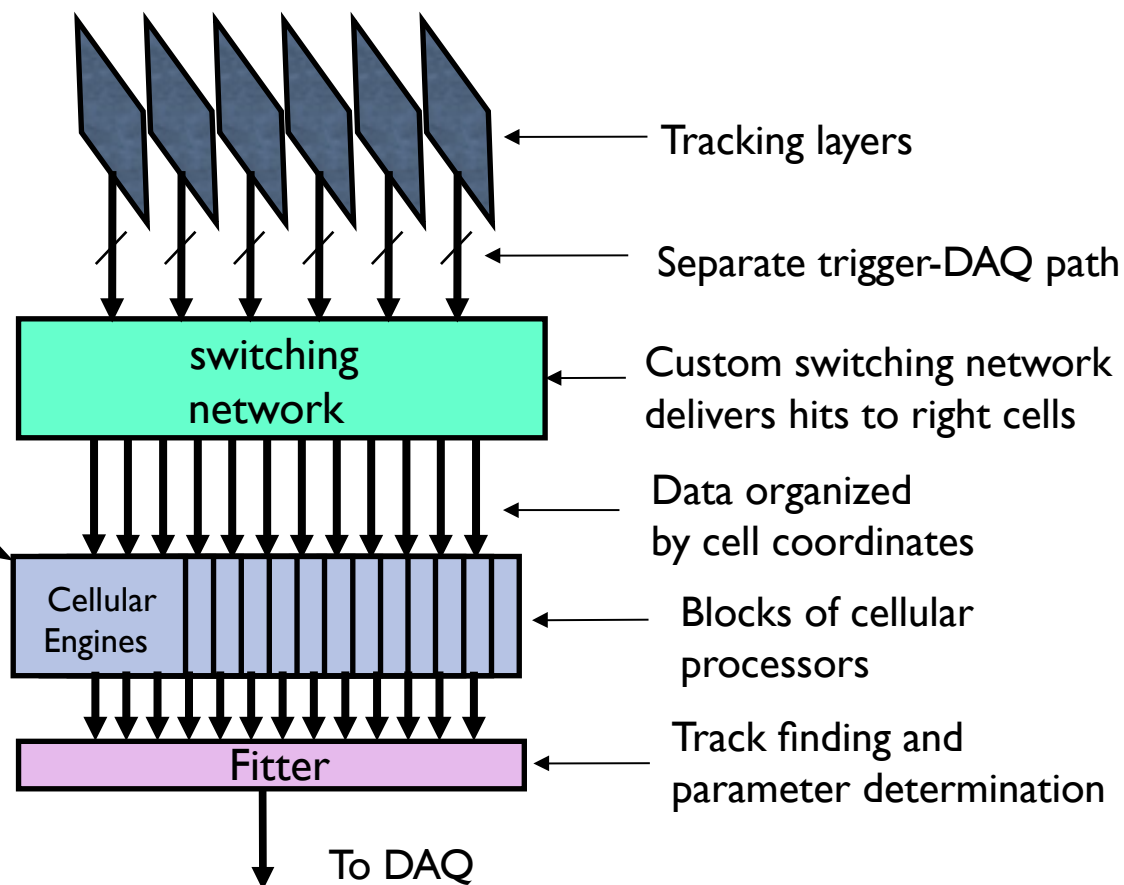
### 3) Event Reconstruction at 40MHz

- What do you do with  $10^{14}$ - $10^{15}$  bits/s ?
  - Storing them means  $>10^{21}$  bits/year = 1000 Esabits
- Even if we could solve this problem... it is not the right problem to solve.
- The problem to solve is how to process this amount of data.  
Storing only procrastinates the issue. And *REprocessing* is a scary thought.
- Consider running reconstruction only ONCE.
  - Then REDUCE the data at this point → **no “raw data” storage**
  - If you are going to go for “one-off” processing, you might as well do it in REAL TIME. This has further advantages.
- Best approach is to get tracks (and other complex primitives) *straight out of the detector*. You want your detector to generate “tracks”, not hits.
- Horrendous amount of data, but still feasible if done in specialized processors.

# Totally parallel, low-latency track reco at 40MHz



Tracks seen as clusters  
("retina algorithm")



*[see talk by GP @INSTR-2014 (Novosibirsk) + related talks @WIT-2014]*

- Proved feasible with today's FPGA at U-LHCb [LHCb-INT-2014-019]
  - Offline-quality tracking with sub- $\mu$ s latency and 40MHz rate at  $L=3 \cdot 10^{33}$
- Electronics progress + ASIC + specially-designed detector  $\rightarrow L \sim 10^{35}$ 
  - Hardware scales linearly with amount of input data

