5D calorimetry to probe Electroweak Symmetry breaking at the HL-LHC

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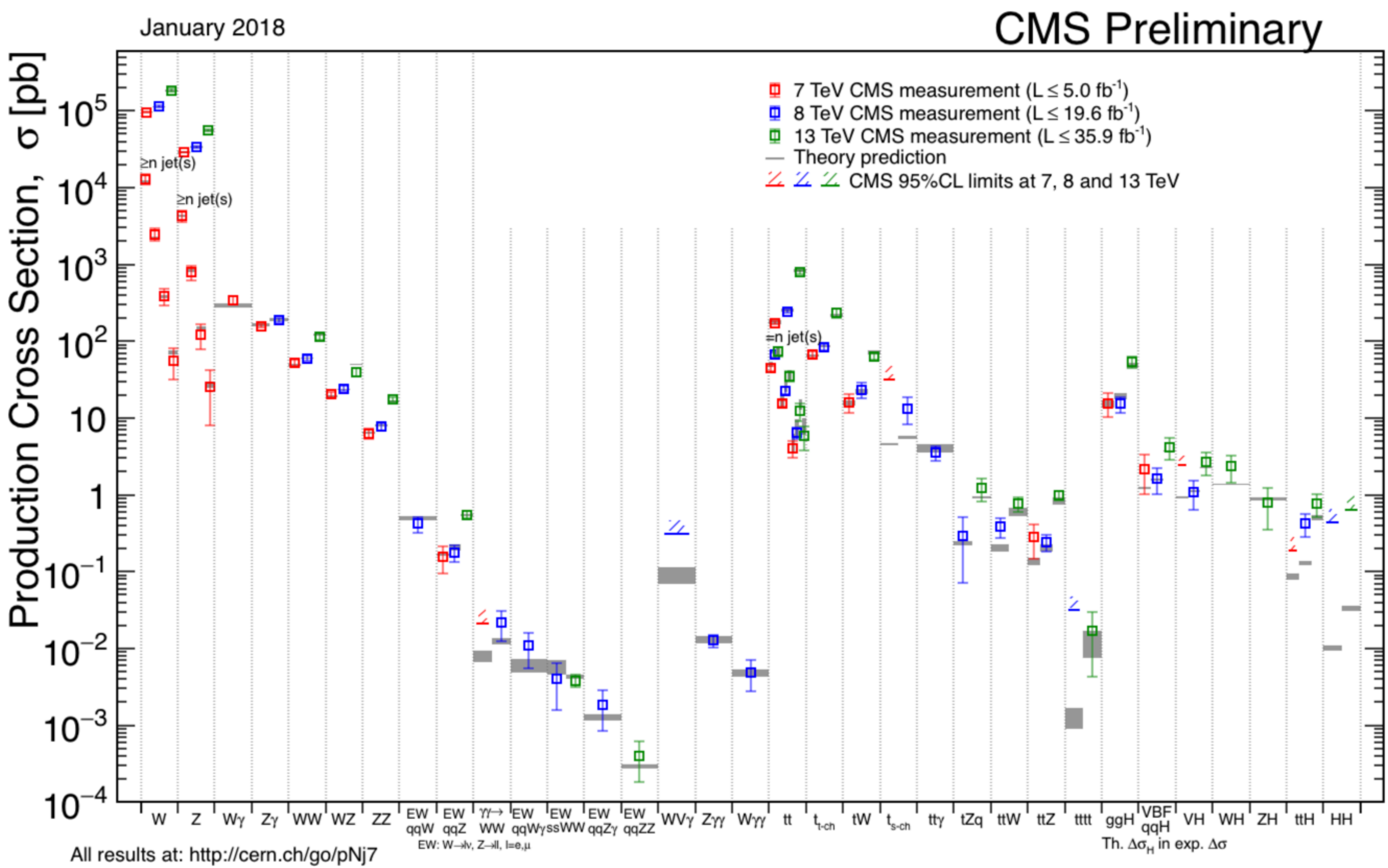
Tuesday 05/02/2018

3rd Lisbon mini-school on Particle and Astroparticle Physics

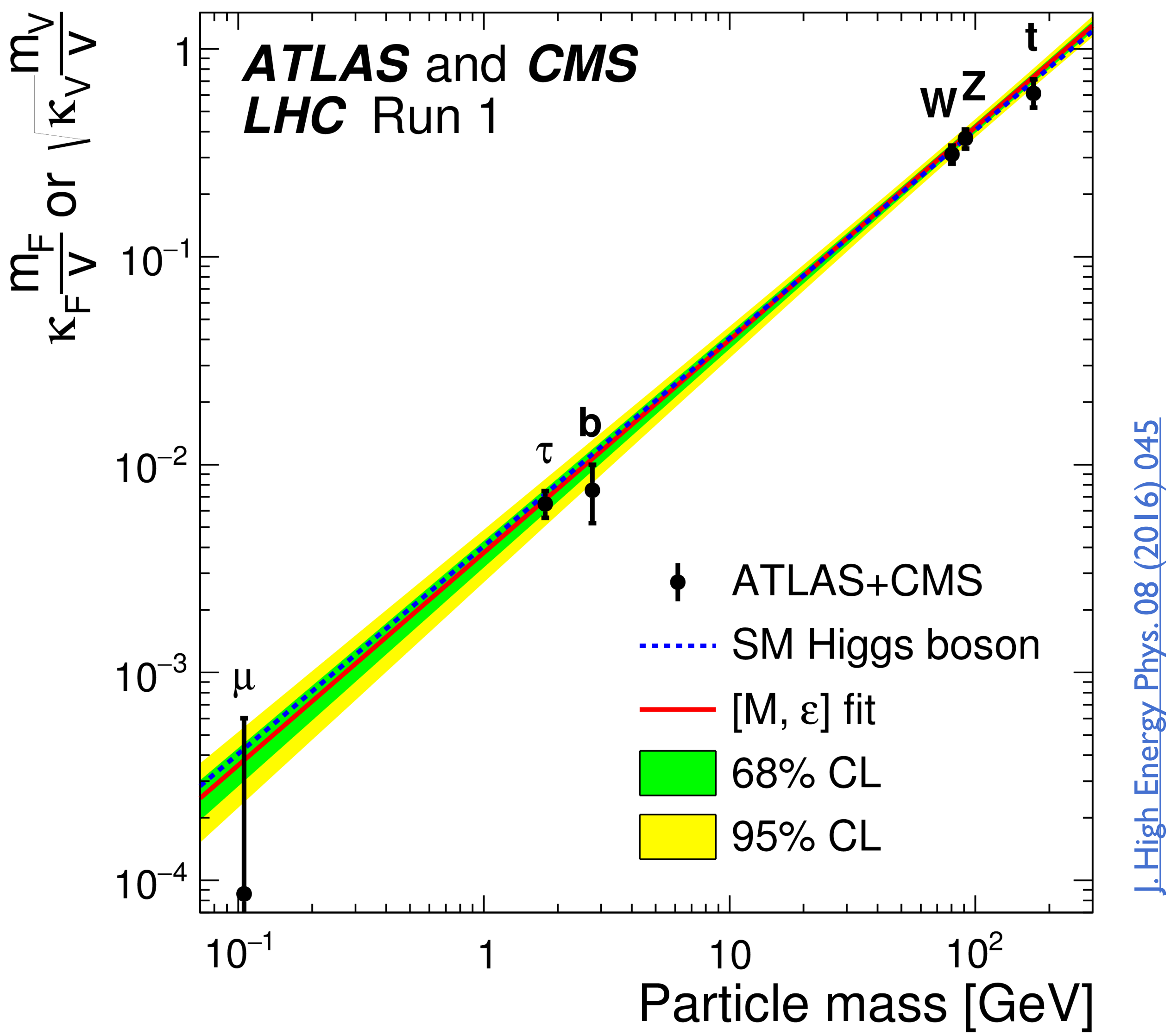


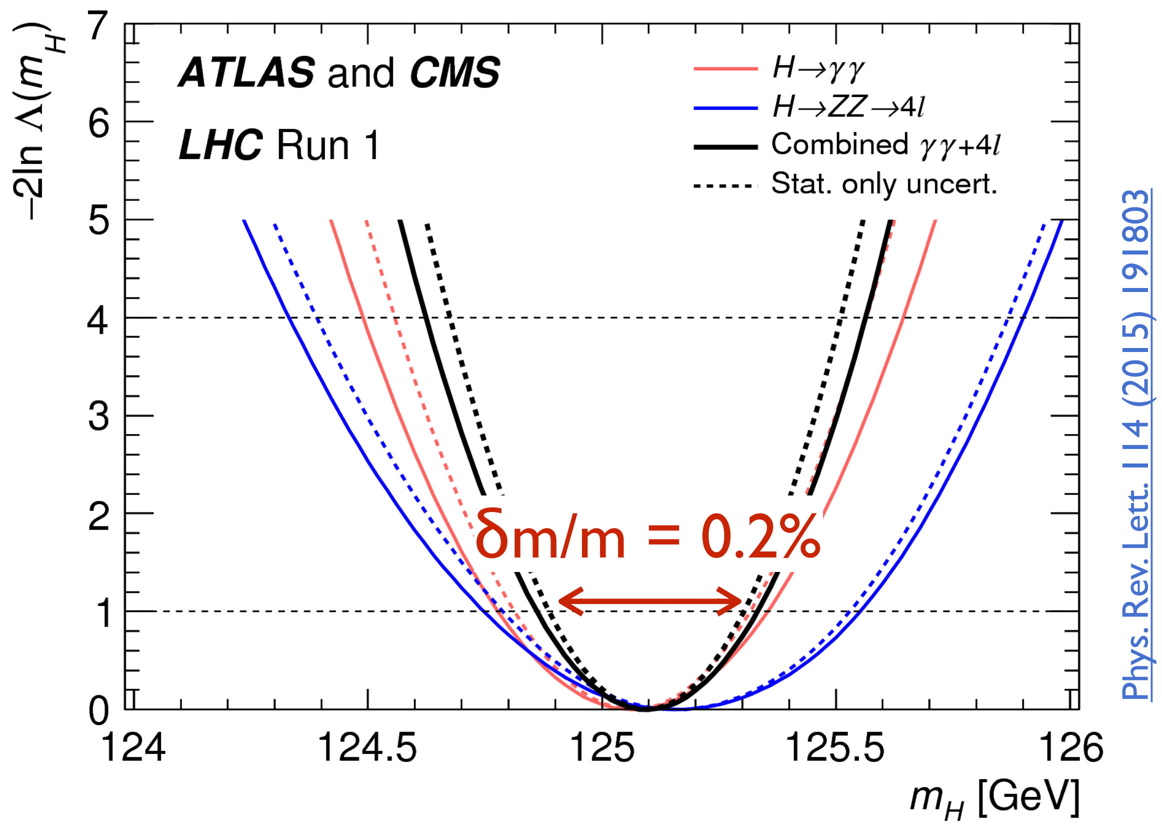
Electroweak bosons

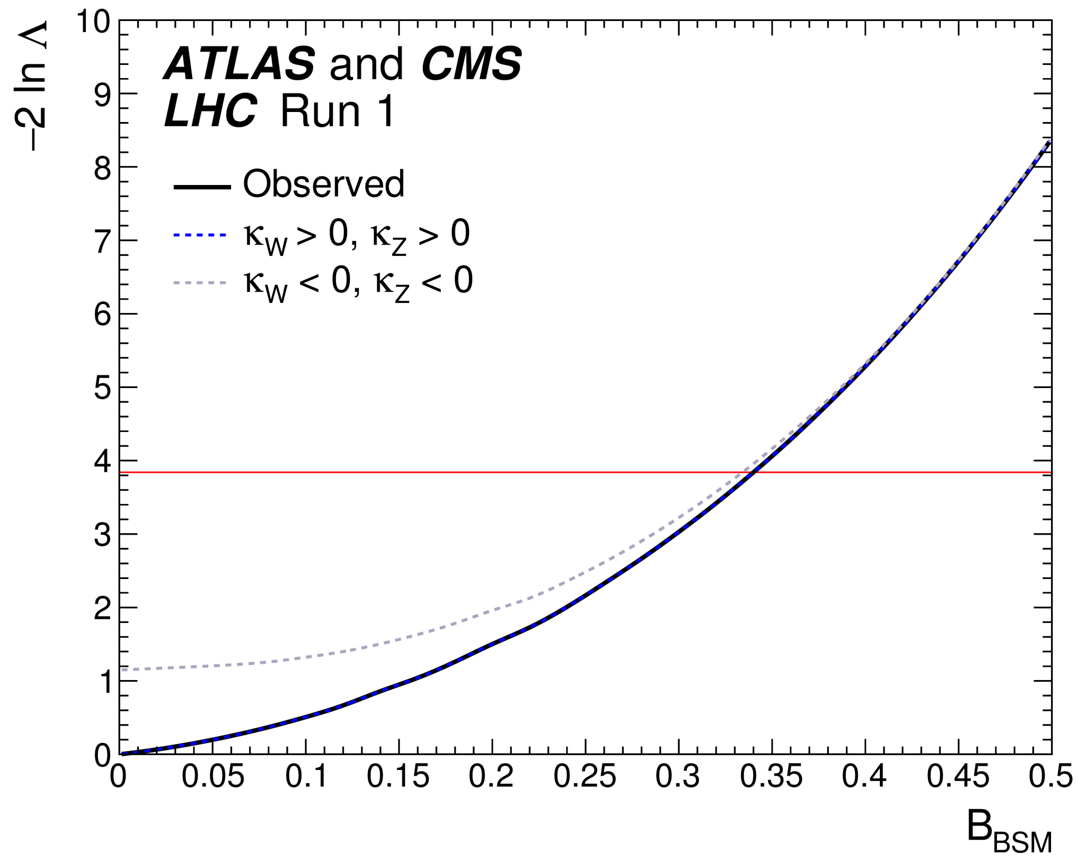
Top

Higgs

With the Higgs the standard model is now complete







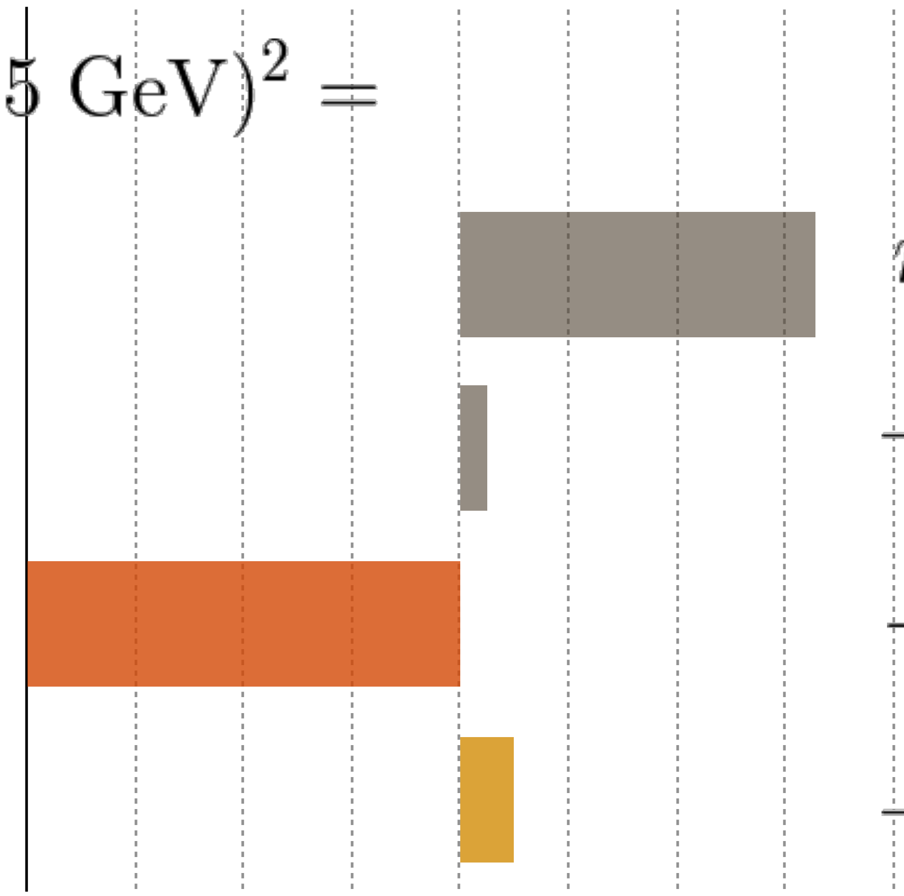
- **Run I discovery behaving like the SM Higgs**
  - not all couplings are yet measured
  - no coupling is measured to the % level
  - still a large room for BSM contributions

With the Higgs the standard model is now incomplete

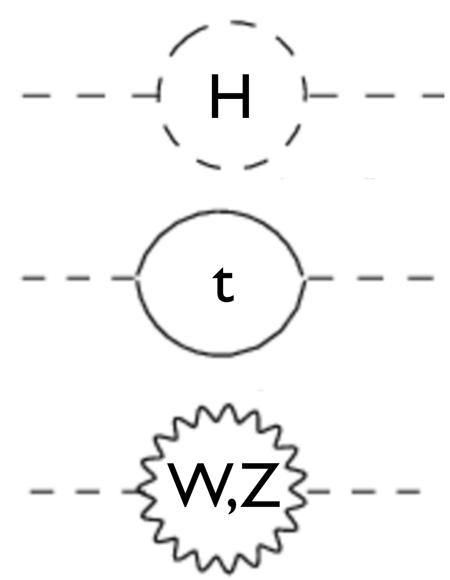
Corrections to Higgs mass from loops:

un-natural balance with the top quark in the SM

$$m_H^2 \approx (125\ \mathrm{GeV})^2 =$$



$$m_{H0}^2 + \frac{1}{16\pi^2}\lambda_H^2\Lambda^2 - \frac{3}{8\pi^2}\lambda_t^2\Lambda^2 + \frac{9}{64\pi^2}g^2\Lambda^2$$



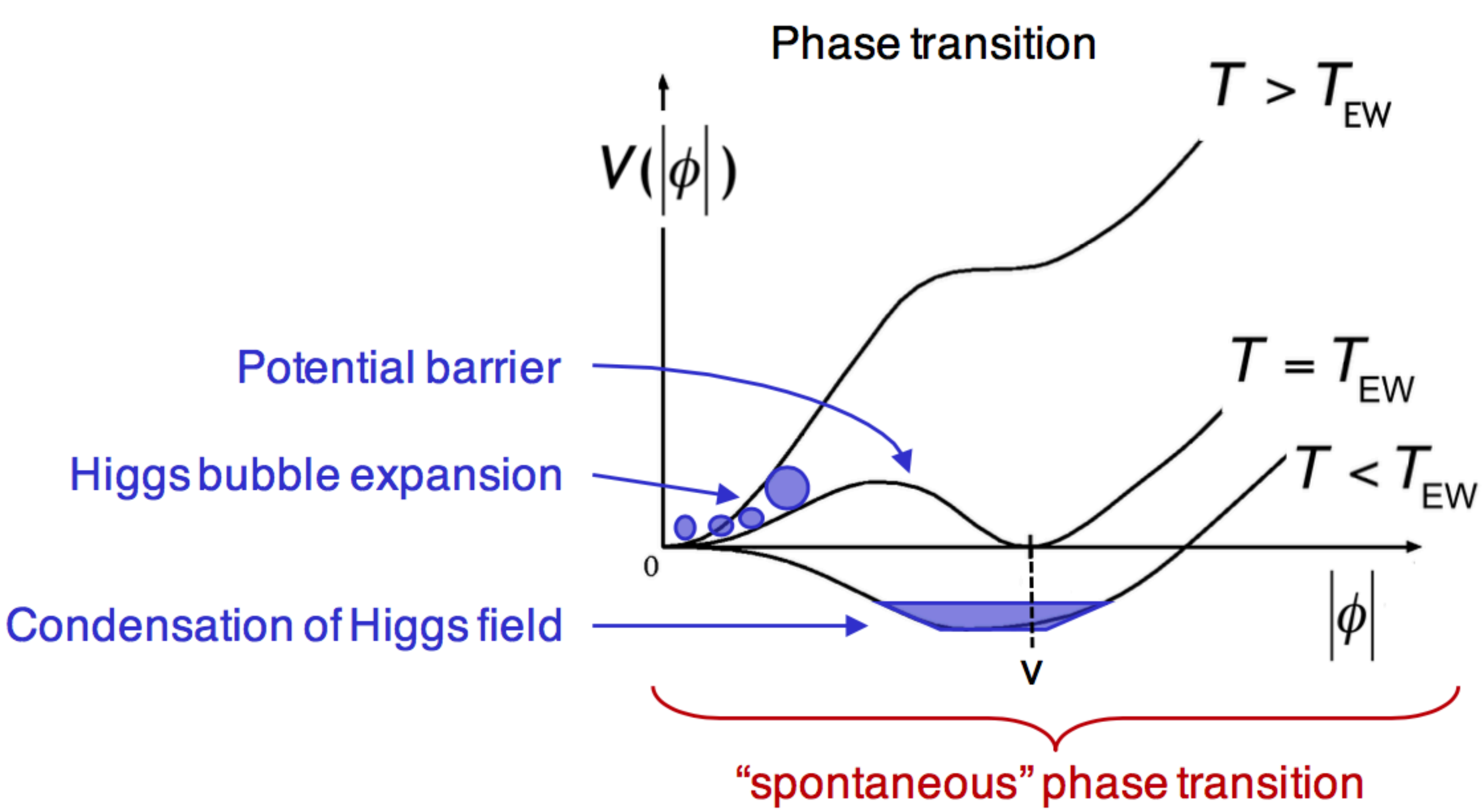
⇒ part of the clues are in the Higgs self-interaction and m_t

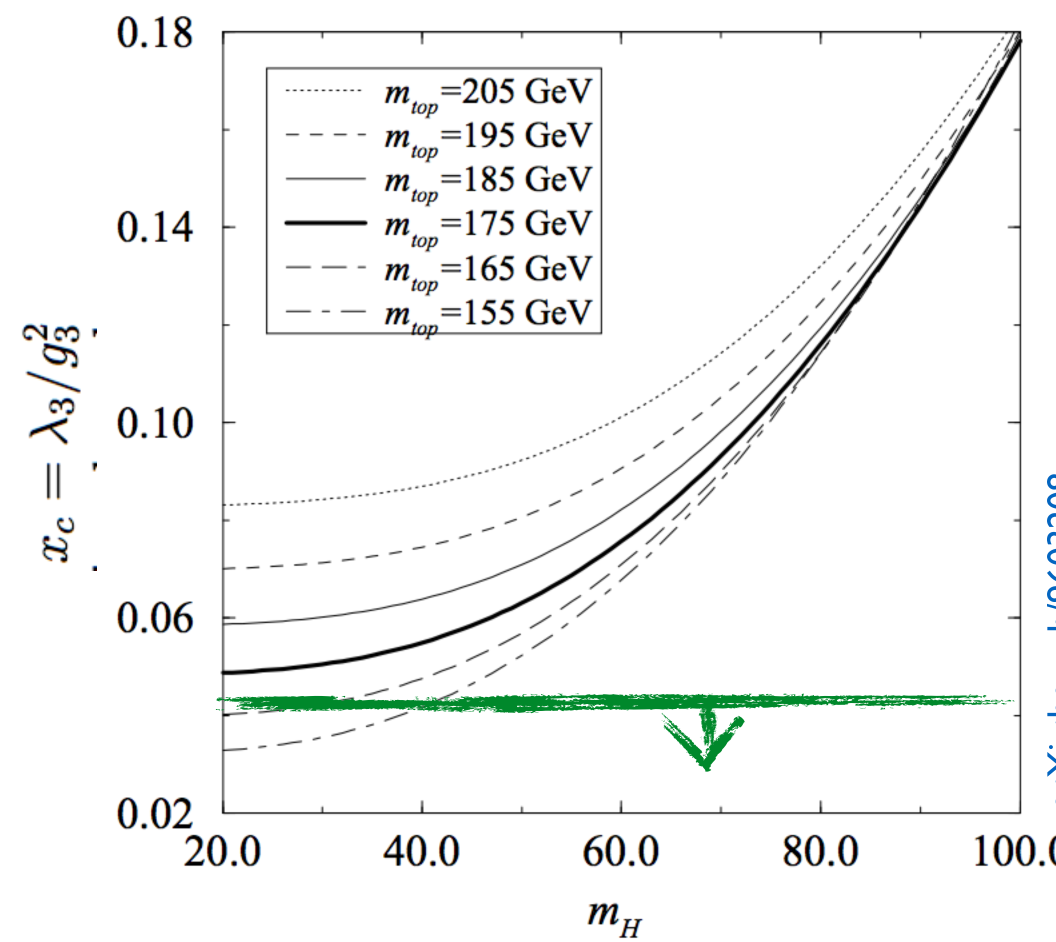
Tracing back from the early universe I

- **A phase transition should occur for T_{EW} (~10^{-10}s after the big bang)**
  - strong first order transition is possible if $<\phi_C> > T_{EW}$
  - in the SM this favours m_H<80 GeV but experimental evidence contradicts this

  m_H~125 GeV is observed and cosmological remnants from the electroweak epoch exist

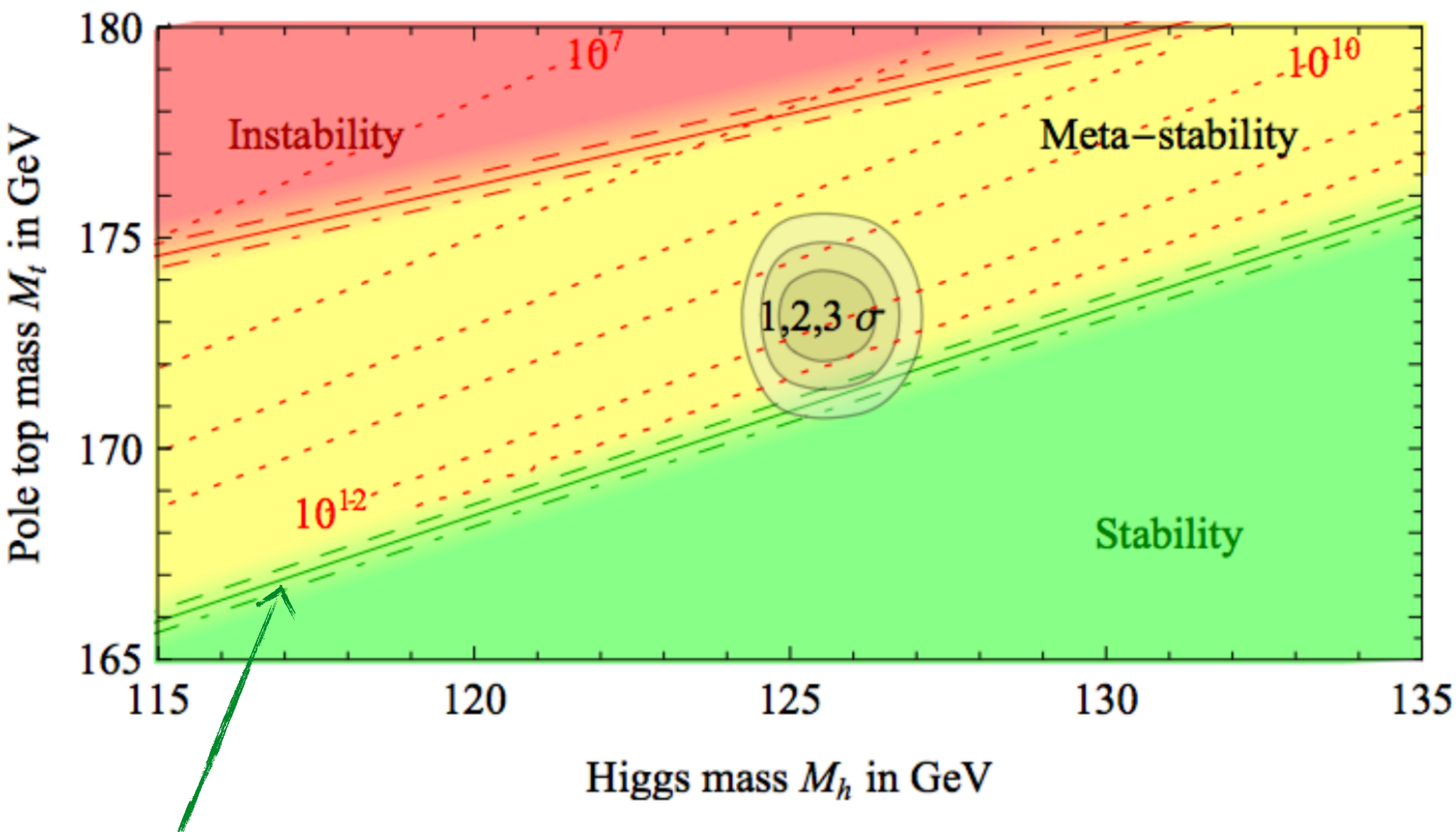
  ⇒ new physics coupling to H at the TeV scale? additional Higgs bosons?





arXiv:hep-ph/9603208

Tracing back from the early universe II

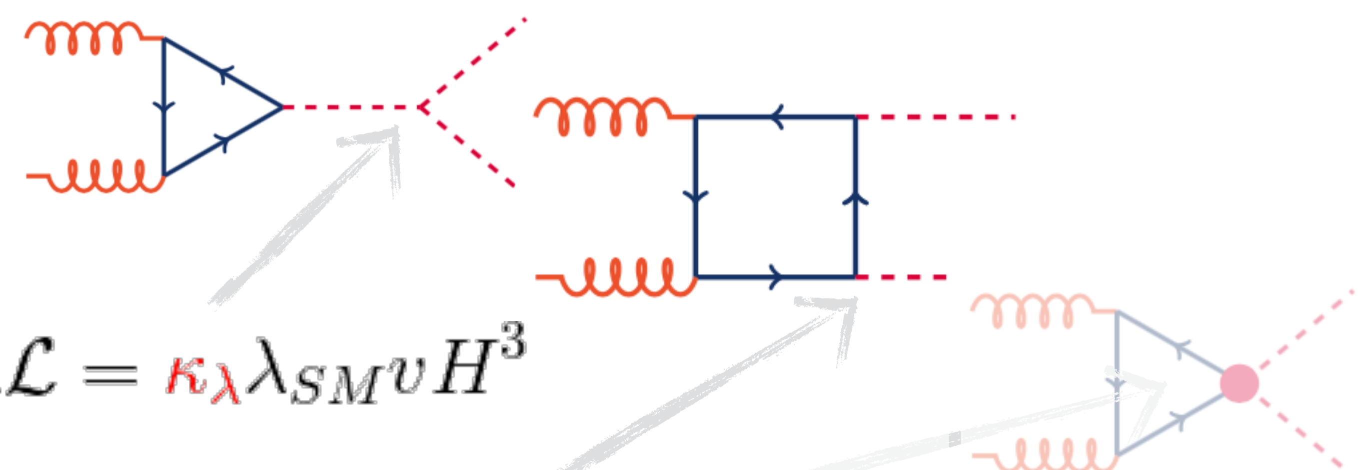


$$M_h\ [\mathrm{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\mathrm{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\mathrm{th}}$$

- **Running λ and m_H to the Planck scale : some tension regarding the vacuum stability**
  - experimentally δM_H ~100 MeV is within reach (10x smaller than theory prediction)
  - how far can we get in the experimental sources: top quark mass and α_S?

