Studies on $Z\gamma$ Scattering and Liquid Argon Electronic Calibration with ATLAS Detector

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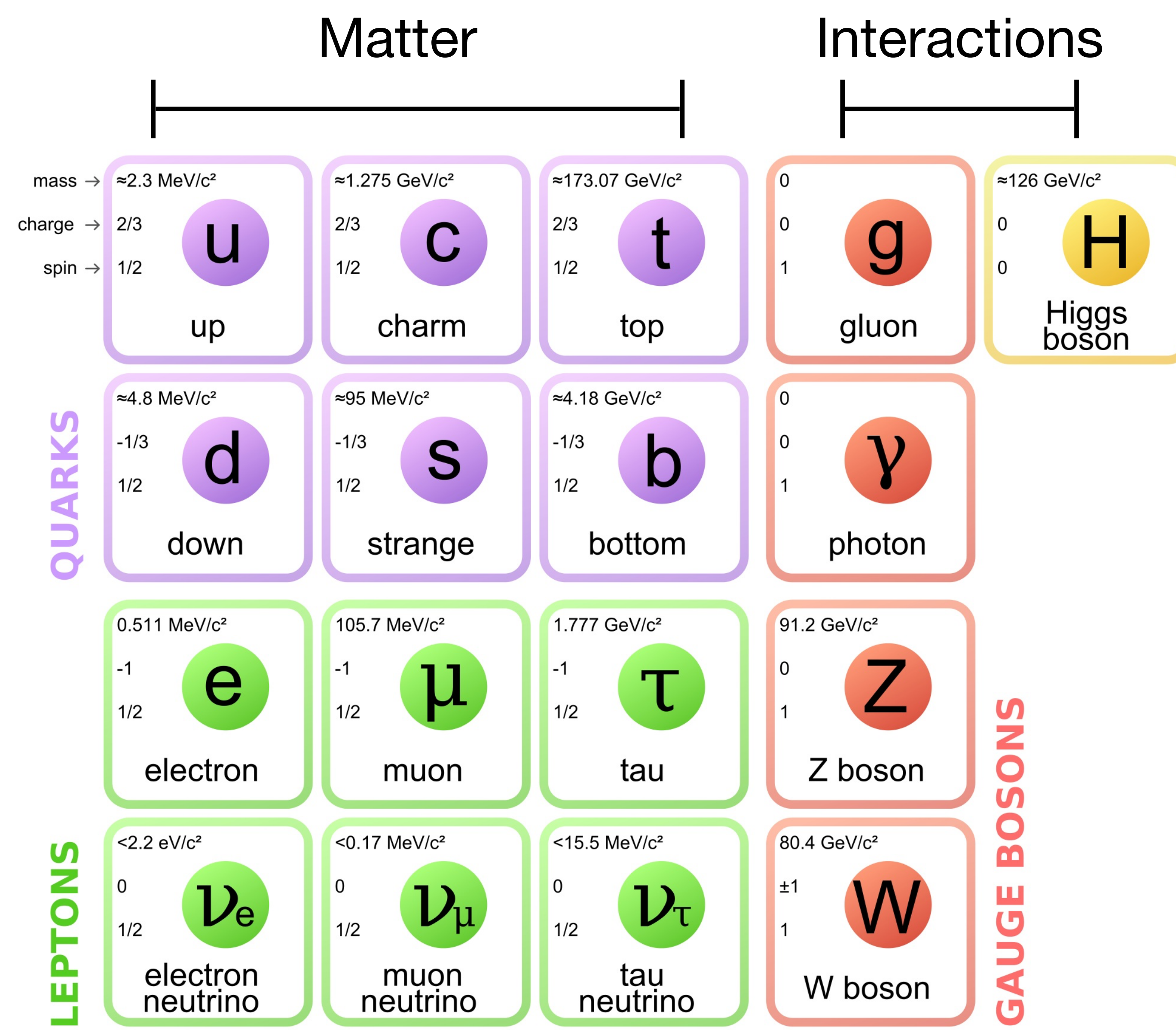
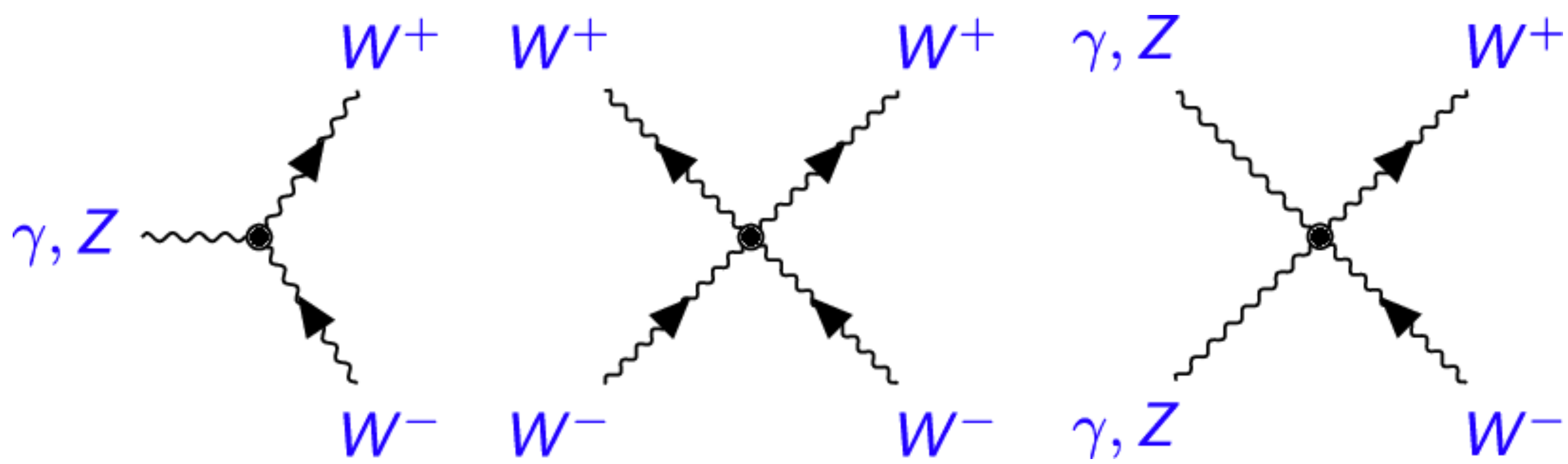
The Standard Model (SM)

