Near future at PP collider

An overview of the challenges and opportunities of the High Luminosity LHC program

Disclaimer: will use mostly CMS based material as I am more familiar with it , but similar issues and performances are expected from ATLAS

Why is the the standard Model incomplete?

- Does not explain Dark Matter
- Does not explain the dynamics of the Baryon-antibaryon asymmetry of the universe
- Does not explain the Neutrino masses
- ..and has an hard time making a consistent picture for a light Higgs Mass

→ all of this require some new phenomena 'Beyond the SM'

And more esthetic issues

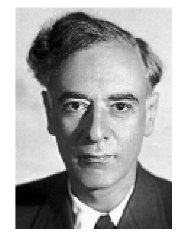
The Weirdness of the Standard Model

- Three families

"who ordered that ?" I. Rabi

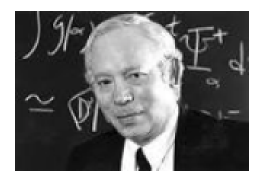
- Fundamental breaking of Parity

"space cannot be asymmetric!" L. Landau



- Predictivity: 3 gauge couplings+ 16 higgs couplings (+ 7 higgs-neutrino) !

"has too many arbitrary features for [its] predictions
to be taken very seriously" S. Weinberg '67



Courtesy of Pilar Hernandez

Trying to address the questions

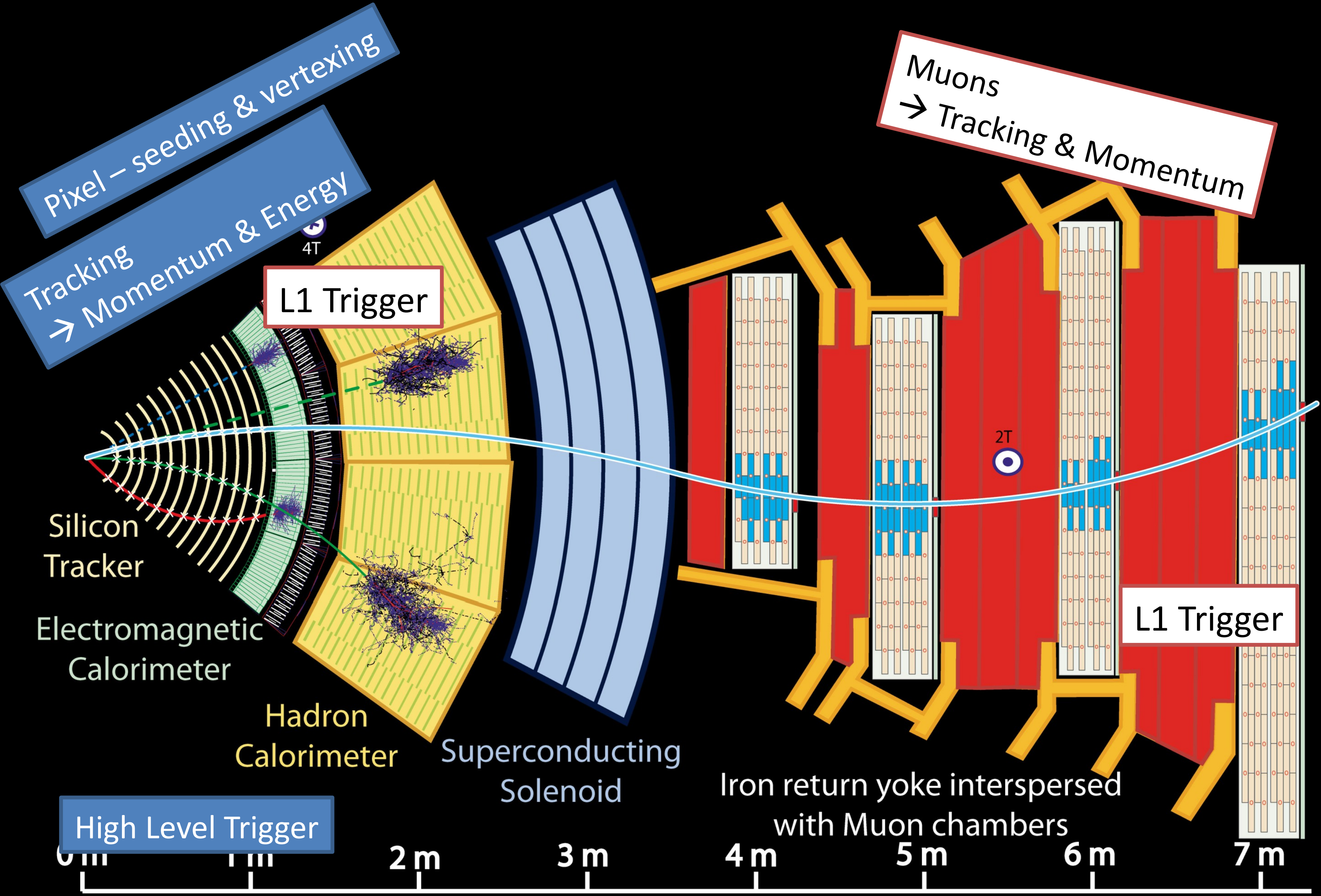
- The LHC and its experiments at CERN are the main instruments which the community has to try to explore the BSM world…
- So far it has succeeded in discovering the Higgs boson and exploring several areas of the heavy flavor physics …but no significant evidence of new physics
- The HEP community has agreed to exploit to its full extent the LHC by upgrading its capability so to reach the statistical (and systematic) limits for possibly discovering sign of new physics
- It is also in the process to discuss possible future accelerators which could extend the reach of the LHC

The experiments

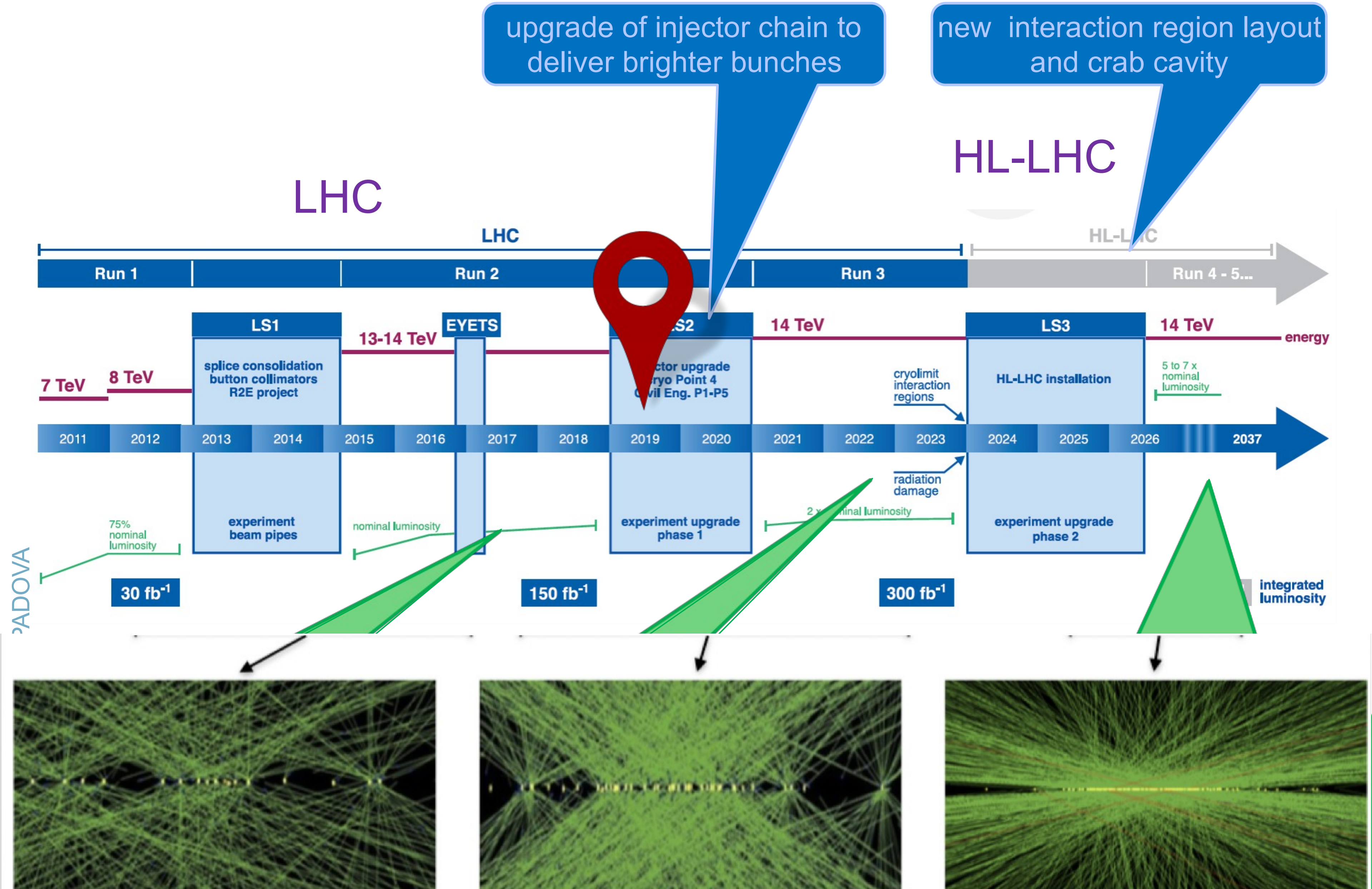
CMS, ATLAS and LHCb are the experiments exploiting the pp program

All have techniques to measure and identify the products of the collisions

I know best the CMS experiment and for sake of efficient use of time I will use its performance and issues in the following.



Confirm and refine L1 trigger decision (add tracking to calo+ muon confirmed L1 trigger)



⟨Pile-up⟩ ~ 20

⟨Pile-up⟩ ~ 40-50

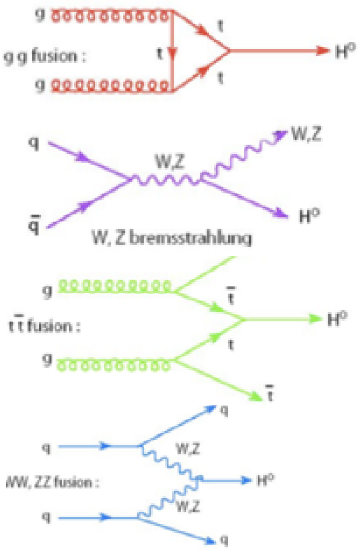
⟨Pile-up⟩ ~ 140-200

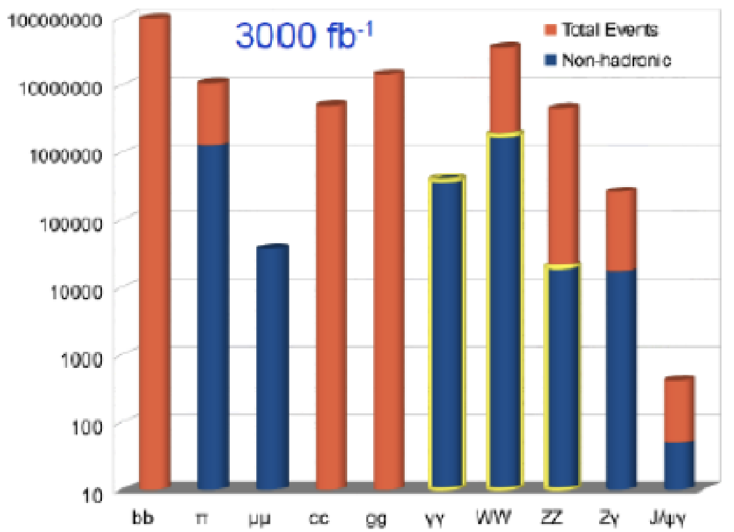
The physics reach

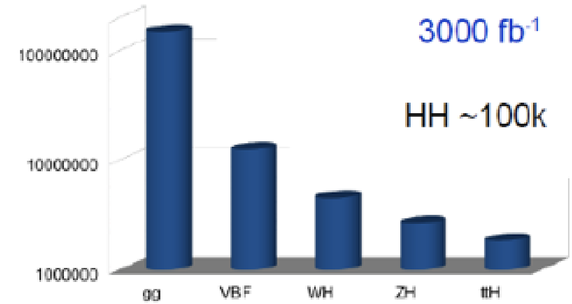
- The physics program of LHC (and of High Lumi LHC) is too rich to be able to cover it extensively (CMS and ATLAS have published more than 900 papers to date) , so I will make a choice of exemplary expected achievements
- Many of the searches are based on extension of present LHC approaches … the challenge will be to beat the pileup

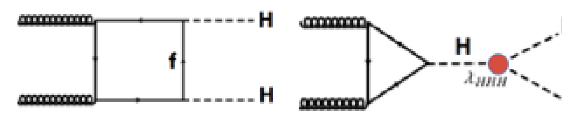
Hi Lumi LHC : a Higgs factory

- At HL-LHC, we expect to produce ~170M Higgs Bosons, including ~120k of pair produced events
- Over 1Million for each of the main production mechanisms, spread over many decay modes



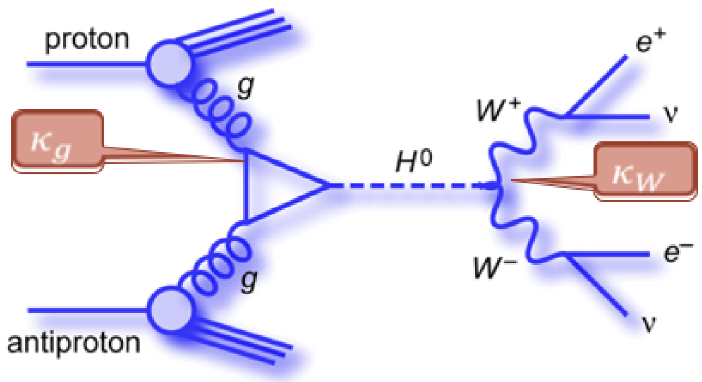






- Enables a broad program:
  - Precision O(few%) measurements of couplings across broad kinematics
  - Exploration of Higgs potential (hh production)
  - Sensitivity to rare decays involving new physics
  - extend BSM Higgs searches (extra scalars, BSM Higgs resonances, exotic decays…)

Higgs Couplings



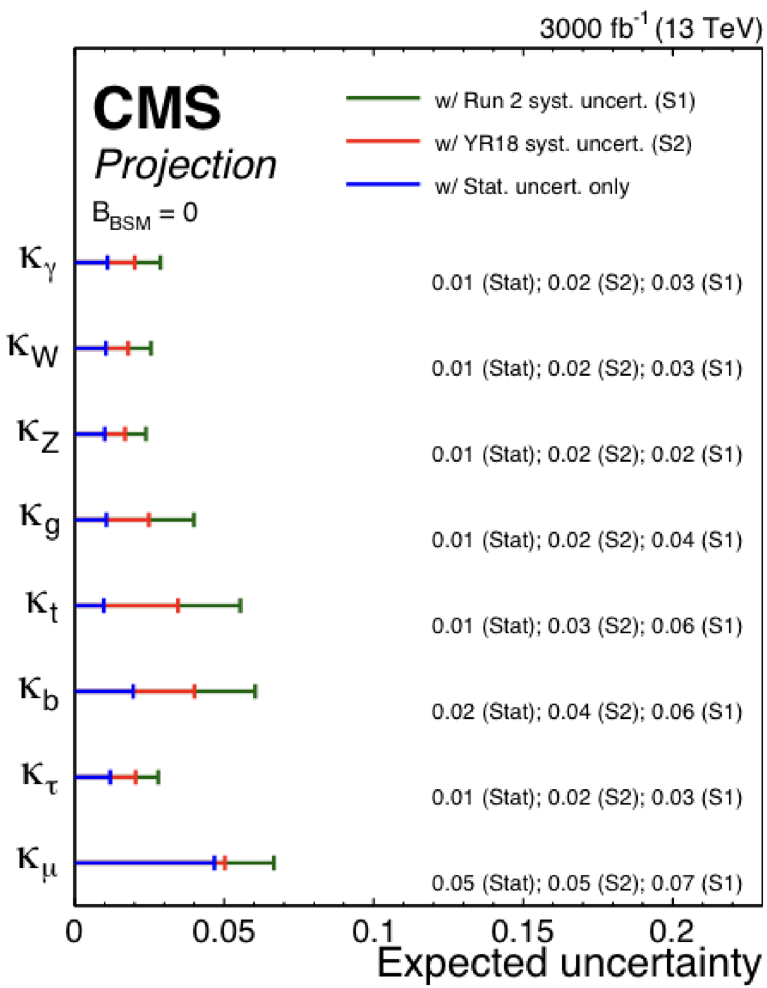
➢Currently κ's are typically measured to ~20%

➢Expected deviation from SM predictions by various models (Singlet mixing, 2HDM, Decoupling MSSM, Composite, Top partner…) predicted to be between 1-10%

New projections based on Run2 results. ATLAS+CMS combination coming soon!