## 4) “Offline-grade” object reconstruction and calibration *in Real Time*

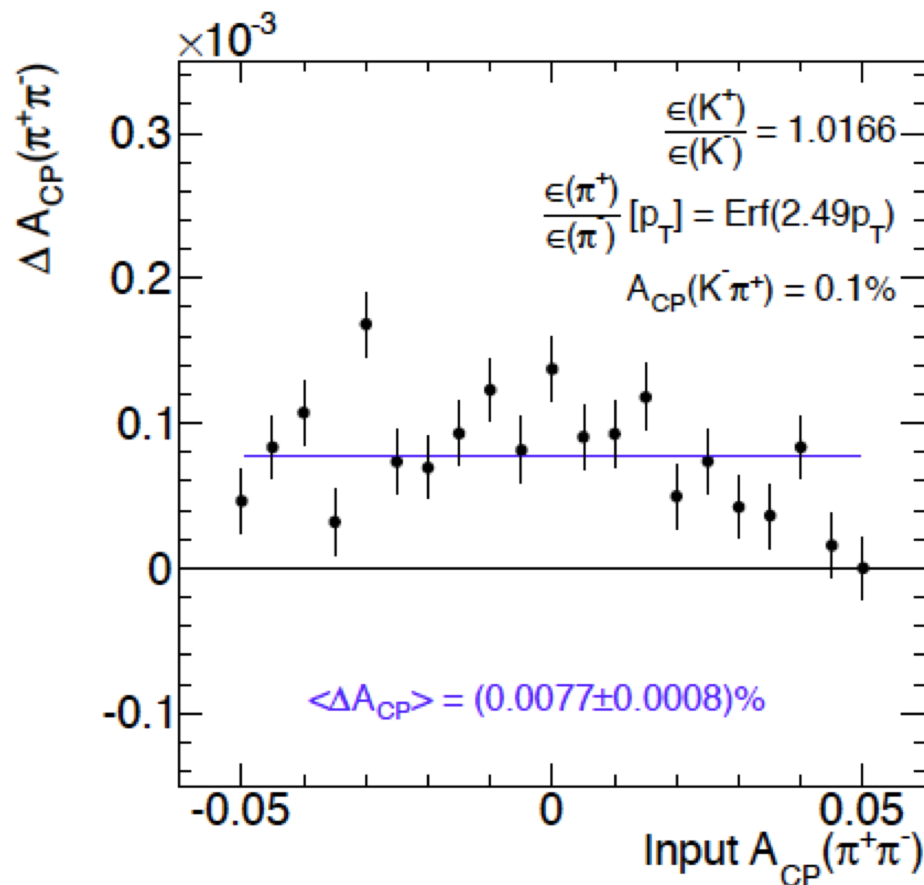
- Naturally connected to previous step
- Find out the decay of interest in the event, vertexes etc.
- *Most* crossings will contain some heavy flavor
- Strategy of triggering by picking specific beam crossings will not work: need to single out the right collision within a crossing
  - better, pick a specific part of a collision
- Calibration must be “live” - calibration database must run “unattended”: updated in real-time, and applied to data in real time
- Progress in CPU power and software engineering makes this feasible.
- Default plan of U-LHCb at  $1-2 \cdot 10^{33}$ , starting from hit level
- Exploit hardware tracking + further Moore to upgrade to  $L \sim 10^{35}$
- Reduce data to few tracks ( $\sim 1\text{kb}$ ) per interesting decay  $\rightarrow \sim 1000 \text{ Pbyte/year}$

## 5) A more advanced Data Analysis model

### Need to move towards “Real Time” Physics Analysis.

- Even taking only a specific piece of data from each interesting crossing may be too much for some high-rate processes (eg. D mixing & CPV)
- Ability to do precision measurements from reduced-size stored samples.
- Go beyond the “event” concept: only save *statistical summaries*
  - By “summary” I mean a statistics whose size grows less than linearly with the amount of collected data (e.g. histograms go as  $\log(N)$ )
- Sounds tough but it can be done – if you do it step by step.
  - Always keep storing a fraction of events in complete form
  - Need superior real-time calibration, and well-chosen control samples.
  - Develop sophisticated systematic-control methods.

# Reliably establish small systematics



$8 \cdot 10^{-5}$  systematics

FIG. 20. Asymmetry residual as a function of the physical  $CP$ -violating asymmetry in  $D^0 \rightarrow \pi^+\pi^-$

[Example from published charm CPV measurement: PRD 85.012009 (2012)]

- Canceling systematic effects by subtraction of control samples.
- Measuring residual effect by simulation of ensemble of “pseudodetectors”

# Further into the future

- The technologies and the concepts developed can be applied to further experiments at Future Colliders
  - Current ideas on an high-intensity experiment at a 100 TeV collider (“flavor” includes top physics...)
- Even higher rates
  - more physics
  - exploit same ideas + further technological progress to win the battle

Conceivable to start an effort towards developing this scenario.

# Conclusions

- The huge flavor production of HL-LHC is a still unexplored gold mine – and does not require building a whole new facility to exploit it. It does open a path forward, though.
- A “High Luminosity Flavor” experiment is challenging – my goal today is not to convince you that it is feasible – but rather that it is feasible (and a good idea) to study its feasibility
- It is the “right level of challenging”: not Science Fiction – but it is not a trivial application of existing products, either. It builds on the great innovation tradition of INFN and encourages progress of smart ideas.
- A lot of study needed to transform the HLF concept → design.
  - Detector, Physics, PR, DAQ...
- Opportunity to continue the discussion: workshop on  
*“The landscape of Flavour Physics towards the high-intensity era”*  
(Pisa 9-11 October)