- Well-tested theory of fundamental particles and their interactions
  - Complete with Higgs boson discovery in 2012
- However, it has its limitations:
  - Gravity
  - Dark matter and dark energy
  - Masses of neutrinos



New physics? → measure deviations from SM predictions

Vector Boson Scattering: Motivation



SM self-couplings of electroweak vector boson ($V = W, Z, \gamma$)

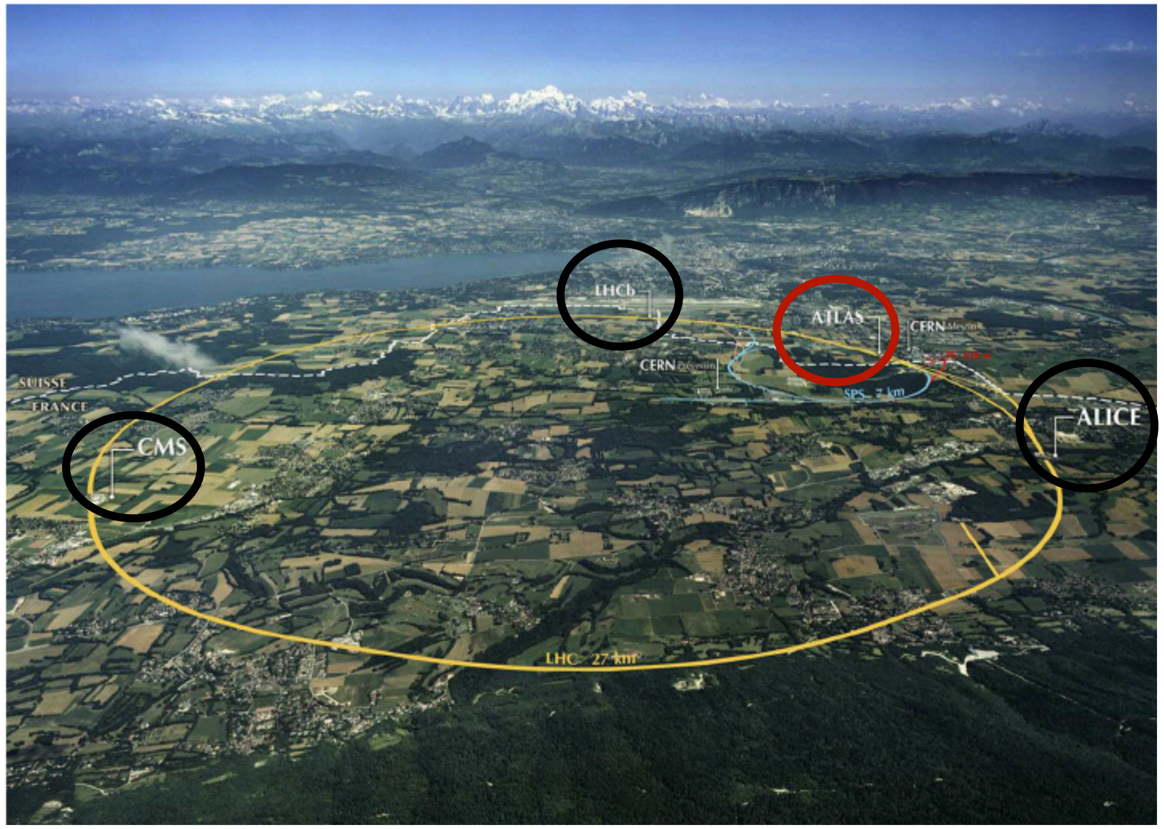
- Deviation from self-coupling predicted by SM
- Existence of neutral quartic self-coupling forbidden by SM