* CMS projection only here. ATLAS similar results (in progress)
* Total uncertainties 4-10%(300 fb-1) and 2-5% (3000fb-1) (except κ_μ) for B_{BSM}=0

CMS-FTR-18-011

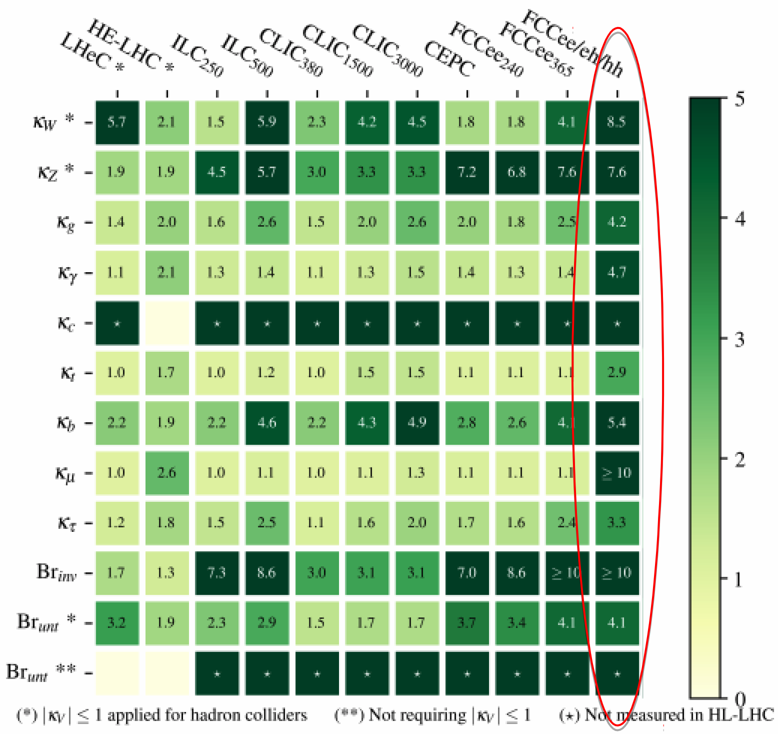


Ultimate higgs coupling

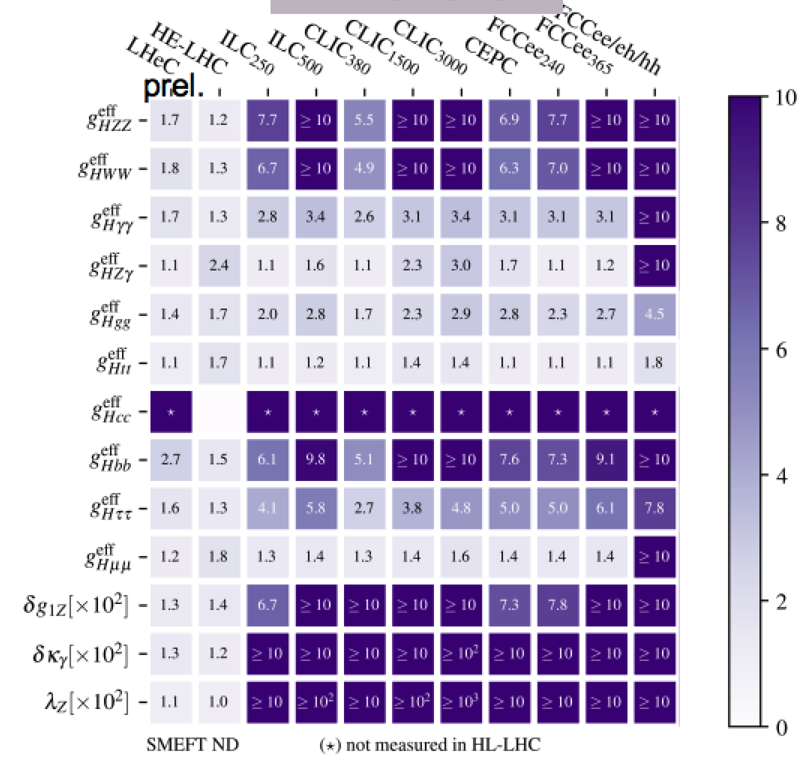
Improvements w.r.t. HL-LHC

M. Cepeda

Kappa-framework

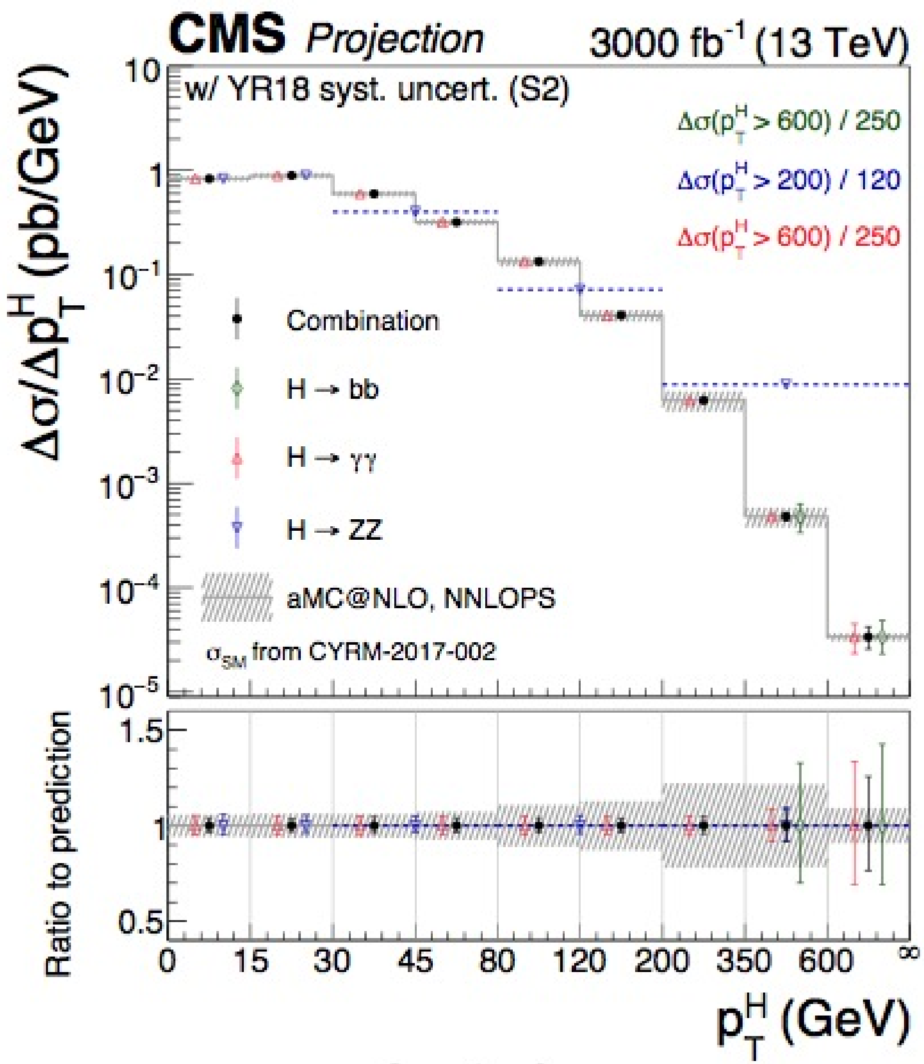


EFT-framework



Light green (violet) gives you an idea of where HL LHC will 'saturate ' our measurement precision…darker areas is the domain of proposed FCC –ee+pp

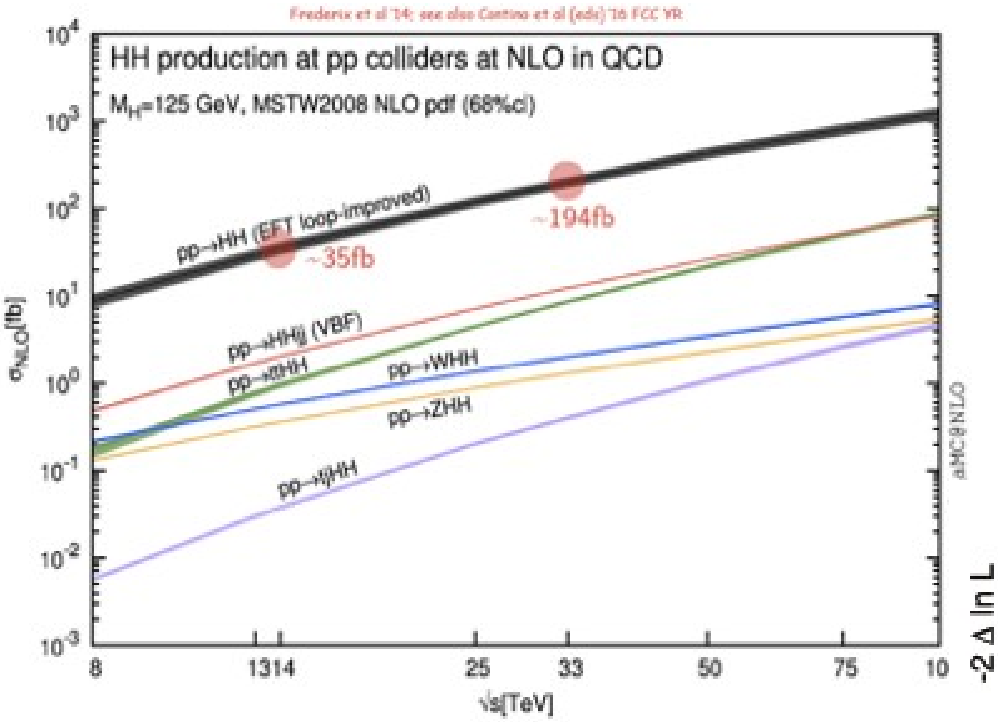
Higgs Differential cross section



Sensitive to
K_b and K_c at low P_t
K_t and BSM at High P_t

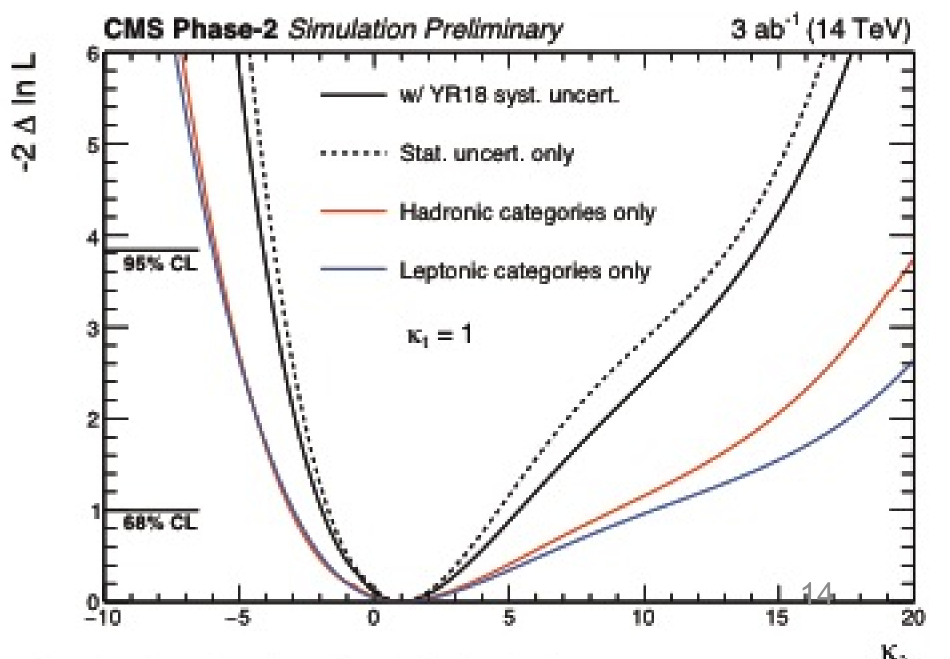
Dominated by statistical uncertainty at High P_t even at 3000 fb^{-1}

HH production and self coupling



HH is a cornerstone of the SM: so far LHC has reached sensitivities around 15 times the SM predictions

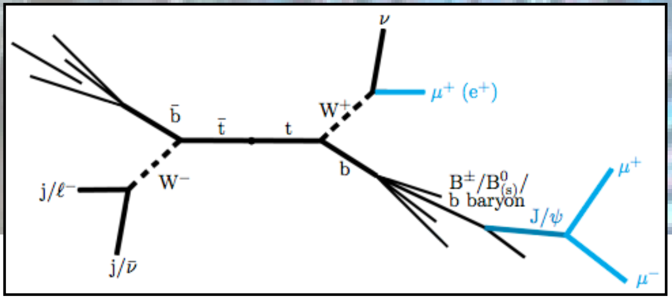
Analysing many final states:
bbγγ,bbττ,4b,bbWW,bbZZ
At $3ab^{-1}$ expect ≤ 2σ per experiment and possibly evidence combining ATLAS and CMS



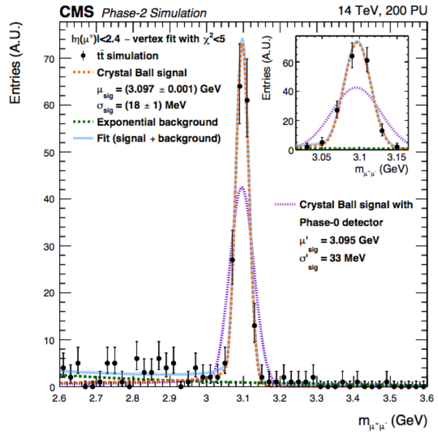
Top Mass

CMS FTR-18-005

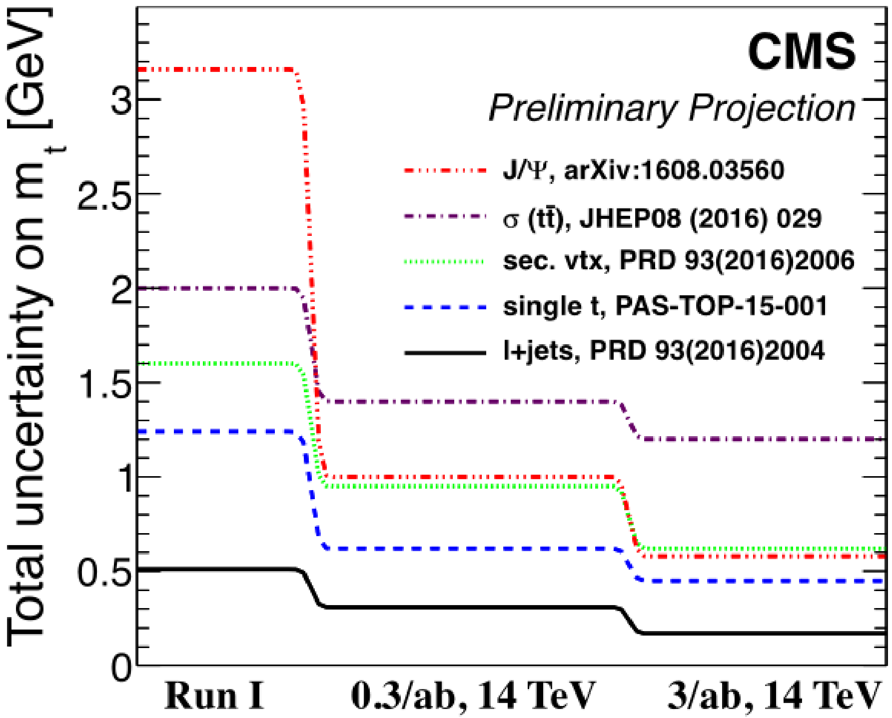
ATLAS in progress



- The methods that can be employed for the top mass reconstruction are characterized by different experimental and theoretical issues and uncertainties.
- High statistics implies also new methods becoming competitive
- Theoretical advances in the contribution to the uncertainties have a major role in the ability to reach the ultimate precision at a hadron collider



« J/ψ » method
CMSTDR-17-001



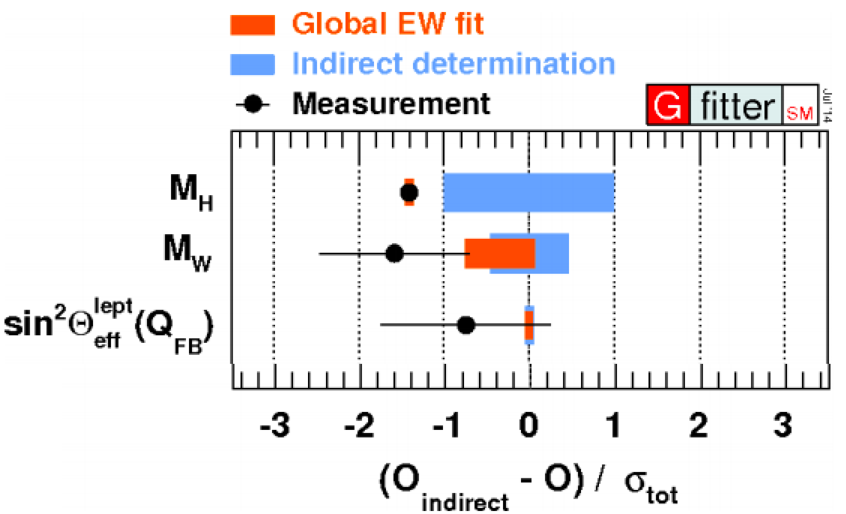
From cross-section
- Limited by theory uncertainty and luminosity measurement

J/ψ and secondary vertex
- Statistically dominated

Single top

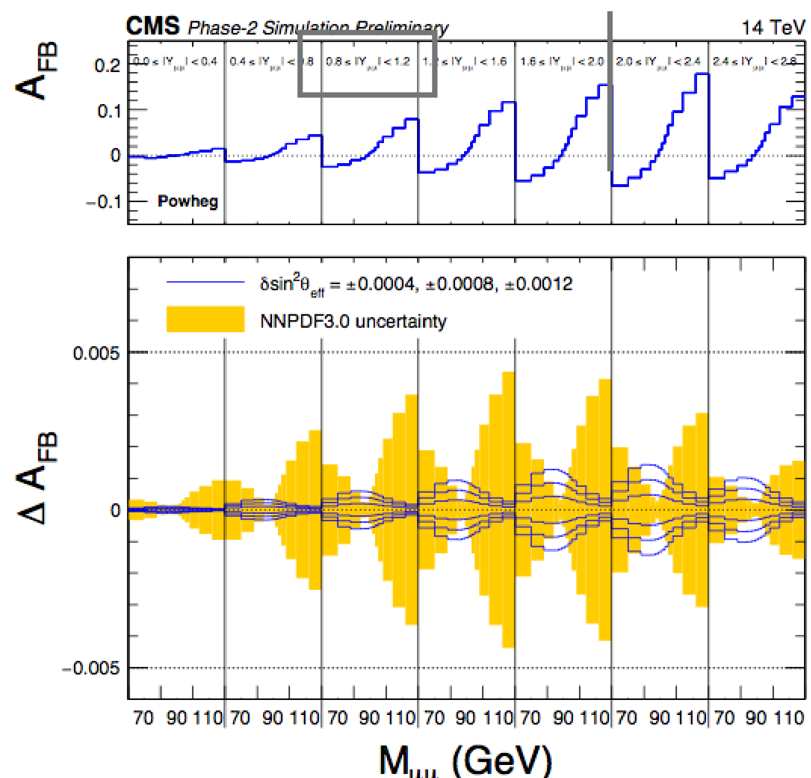
Standard →ℓ+jets measurement
- Expect $\Delta m_{top}/m_{top}$ ~ 0.17 GeV

Electroweak mixing $\sin^2\theta_W$



Indirect determination of Mw and $\sin^2\theta_{eff}$ more precise then the experimental measurement:

- This call for a precise direct Measurement
- Stringent test of the self consistency of the SM