Testing the Higgs potential at the LHC

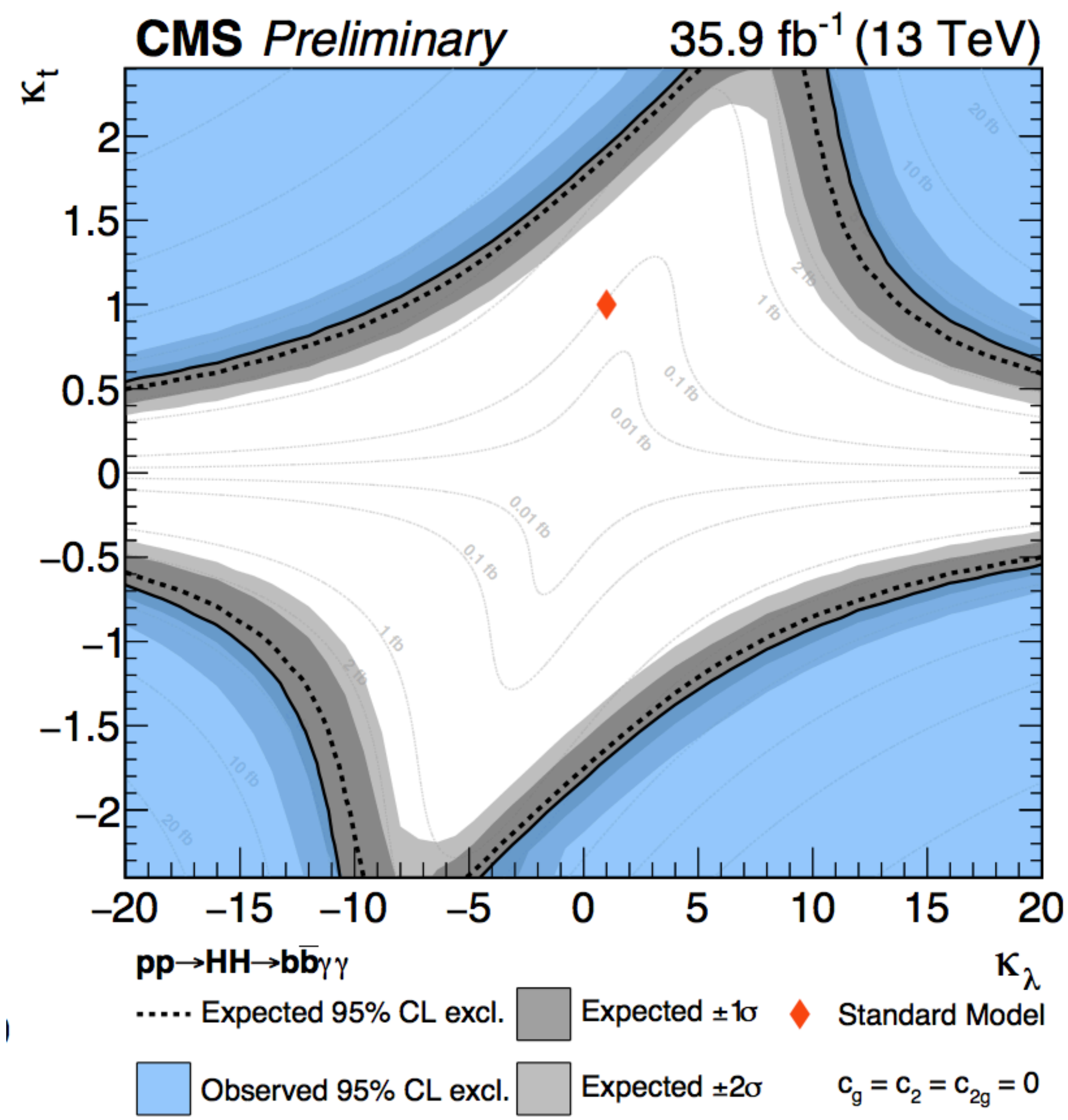
- **Low cross sections for double Higgs production (<40 fb)**
  - non-trivial backgrounds and competition with $(y_t)^2$ processes
  - nevertheless new physics may be contributing to it (new resonances, "low energy" tails)
  - Run 2 data testing O(20-30)x the SM expectations for triple H couplings



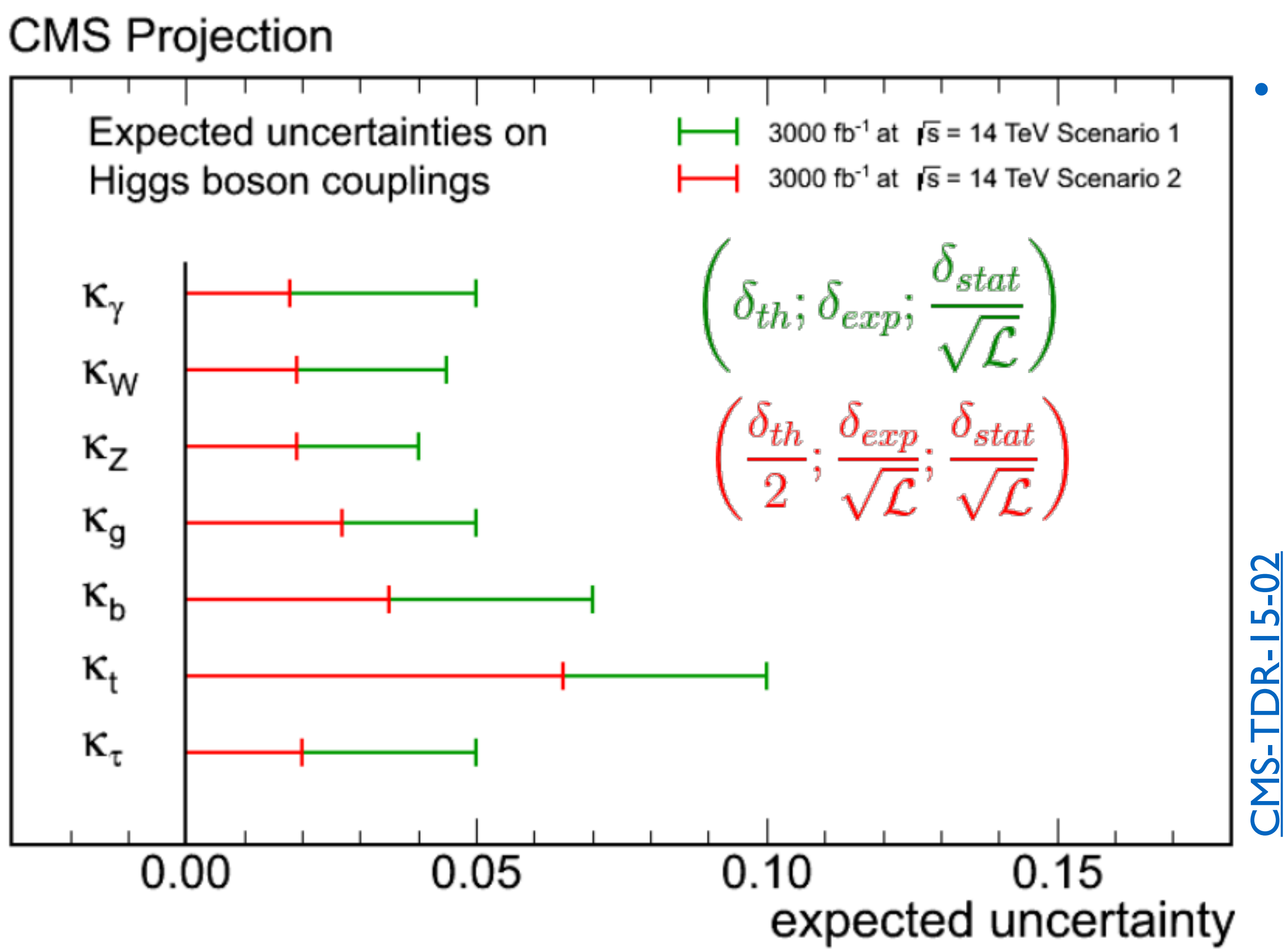
$$\Delta\mathcal{L} = \kappa_\lambda \lambda_{SM} v H^3$$

$$-\frac{m_t}{v}\left(v + \kappa_t + \frac{c_2}{v}H^2\right)(\bar{t}_L t_R + h.c.)$$

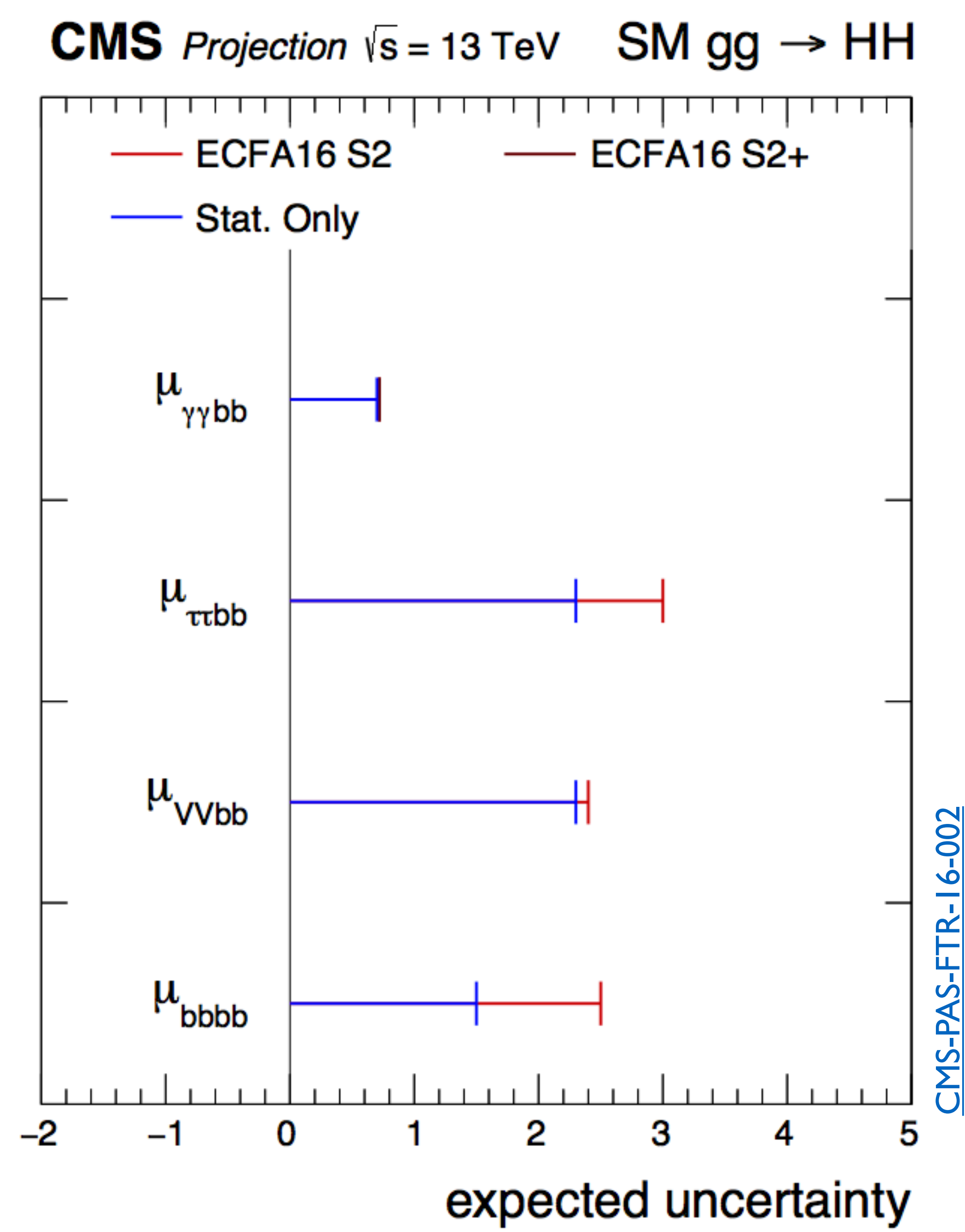
$$+\frac{\alpha_S}{12\pi v}(c_g H - \frac{c_{2g}}{2v}H^2)G^{\mu\nu}G_{\mu\nu}$$



Higgs couplings reach: prospects



- Higgs couplings to bosons and fermions
  - <5-10% (<10-15%) level end of HL-LHC (Run 2)
  - H→μμ measured with 5-8% uncertainty



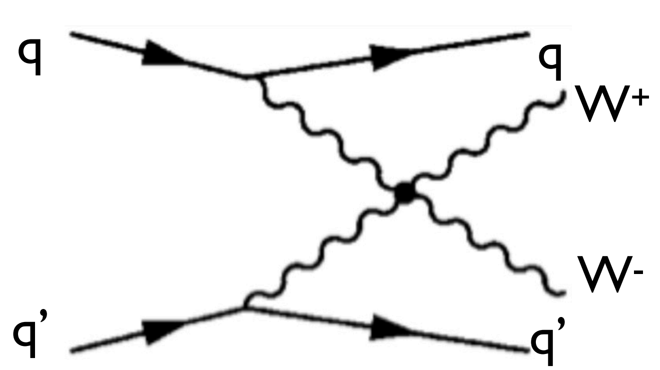
- Higgs self-couplings long road ahead
  - HH @ 3σ after combinations

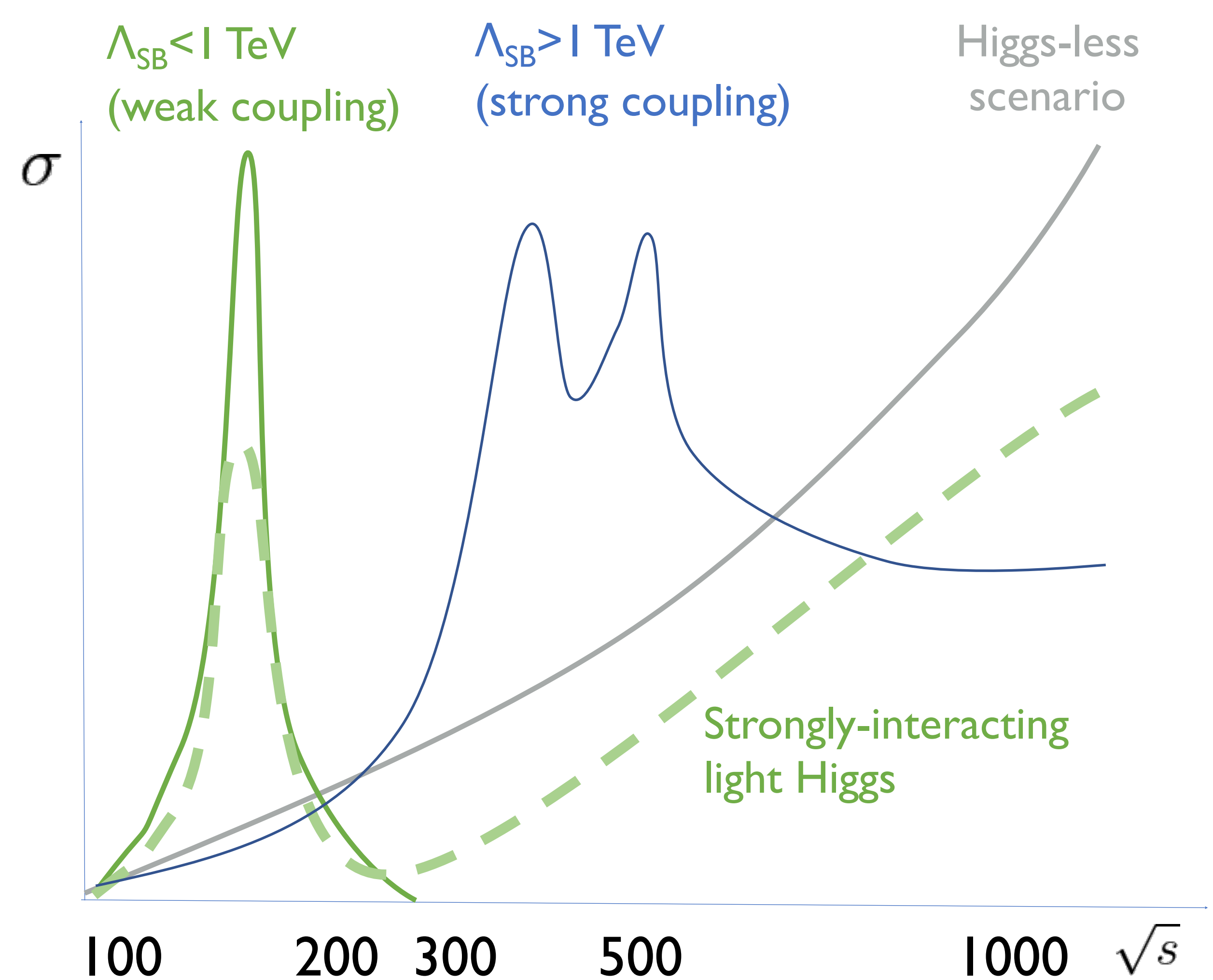
Theory needs to accompany - how far can we get?

LHC is a collider designed to test EWSB

- **Initially designed to uncover what happens at the TeV energy scale:**
  - ensure coverage to produce a Higgs boson candidate
  - maximal sensitivity below WW threshold
  - favoured by indirect fits pre-LHC, confirmed in 2012
- **Is it the SM Higgs? something should happen in polarized boson-boson scattering**

$$A(W^+W^- \to W^+W^-) \to \frac{1}{v^2}\left[s + t - \frac{s^2}{s - m_H^2} - \frac{t^2}{t - m_H^2}\right]$$

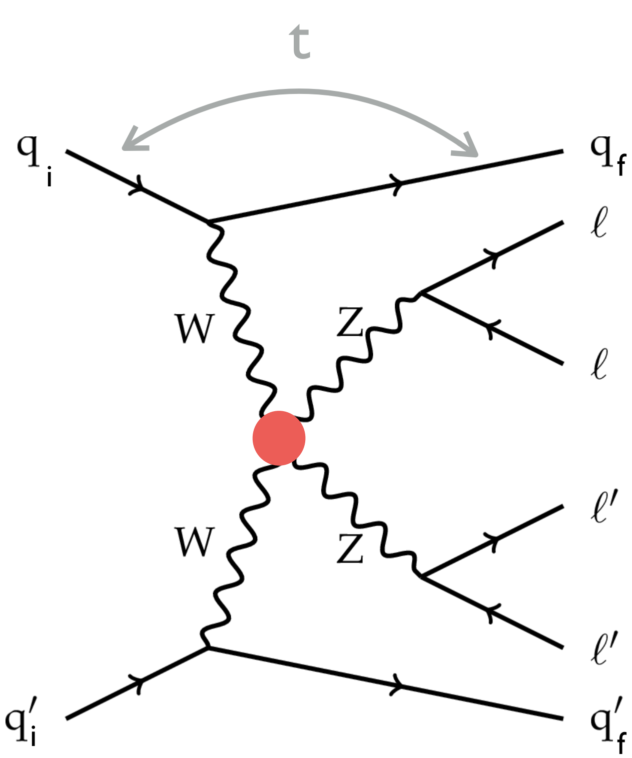




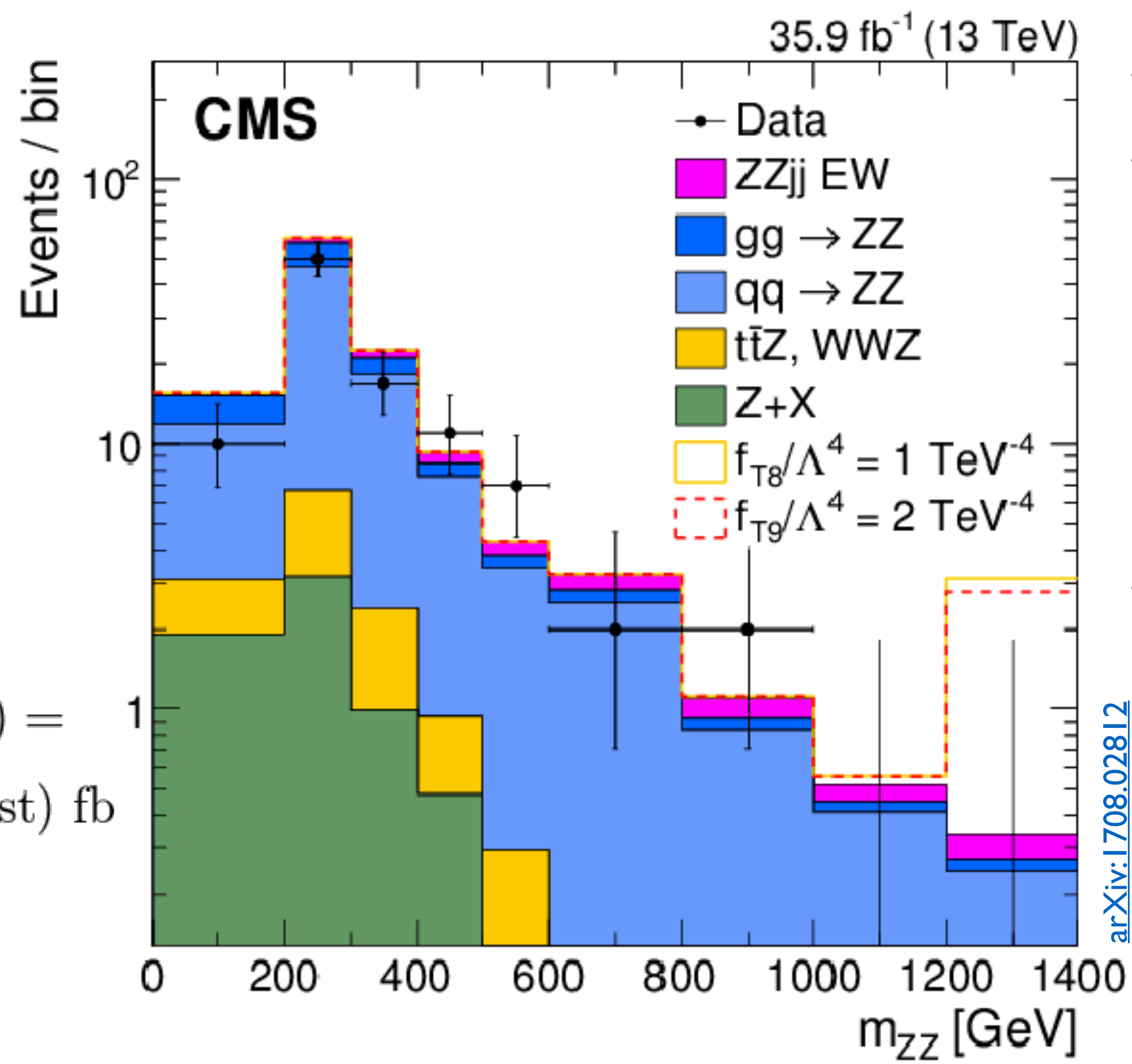
Boson scattering and anomalous couplings

- **Boson scattering topologies are sensitive to anomalous couplings**
  - triple and quartic gauge couplings enter in the diagrams
  - typical t-channel signature: $\boxed{t = (q_i - q_f)^2 = -2|\vec{q}_i||\vec{q}_f|\,(1-\cos\theta) \Rightarrow \Delta\eta \gg 1}$

⇒ coverage in the forward region is crucial



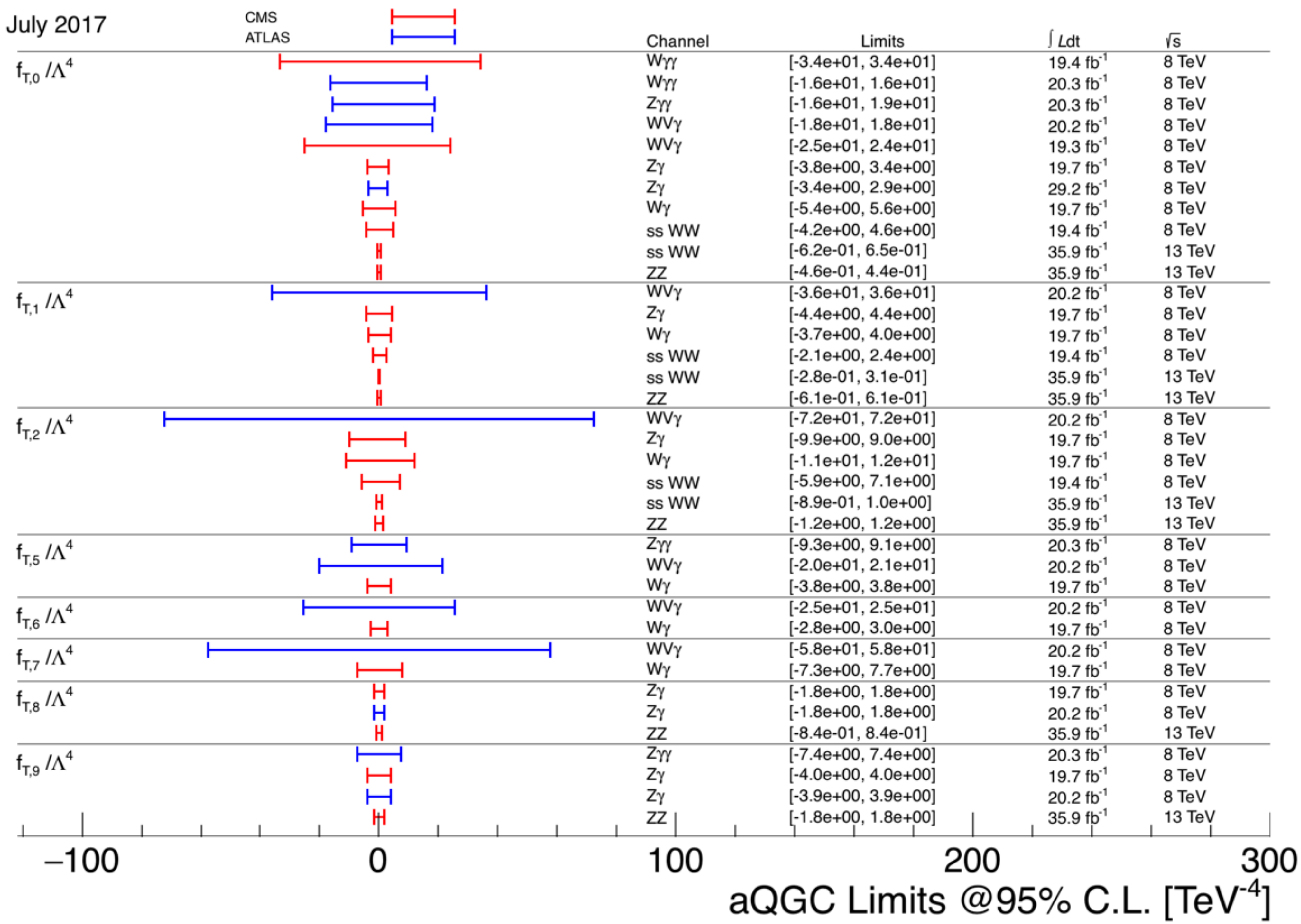
$$\sigma_{\mathrm{EW}}(pp \to ZZjj \to 4\ell jj) = 0.40^{+0.21}_{-0.16}(\mathrm{stat})^{+0.13}_{-0.09}\,(\mathrm{syst})\ \mathrm{fb}$$



Coupling	Exp.	Obs.
f_{T0}/Λ^4	[-0.53,0.51]	[-0.46,0.44]
f_{T1}/Λ^4	[-0.72,0.71]	[-0.61,0.61]
f_{T2}/Λ^4	[-1.4,1.4]	[-1.2,1.2]
f_{T8}/Λ^4	[-0.99,0.99]	[-0.84,0.84]
f_{T9}/Λ^4	[-2.1,2.1]	[-1.8,1.8]

find details on f_{Ti} in arXiv:hep-ph/0606118

Limits on quartic gauge couplings



- Extensive summaries of triple, quartic gauge couplings available @ https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

But are we already supposed to be testing anomalous couplings?