→ New physics!

Probe self-couplings → study Vector Boson Scattering ($VV \to VV$)

Large Hadron Collider (LHC)

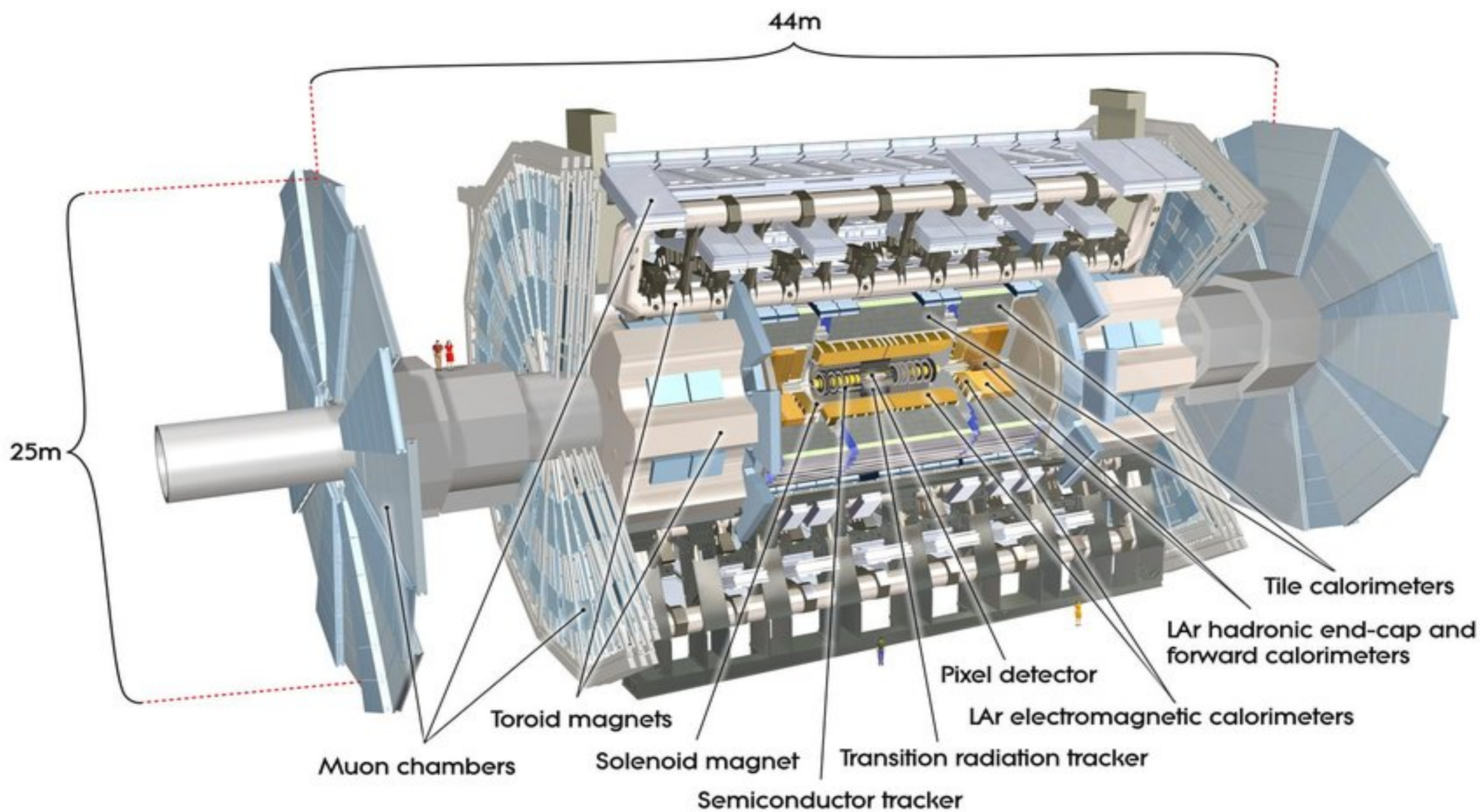
- 27 km ring, 100 m below ground
- Proton-proton* collider
    - 40,000 collisions per second
- 4 detectors: **ATLAS**, CMS, LHCb, ALICE