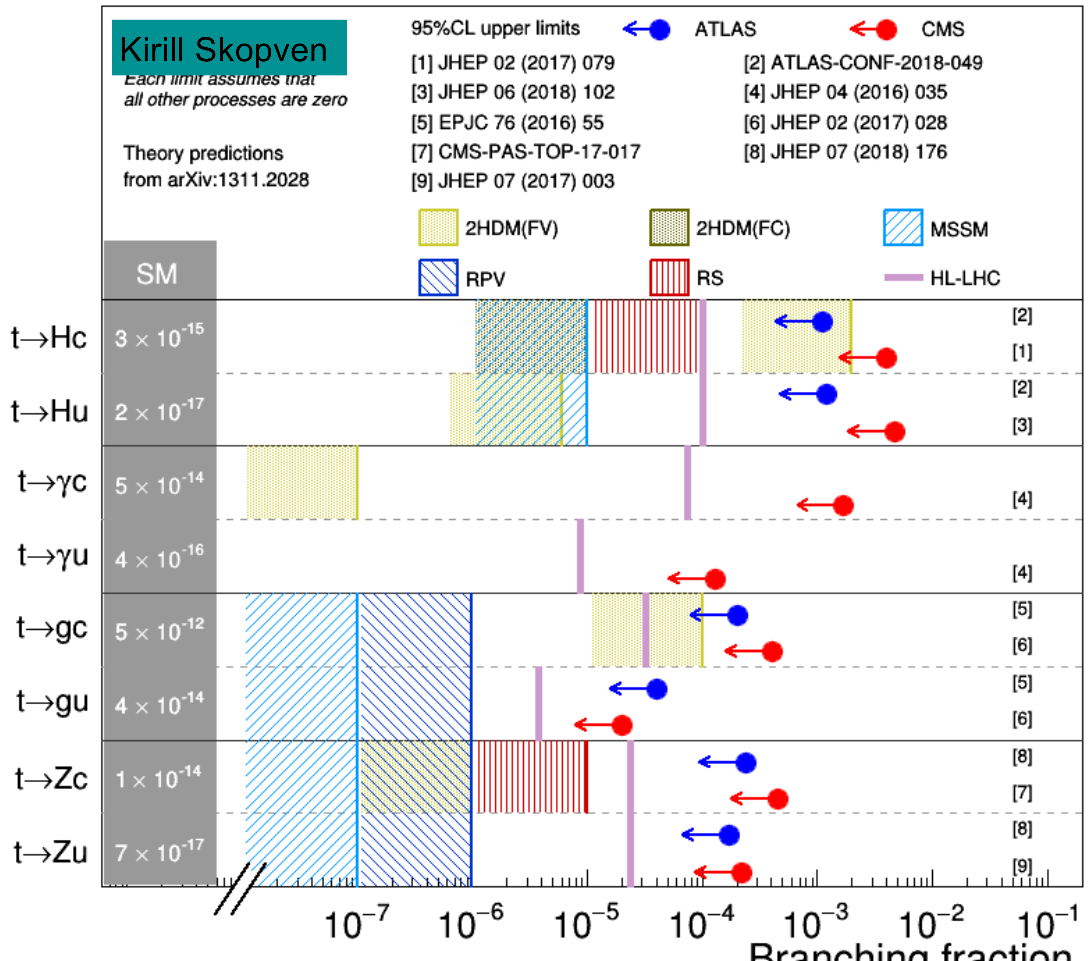


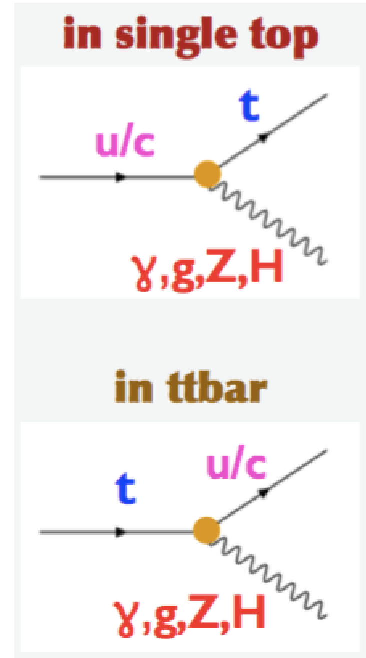
- ➢ Total uncertainty likely reduced by a factor of 3 @ HL-LHC
- ➢ **Individual measurements reach current world-combination uncertainty (16* 10^{-5})**
  - ➢ Strong benefit from tracker/muon system coverage
  - ➢ Complementary ATLAS (electron) and CMS (muon) measurements
- ➢ Study effect of improved PDFs

CMS-FTR-17-001 ATLAS in progress

top fcnc

- In SM: Forbidden at tree level; Only via loops, but highly suppressed
- Vertex present in production (Single top) and in decay (top pair)
- Several analyses, but full potential far from being exploited





CMS-FTR-17-001 tγq

CMS-FTR-18-004 tgq

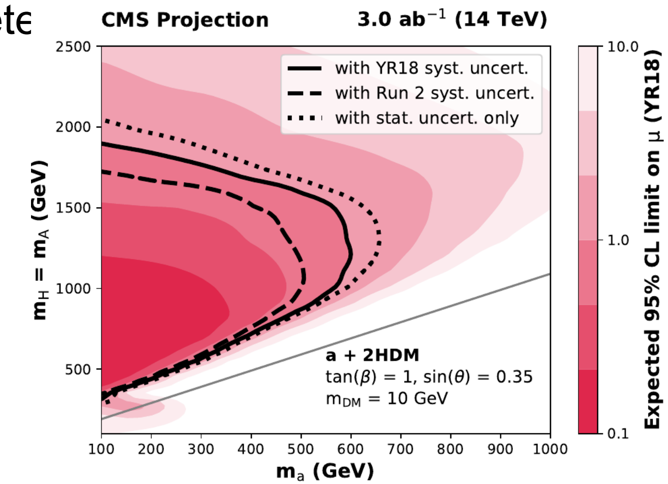
ATL-PHYS-PUB-2016-019 tZu, tHq

ATL-PHYS-PUB-2018-024

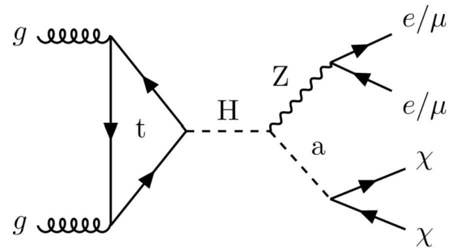
CMS FTR-18-007

DARK MATTER SEARCHES

- Searches based on Simplified Models with Dirac WIMP mediators (scalar, pseudoscalar, vector/axial-vector) give distinct kinematic distributions. Helpful as benchmarks. Complementary to direct dete

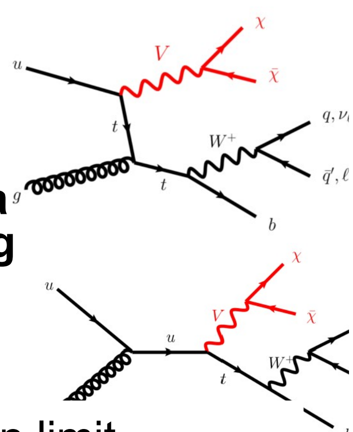


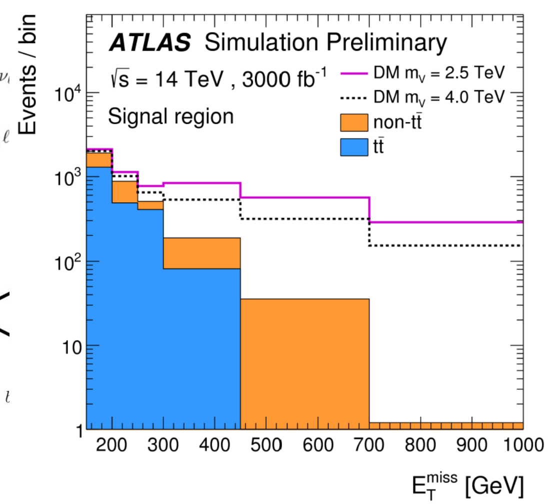
➢ **Non resonant production of a Z accompanied by a mediator decaying to DM particles**



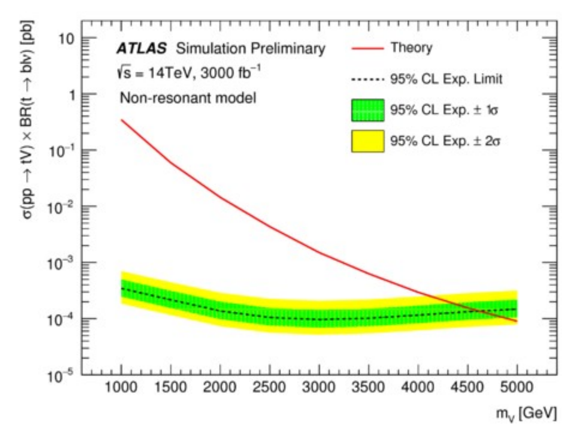
PSEUDOSCALAR - 2HDM

➢ **Non resonant production of a single top quark accompanied by a mediator decaying to DM particles**



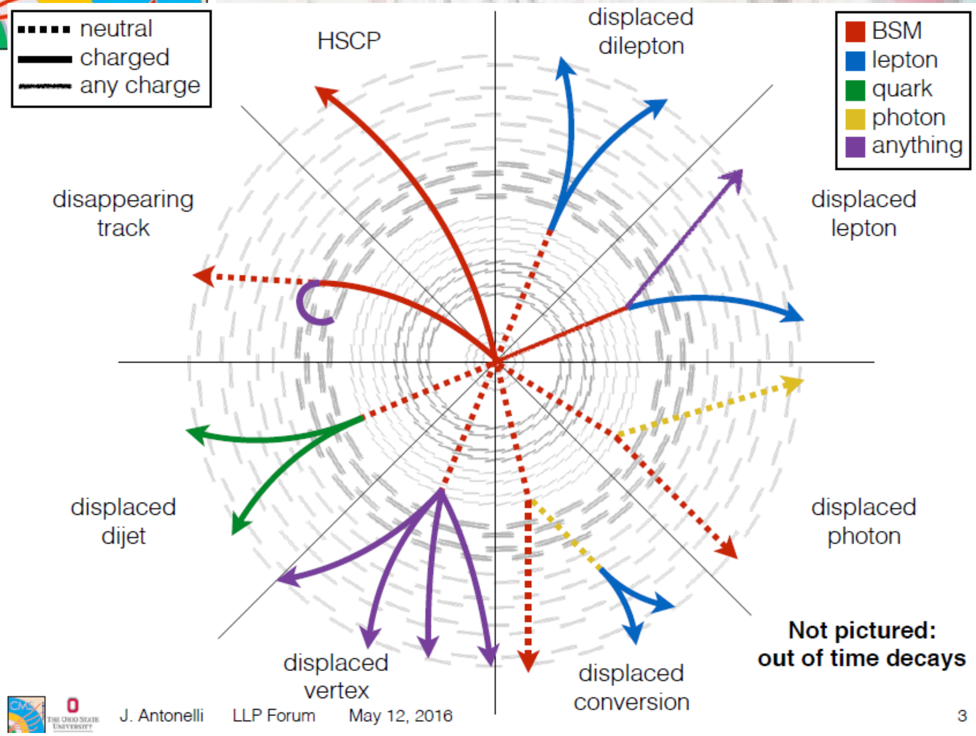


VECTOR



➢ HL-LHC Exclusion limit (discovery reach) = 4.6 (4.0) TeV

Long Lived Particles (LLP)

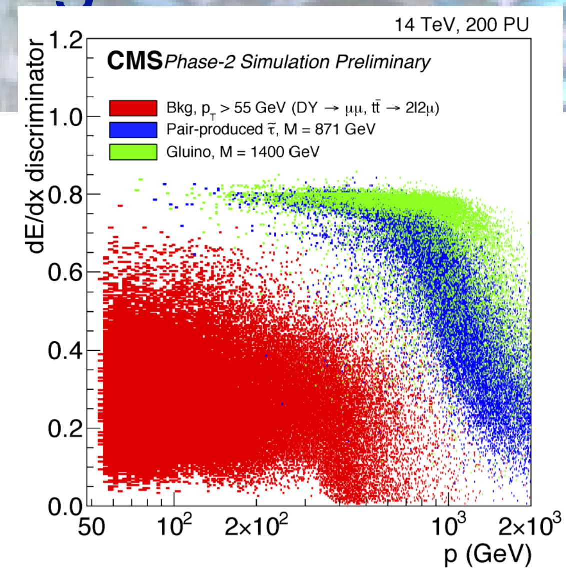


Target complementary lifetimes,ranges and signatures.
Variety of dedicated techniques to cover whole range of lifetimes (cτ)

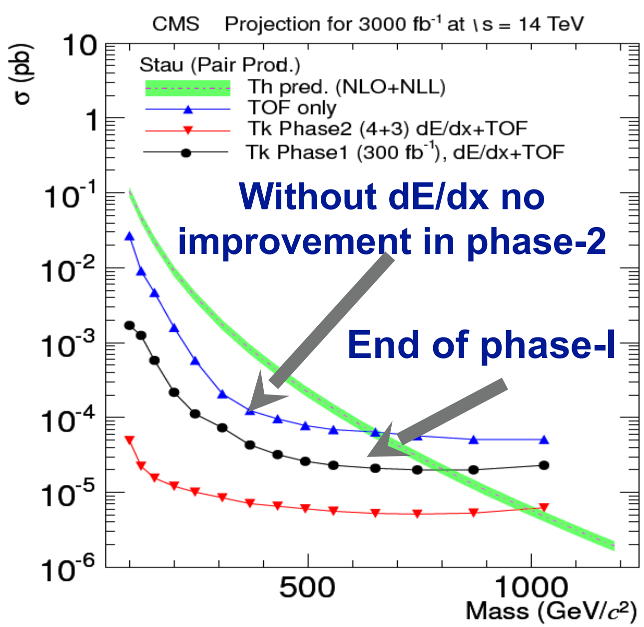
- Unusual signatures are a new focus at the LHC, for present and future
- Search for long-lived particles (HSCP, disappearing tracks) or their displaced decay products (leptons, jets…)
- Signature driven searches, with great discovery potential:
  - Need dedicated tools for non-standard objects, custom trigger/reconstruction/simulation
  - Potential gains from high luminosity, track-trigger, fast timing, better directionality.

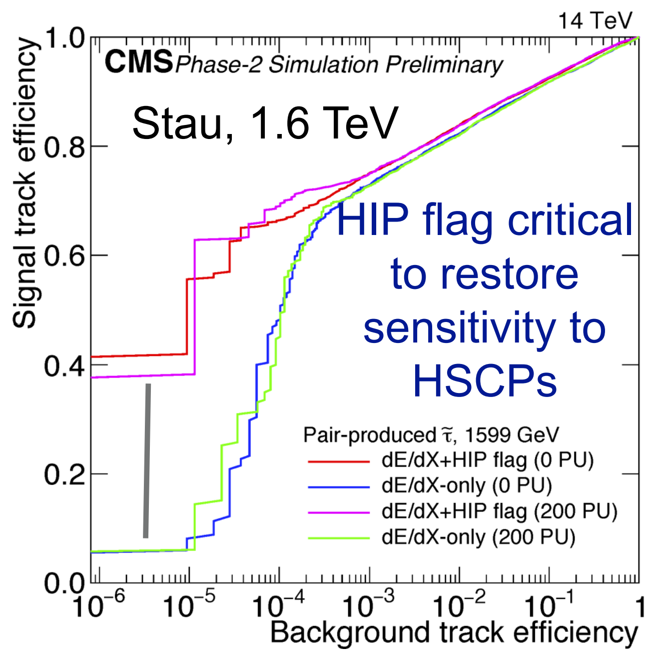
Heavy Stable Charged Particles

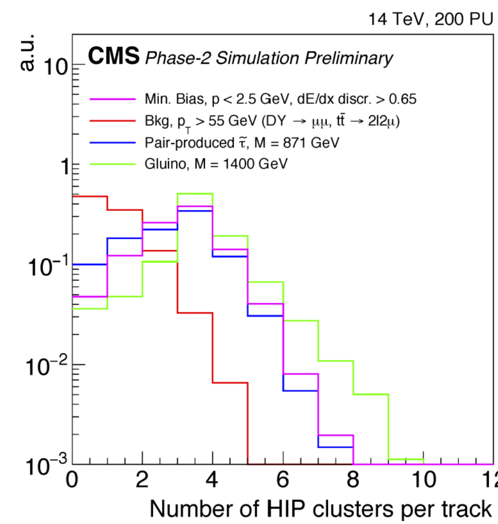
- HSCPs: New, heavy particles could propagate through the detector before decaying
- Needs HL-LHC for sensitivity because of small xsec.
- Detection technique
  - Could look like heavy, highly-ionizing, slow-moving muons
  - dE/dx discriminator shows large separation between signal and background
  - Physics studied demonstrated the need to keep dE/dx