- **Note: unitarity bounds are however strict on possible new physics contributions**
  - decomposing the amplitude in partial waves (S, P, etc.)

$$A = 16\pi \sum_{l=0}^{\infty} (2l+1) P_l(\cos\theta) a_l$$

  - contributions to each wave are therefore limited to

$$\hat{\sigma} = \frac{16\pi}{\hat{s}} \sum_{l=0}^{\infty} (2l+1)|a_l|^2 \longleftrightarrow \hat{\sigma} = \frac{1}{\hat{s}} \mathrm{Im}\left[A(\theta=0)\right]$$

optical theorem

$$\boxed{|\mathrm{Re}(a_l)| < \frac{1}{2}}$$

Coupling	Exp.	Obs.
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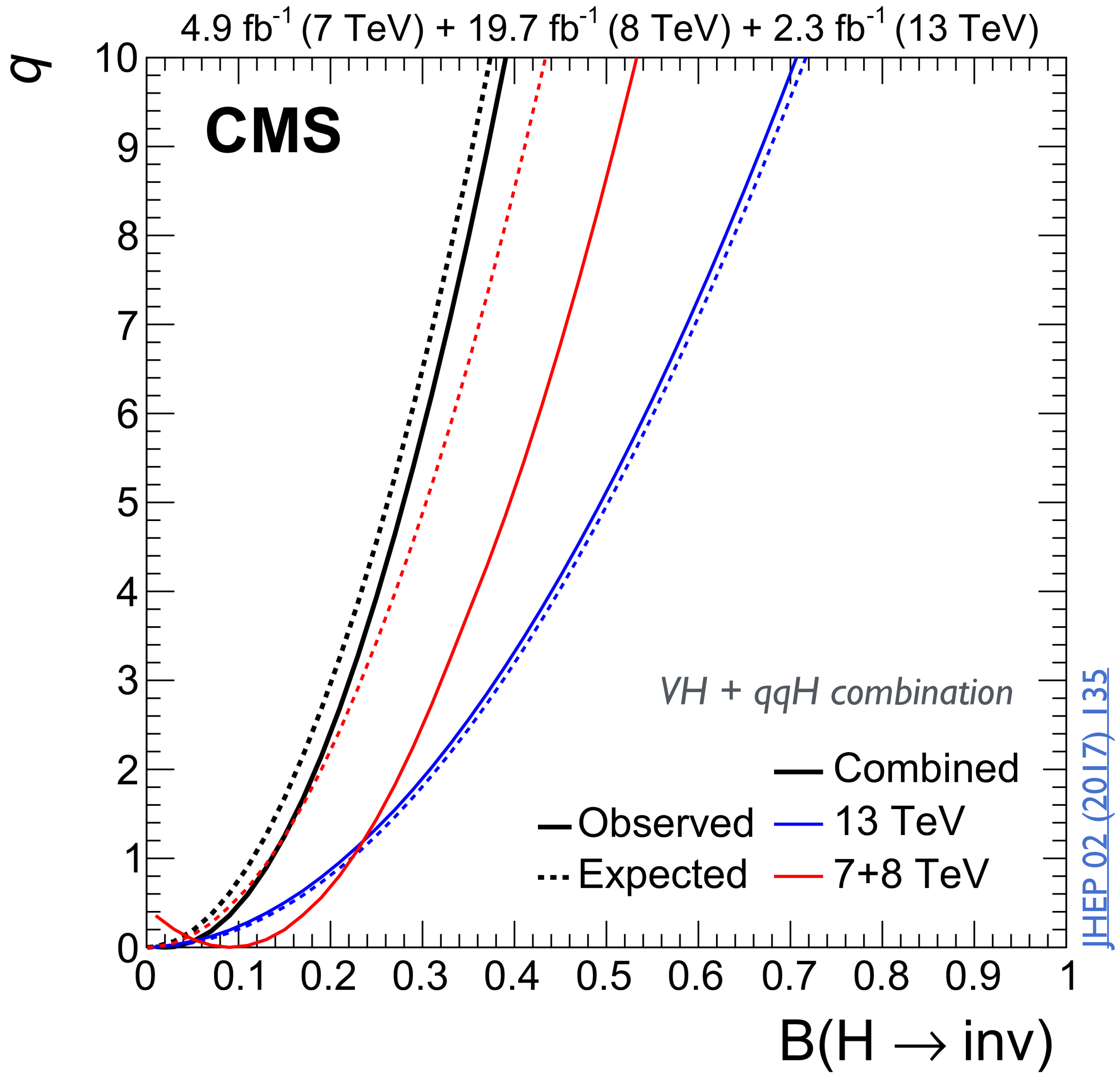
find details on f_{Ti} in arXiv:hep-ph/0606118

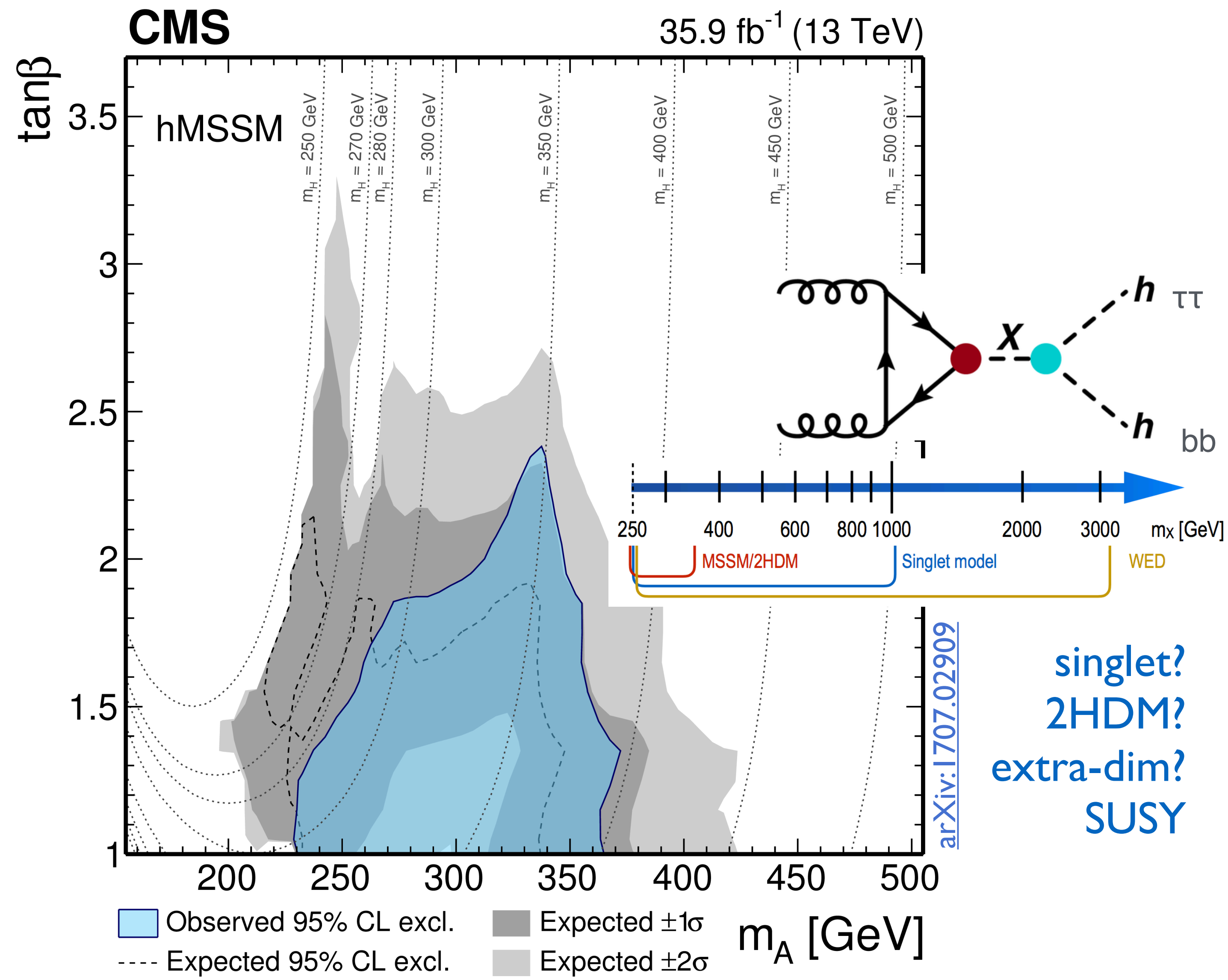
unitarity bounds ~2-3 TeV
(~10^{-4} smaller than current limits)

⇒ (much) more data is needed

Higgs as a portal

- **Still a (experimental) large room for invisible Higgs decays: BR<0.24 @ 95%CL**
  - significant changes in this BR could be due to new neutral particles : dark matter?
- **It may also be that the Higgs sector is more complex and accompanied by partners**
  - resonant associated (VH) and hh production, high-mass diboson resonances, ….





singlet?
2HDM?
extra-dim?
SUSY

Dark matter and Higgs

- **The limits on the invisible BR of the Higgs can be re-casted to limits dark matter production**

$$\sigma^{SI}_{S-N} = \frac{4\Gamma_{inv}}{m_H^3 v^2 \beta} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2},$$

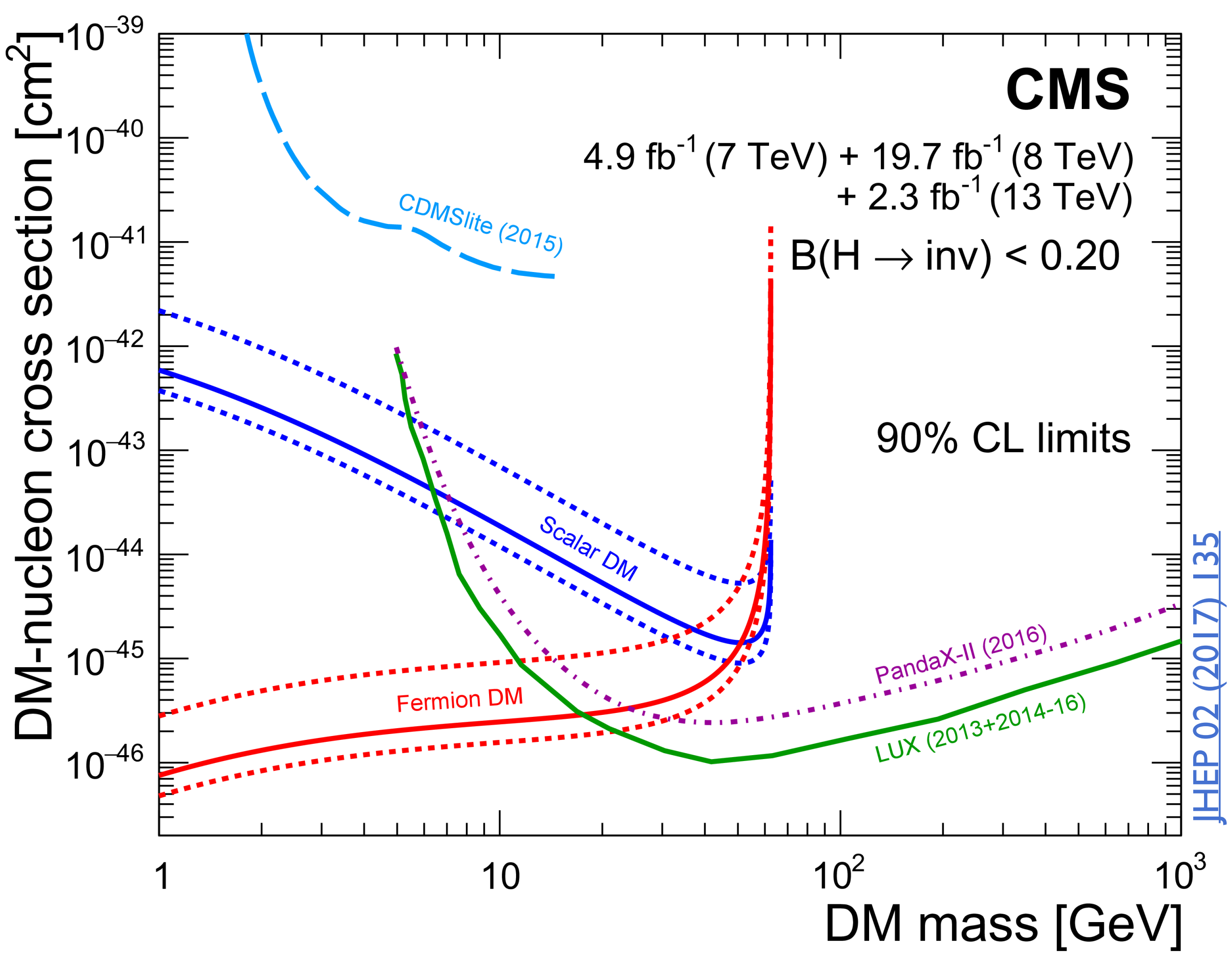
$$\sigma^{SI}_{V-N} = \frac{16\Gamma_{inv} M_\chi^4}{m_H^3 v^2 \beta (m_H^4 - 4M_\chi^2 m_H^2 + 12 M_\chi^4)} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2}$$

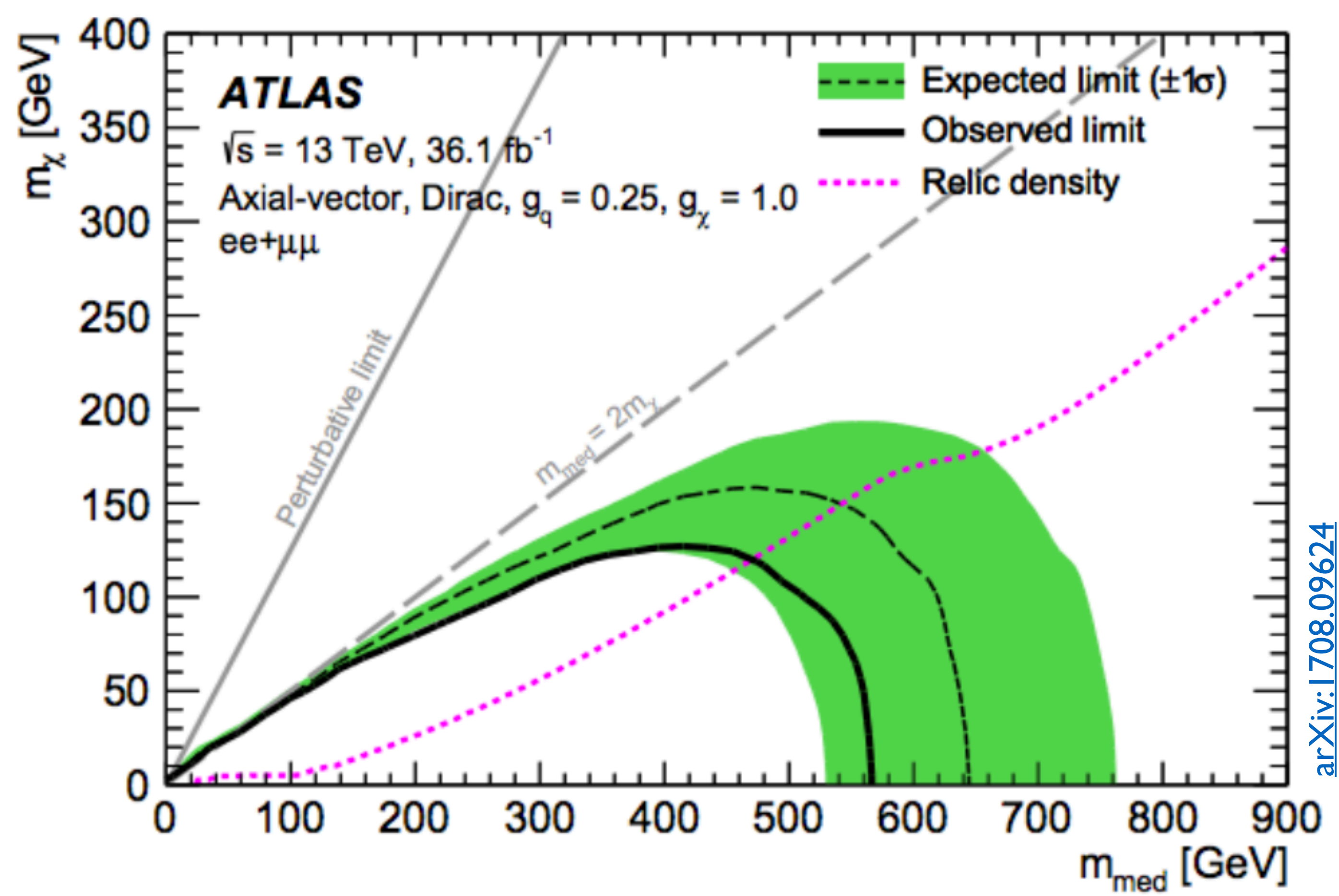
$$\sigma^{SI}_{f-N} = \frac{8\Gamma_{inv} M_\chi^2}{m_H^5 v^2 \beta^3} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2}.$$

m_N - nucleon mass ~0.939 GeV
$v = 246/\sqrt{2}$ GeV (vev)
f_N~0.326 central value for coupling (from lattice*)
$\beta = \sqrt{1 - 4M_\chi^2/m_H^2}.$
$\Gamma_{inv} = \Gamma_{SM} BR_{inv}/(1-BR_{inv})$

**PRD 81(2010) 014503, PRL 103(2009) 122002*

- **Latest re-interpretations in terms of mediator-WIMP mass** (see CERN-LPCC-2016-001)





Outstanding questions

@ middle of LHC Run 2

Electroweak symmetry breaking

- m_H natural or fine-tuned ?
- if natural: what new physics/symmetry?
- does it regularize the divergent $V_L V_L$ cross-section at high $M(V_L V_L)$? new dynamics ?
- elementary or composite Higgs ?
- is it alone or are there other Higgs bosons ?
- origin of couplings to fermions
- coupling to dark matter ?
- does it violate CP ?
- cosmological EW phase transition

Dark matter

- composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ...
- one type or more ?
- only gravitational or other interactions ?

Quarks and leptons

- why 3 families ?
- masses and mixing
- CP violation in the lepton sector
- matter and antimatter asymmetry
- baryon and charged lepton number violation

Neutrinos

- ν masses, their origin - H(125) role?
- Majorana or Dirac ?
- CP violation
- additional species?
- sterile ν ?

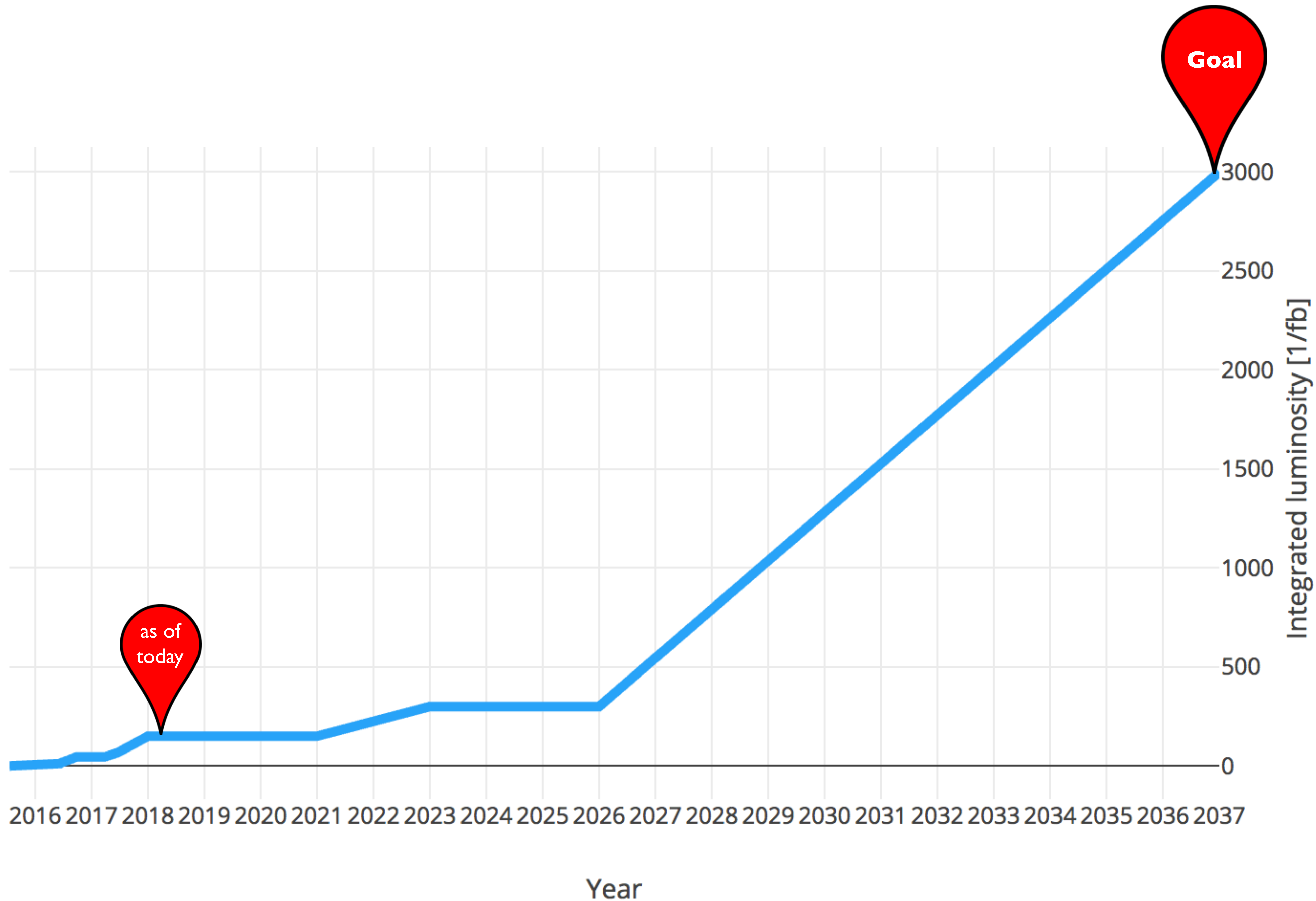
Physics at the highest E-scales:

- how is gravity connected with the other forces ?
- do forces unify at high energy ?

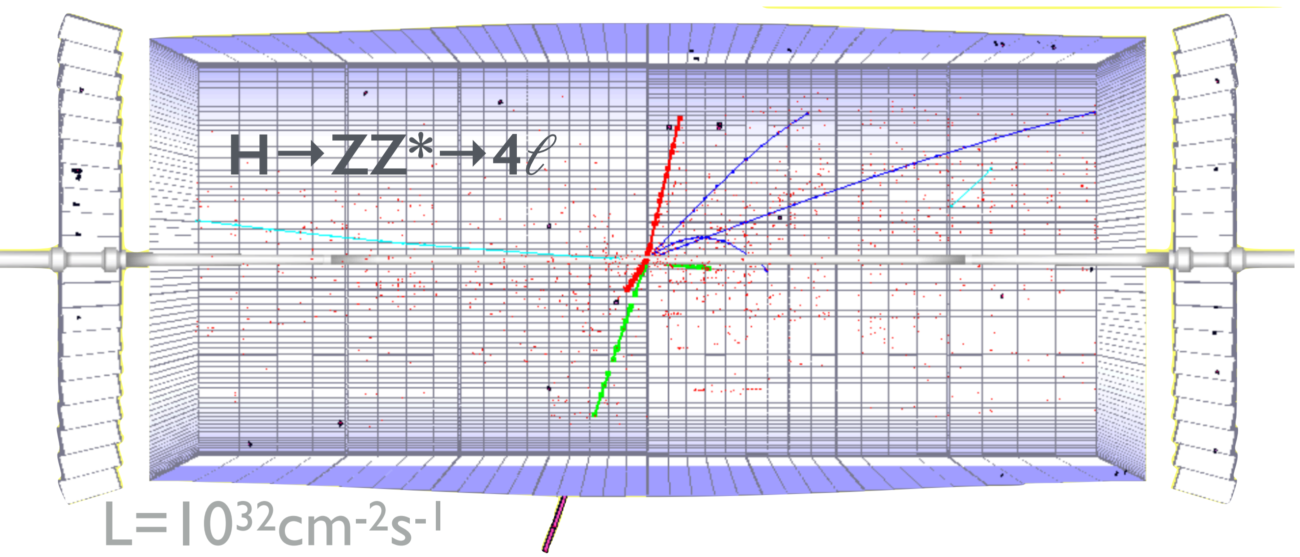
Universe's accelerated expansion:

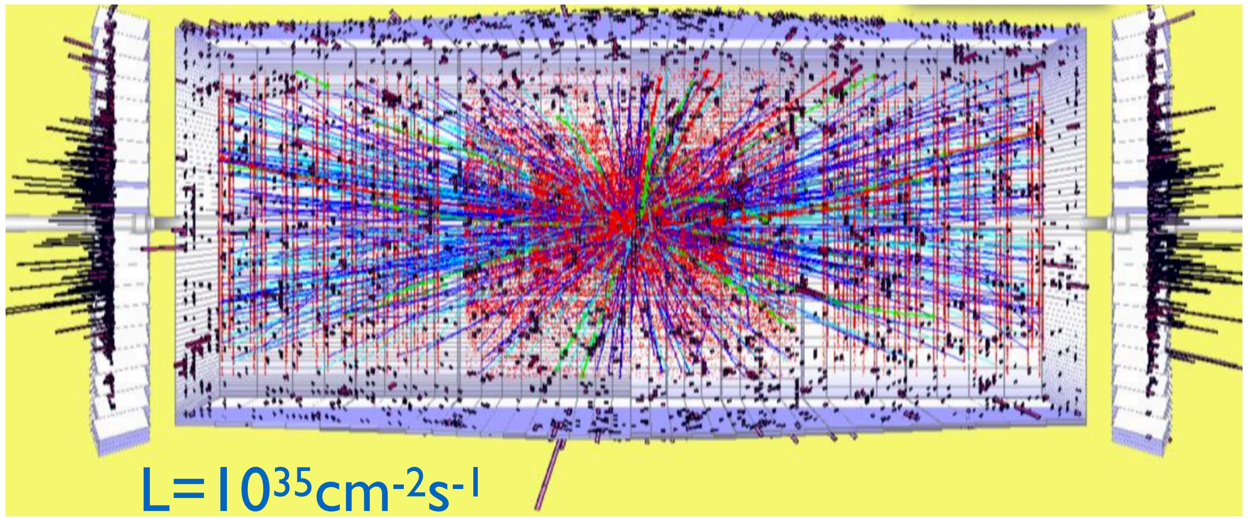
- primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- today: dark energy (why is Λ so small?) or gravity modification ?

adapted. from
I. Shipsey @ ICHEP2016


Goal
as of
today
3000
2500
2000
1500
1000
500
0
Integrated luminosity [1/fb]
2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037
Year

Road ahead for detector upgrades





140 pileup events super-imposed

Phase 0
2013-2014

Consolidate detectors, address operational issues, prepare for high pileup

- complete muon coverage, improve muon trigger, new smaller radius beam pipes
- Replace HCAL forward PMTs and outer HPD → SiPM

Phase I
2018-2019

Maintain / improve performance at high pileup

- new pixels, HCAL SiPMs, electronics, and L1-Trigger

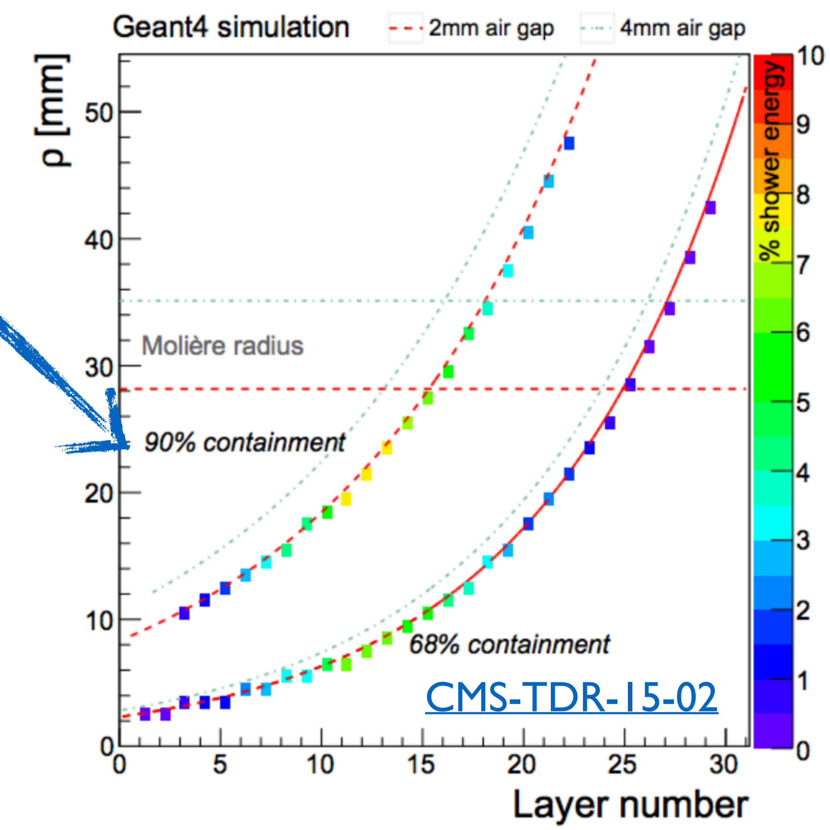
Phase II
2023-2024

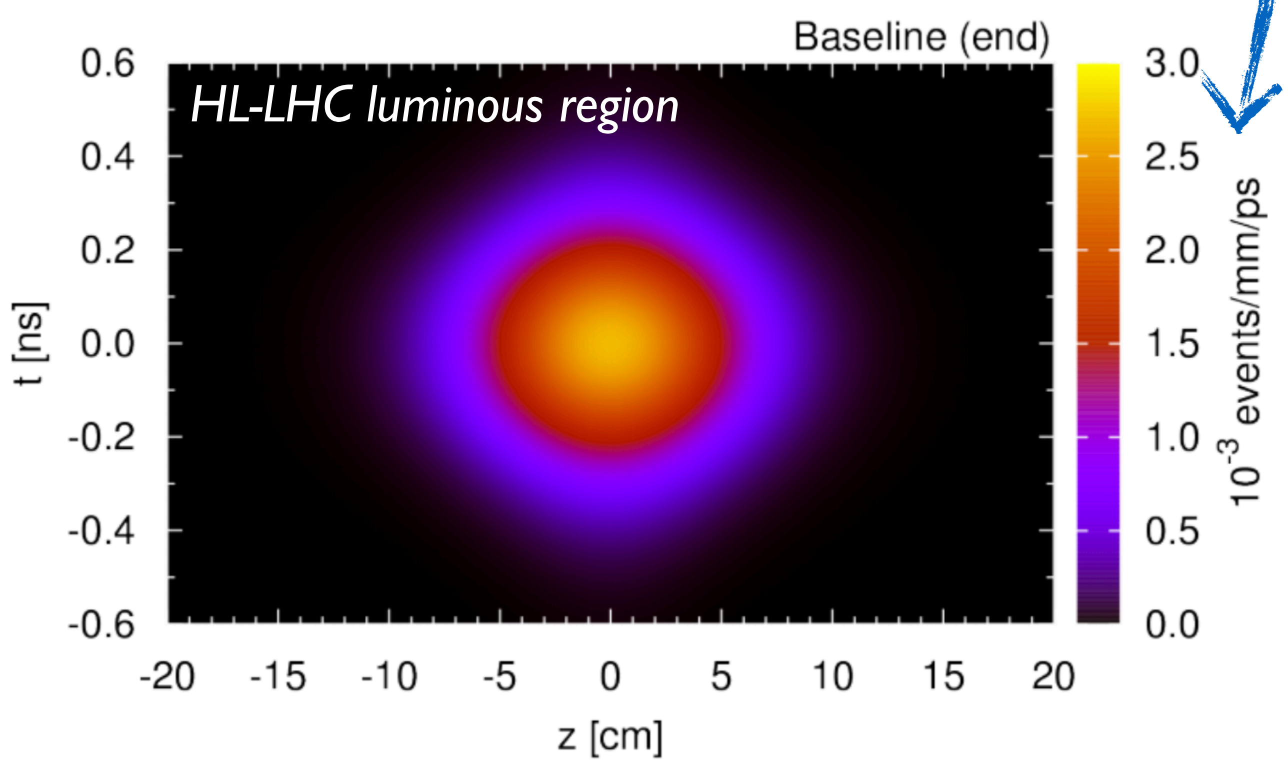
Maintain / improve performance at extreme pileup : sustain rate + radiation doses