CMS-PAS-EXO-14-007

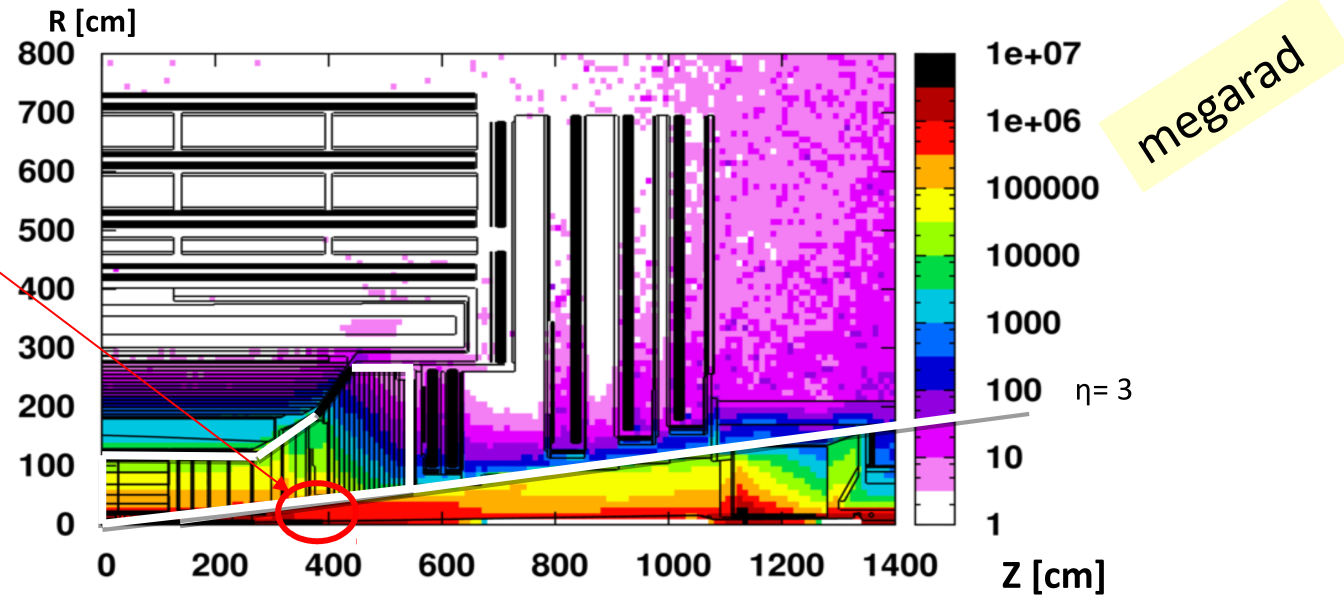


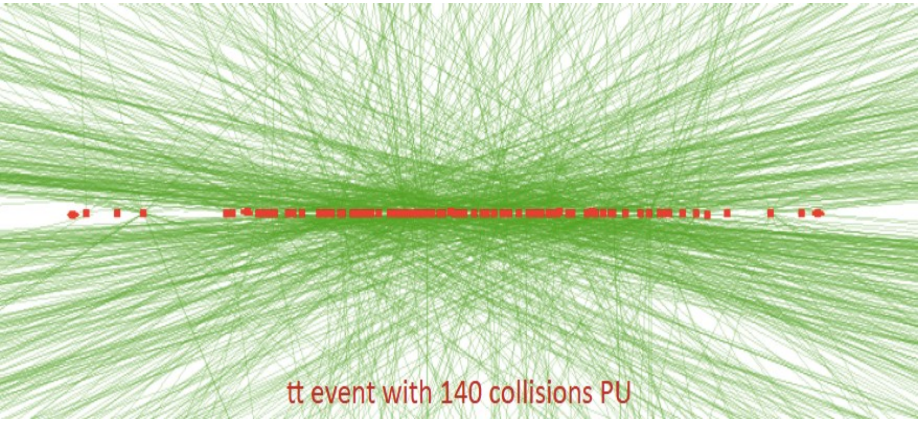




The Challenges of High Lumi LHC

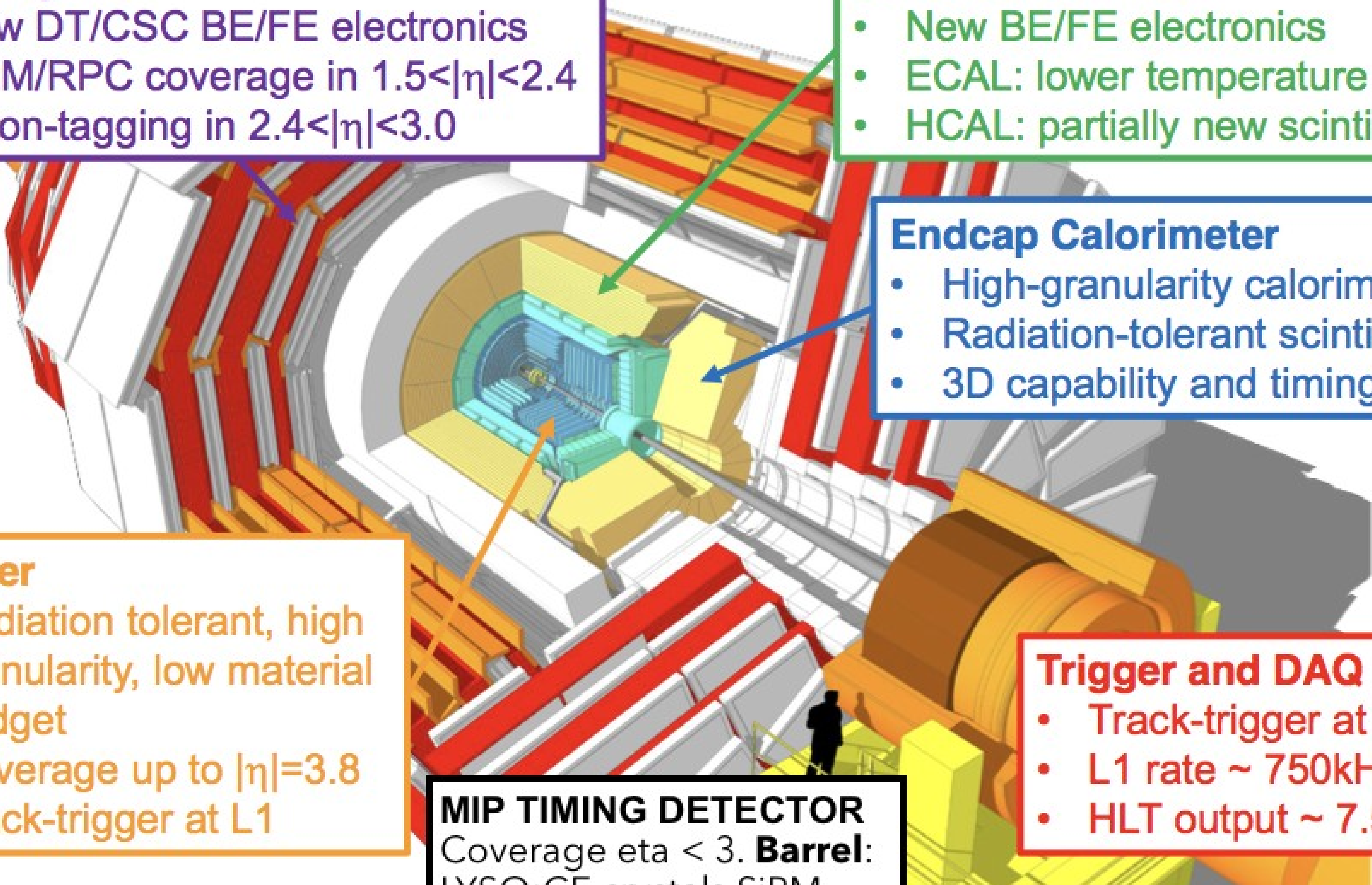
CMS @ HL-LHC:
~**1x10^{16}** 1 MeV n_{eq} cm^{-2}
and up to **2 MGy**
absorbed dose
in endcap calorimeters





High Pile-Up: ultimately
~200 concurrent collisions
per beam crossing
Extreme high data flow rate :
several times Global Internet flow

Phase II upgrade



Muon System
- New DT/CSC BE/FE electronics
- GEM/RPC coverage in $1.5<|\eta|<2.4$
- Muon-tagging in $2.4<|\eta|<3.0$

Barrel Calorimeter
- New BE/FE electronics
- ECAL: lower temperature
- HCAL: partially new scintillator

Endcap Calorimeter
- High-granularity calorimeter
- Radiation-tolerant scintillator
- 3D capability and timing

Tracker
- Radiation tolerant, high granularity, low material budget
- Coverage up to $|\eta|=3.8$
- Track-trigger at L1

MIP TIMING DETECTOR
Coverage eta < 3. **Barrel**: LYSO:CE crystals SiPM. **EndCap**: Silicon Sensors (LGAP). **Timing ~**

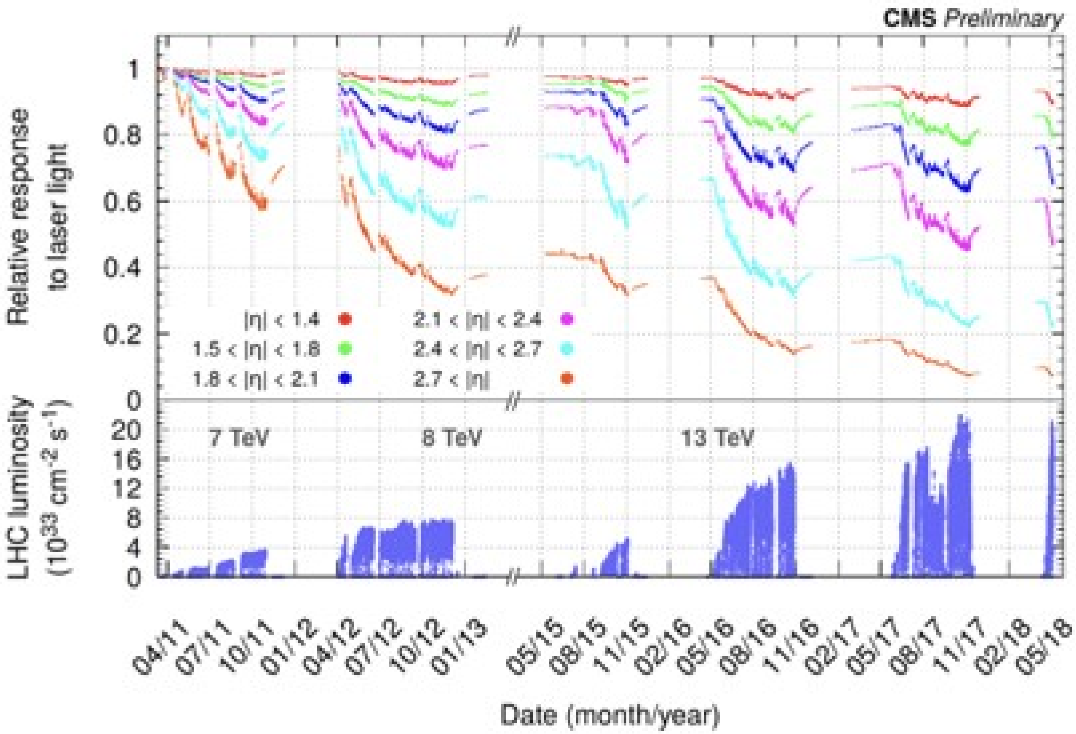
Trigger and DAQ
- Track-trigger at L1
- L1 rate ~ 750kHz
- HLT output ~ 7.5kHz

need of extensive surgery

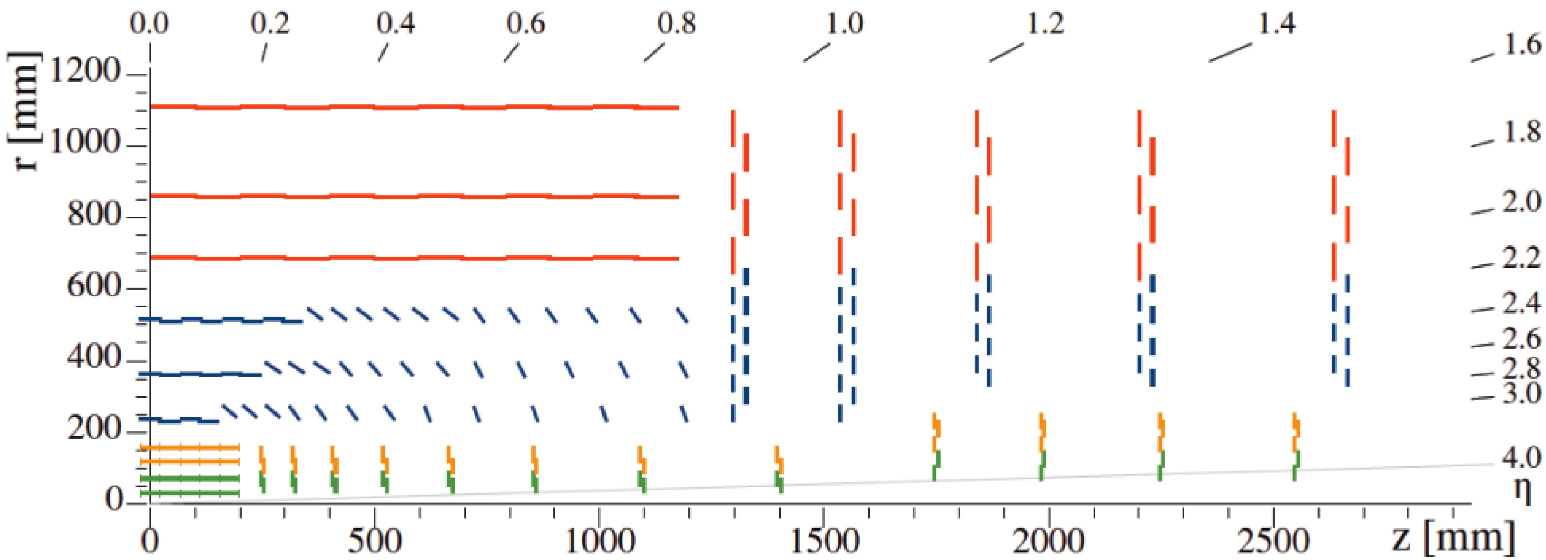
Original experiment was designed for an integrated lumi of $< 300 fb^{-1}$

The radiation toll will impair performance beyond that !

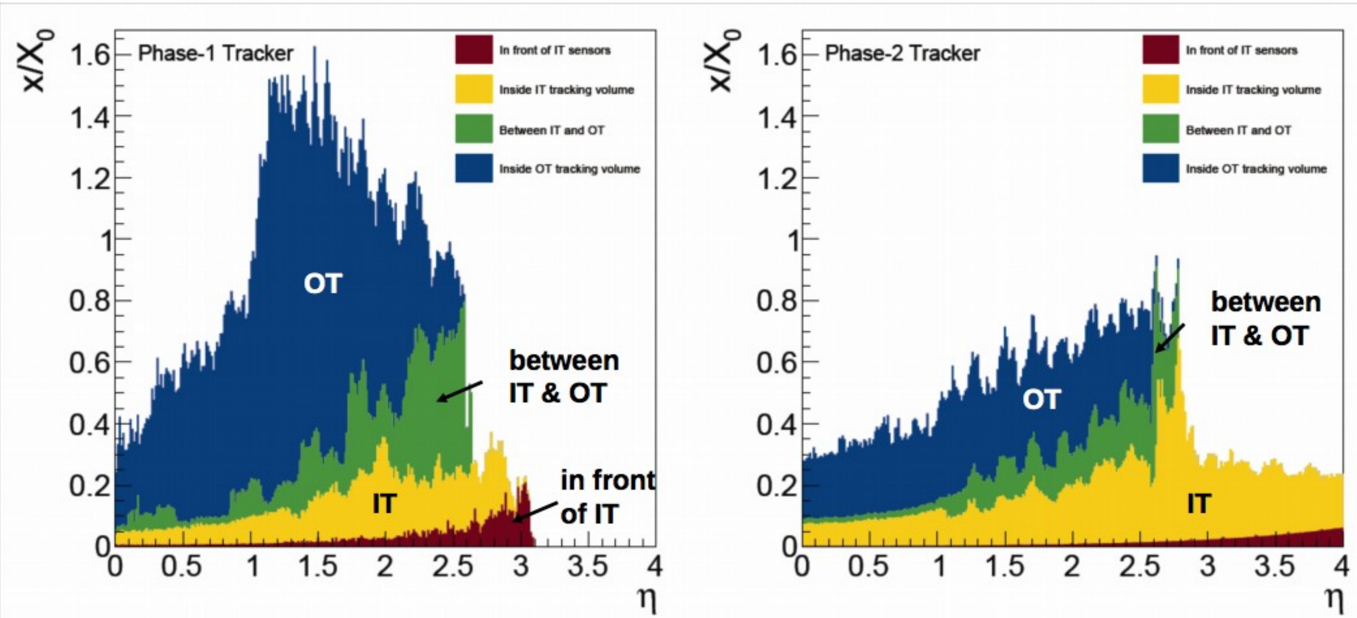
Example: Crystal calorimeter (in the forward region)



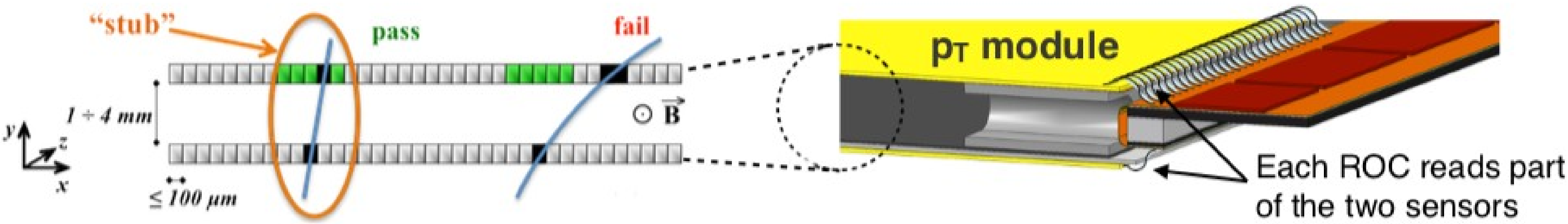
Tracker upgrade

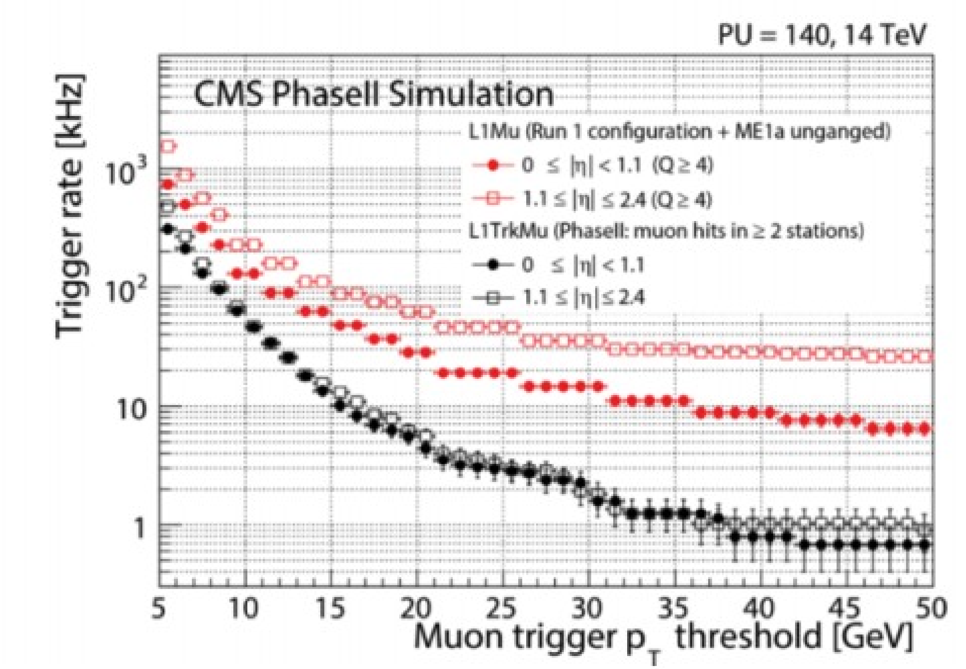


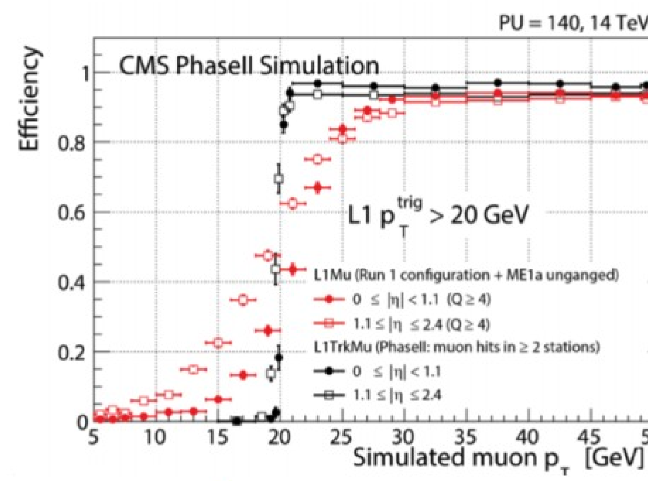
Accep
• Inn
4.9
• Out
13 2
Inn



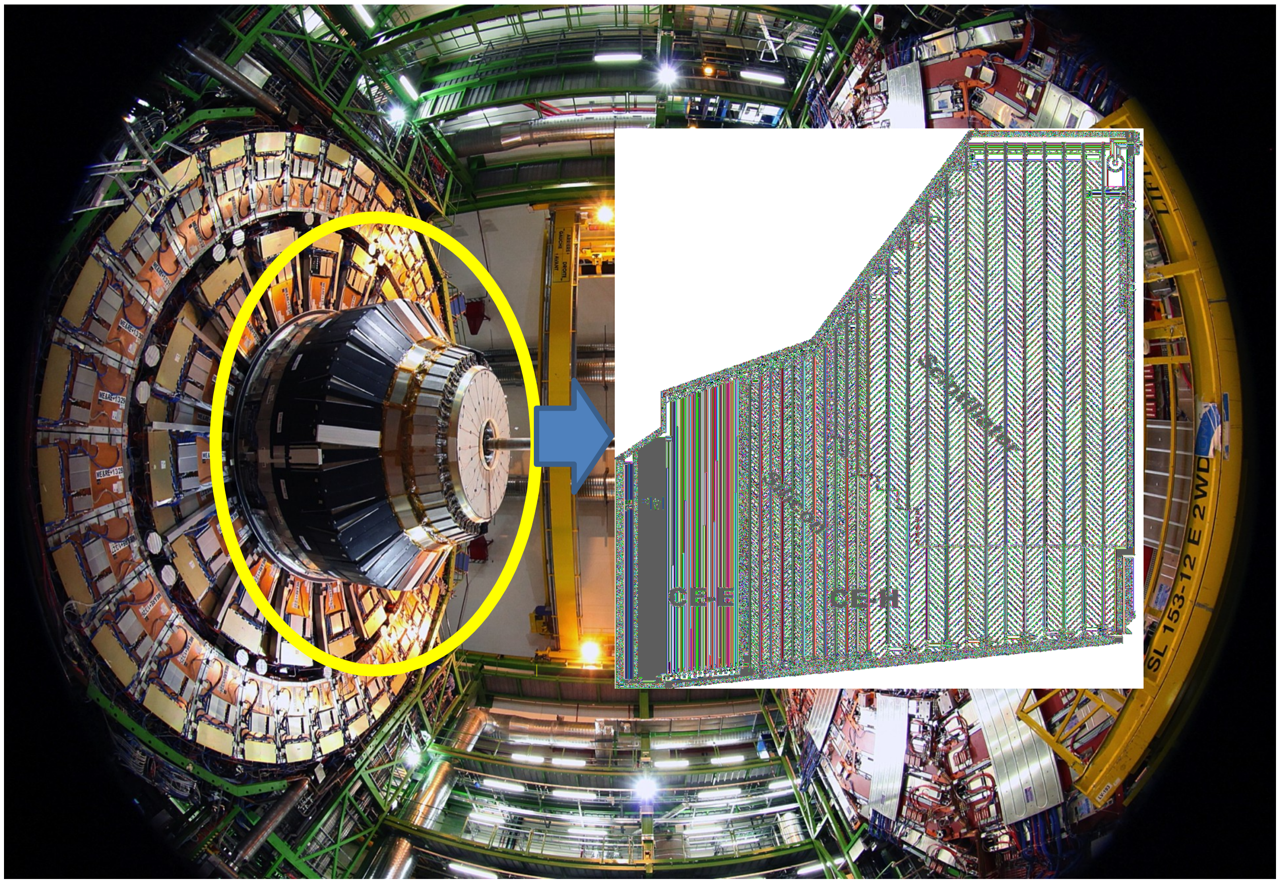
Novel feature: tracking at First level trigger







Endcap calorimeter

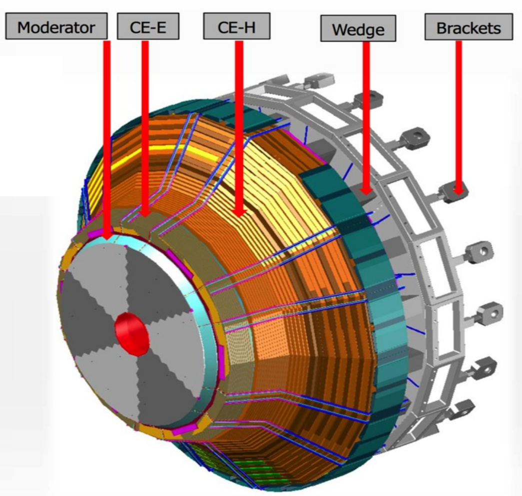


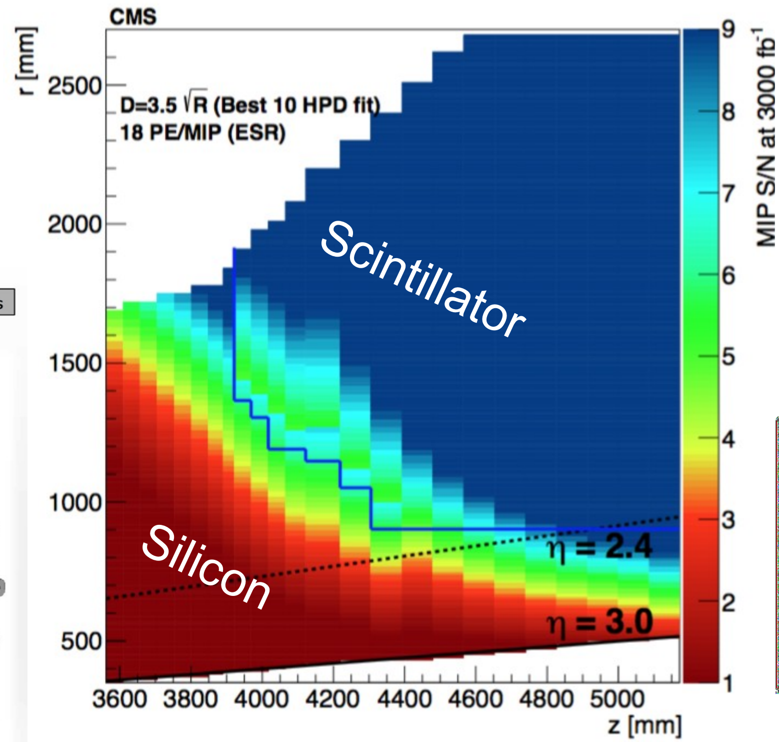
Silicon detector: a modern commodity

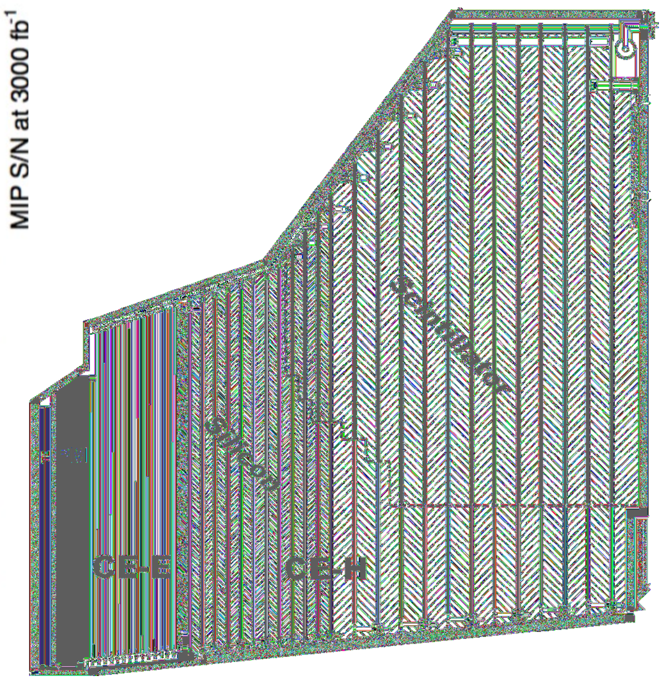
Regions of silicon or silicon + scintillator/SiPM governed by radiation field

Silicon in high-radiation regions

HGCAL design

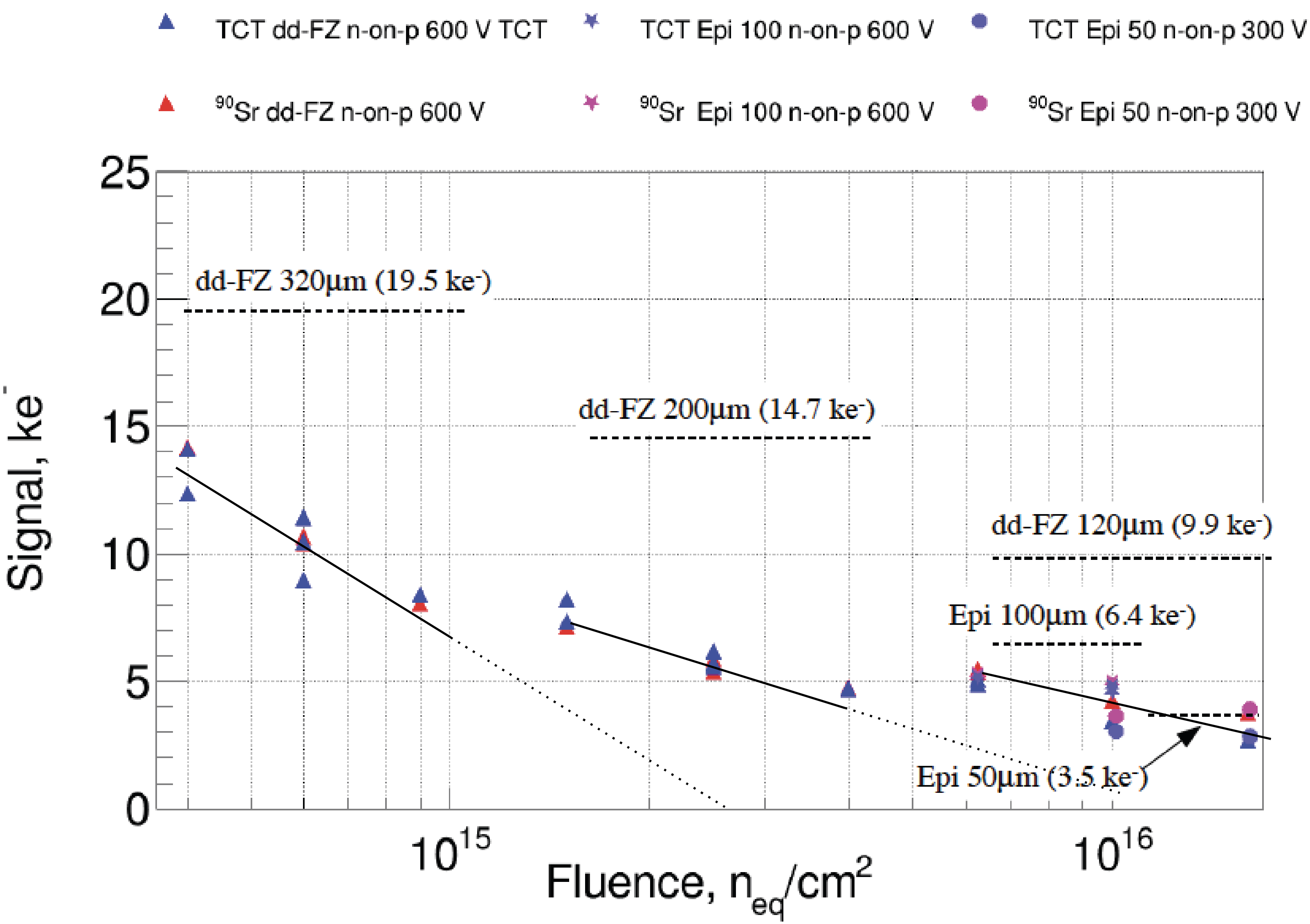






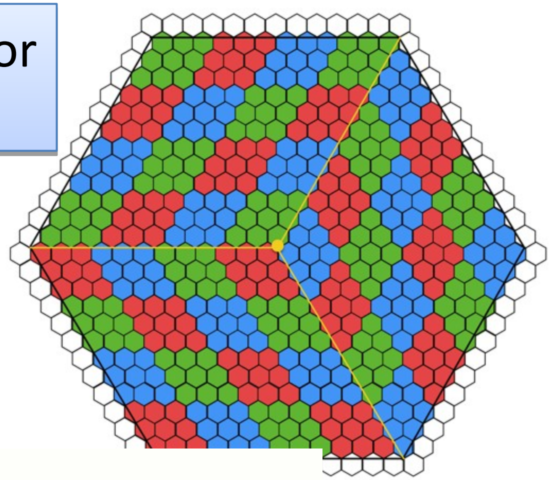
Need to be able to 'use' (sense) Minimum Ionising particles for calibration..Mip signal/noise ~3 even after maximum radiation exposure

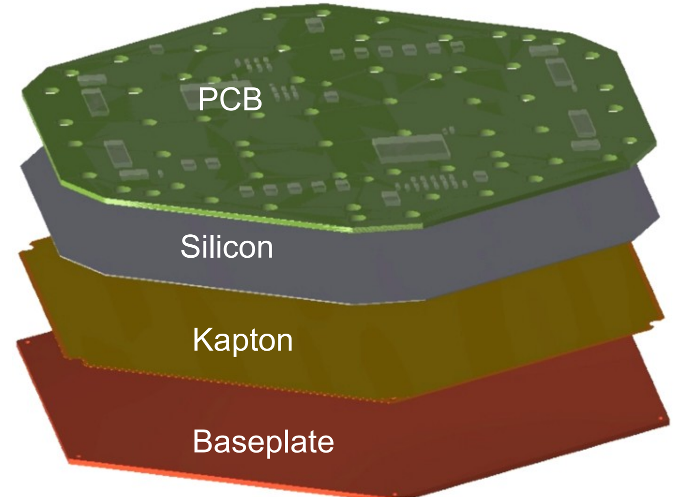
Silicon: the rad hard solution

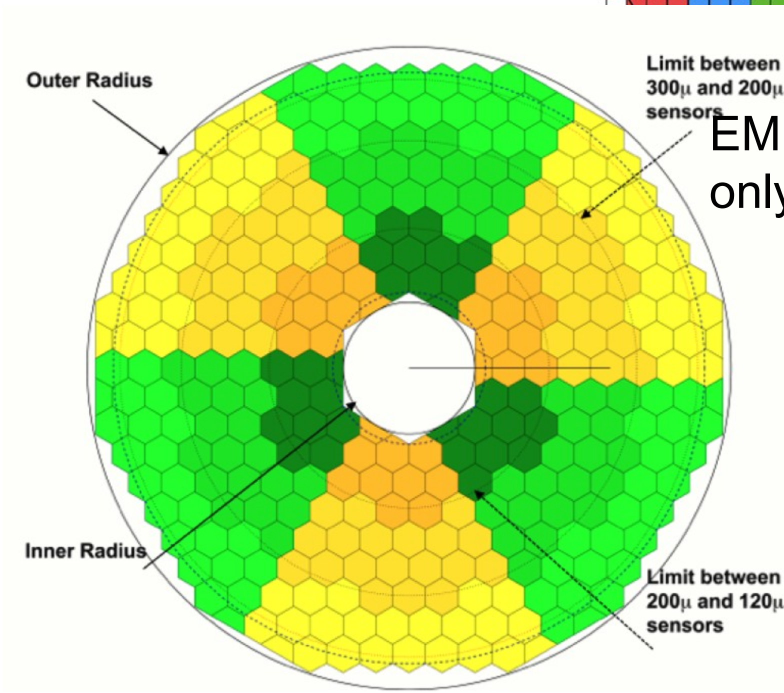


Smart use of large Silicon wafers

120μm: 432 cells/sensor
From 8 inches wafer

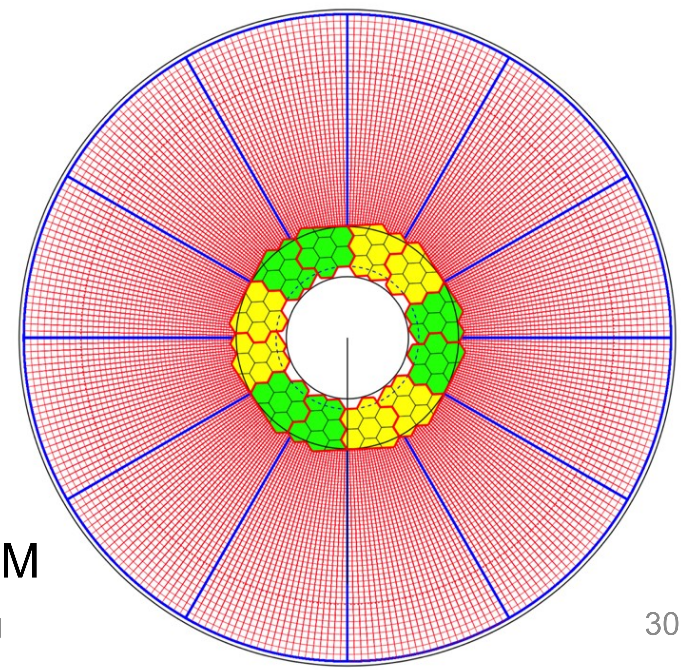






EM section: only Silicon

Had section: Silicon +scintillator tiles and SiPM

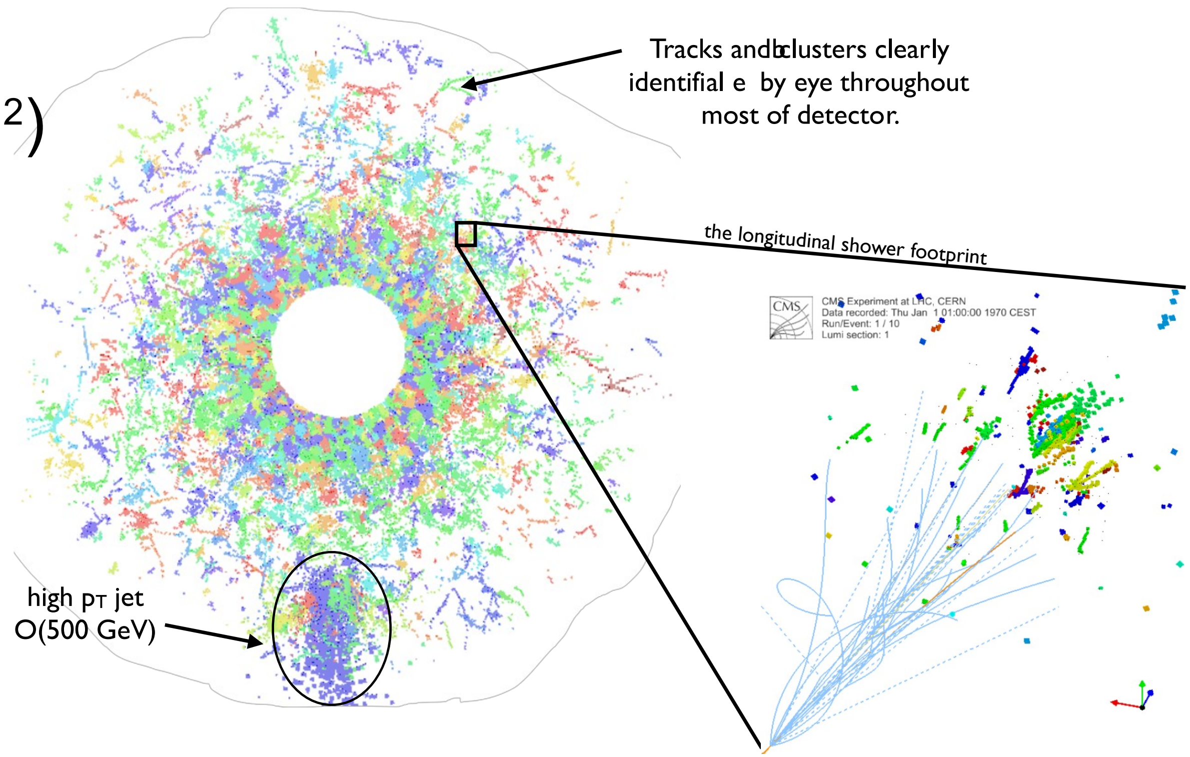


HGCAL has the potential to visualize individual components of showers

600 m^2 of silicon diodes (individual sensor surface ~1cm^2)
500 m^2 of scintillator tiles