- New inner detector, new calorimeter electronics, muon extension, trigger and DAQ upgrade
- track trigger, replace endcap calorimeters

Detector strategies to mitigate pileup at HL-LHC

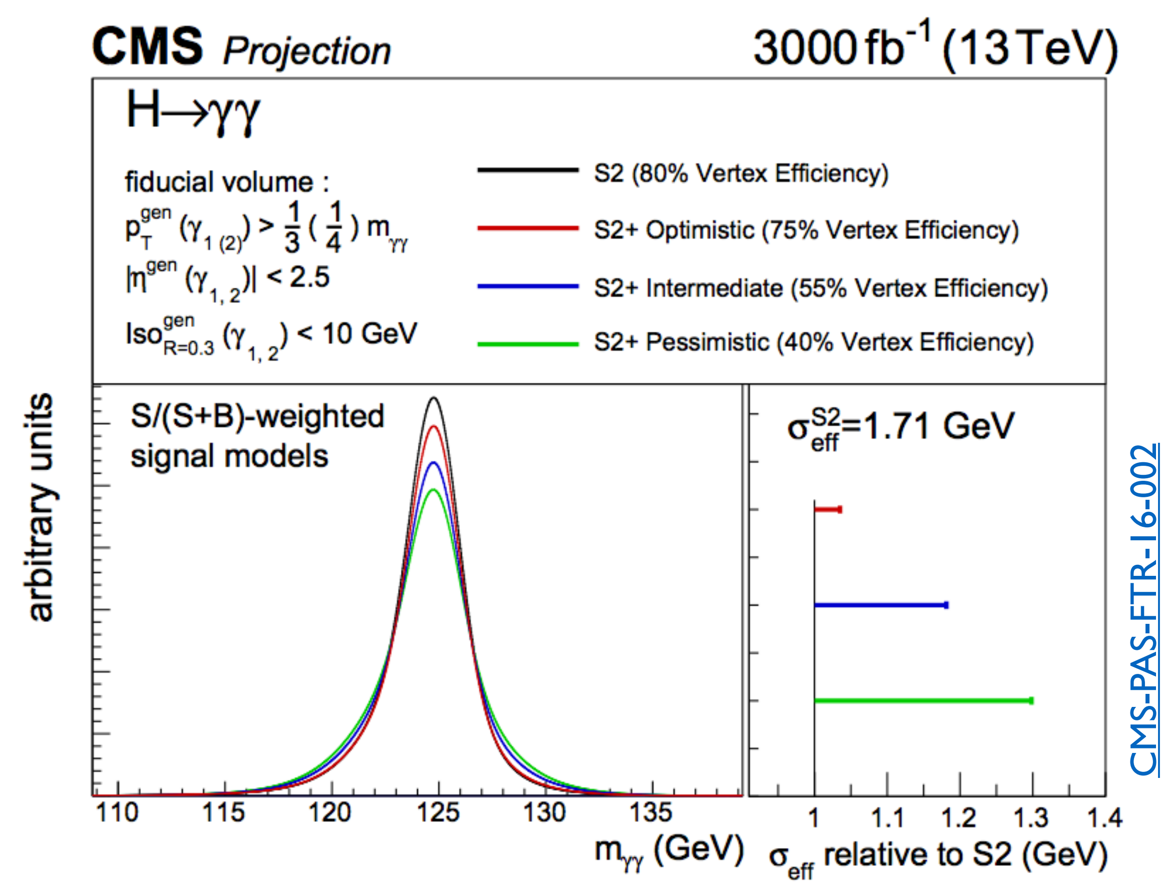
- **Use fine granular detectors**
  - *transverse*: reduce flux per calorimeter cell, resolve fine structures
  - *longitudinal*: absorb low energy pileup in the first layers
  - *3D reconstruction+timing*: associate deposits to primary vertices



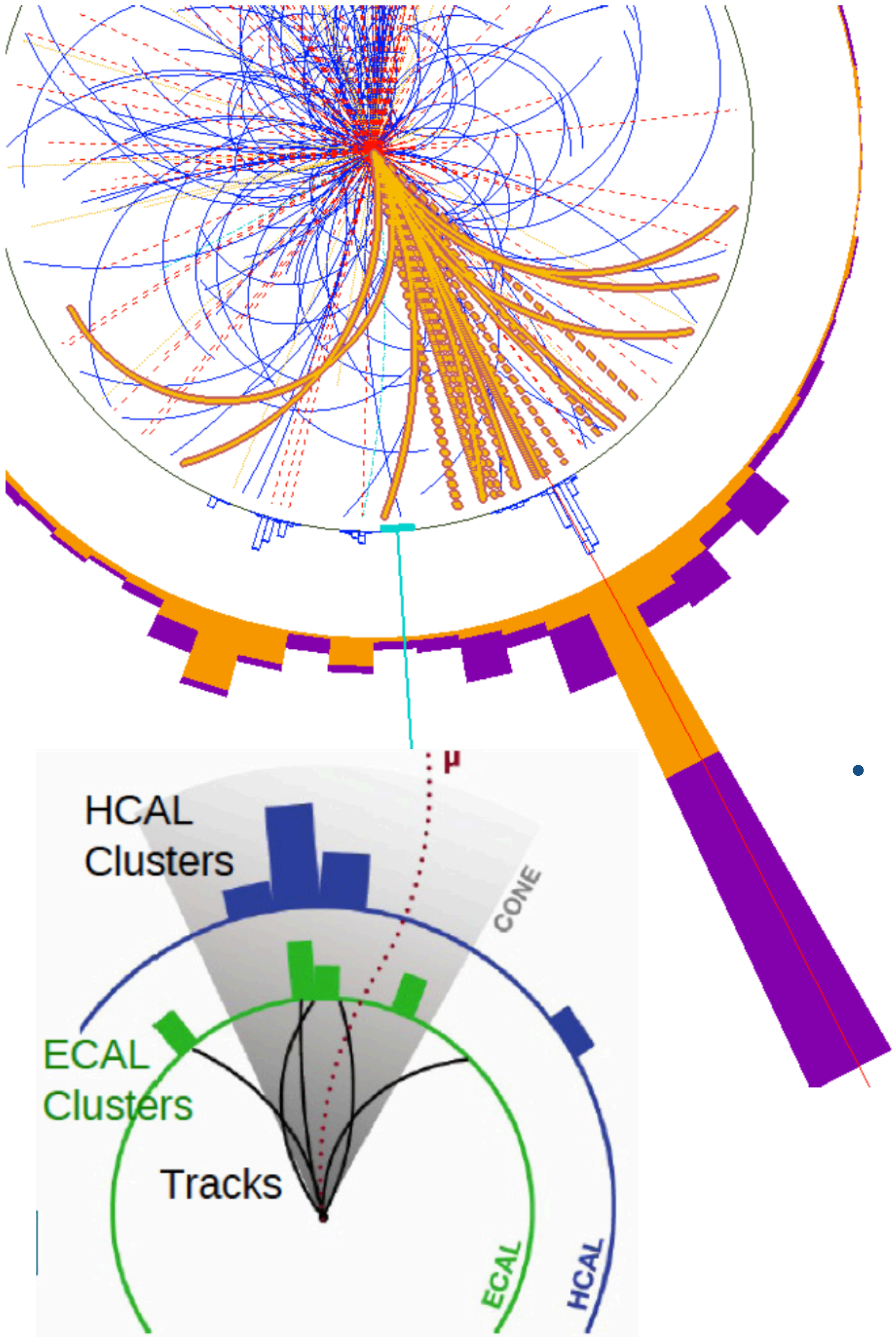


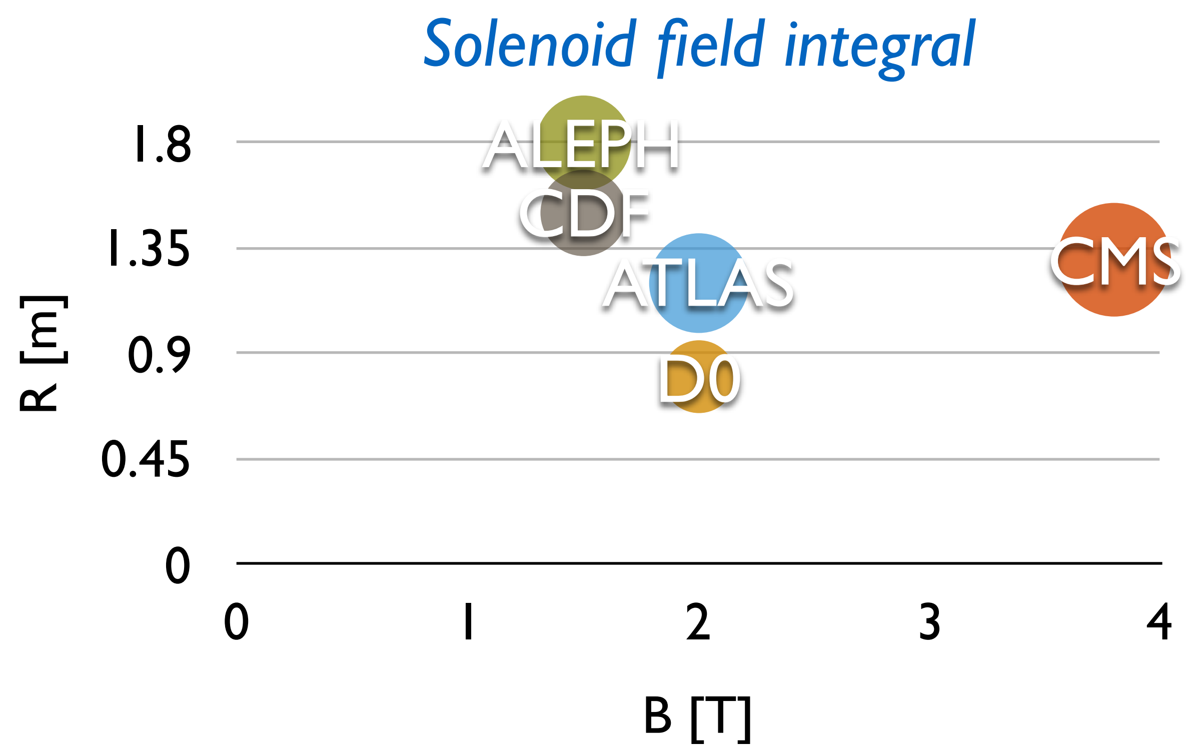
- **Example: H→$\gamma\gamma$ association to primary vertex**
  - loose 30% in resolution with "tracker only" informat

    ⇒ up to 20% larger uncertainty in cross section



Particle flow as the reconstruction backbone

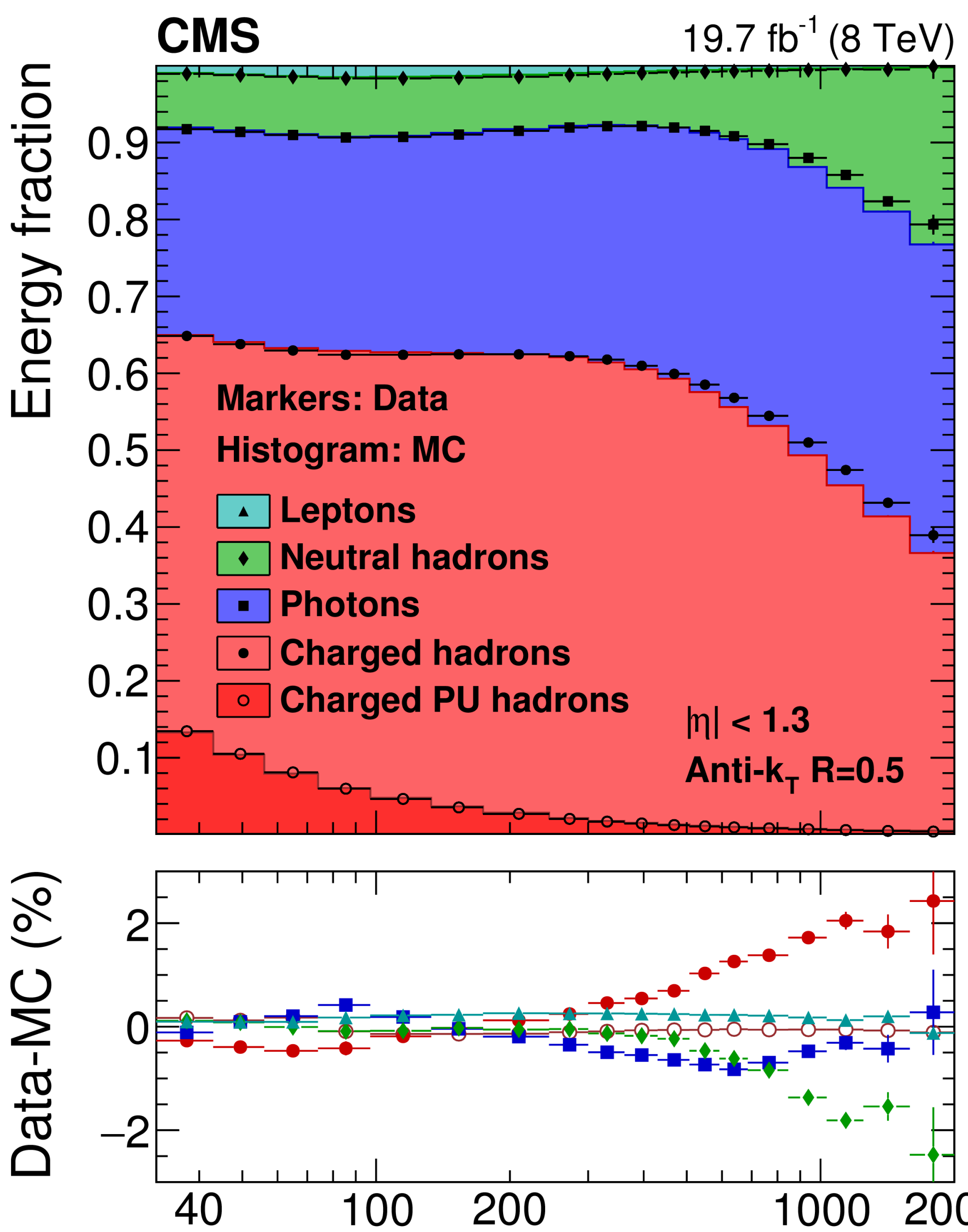




- **Particle flow algorithms benefit from larger B.R**
  - well separated tracks
  - reconstruct conversions, nuclear interactions, V^0 decays
  - easier to link with calorimeter deposits
  - dedicated calibrations from identified π^+, K^0, e, γ, μ

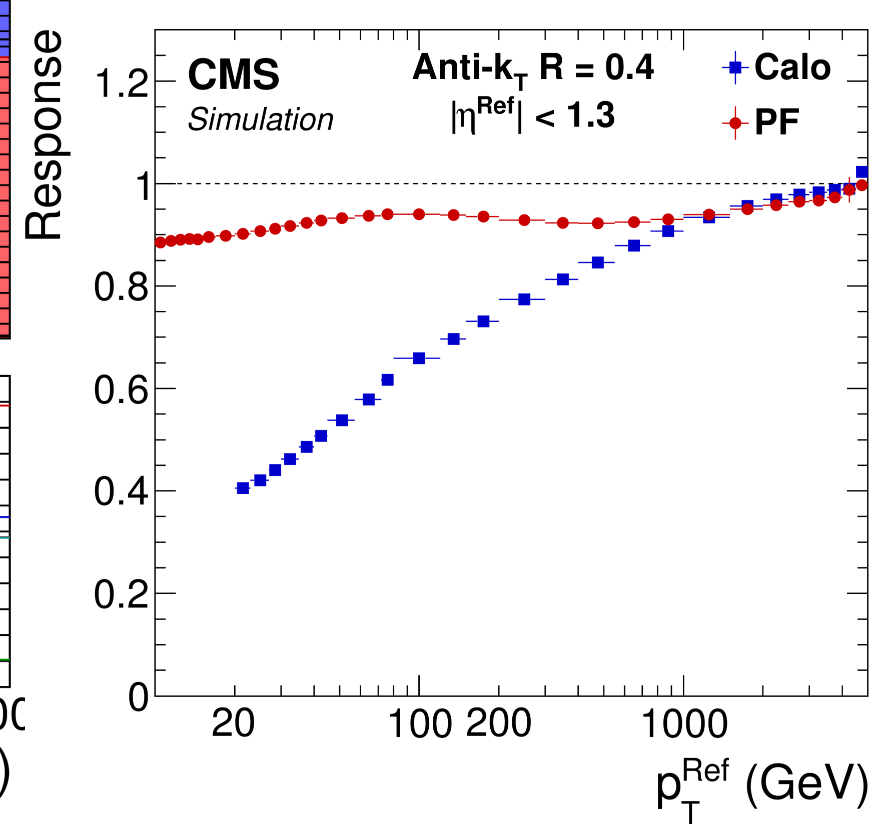
Particle flow performance

- **>80% of the jet components are reconstructed using high resolution detectors**
    - *tracking*: π^+,K^+ and other charged hadrons are approximately O(60%)
    - *ECAL*: by isospin symmetry $\pi \to \gamma\gamma$ contribute in second place with O(20%)

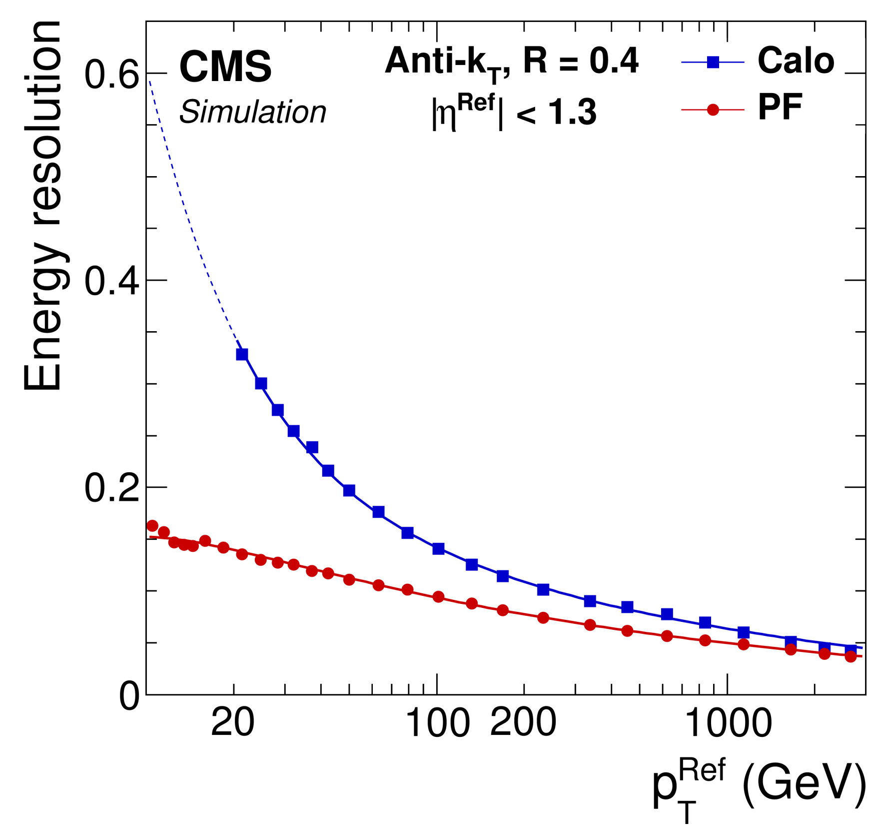


[arXiv:1706.04965](https://arxiv.org/abs/1706.04965)

Excellent out-of-the-box response (p_T^{reco}/p_T^{ref})



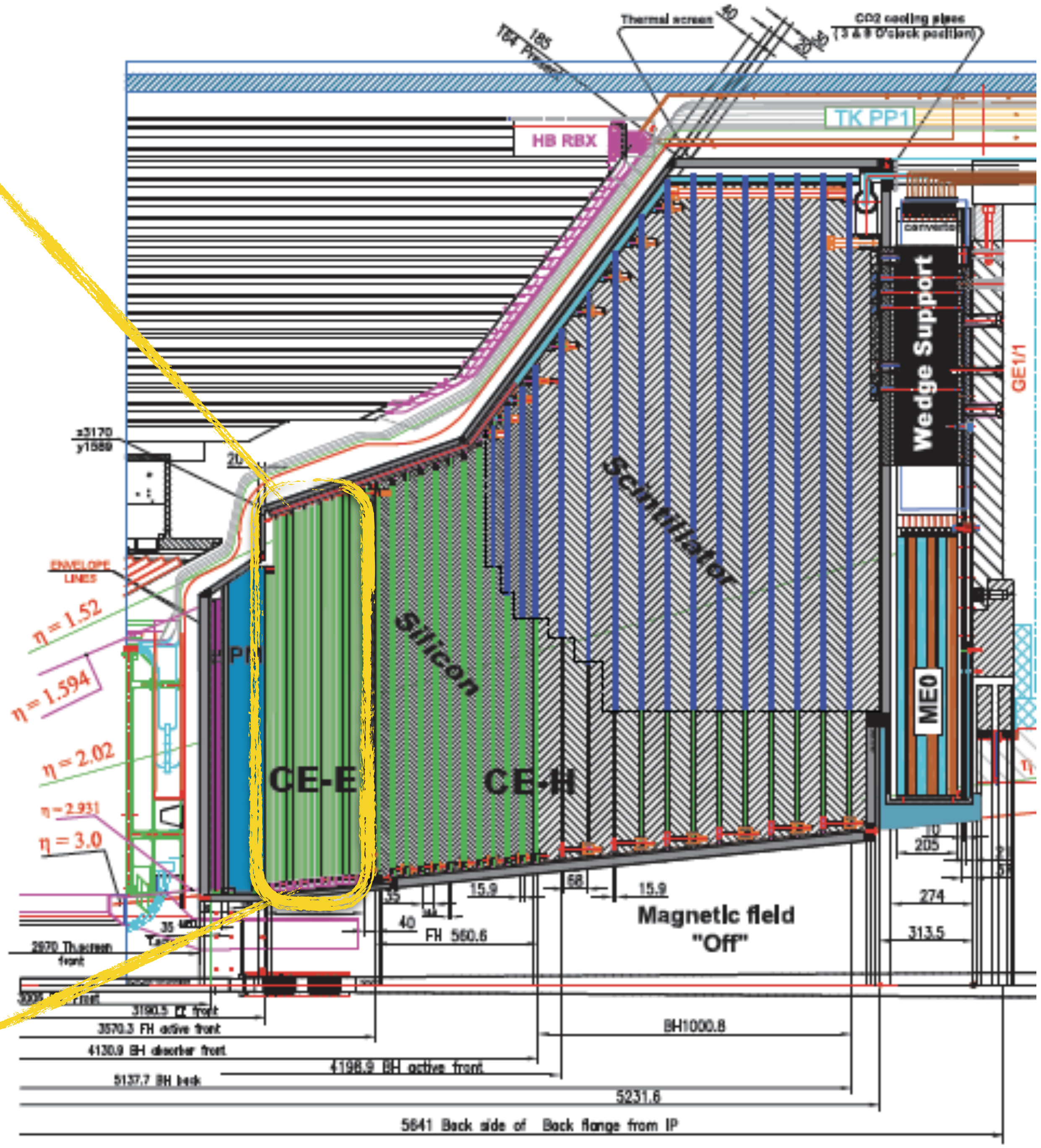
Ability to reconstruct jets at lower pT, gain>60% in resolution ($\Delta p_T/p_T^{ref}$)



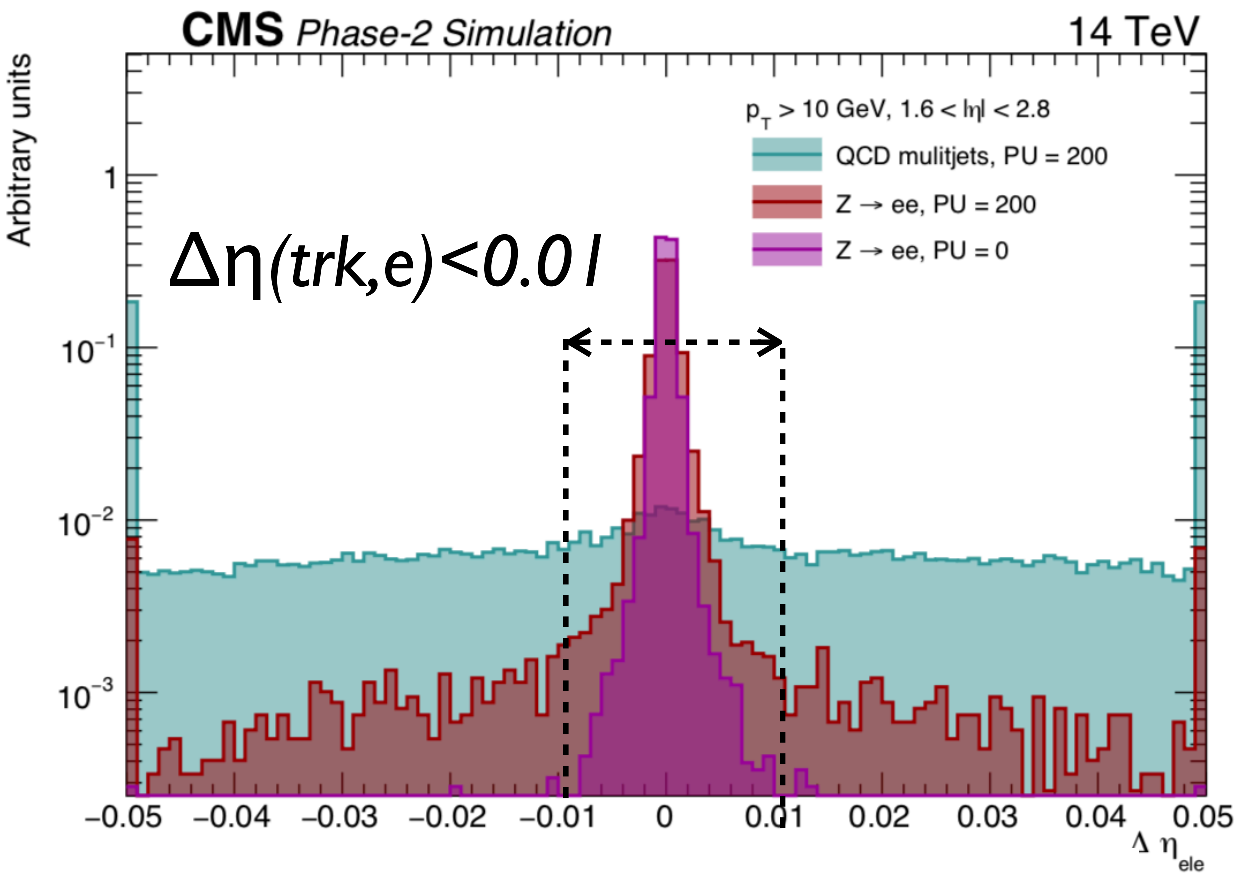
High Granularity Calorimeter

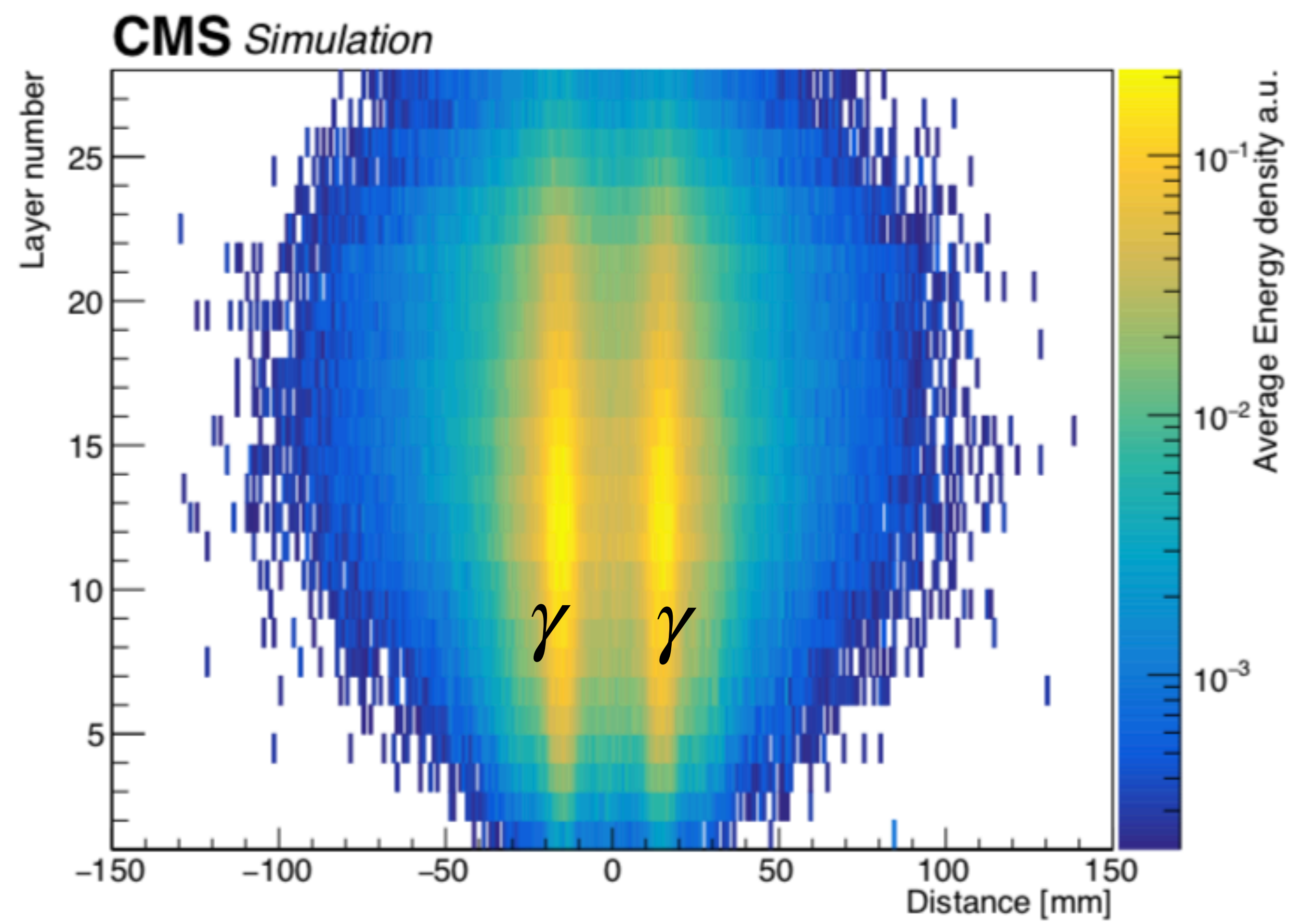
- **A dense/compact sampling calorimeter with high lateral/longitudinal segmentation**
- **Total of 585m² of 8" Si sensors (≈3x CMS tracker area) + 480m² of Scintillator**
  - 28 (24) layers with Cu/ WCu/Pb (st. steel/Cu) absorbers used in ECAL (HCAL) sum to $26X_0$ (10.7λ)

Active thickness [μm]	120	200	300
Cell size [cm²]	0.52	1.18	1.18
η coverage	2.3-3	1.7-2.3	1.5-1.7
C [pF]	50	65	50
Bulk polarity	p	p	p / (n)
Fluence [10^{15} n_{eq}/cm^2]	2.0-7.0	0.5-2.5	0.1-0.5
Lifetime dose [M_{rad}]	100	20	3
S/N (initial→after 3 ab^{-1})	4.5→2.2	6→2.3	11→4.7

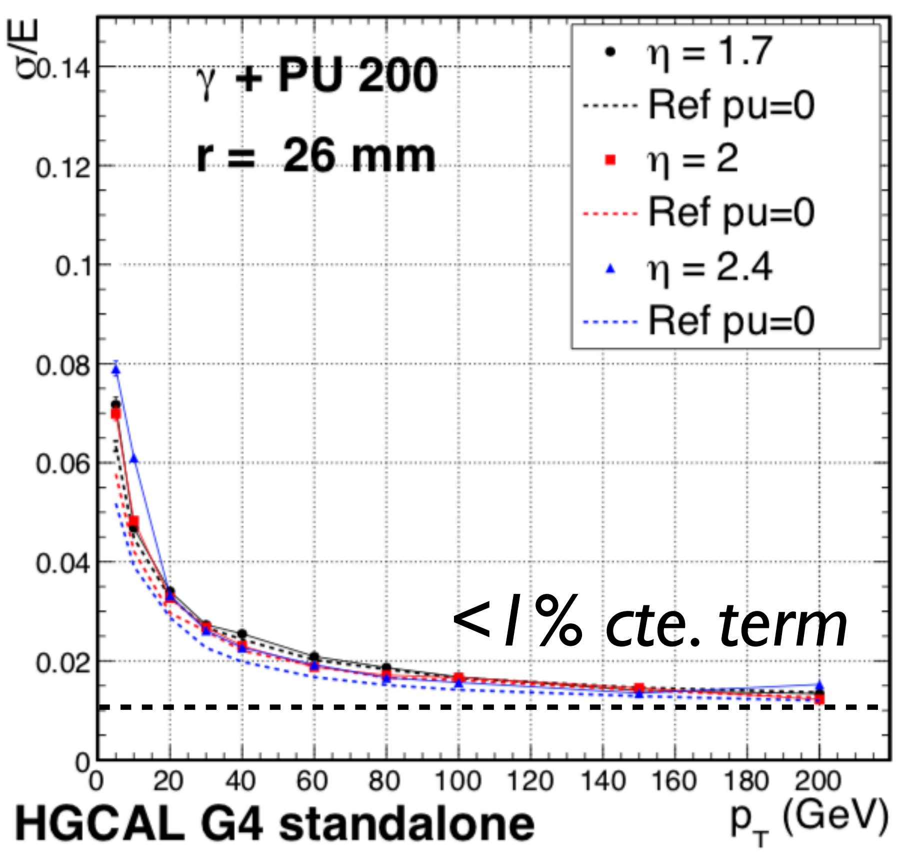


Towards fine-grained particle flow at high pileup





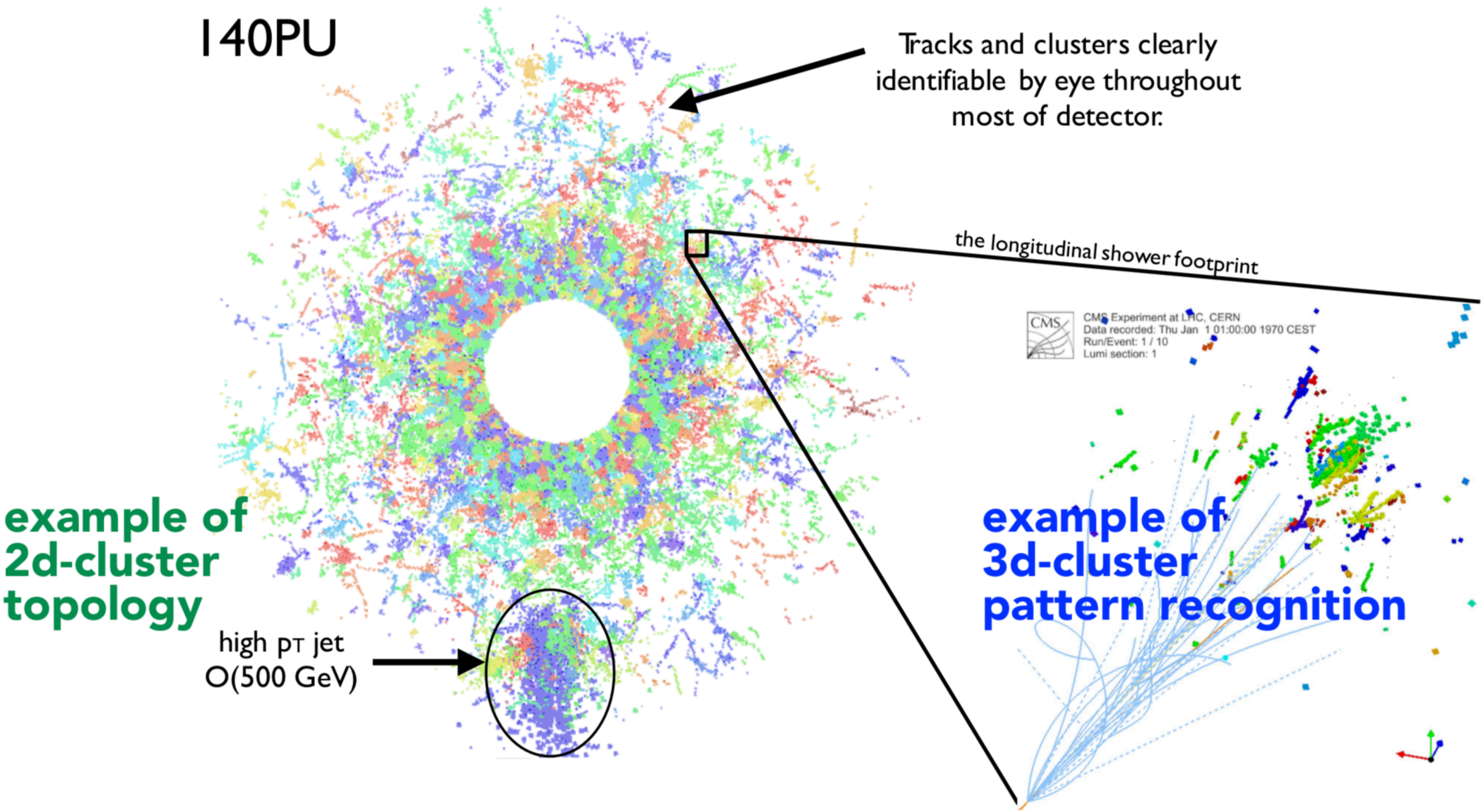
p_T=14.4 GeV η=2.4 ΔR=0.05



Promising capabilities

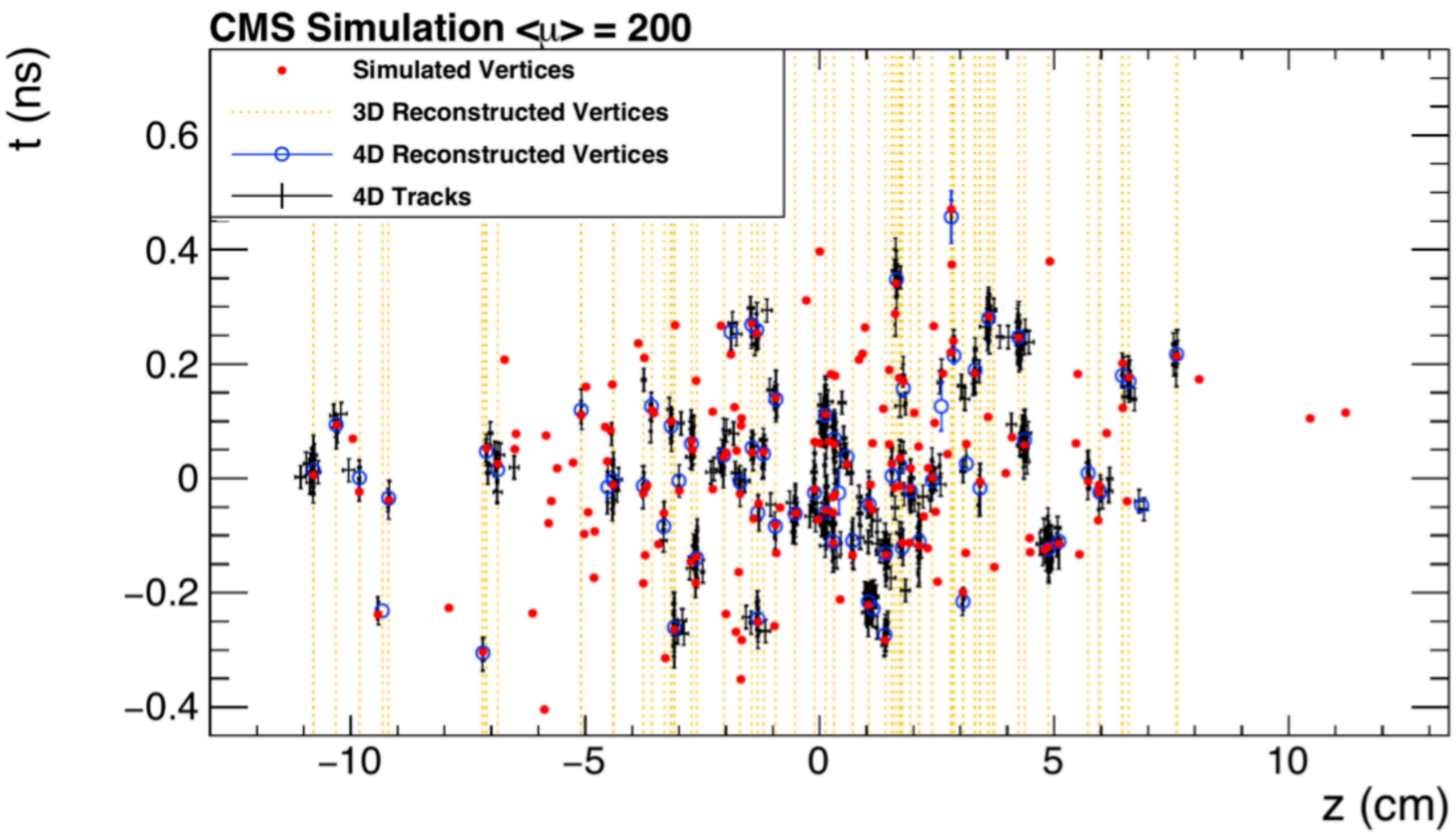
- track-like reconstruction + resolution ⇒ **linking**
- spatial separation ⇒ **feature extraction**

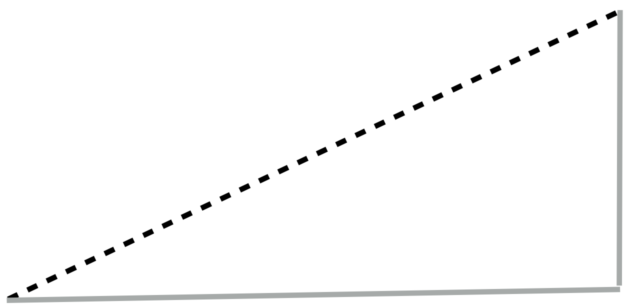
Towards fine-grained particle flow at high pileup



Particle flow will naturally evolve towards the usage of machine learning algorithms.

Usage of time information

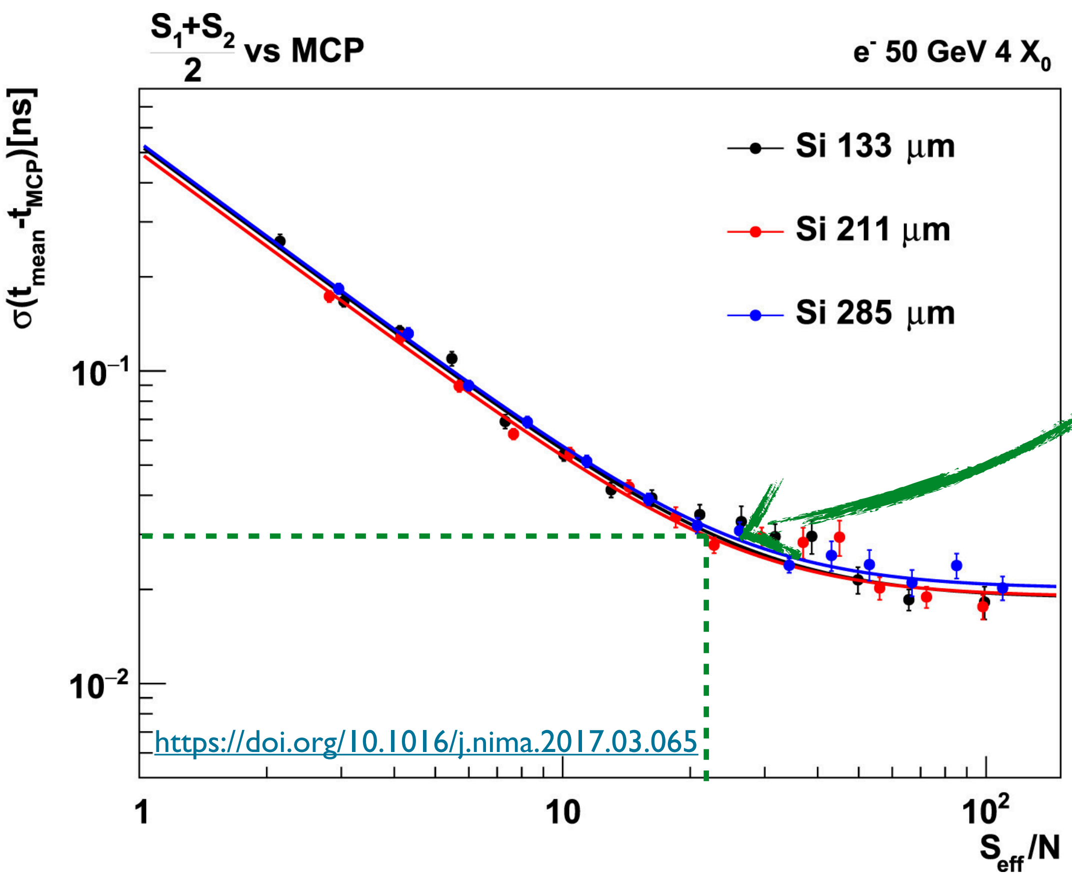




3.190m≈10.6ns

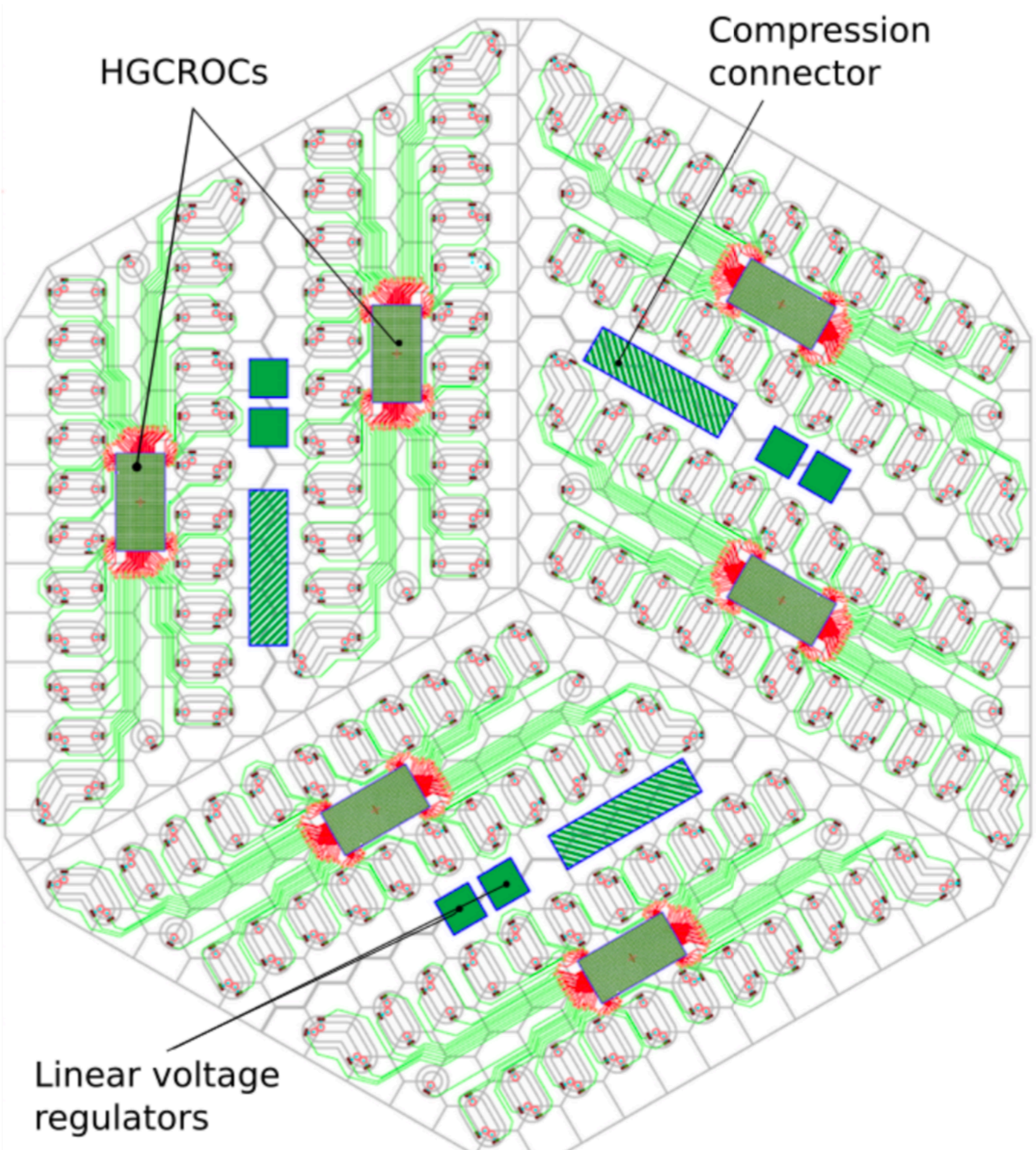
$\delta t \approx (z+z_0)/c \cdot \delta z/z$

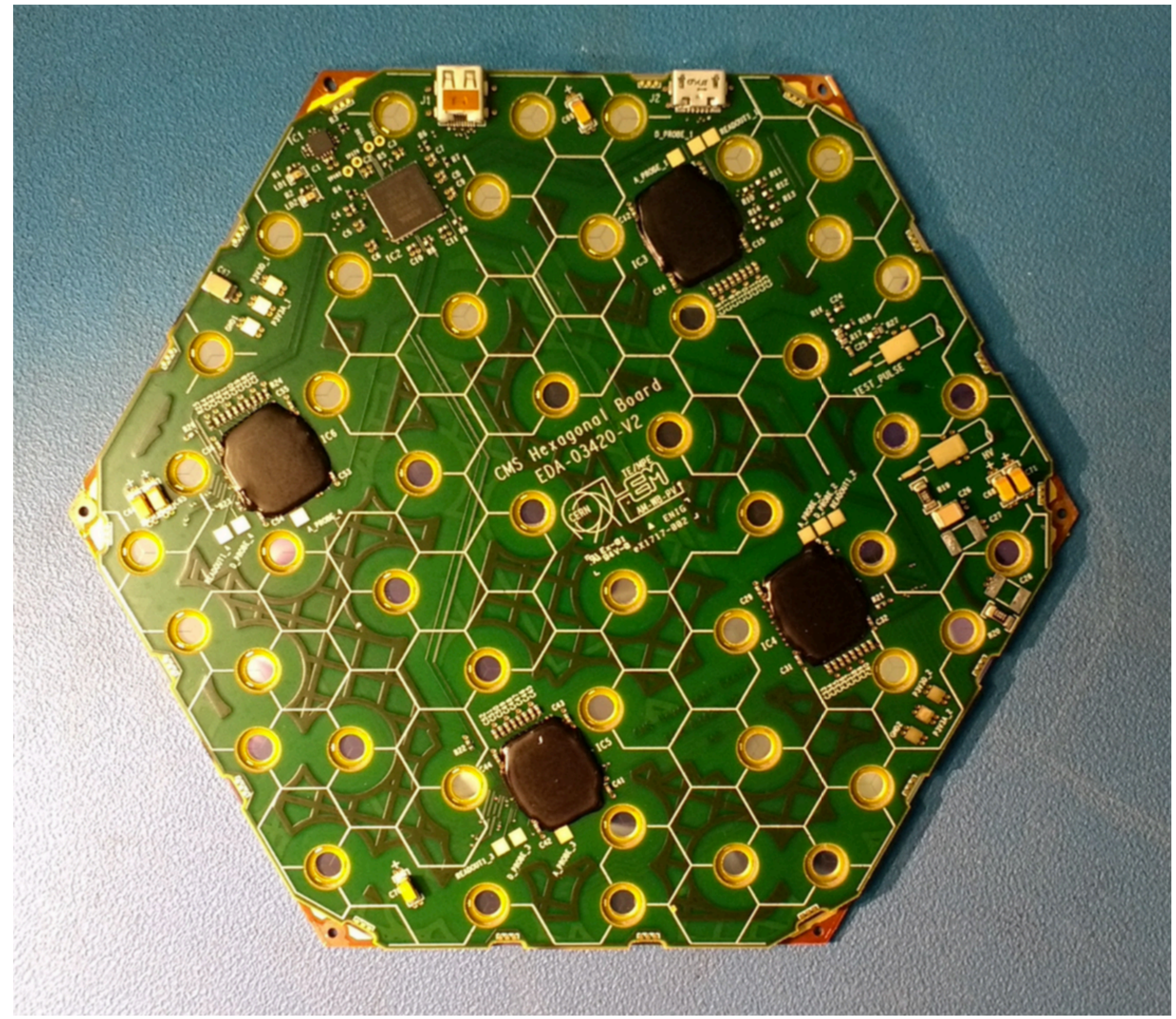
~30ps ~1cm



Single Si sensors can do it!

Module design



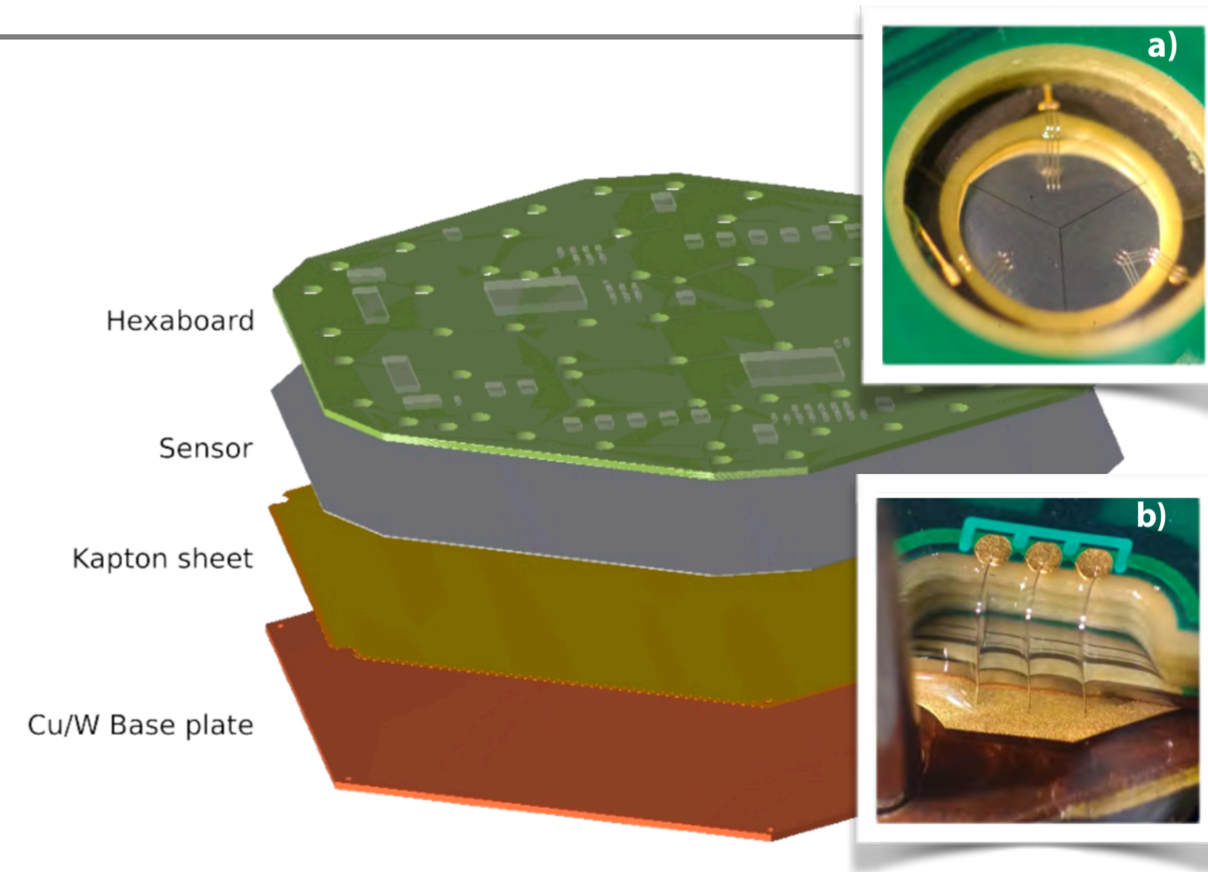


- **432ch module PCB layout**
  - oblong holes are used for wirebonding
- **6” module prototype before wirebonding**
  - readout with SKIROC2-CMS FE chips
  - used in beam tests

Rationale behind sensor/module design

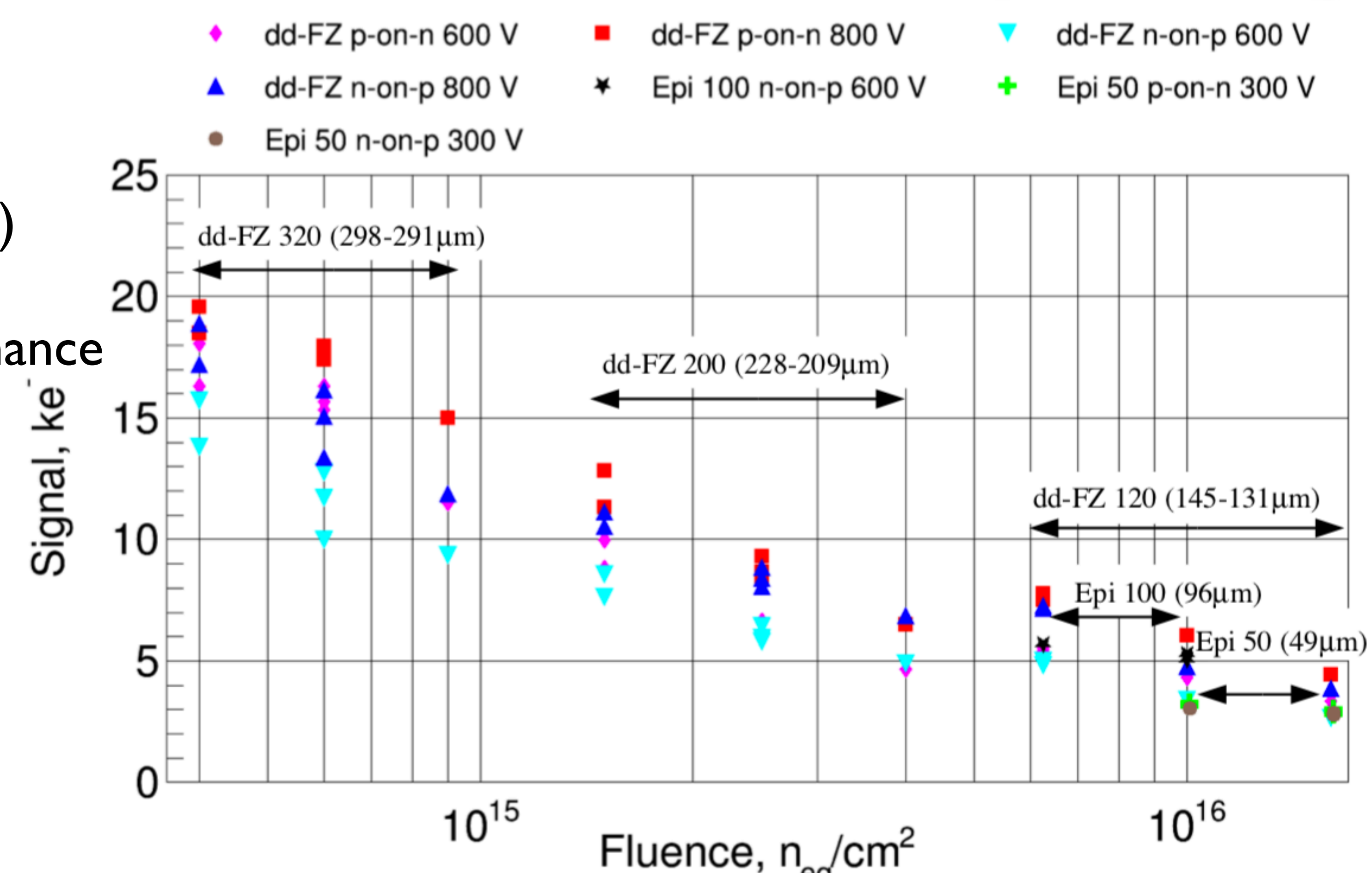
- **Hexagonal 8” sensors with DC-coupled pads**
  - maximise available wafer area
  - reduce number of sensors produced / assembled
  - ⬢ vs ■ cells factor ~ 1.3