Absorber:
Pb/steel/copper
Steel for the back part

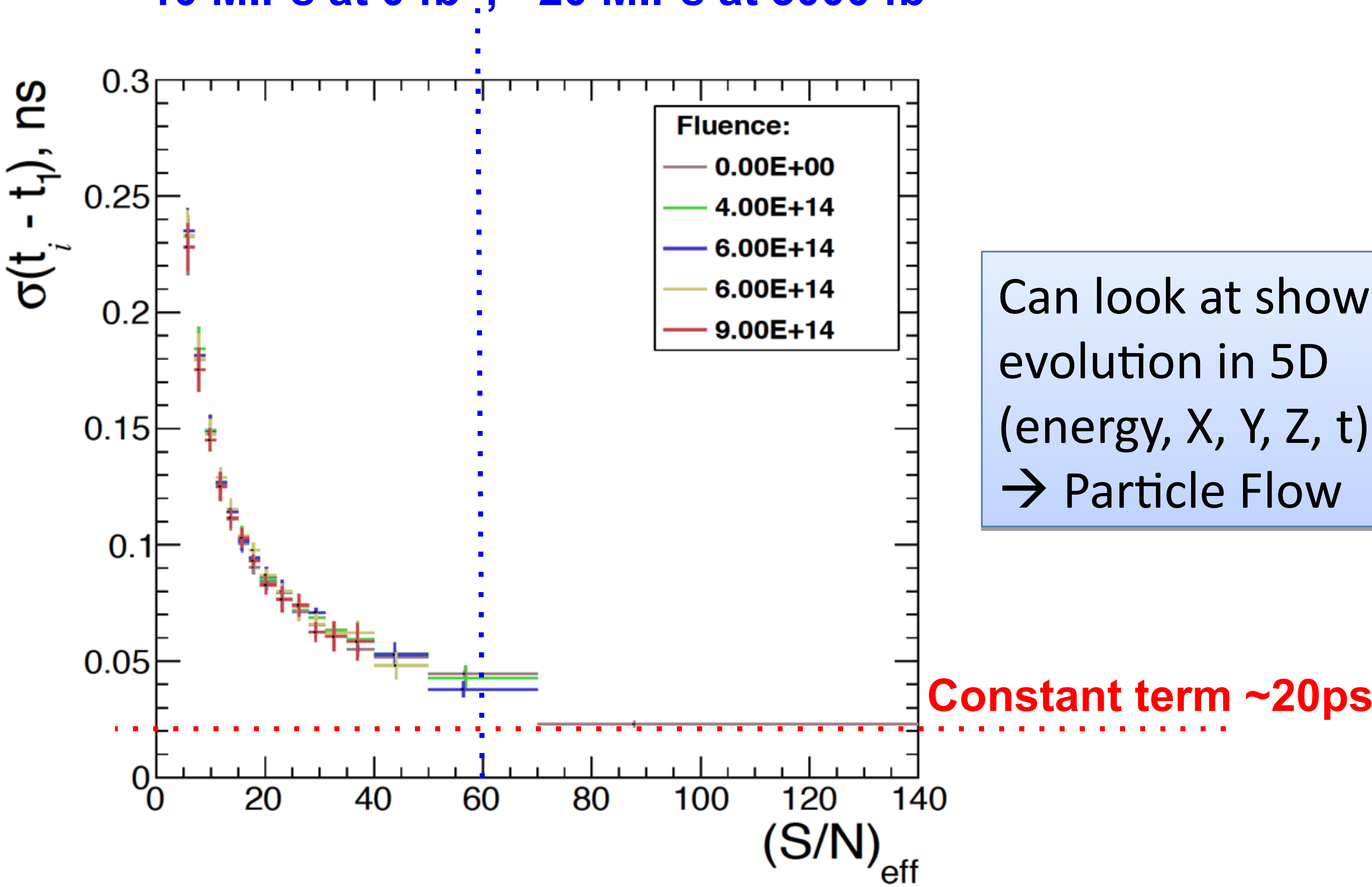
Simulation of 140 pileup events in CMS



Challenge: keep the 400 tons object at -40 degrees with ~150 Kwatt power dissipated inside the volume
Challenge: exploit the huge amount of information… a playing ground for Deep Learning/AI aficionados

Added benefit: 5D reco

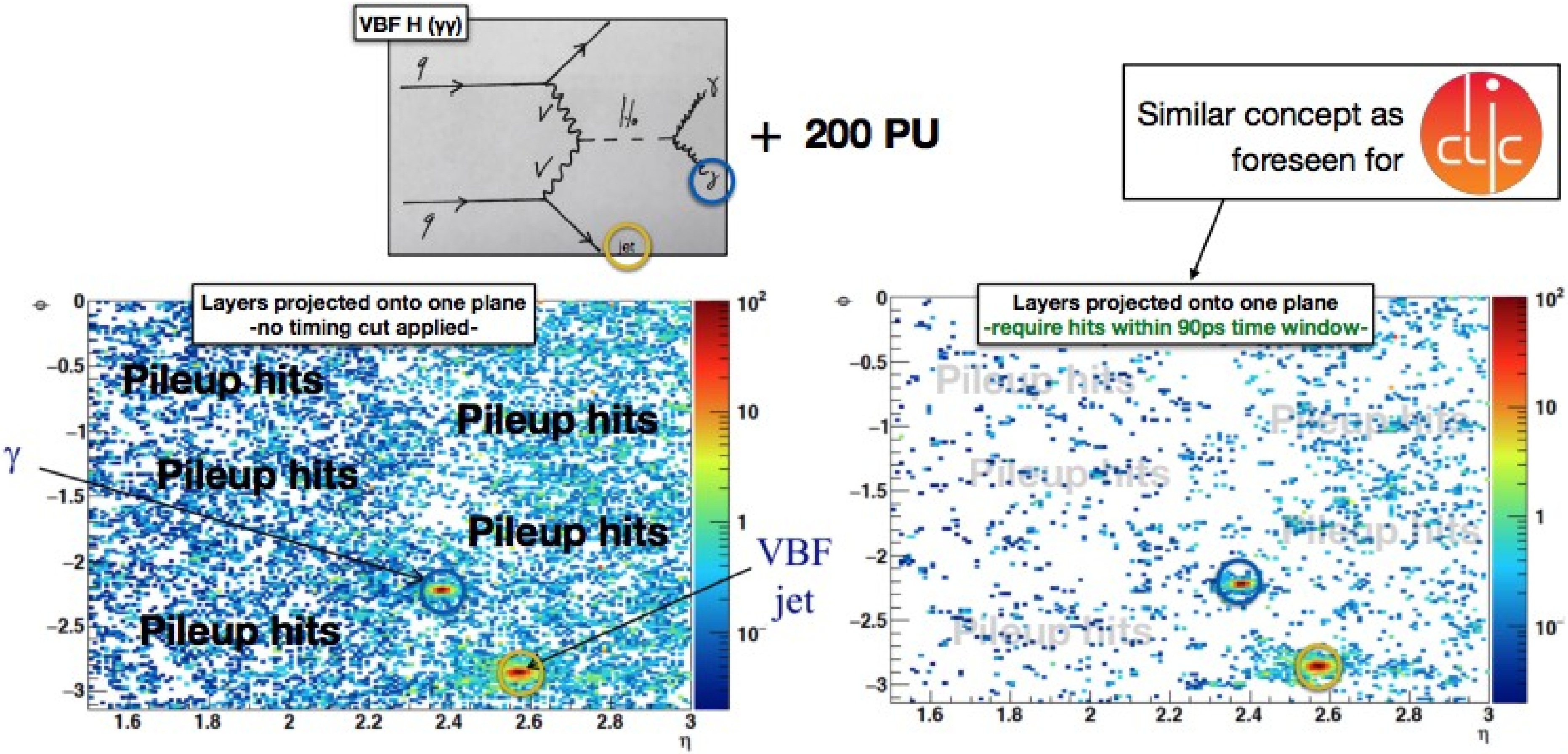
~10 MIPs at 0 fb^{-1}; ~20 MIPs at 3000 fb^{-1}



Can look at shower evolution in 5D (energy, X, Y, Z, t)
→ Particle Flow

5D reconstruction

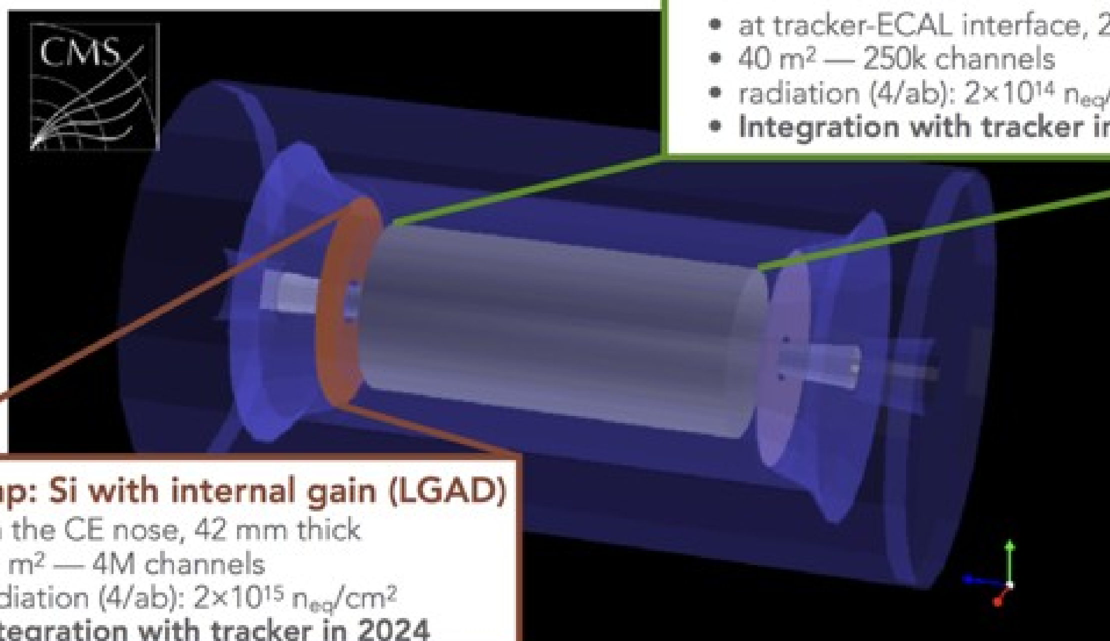
Besides spatial positioning of shower and energy deposit
Si fast response allows usage of time as discriminant



The 4th dimension: timing

- Proposed MIP Timing Detector (MTD):
  - thin layer between tracker and calorimeters, minimal impact on cal.
  - ~30 ps resolution for charged tracks (above 0.7 GeV)
  - hermetic coverage for $|\eta| < 3.0$

Barrel: LYSO tiles + SiPM readout BTL
- at tracker-ECAL interface, 25 mm thick
- 40 m^2 — 250k channels
- radiation (4/ab): 2×10^{14} n_{eq}/cm^2
- **Integration with tracker in 2022**



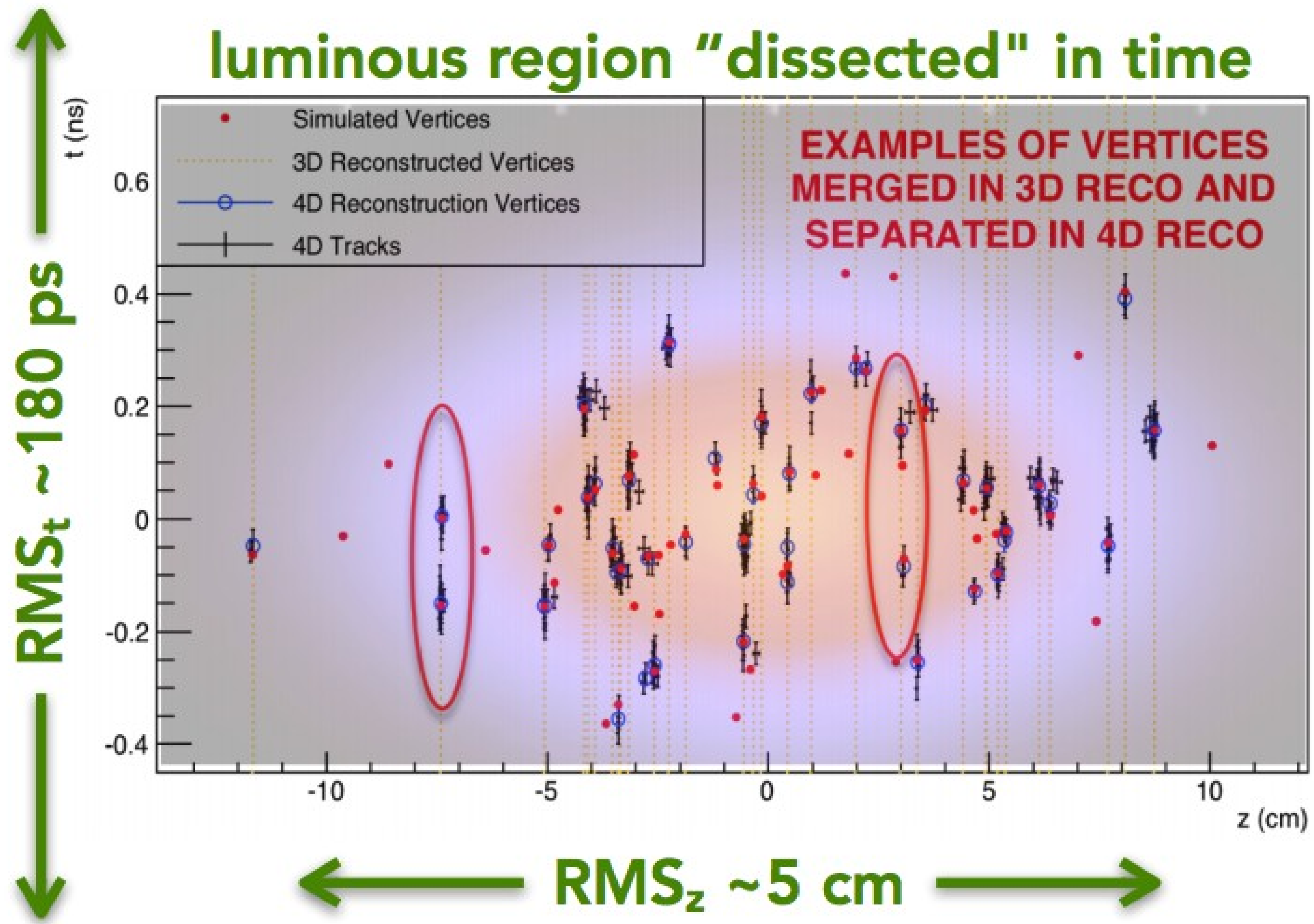
ETL **Endcap: Si with internal gain (LGAD)**
- on the CE nose, 42 mm thick
- 12 m^2 — 4M channels
- radiation (4/ab): 2×10^{15} n_{eq}/cm^2
- **Integration with tracker in 2024**

7

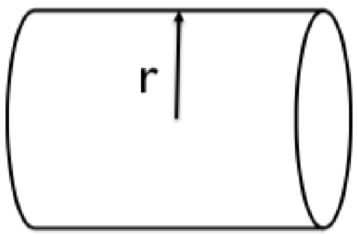
Aim to achieve 30ps resolution (and better than 50 ps at end of operation)

Beating the pile-up

At High Lumi LHC average density of vertices will be 1.7 vertex/mm



Added benefits

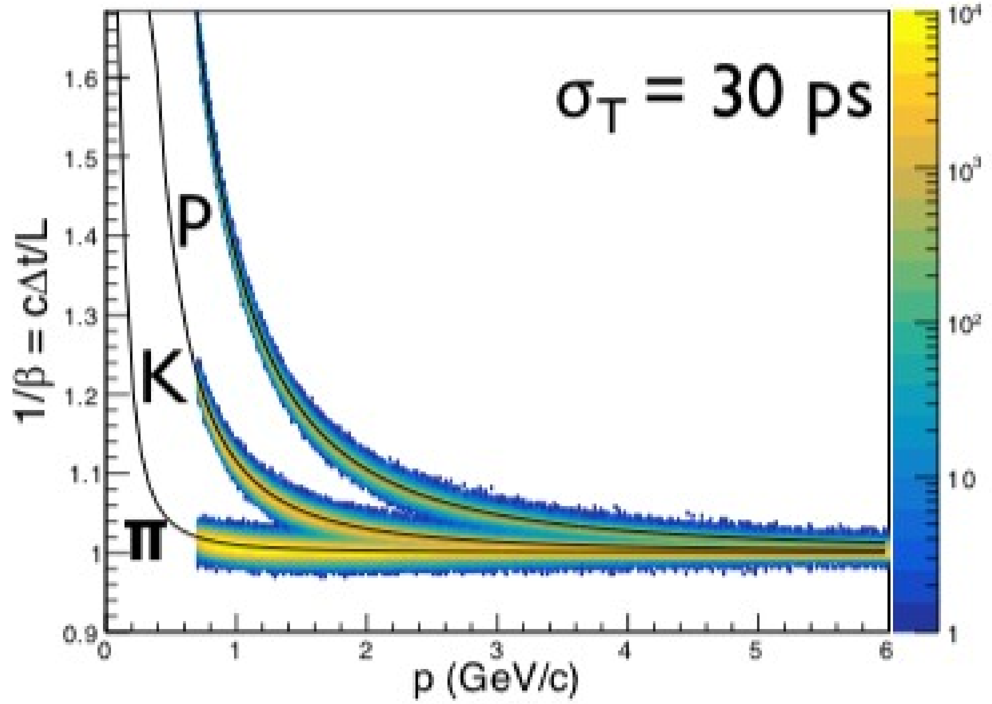


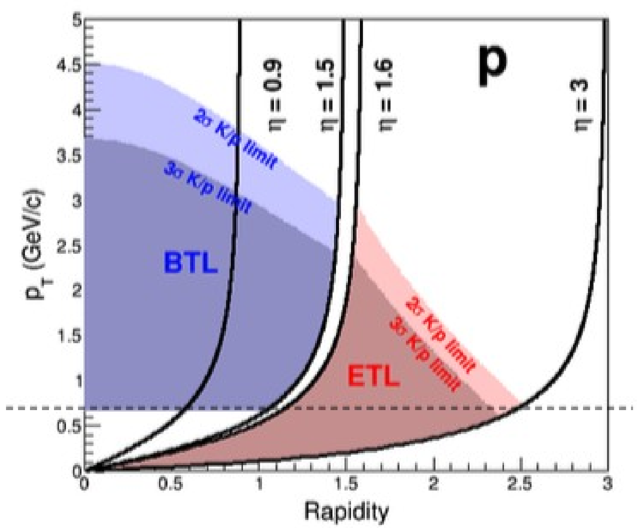
$$p = mc\frac{\beta}{\sqrt{1-\beta^2}}$$

Particle Id. for low momenta particles!

Time-of-Flight difference

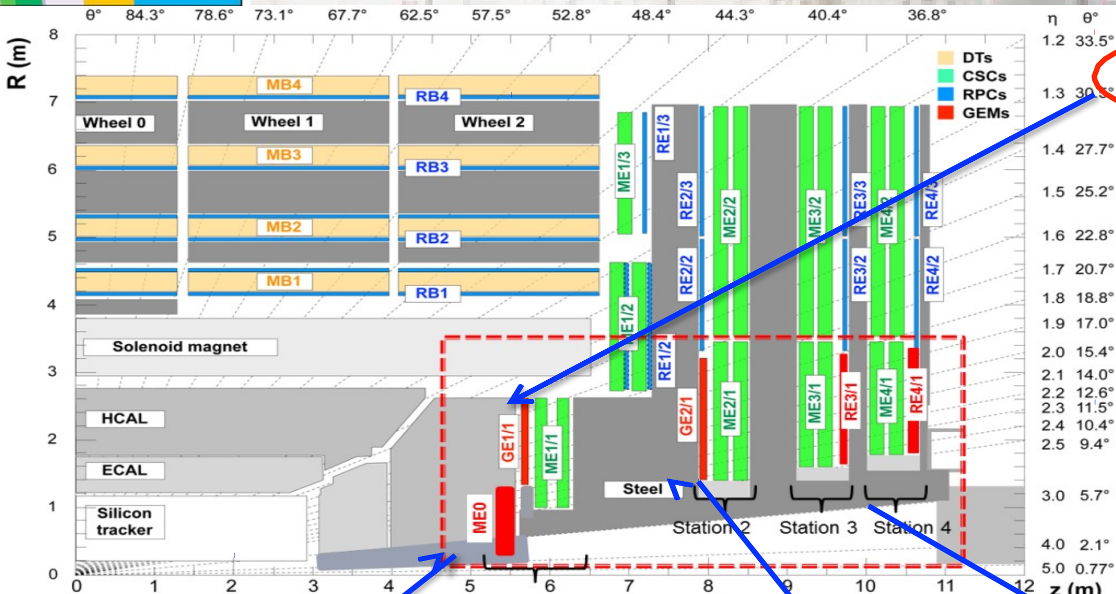
$$\Delta t = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right)$$





Competitive with ALICE Particle ID !