  8” vs 6” sensors factor ~1.8

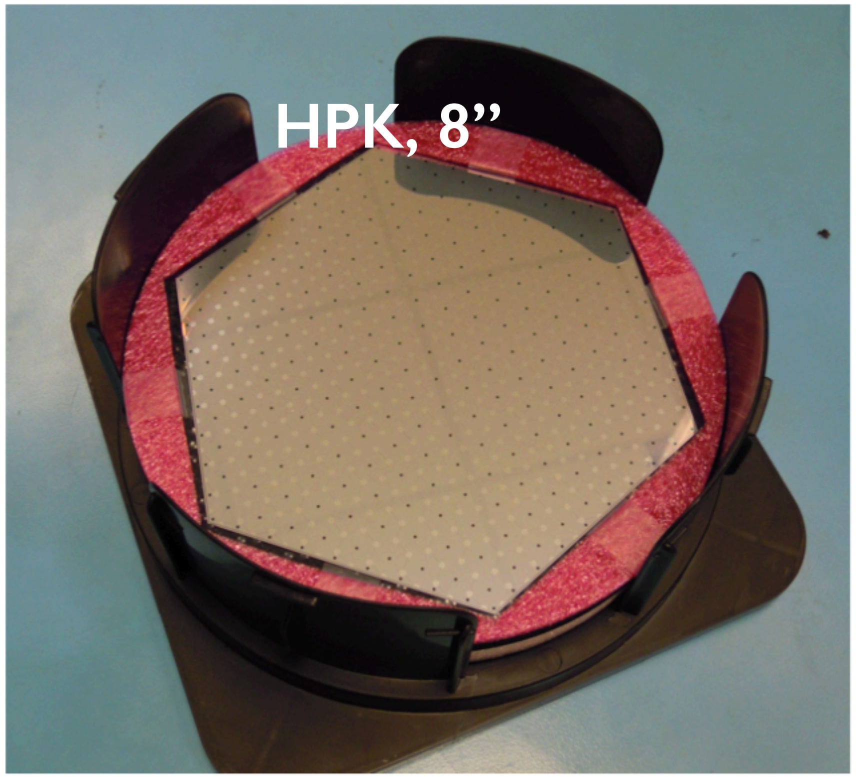


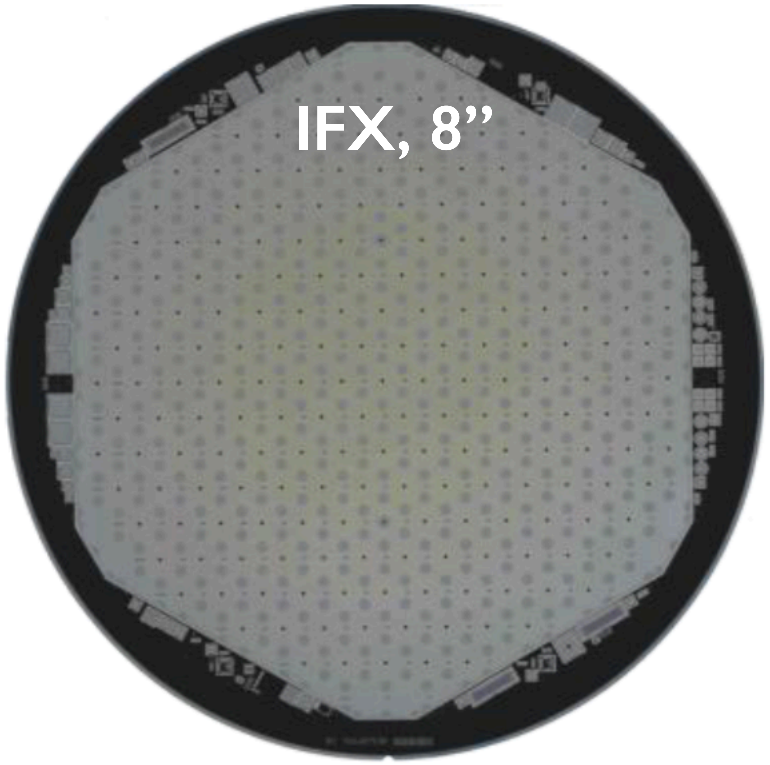
- **Varying sensor thickness**
  - only small effect on resolution (stochastic)
  - dictated by n fluence, for optimal performance

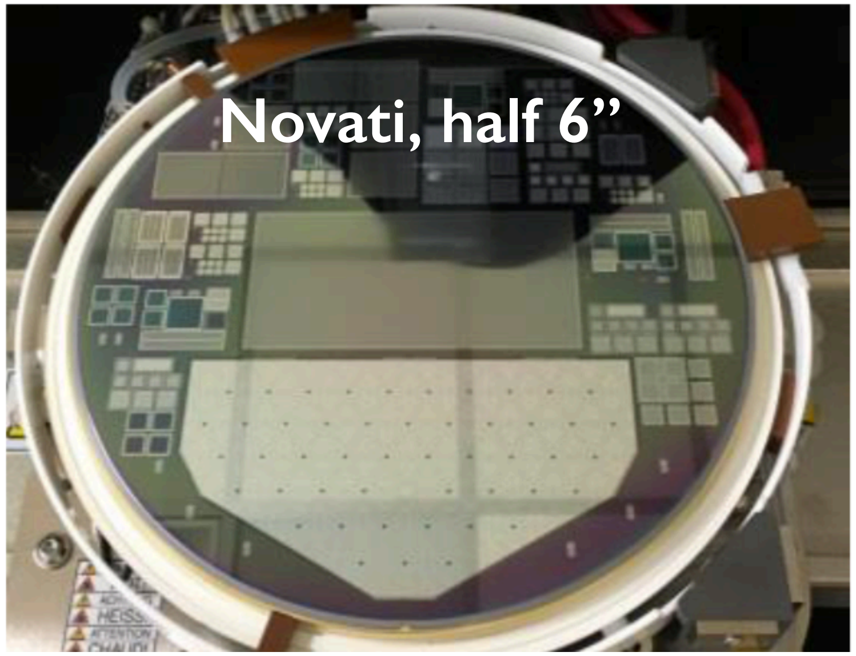
Simple, rugged module design, automated assembly



Prototyping examples: Si sensors available for testing







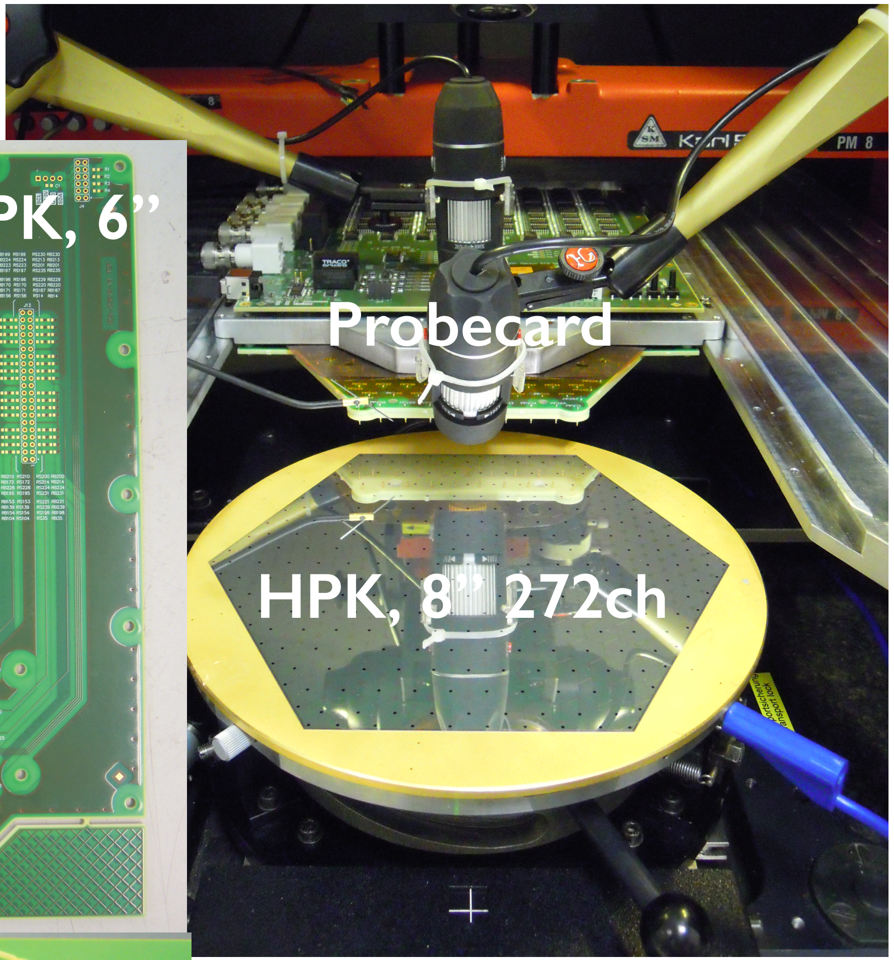
- **Hamamatsu (HPK), Japan**
  - ~200 6” used for beam tests
  - several 6” with different diffusion techniques, thicknesses, n and p-types, geometries, p-stop options
  - first 15 8” prototypes
- **Infineon (IFX), Austria**
  - 6” (n-type) and 8” (p-type) production for CMS tracker
  - 25 8” p-type prototypes
- **Novati, US**
  - 6” half sensors on 8” wafers
  - 8” sensors in production

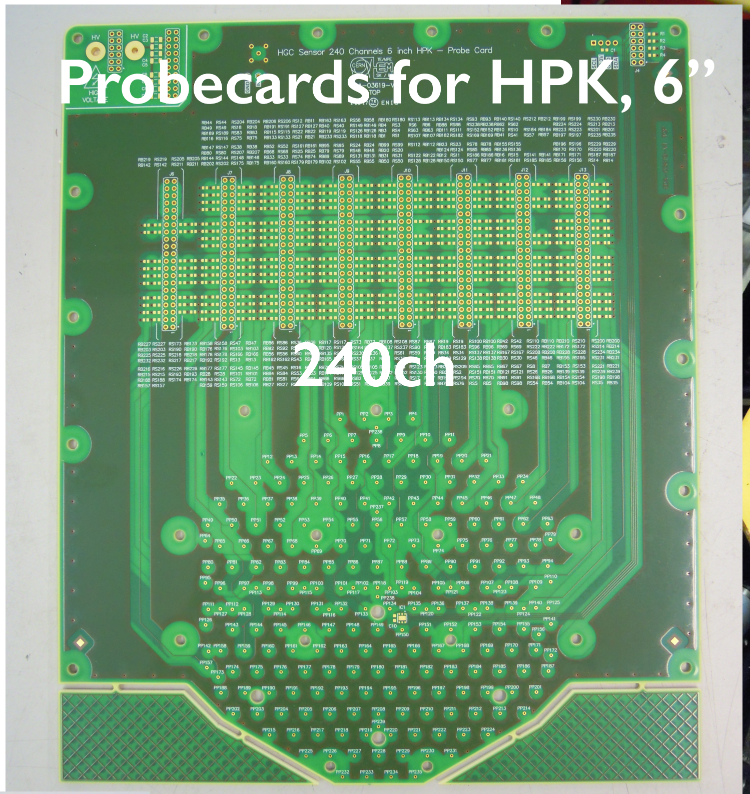
Sensor testing for HGCAL on-going at CERN, HEPHY (Vienna), Fermilab (US)

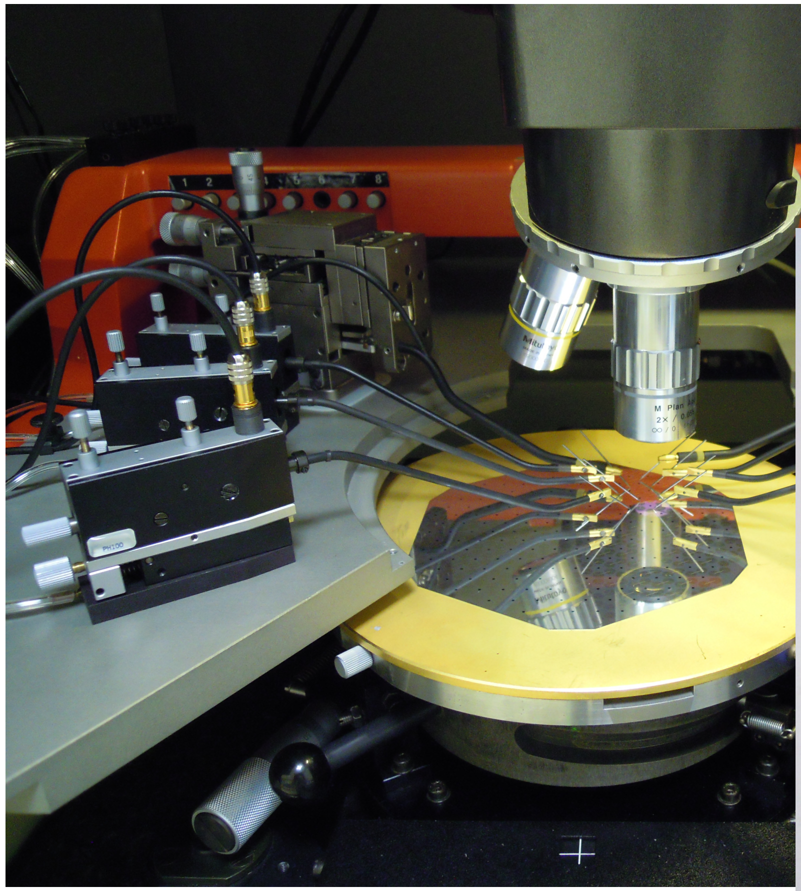
Aim for close-to-final design by Summer 2018

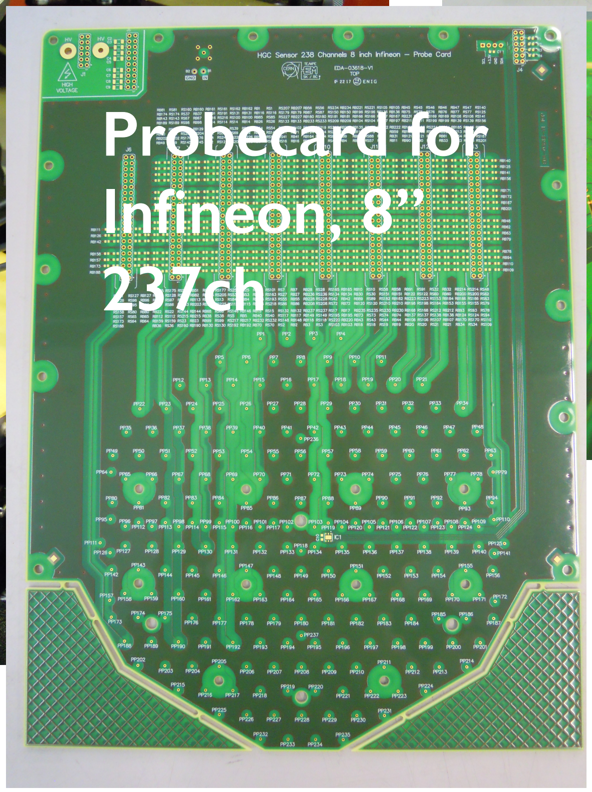
Setup at CERN for sensor testing

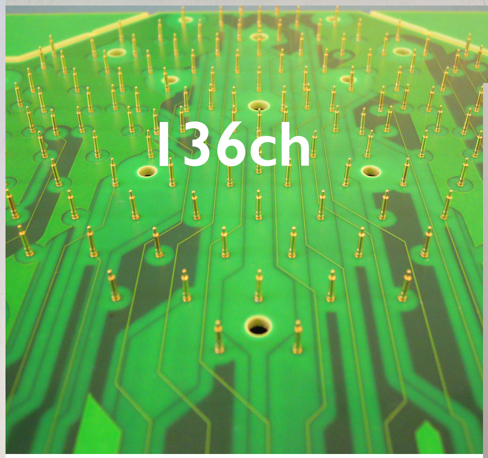
- **Tests have been made so far with a manual probe station**
  - single/multi-point needle measurements
  - dedicated probe-cards + switch card
  - irradiation tests to be done this year
- **LabView / python-based DAQ** (GPIB)

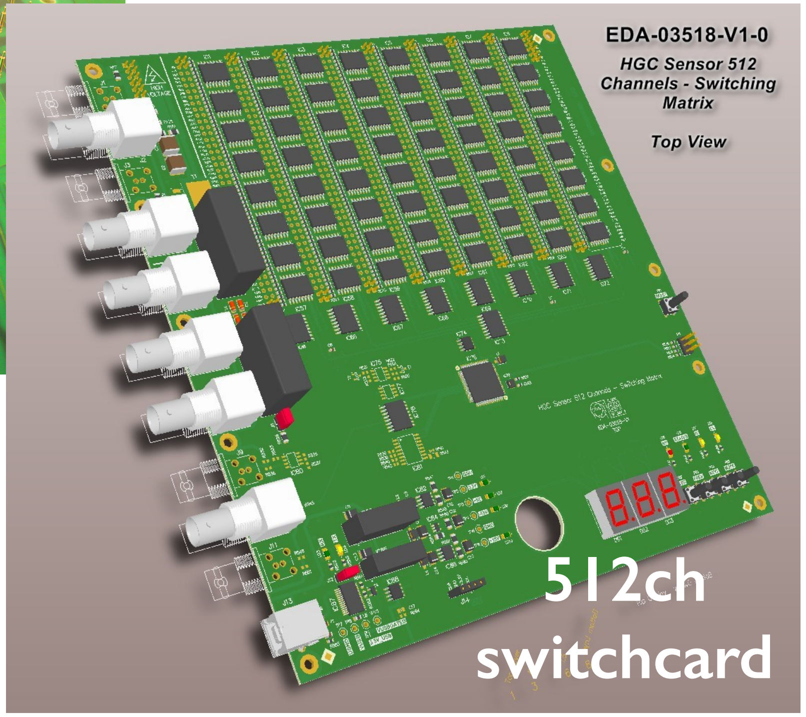






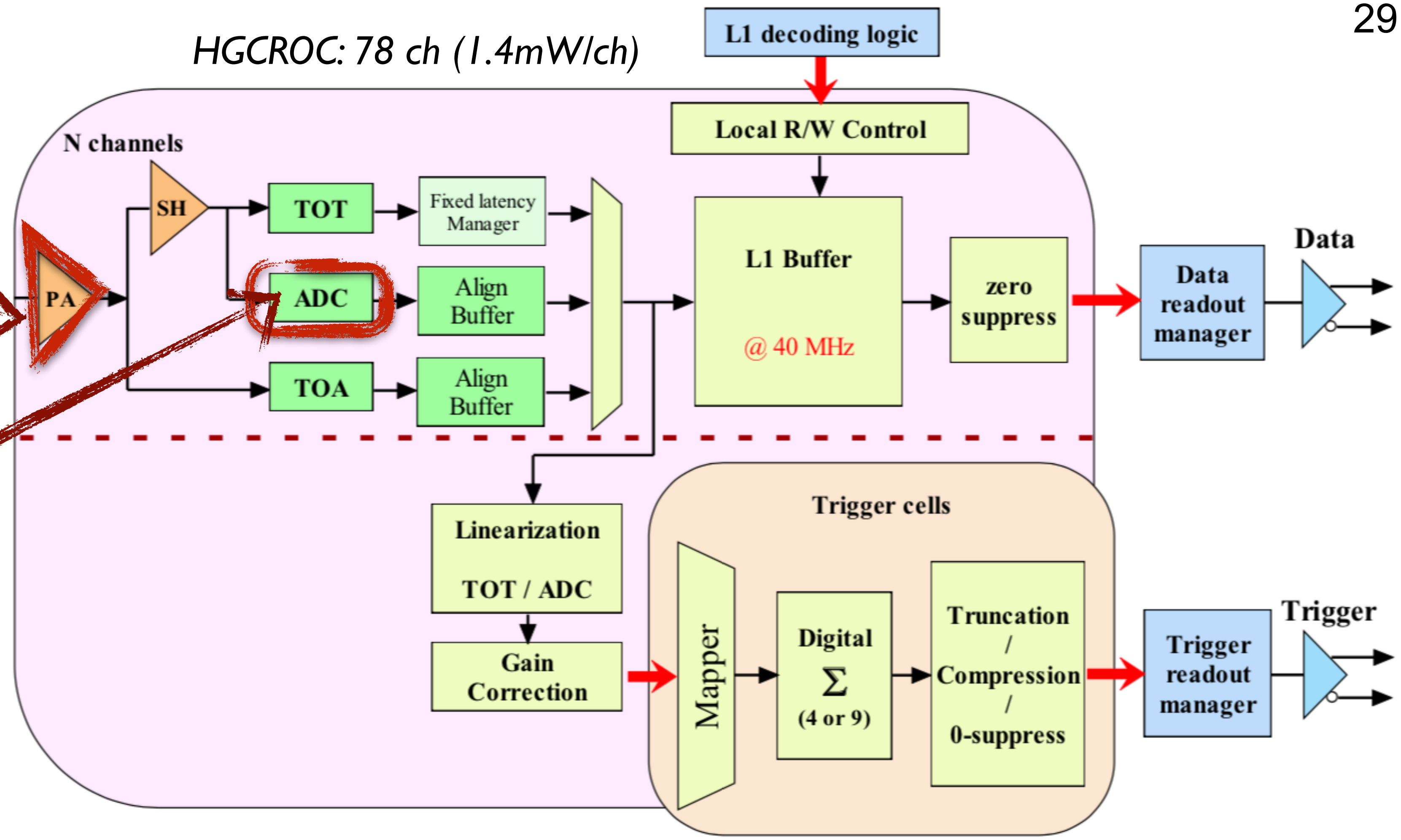






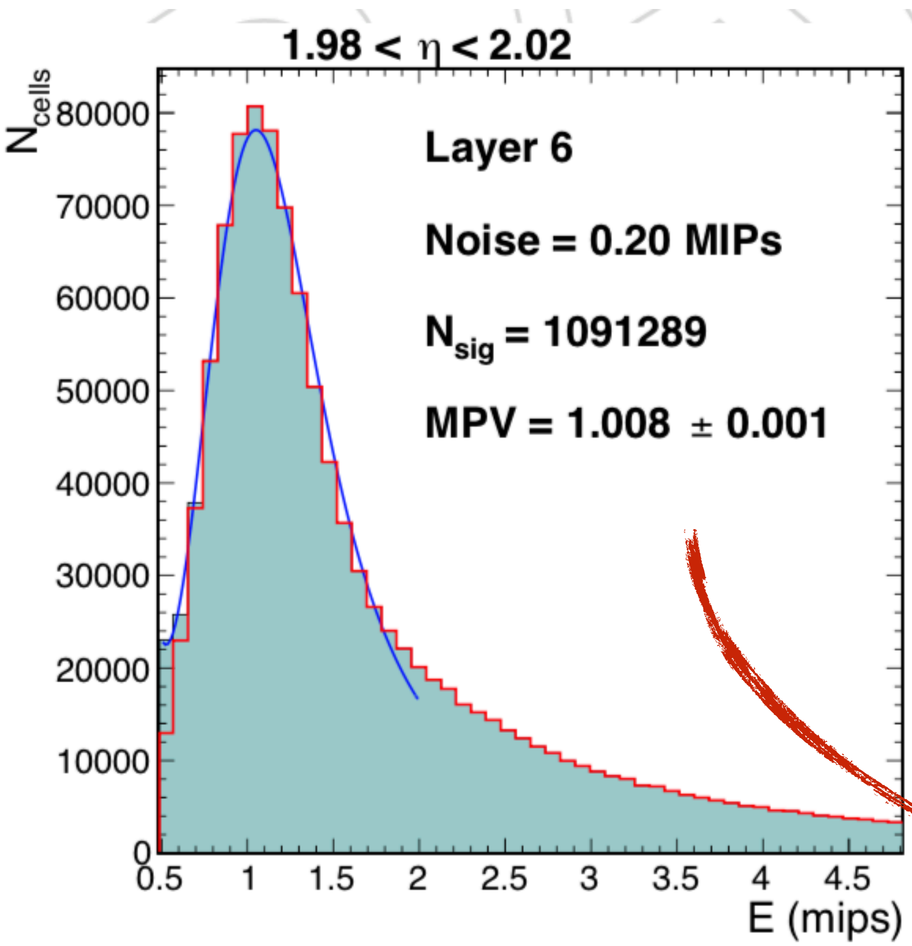
Readout I

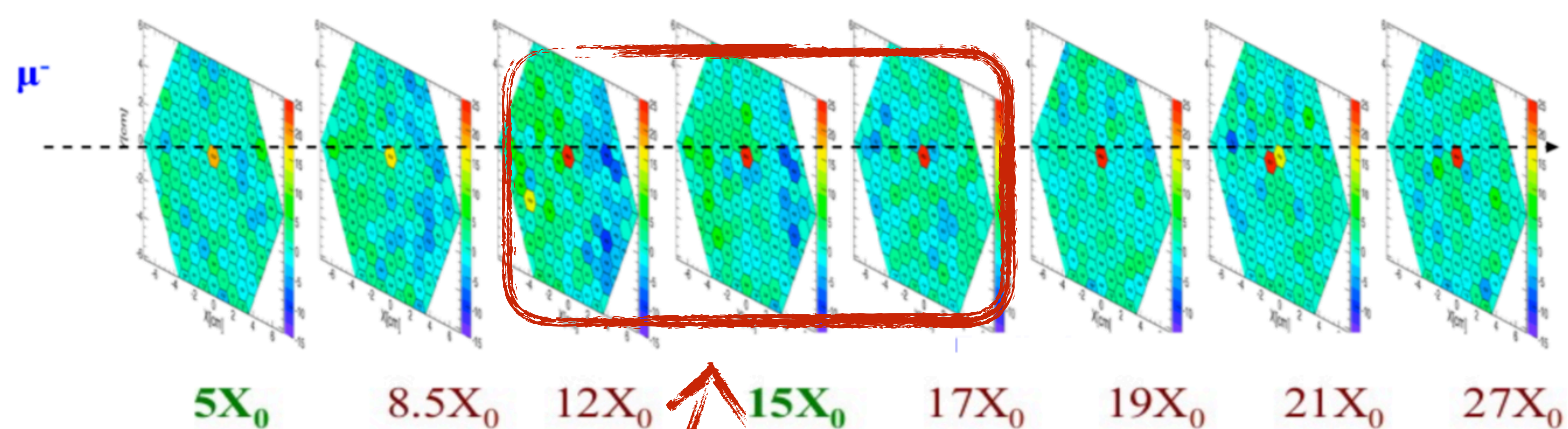
HGCROC: 78 ch (1.4mW/ch)



<20ns shaping
<20% leakage to next bx crossing

10bit
up to 100-150fC
preserve MIP peak for calibration





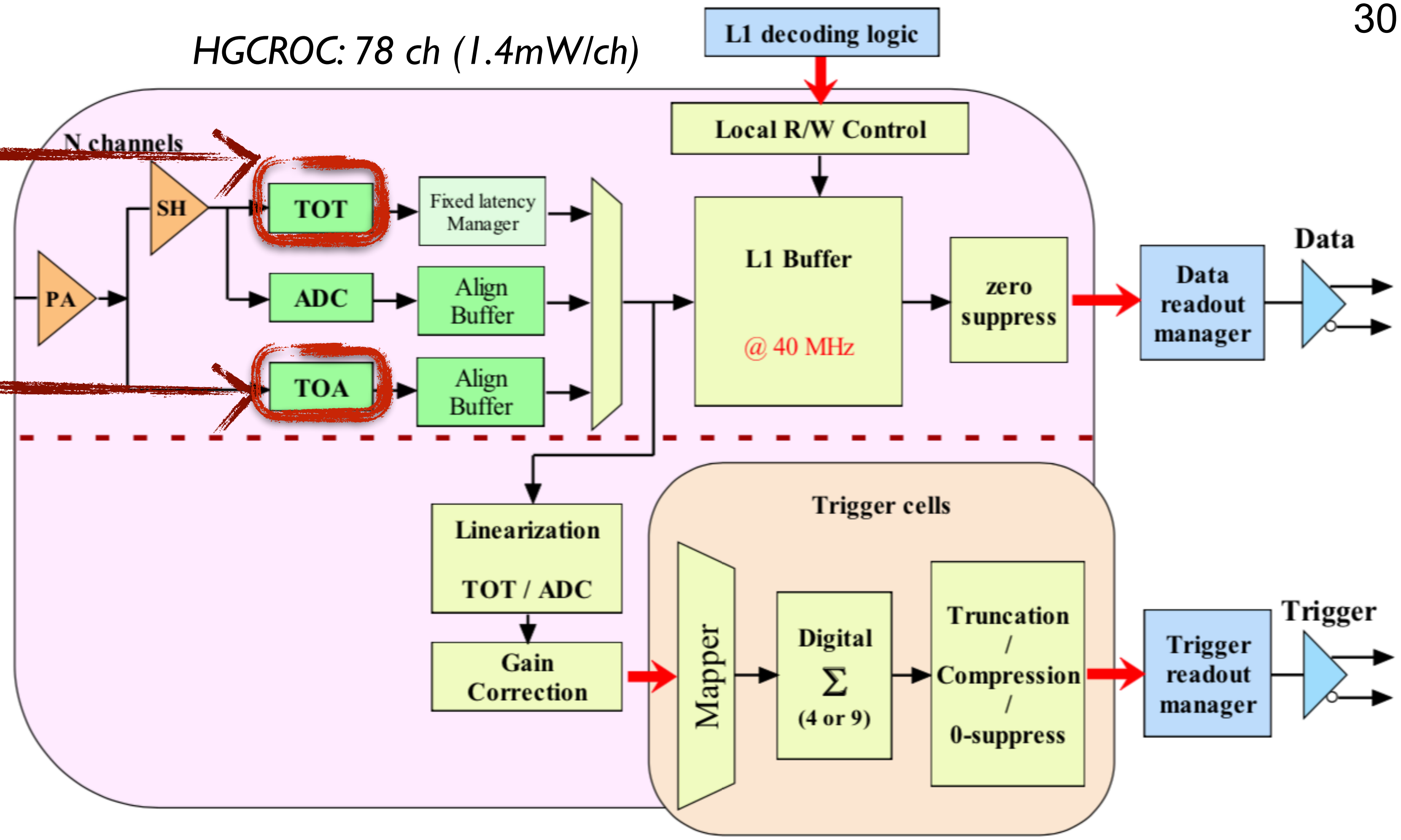
3 layer MIP-tracking
<3% inter-calibration unc.
⇒ 50M events O(min) at S/N~2.5

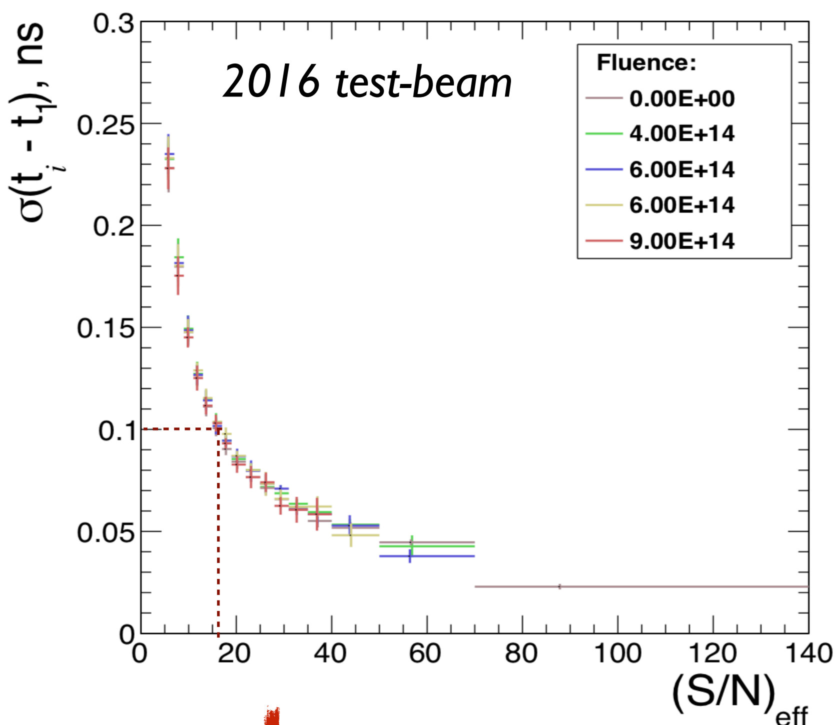
Readout II

HGCROC: 78 ch (1.4mW/ch)

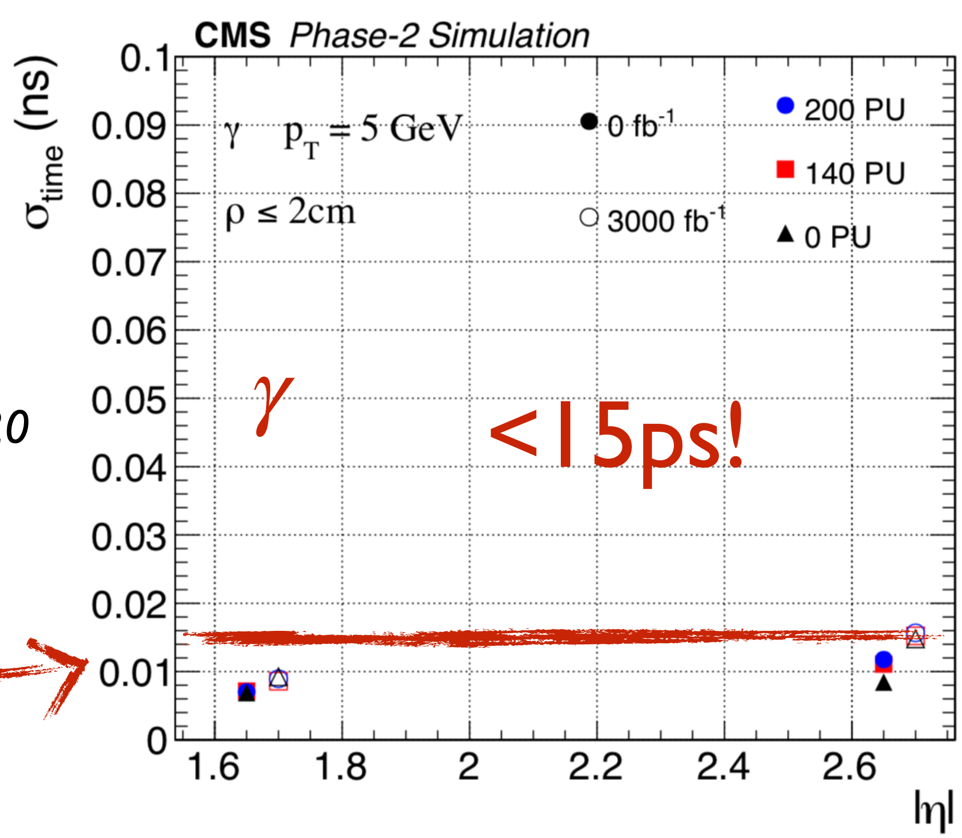
12bit
50fC-10pC
(50ps binning)

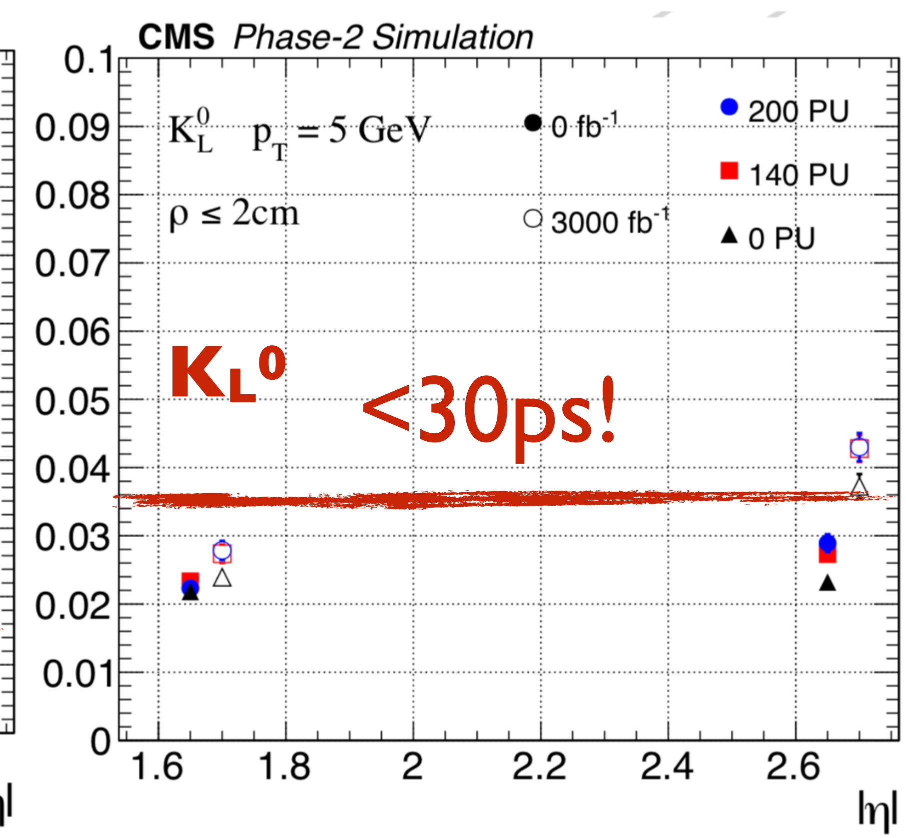
time-of-arrival through 10b TDC
for q>12fC (25ps binning)





single cell time resolution <100ps for S/N>20
Si width and fluence-independent
combine N-cells for a full shower





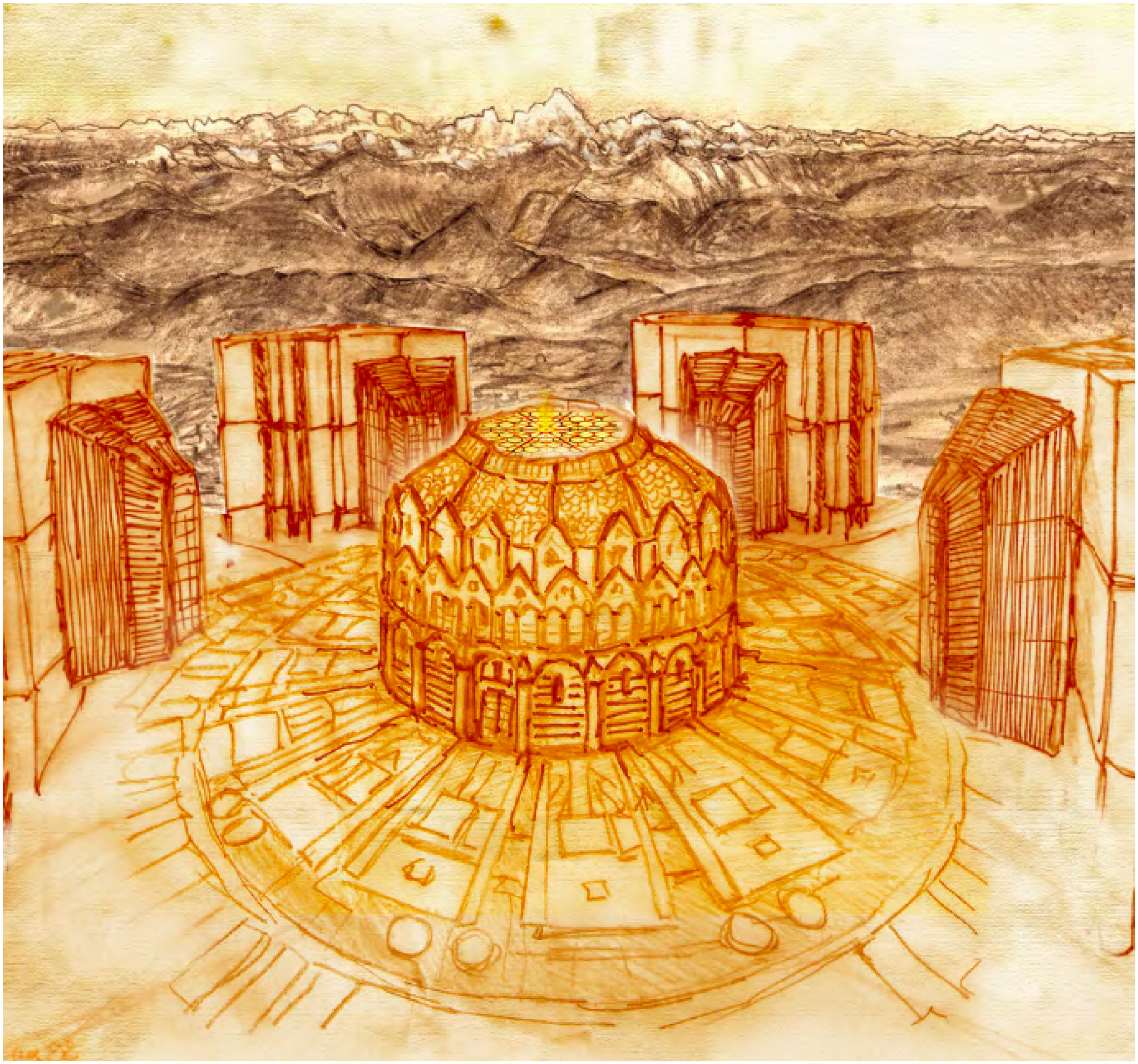
Conclusions

- **Still a long way to complete the LHC Physics Programme**
  - cherry-picked some favourite examples on electroweak symmetry breaking

    Higgs (self-)couplings, vector boson scattering and anomalous couplings
  - but much more to explore ahead

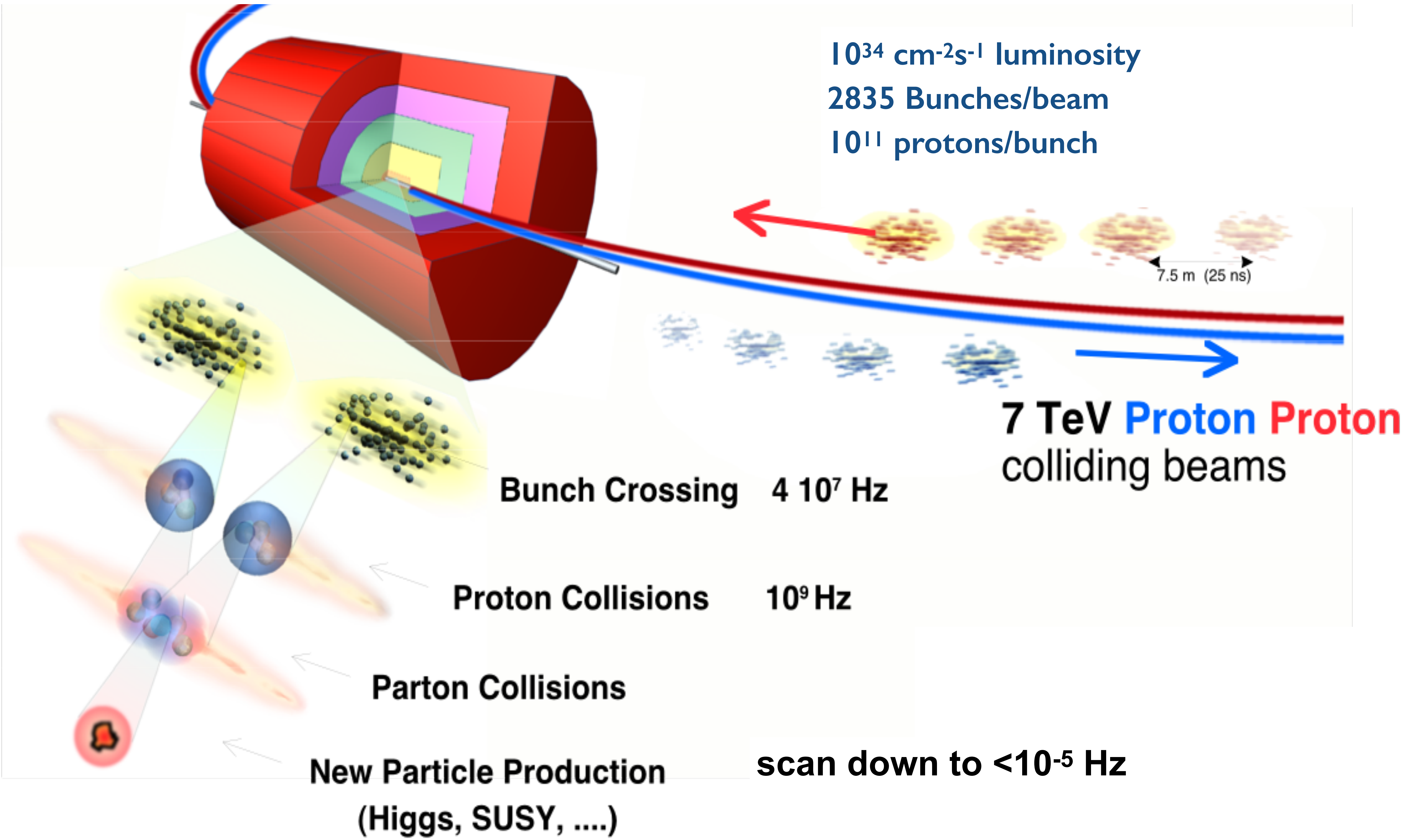
- **Detectors must be upgraded to step up with the increase in luminosity**
  - higher radiation doses, up to 200 simultaneous pileup interactions
  - particle flow reconstruction driving the design of the upgraded CMS detector
  - HGCal providing the maximum information possible (E, x, t) using ~585m^2 of Si sensors

- **Plenty of opportunities ahead: phenomenology, analysis, detector development!**



Backup

Collisions at the LHC: a summary



Need to select 1 / 10^{13} events produced and reject pileup!

Sensor characteristics for ECAL/HCAL

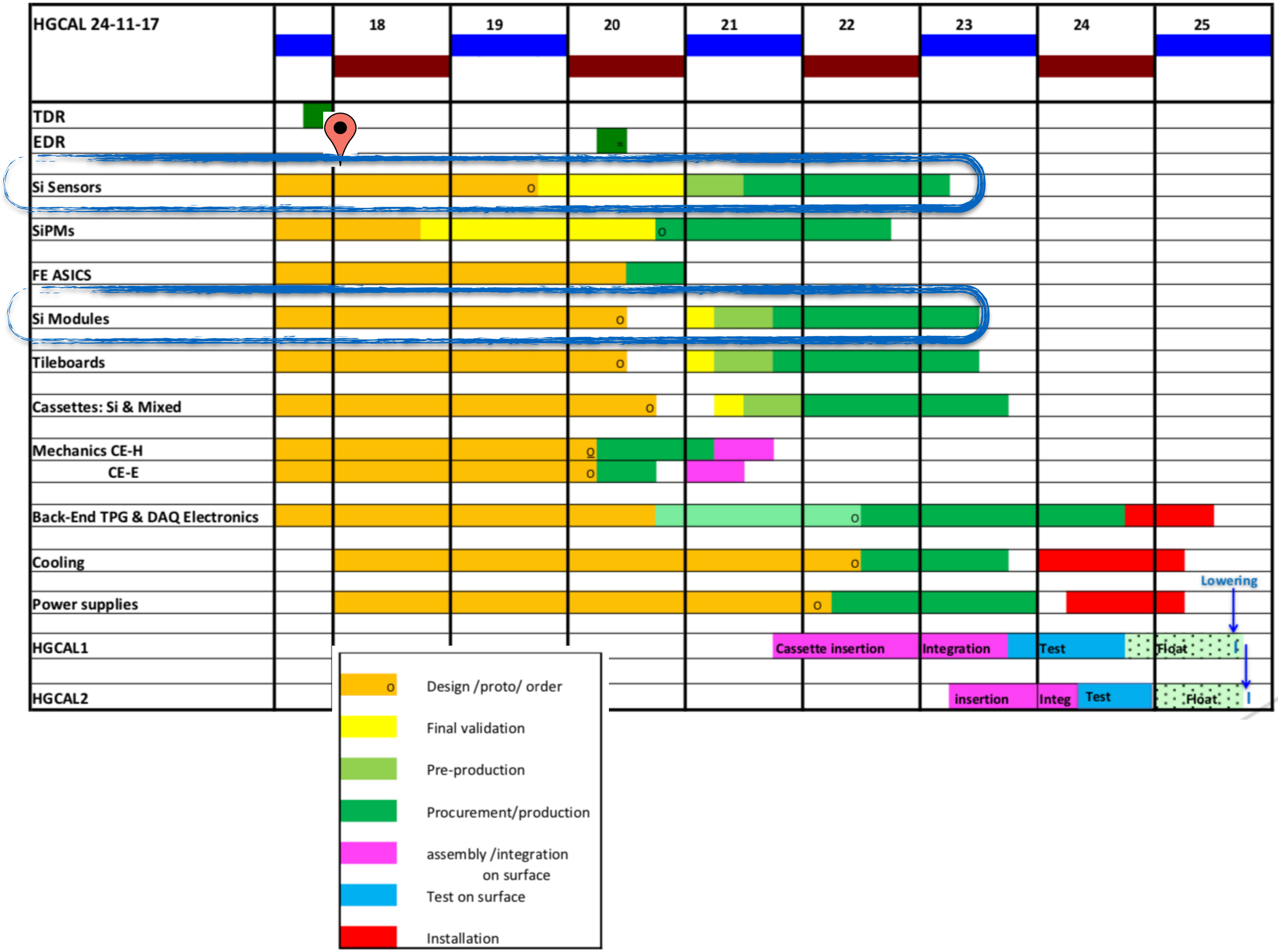
CE-E

Active thickness (μm)	300	200	120
Area (m^2)	245	181	72
Largest lifetime dose (Mrad)	3	20	100
Largest lifetime fluence (n_{eq}/cm^2)	0.5×10^{15}	2.5×10^{15}	7×10^{15}
Largest outer radius (cm)	$\approx$180	$\approx$100	$\approx$70
Smallest inner radius (cm)	$\approx$100	$\approx$70	$\approx$35
Cell size (cm^2)	1.18	1.18	0.52
Initial S/N for MIP	11	6	4.5
Smallest S/N(MIP) after 3000 fb^{-1}	4.7	2.3	2.2

CE-H

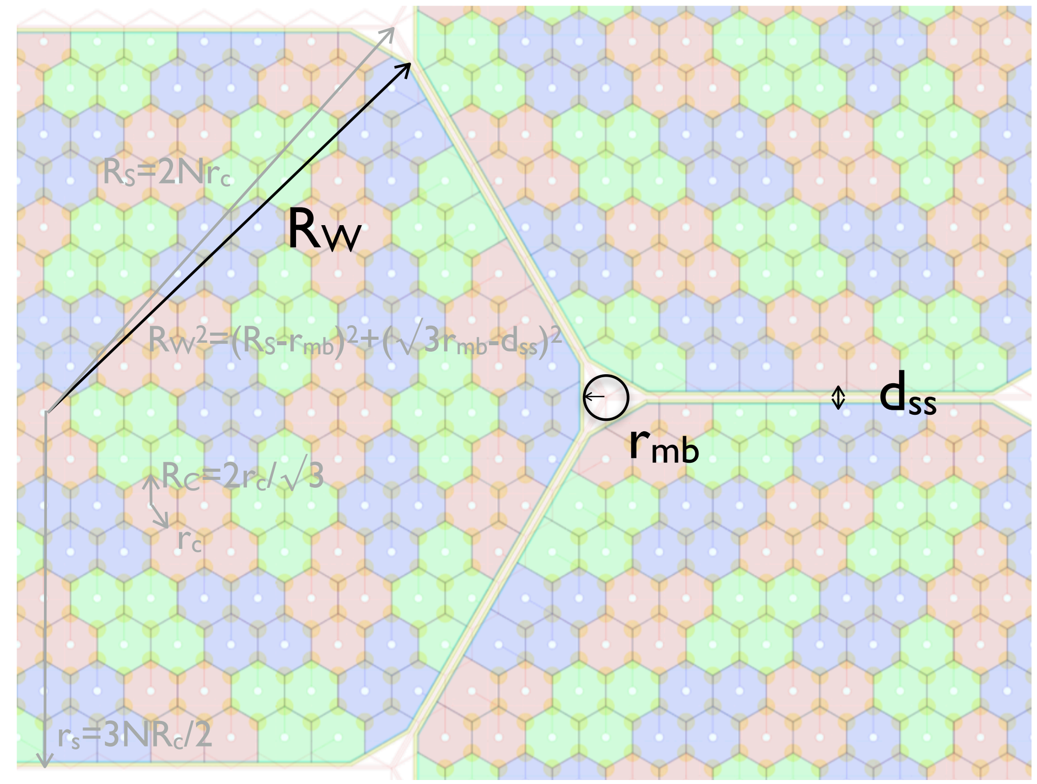
Sensor thickness	Scintillator 3 mm	Si 300 μm	Si 200 μm
Area (m^2)	480	71	15
Largest lifetime dose (Mrad)	<0.3	30	100
Largest lifetime fluence (n_{eq}/cm^2)	8×10^{13}	5×10^{14}	2.5×10^{15}
Largest outer radius (cm)	$\approx$235	$\approx$160	$\approx$100
Smallest inner radius (cm)	$\approx$90	$\approx$80	$\approx$45
Cell size (cm^2)	2×2 to 5.5×5.5	1.18	1.18
Initial S/N for a MIP	$\gg$5	11	6
Smallest S/N(MIP) after 3000 fb^{-1}	5	4.7	2.3

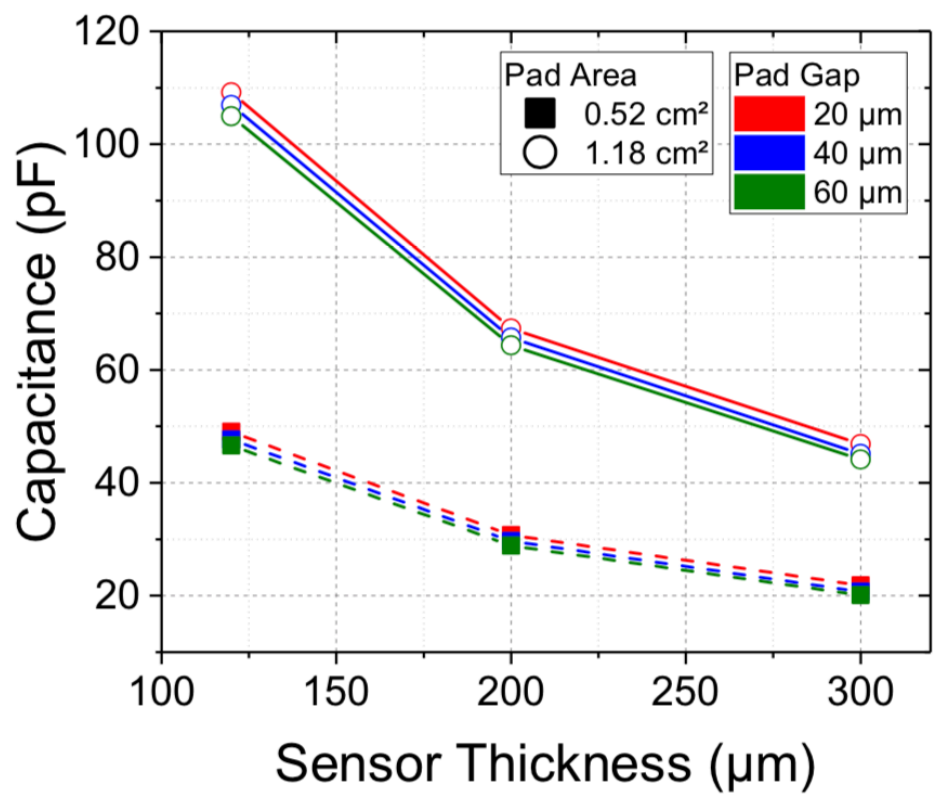
Project timeline and milestones

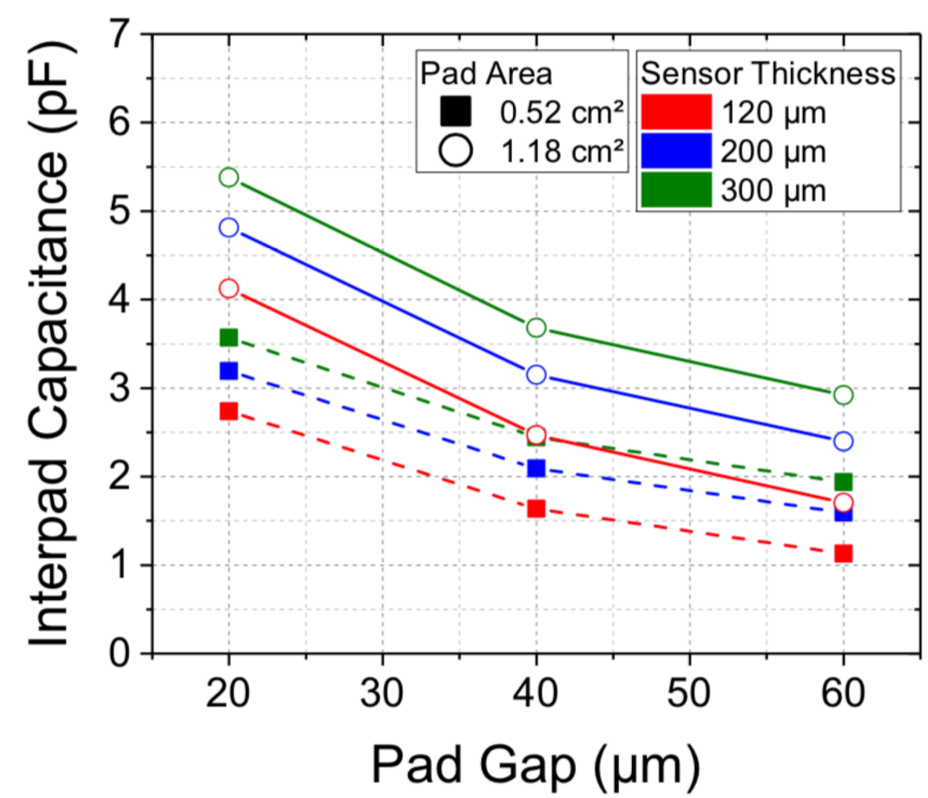


Sensor design parameters and layout optimisation

- **Cells are centred on uniform grid across detector**
  - geometry is fully determined by very few parameters
  - TCAD package used to verify optimal design of the sensor
- **Small interpad capacitance expected (<5 pF)**
  - simulation with two diodes with 5μm metal overhang
  - other features being studied: p-stop type, inter-pad gap, dimensions between edge implant floating or grounded guard ring, etc.