Forward muon system enhancement



GE1/1:

Trigger and reconstruction

- 1.55 < |η| < 2.18
- **baseline detector for GEM project**
- 36 staggered super-chambers (SC) per endcap, each super-chamber spans 10°
- One super-chamber is made of 2 back-to-back triple-GEM detectors
- Installation: LS2 (2018-19)

ME0:

- **Muon tagger** at highest η
- **6 layers of Triple-GEM**
- each chamber spans 20°
- Installation: LS3 (2022-24)

GE2/1:

Trigger and reconstruction

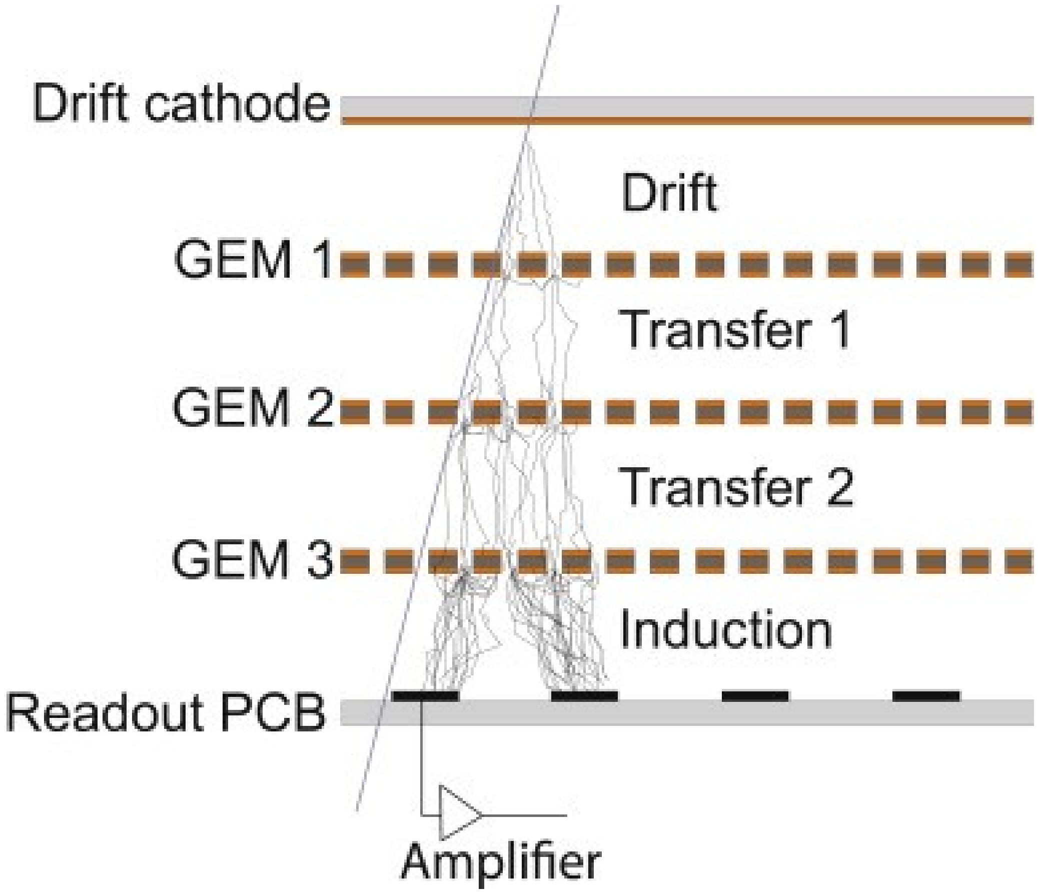
- 1.55 < |η| < 2.45
- 18 staggered SC per endcap, each chamber covers 20°, **3.5 x GE1/1 area**
- Installation: LS3 (2022-24)

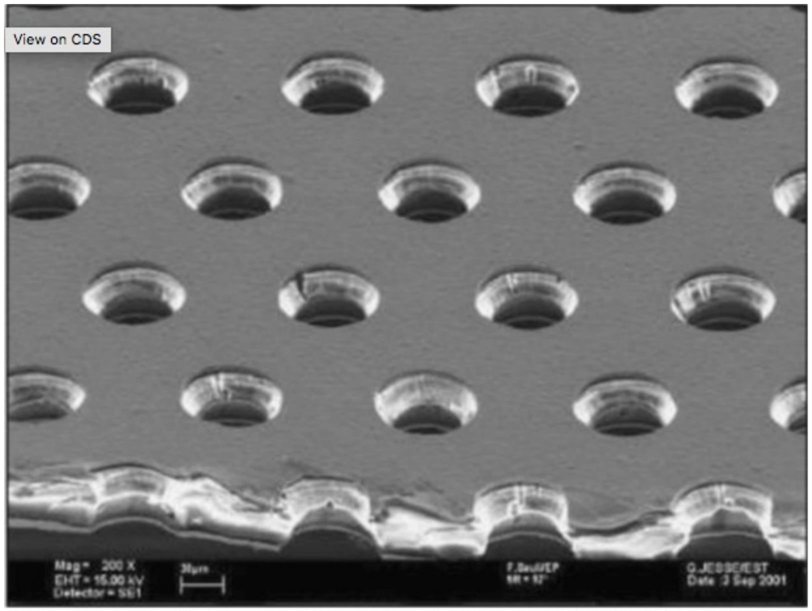
RE 3/1 –RE4/1 :

Trigger and reconstruction

- 1.8 < |η| < 2.4
- **Improved RPC (iRPC), finer pitch**
- 18 chambers per endcap, each chamber spans 20°
- Installation: LS3 (2022-24)

Gaseous Electron Multipliers (GEM) chambers

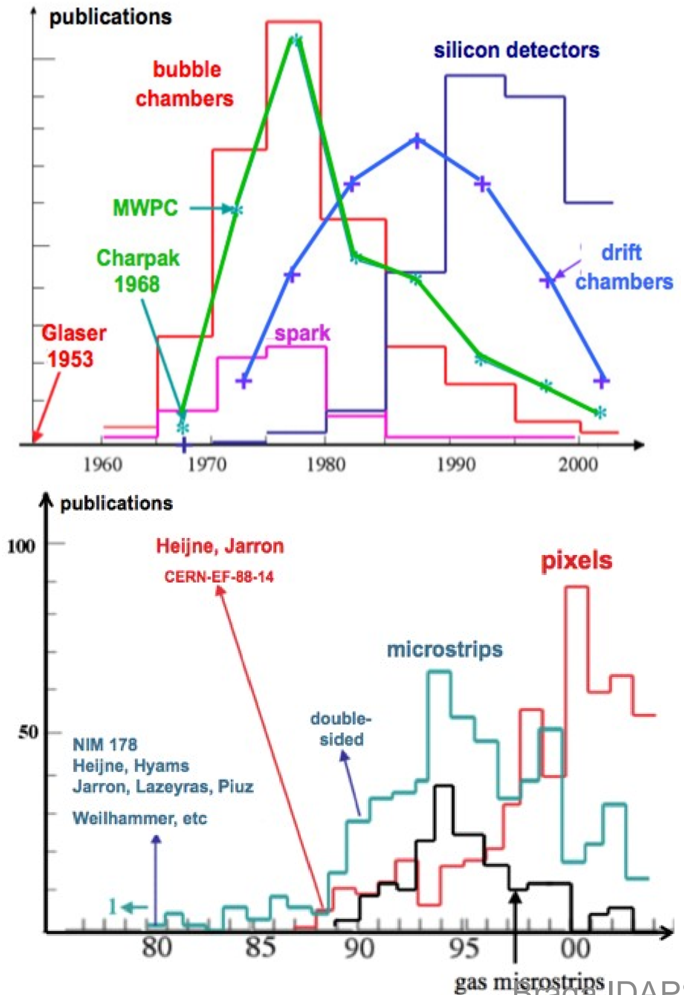


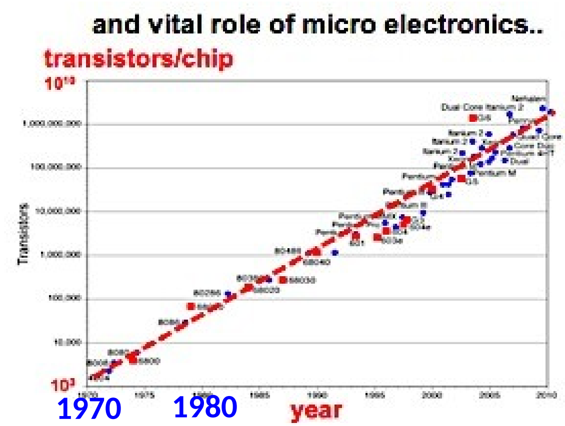


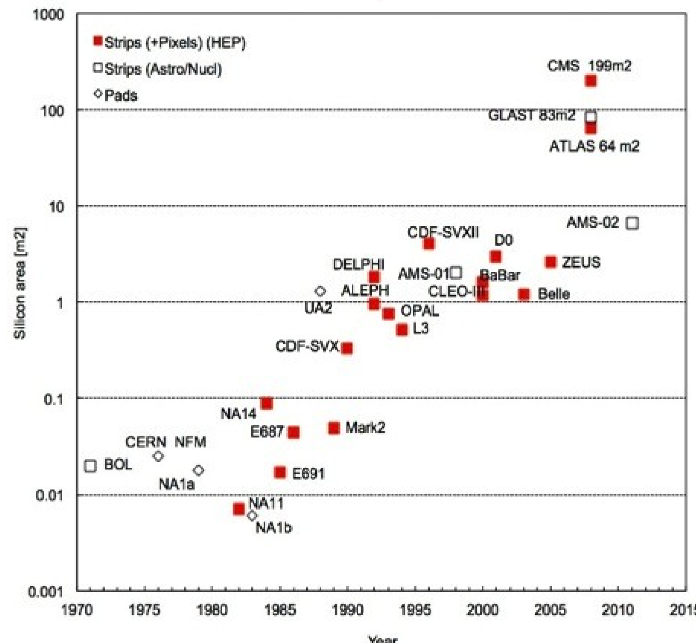
Electron microscope picture of a section of typical GEM electrode, 50 μm thick. (Image: F. Sauli)

Tracking evolution

…. experimentally







Summary

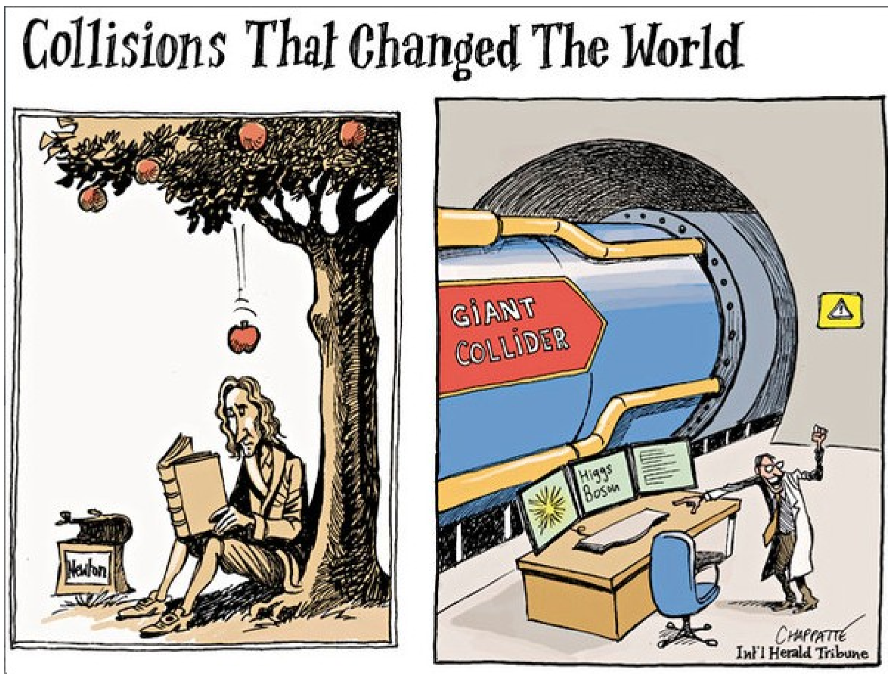
- We are far from having satisfactory answers to several fundamental questions
- Collider physics has still a lot of potential to improve our knowledge of Nature
- The HI Lumi LHC program allows full exploitation of this major investment of the HEP community
- ... and proves that with adequate resources we have not yet reached the limit of what could be done with colliders: the European strategy group will define soon what we could achieve with future colliders
- We are witnessing a change of paradigm... >>>>>

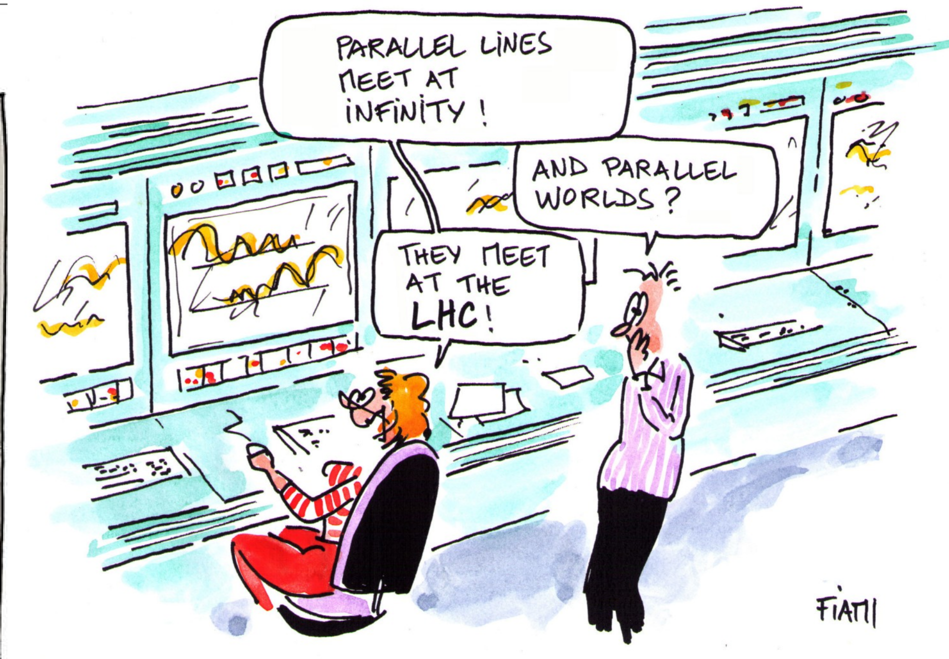
Relations between theory and experiment (as seen by theorists)

A defendable picture when you have very tight predictions: e.g. Higgs boson, rare decays rate

Courtesy of H. Yamamoto

..as seen by experimentalists


Collisions That Changed The World
Newton
GIANT COLLIDER
Higgs Boson
CHAPPATTE
Int'l Herald Tribune


PARALLEL LINES MEET AT INFINITY !
THEY MEET AT THE LHC !
AND PARALLEL WORLDS ?
FIAMI

- Backup

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W{}^2} = \frac{1}{2v^2}$$

$$\boxed{v^2 = (\sqrt{2}G_F)^{-1} = (246\ GeV)^2}$$

Higgs Potential

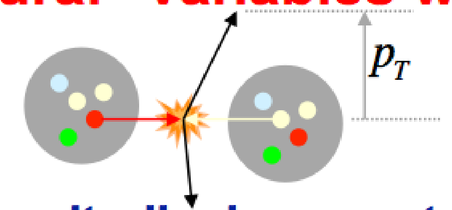
$$V = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

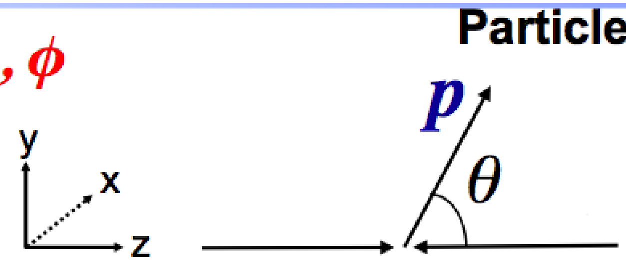
$$v^2 = -\frac{\mu^2}{2\lambda}$$

$$M_H{}^2 = 2v^2\lambda$$

Reminder : pp kinematics

- **"Natural" variables would be p, θ, ϕ**

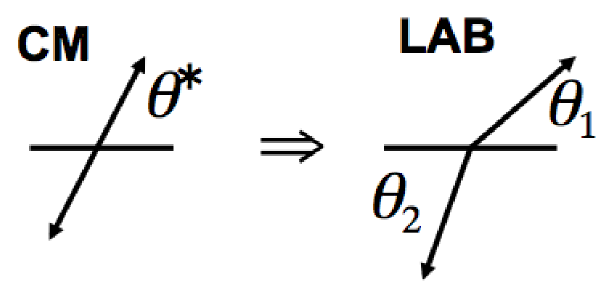




  - **Longitudinal momentum & energy, p_z & E: not useful**
    - **Particles escaping detection have large p_z; visible p_z not conserved: $\sum_i p_{z,i} \neq 0$**
  - **More useful: transverse momentum, pT**
    - **Particles escaping detector (low θ) have pT≈0; visible p_T conserved: $\sum_i p_{T,i} \approx 0$**
- **LAB ≠ parton-parton CM system**

Parton CM $(\text{energy})^2 \rightarrow \hat{s} = x_1 x_2 s$

Worse: p, θ not invariant under Lorentz boosts along z (not good, especially in two-particle correlations)



Kinematics continued

- **Using rapidity and pseudorapidity instead**

Rapidity (y)

$$y \equiv \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \frac{1}{2}\ln\frac{1+\beta\cos\theta}{1-\beta\cos\theta}$$

$$\beta \to 1 \ (m << p_T):$$

Pseudo-rapidity (η)

$$\eta \equiv -\ln\tan\frac{\theta}{2}$$

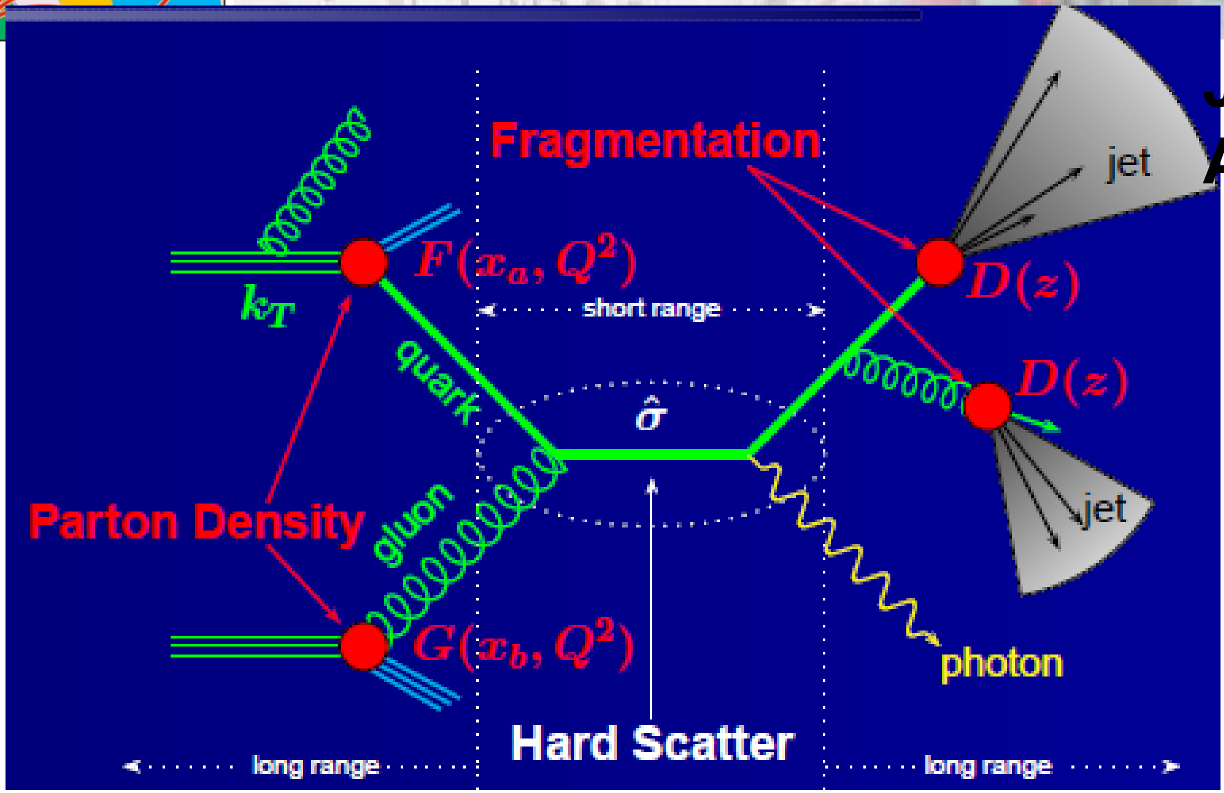
$\Delta y, \Delta\phi$: invariant under Lorentz boosts along z

Distance between two particles:

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

Bottom line: particles described by p_T, η and ϕ

The Hard Scatter



Jet Algorithm
Anti-k_T, R=0.5

Typical of hard scatter
e, m, γ : E_T > 20 GeV
Jets: E_T > 20 GeV

Isolation
E_T,p_T < thresh in cone

$$\Delta R \equiv \sqrt{\Delta\eta + \Delta\phi}$$

ΔR ~ 0.3-0.4

H_T - scalar sum of E_T of all jets with e.g. P_T > 30 GeV/c
S_T - scalar sum of E_T of N individual objects (jets, e, μ, γ) with e.g. E_T > 50 GeV/c

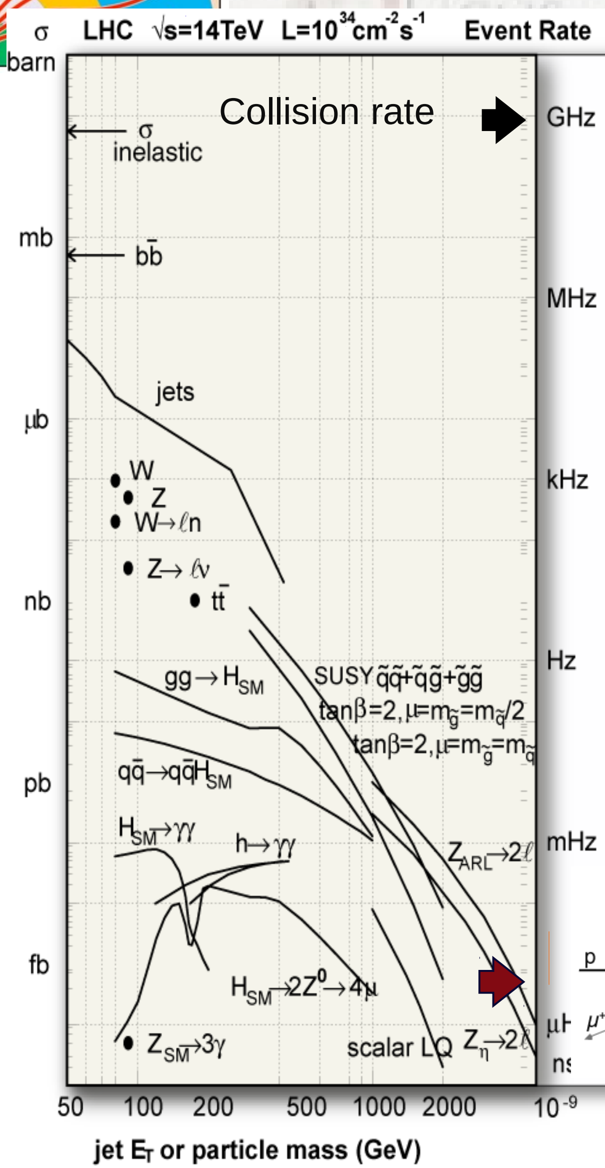
Transverse Mass,

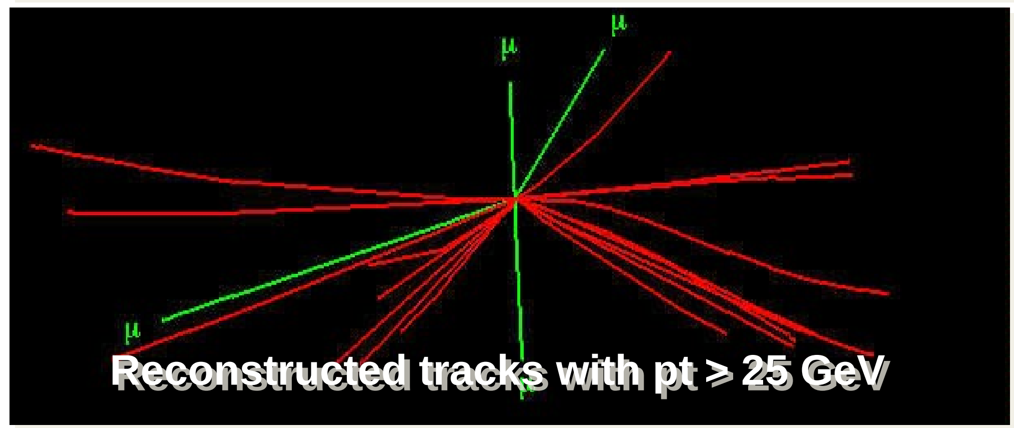
$$M_T = \sqrt{2E_T^{\mu}E_T^{miss}(1-\cos\Delta\phi_{e,miss}}$$

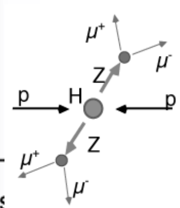
$$\alpha_T = \frac{E_{T2}}{M_T} \leq 0.5$$

Typical variables used in analysis

Data detection and data filtering







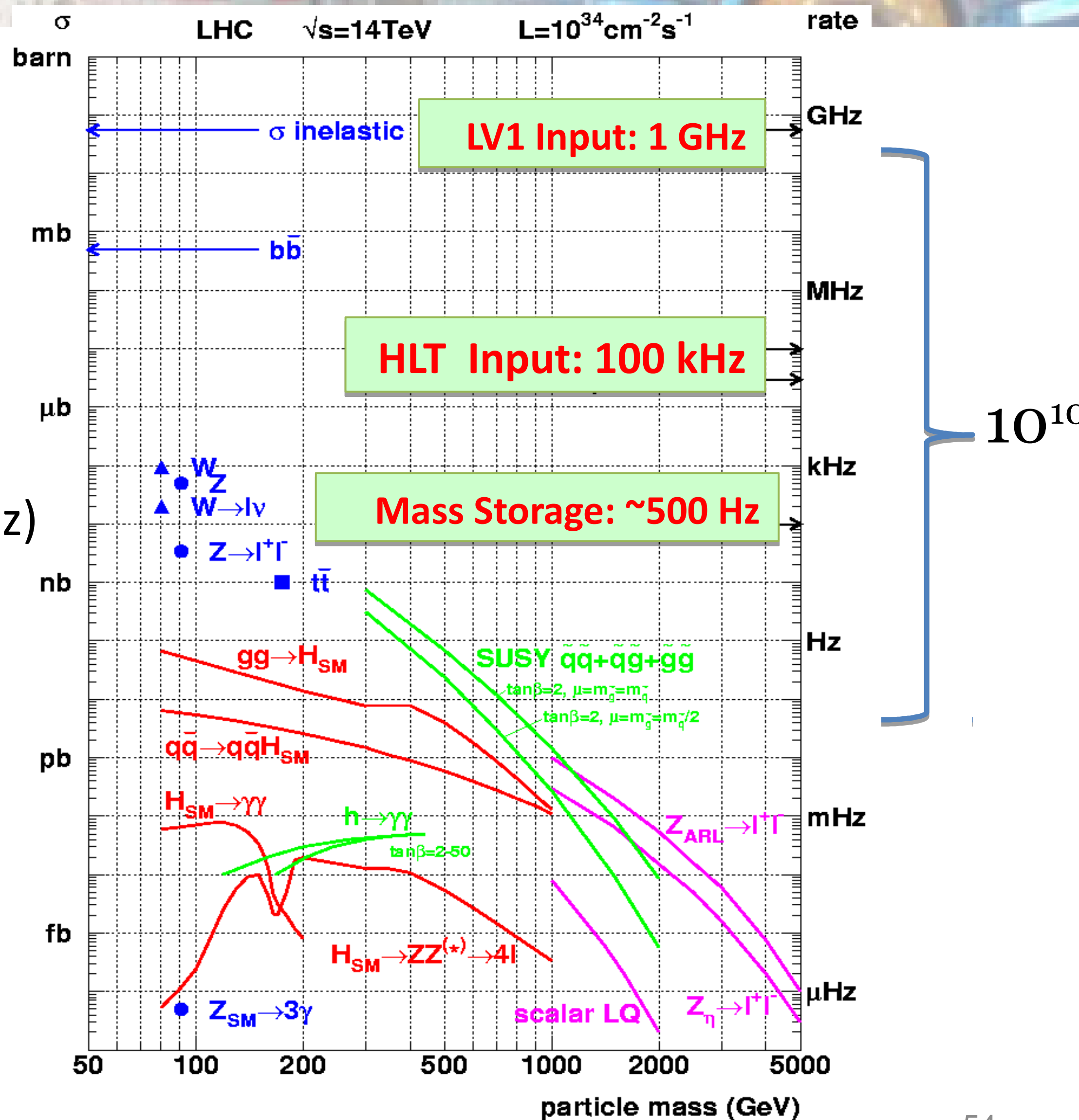
Detector granularity	~ 10^8 cells
Event size:	~ 1 Mbyte
Processing Power:	~ Multi-TFlop

Towards physics: CMS triggers

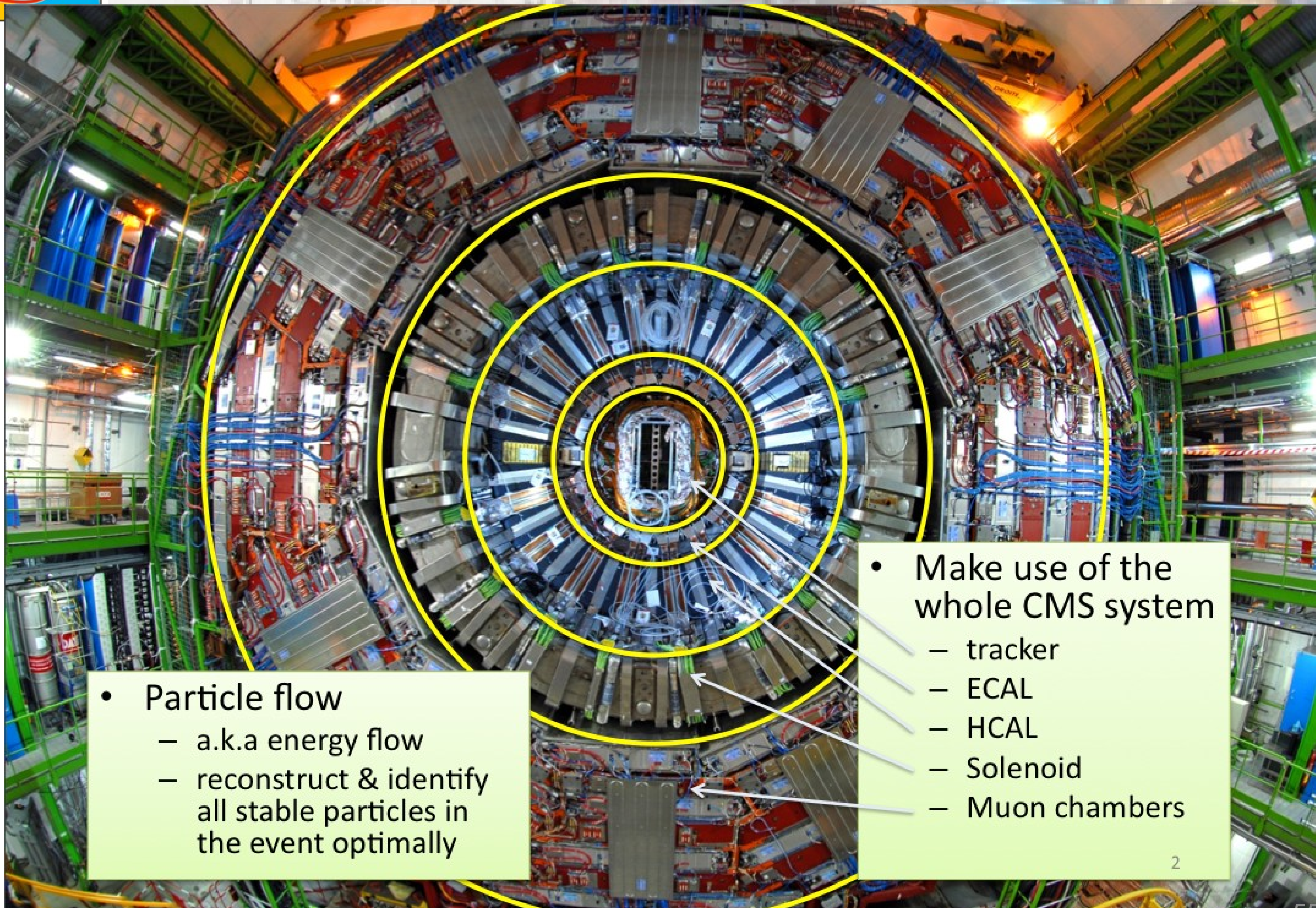
At LHC the p-p crossing rate is 40 MHz (collision rate up to 2 GHz)
The Event size <1 Mbyte

Band width limit ~ 200 GB→
Mass storage design rate
~300-500 Hz (today 1000-1500 Hz)

First step in 'analysis' is trigger



Event reconstruction

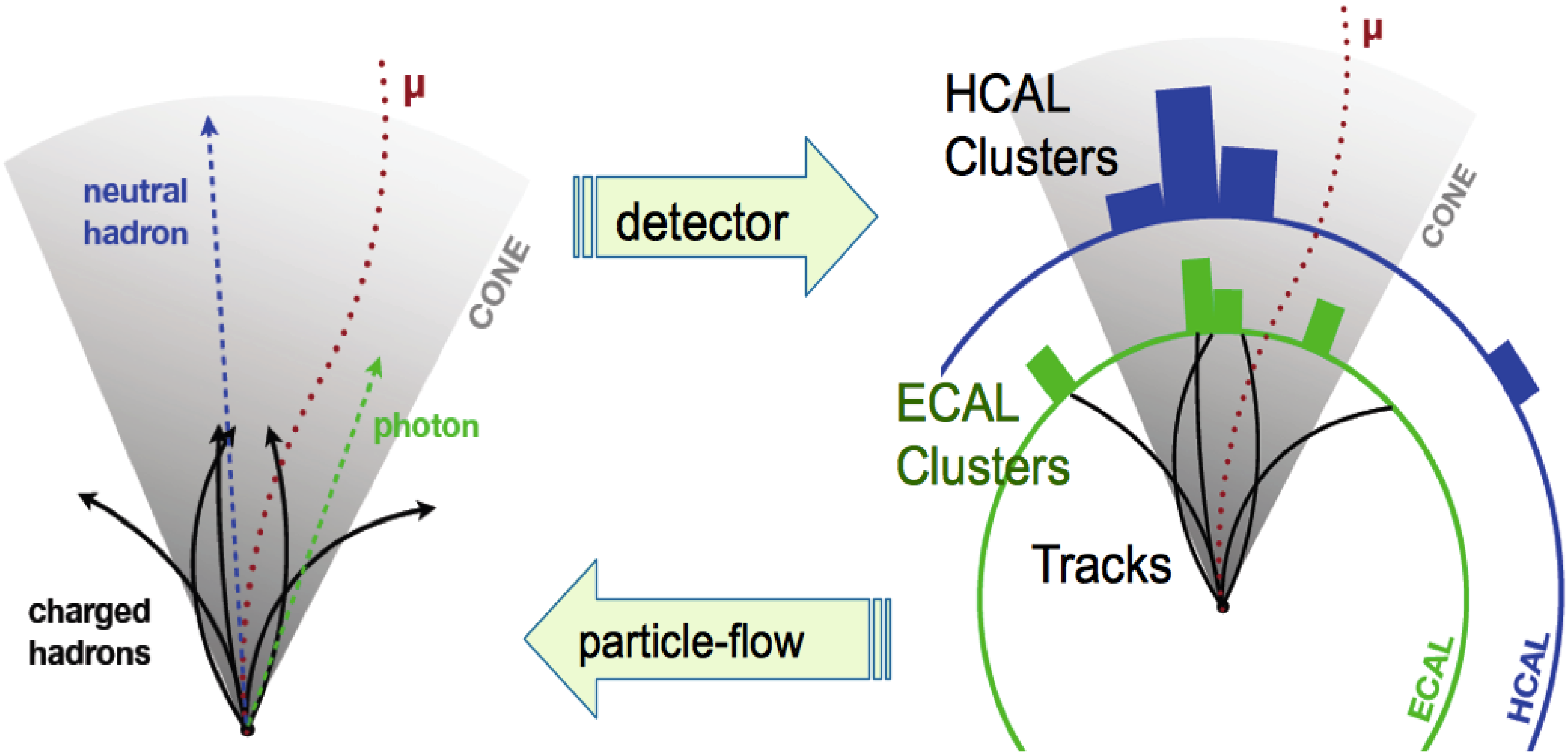


- Particle flow
  - a.k.a energy flow
  - reconstruct & identify all stable particles in the event optimally

- Make use of the whole CMS system
  - tracker
  - ECAL
  - HCAL
  - Solenoid
  - Muon chambers

2

Particle flow



Why Particle Flow?

Idea: for each individual particle in a jet, use detector with best energy/momentum resolution

Charged tracks = Tracker

e/photons = ECAL

Neutral hadrons (only 10%) = HCAL

- Calorimeter jet:
  - $E = E_{HCAL} + E_{ECAL}$
  - $\sigma(E)$ ~ calo resolution to hadron energy: 120 % / √E
  - direction biased (B = 3.8 T)
- Particle flow jet:
  - 65% charged hadrons
    - $\sigma(pT)/pT$ ~ 1%
    - direction measured at vertex
  - 25% photons
    - $\sigma(E)/E$ ~ 1% / √E
    - good direction resolution
  - 10% neutral hadrons
    - $\sigma(E)/E$ ~ 120 % / √E