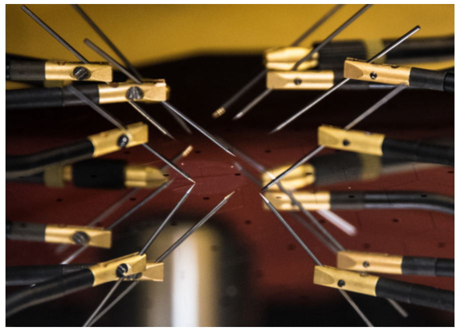
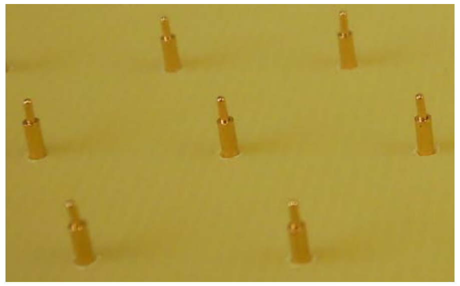






Sensor characterisation

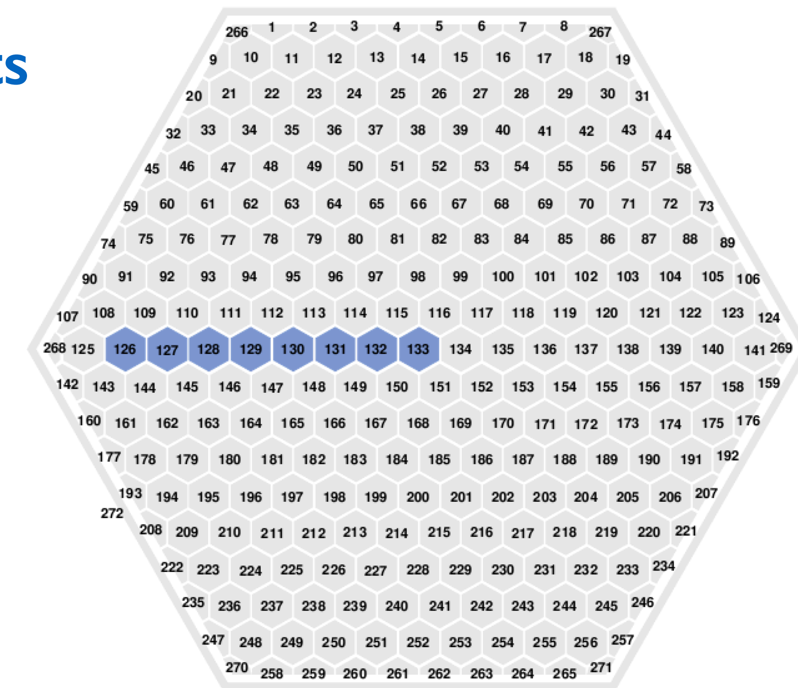
- **Measure I-V and C-V curves for the prototype sensors**
  - interpad capacitance and resistance
  - noise, charge collection efficiency

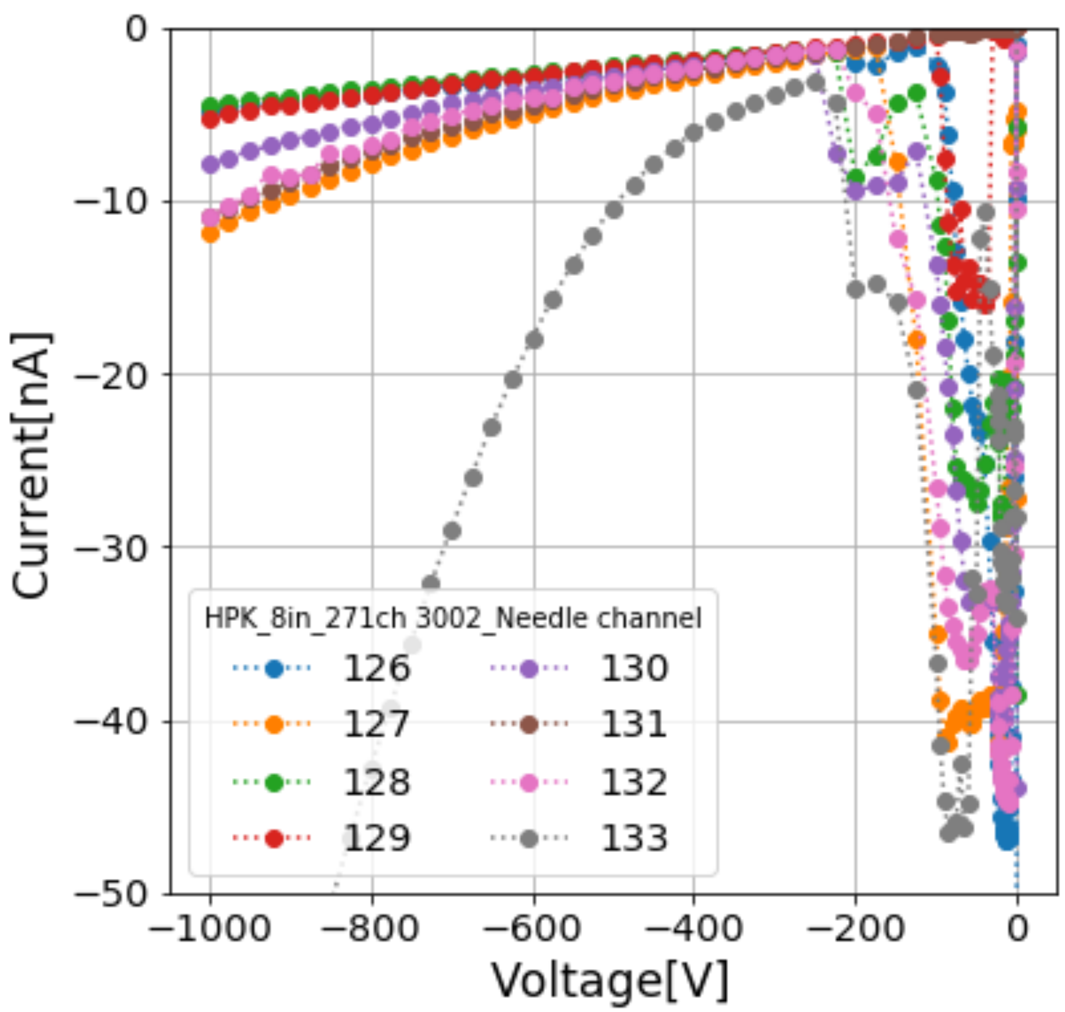
Measurement	Contact	Procedure	Pros	Cons
Needle		Bias cell under test + direct neighbours	Flexible	Time consuming, no voltage applied to most pads
Probe-card		Bias all pads and switch channel under test with dedicated card	All pads biased Mocks-up real operation	Dedicated probecard per sensor, parasitic capacitances, initial alignment (when manual)

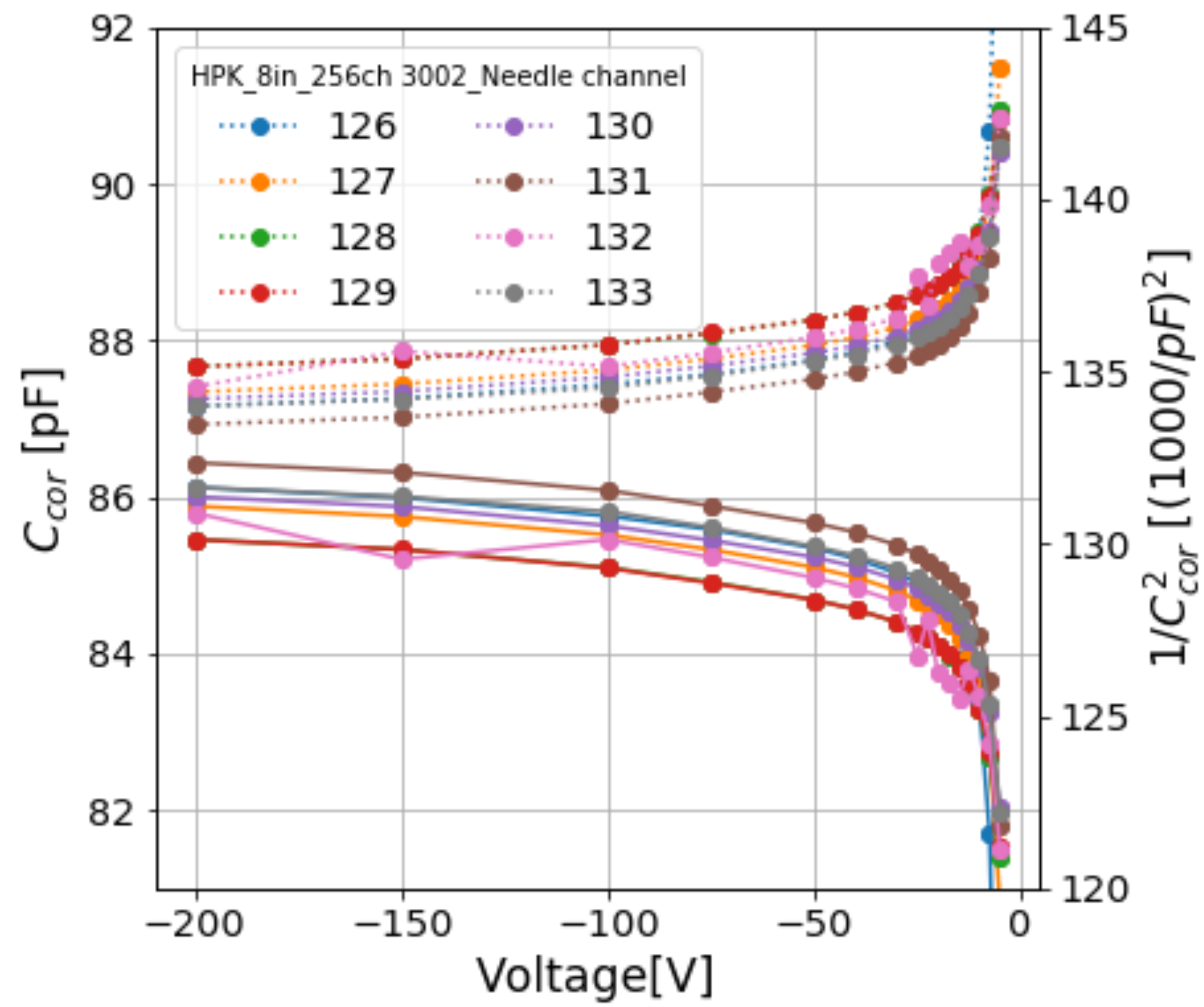
Example of detailed characterisation a sensor

- Characterisation of selected cells through needle measurements
  - open correction derived without bias on central cell (~50pF)
  - I-V curves show a peak and shoulder effect (also observed in Vienna)
  - C≈87 pF V_{dep}≈20 V and d≈115 µm

using point of max. curvature as initial estimate of V_{dep} and $d=\varepsilon_0\varepsilon_r A/C$ ignoring additional contributions to C



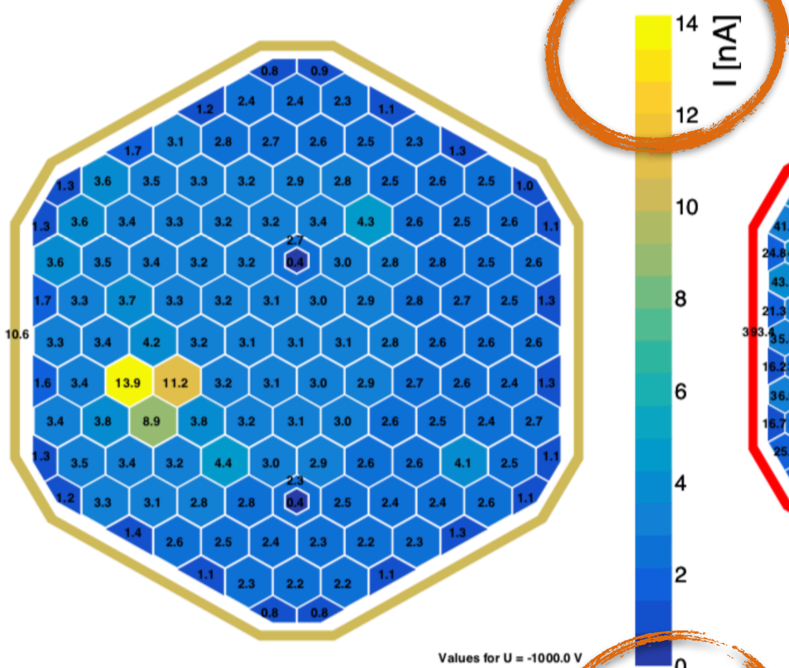


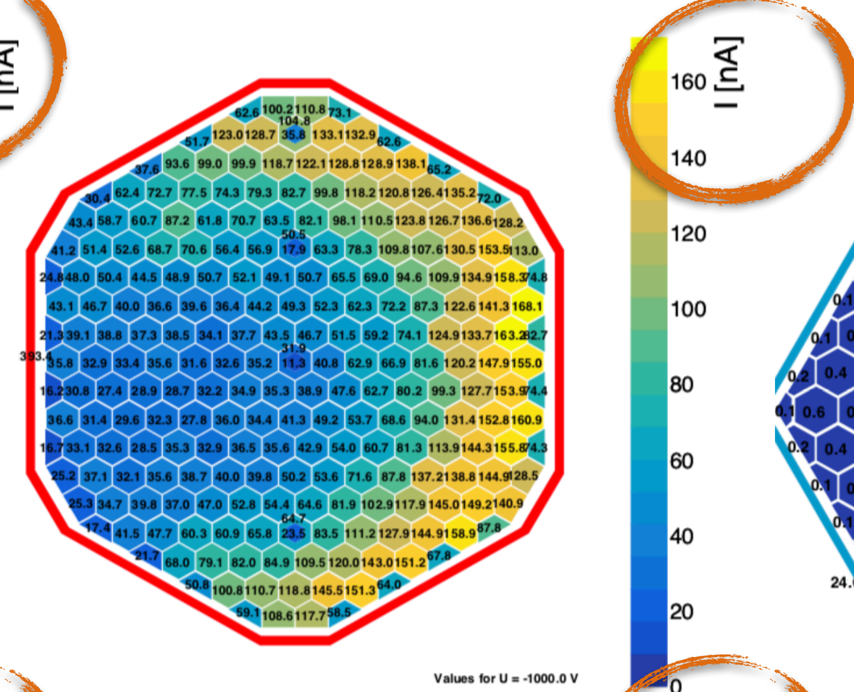


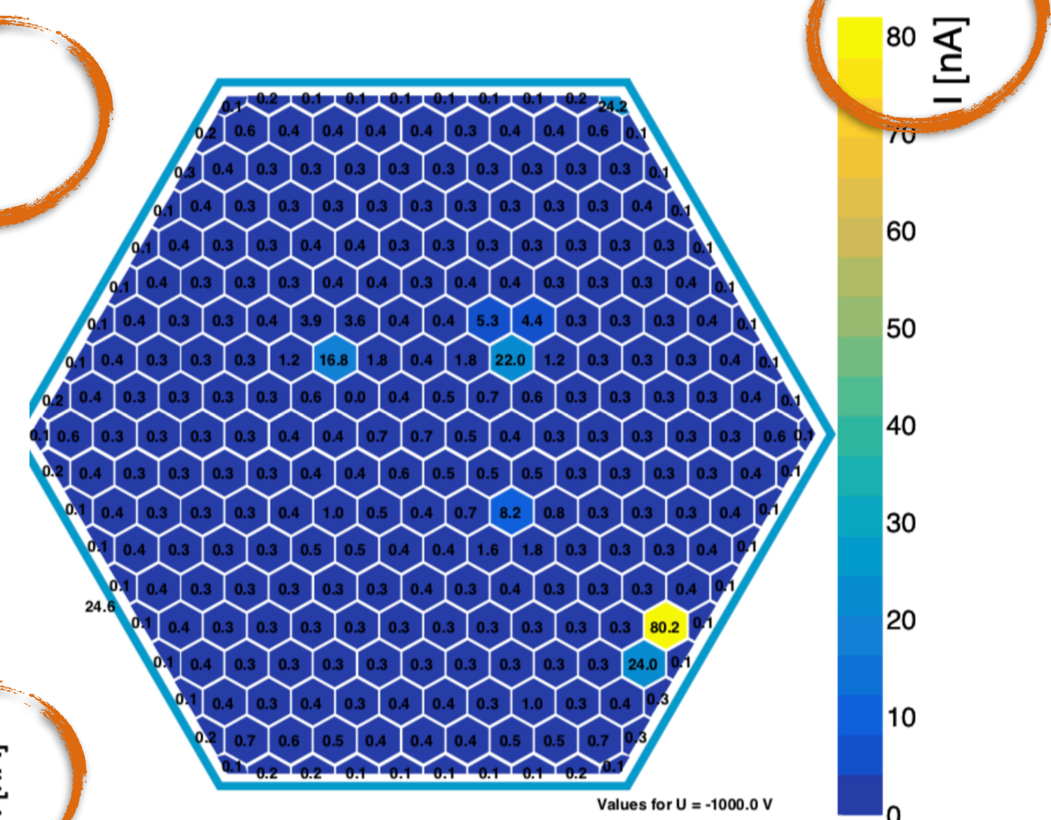
Leakage current examples @ 1kV

	6" 135ch 320µm float zone, standard diff.	6" 239ch 120µm float zone, deep diff.	8" 271ch 120µm epitaxial growth

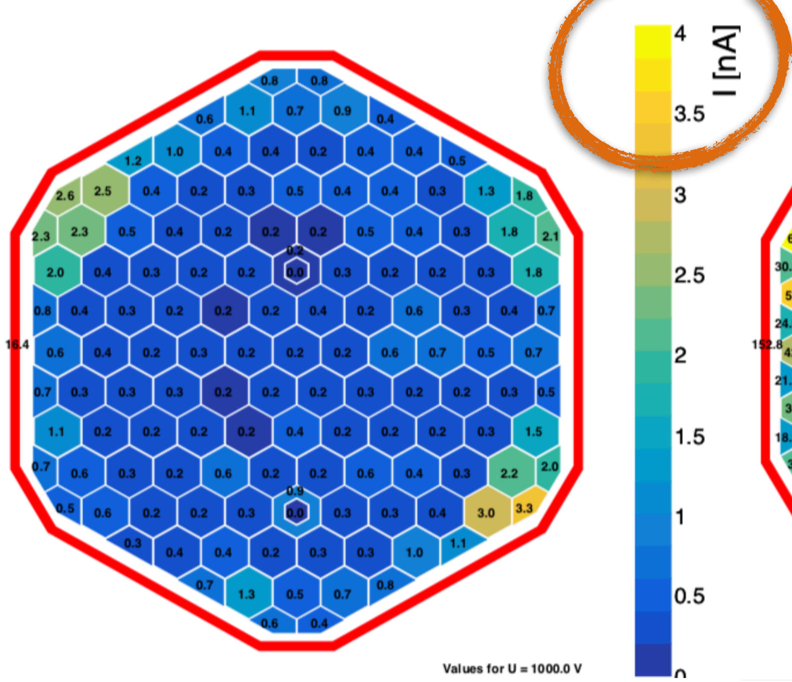
p-in-n

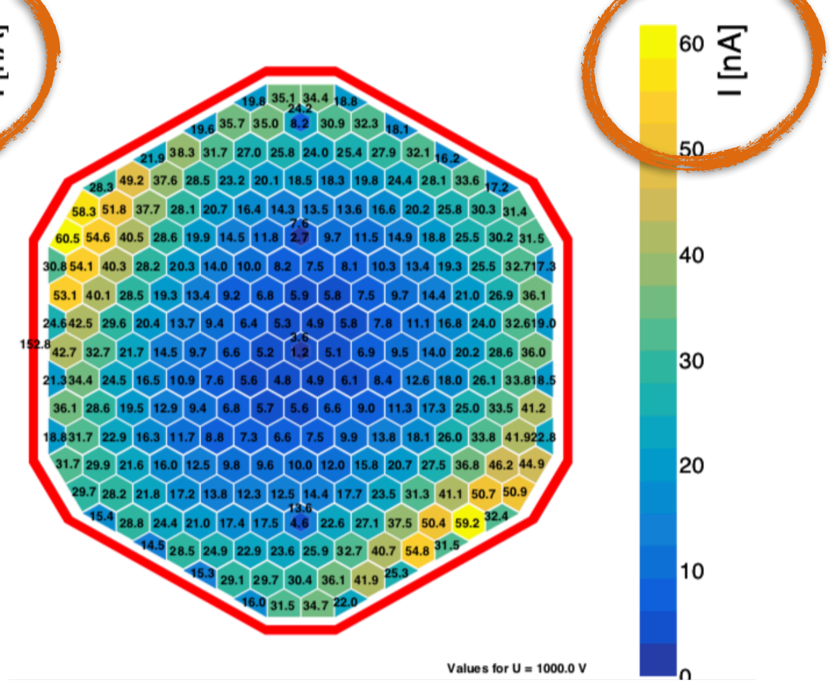






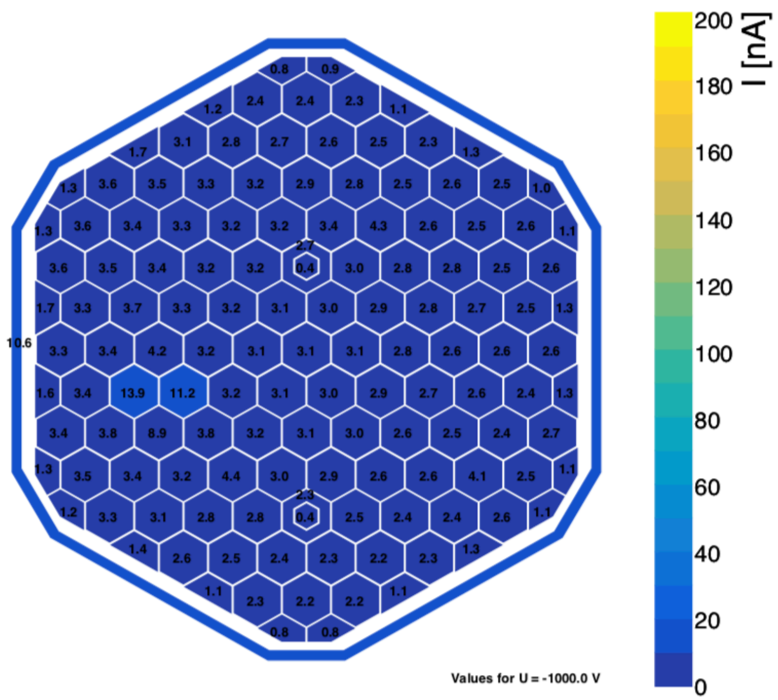
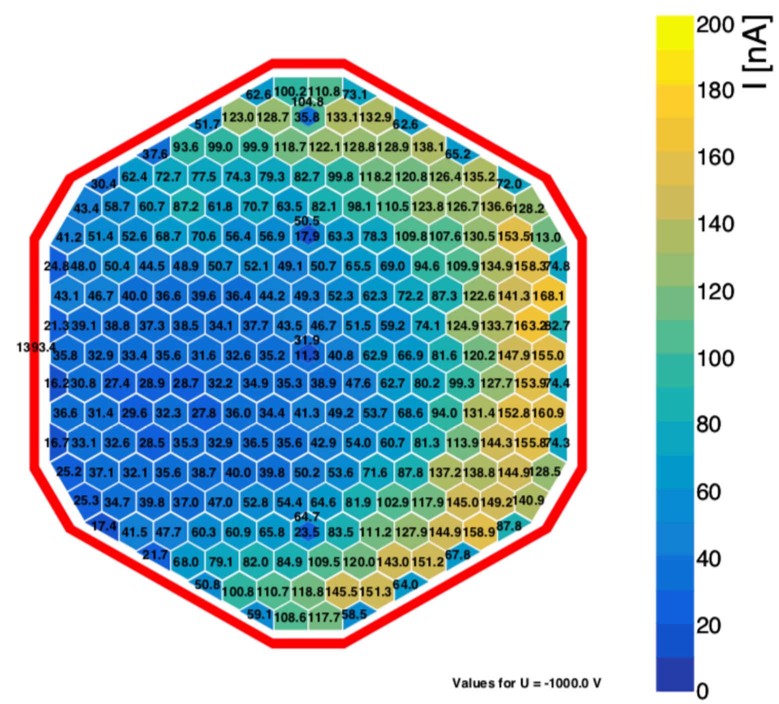
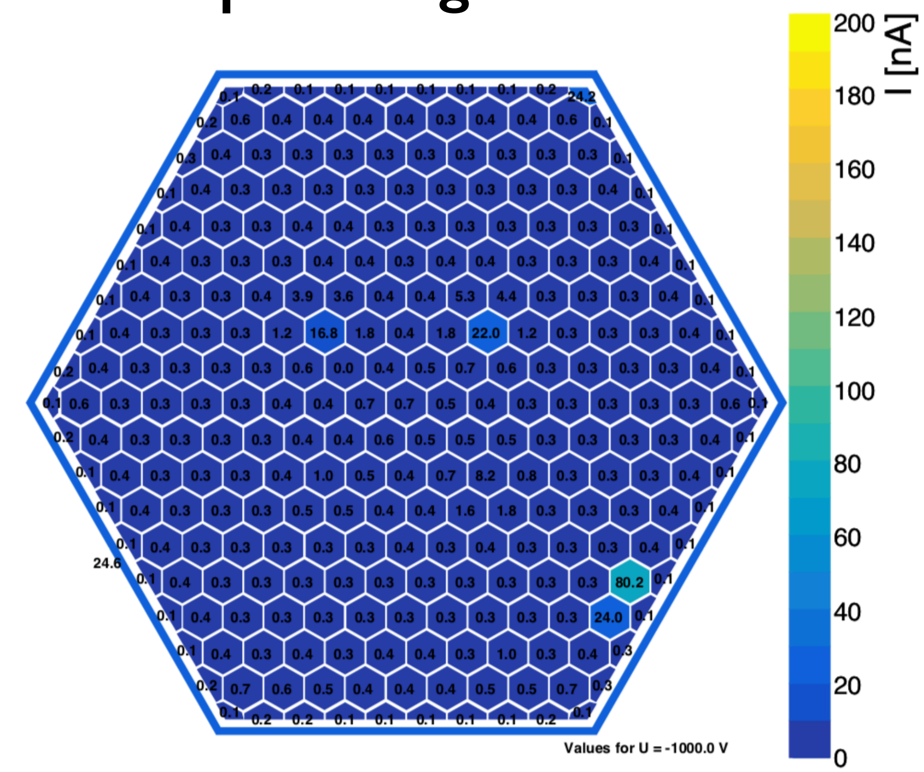
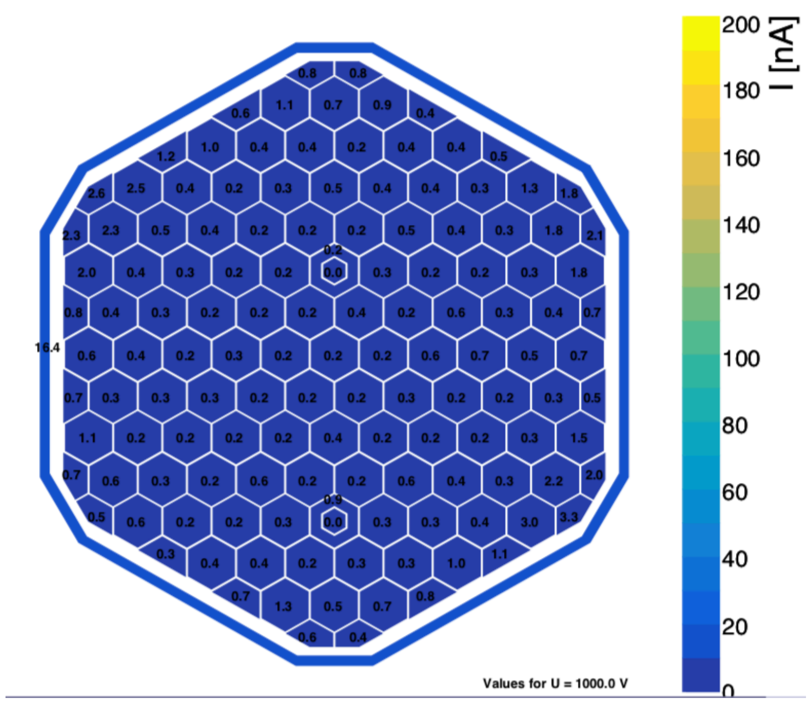
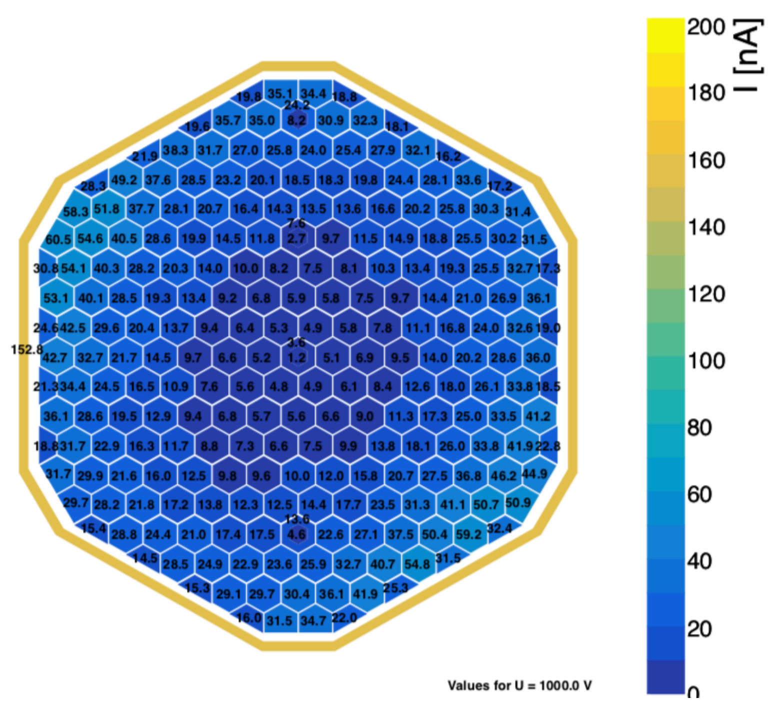
n-in-p





- Investigate dependence on growth, thickness, diffusion technique, n/p-type, p-stop type, position in the wafer, time, interpad distance, batch, irradiation …

Leakage current examples @ 1kV

	6” 135ch 320µm float zone, standard diff.	6” 239ch 120µm float zone, deep diff.	8” 271ch 120µm epitaxial growth
p-in-n			
n-in-p			

- Investigate dependence on growth, thickness, diffusion technique, n/p-type, p-stop type, position in the wafer, time, interpad distance, batch, irradiation …

Readout III

HGCROC: 78 ch (1.4mW/ch)

1.44 Gb/s (e-link to motherboard)

8 bit sum up 4 to 9 cell energies up to 16bx latency