*also collides heavy ions

The ATLAS Detector

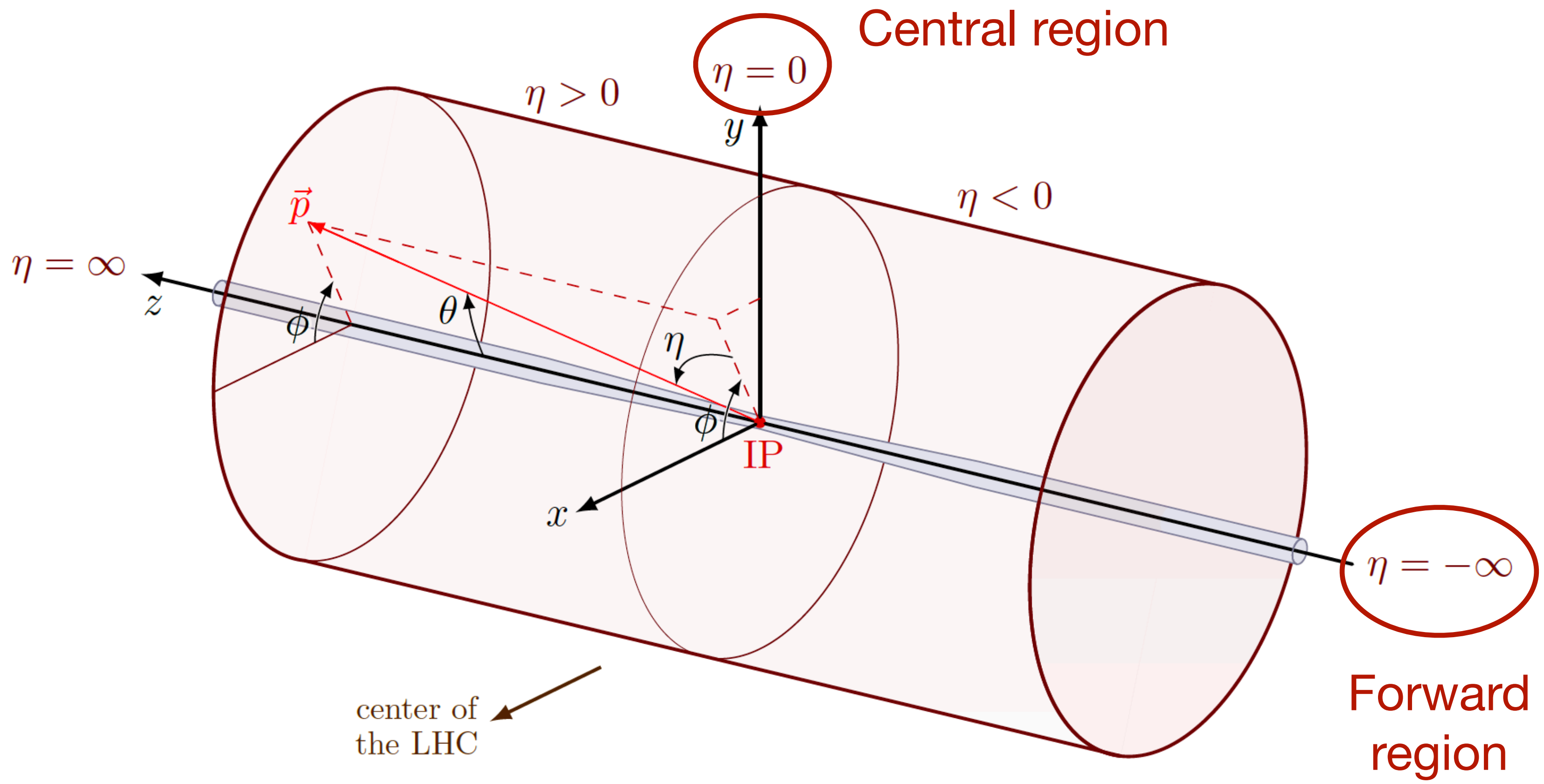
- **Inner Detector**: trajectories of charged particles
- **Calorimeters** (EM and hadronic): energy of electrons, photons and hadrons
- **Muon Spectrometer**: momentum of muons



ATLAS Coordinate System

Spherical coordinates:

- r: distance from z-axis
- θ: angle from z-axis
- ϕ: rotation around z-axis



Typical variables:

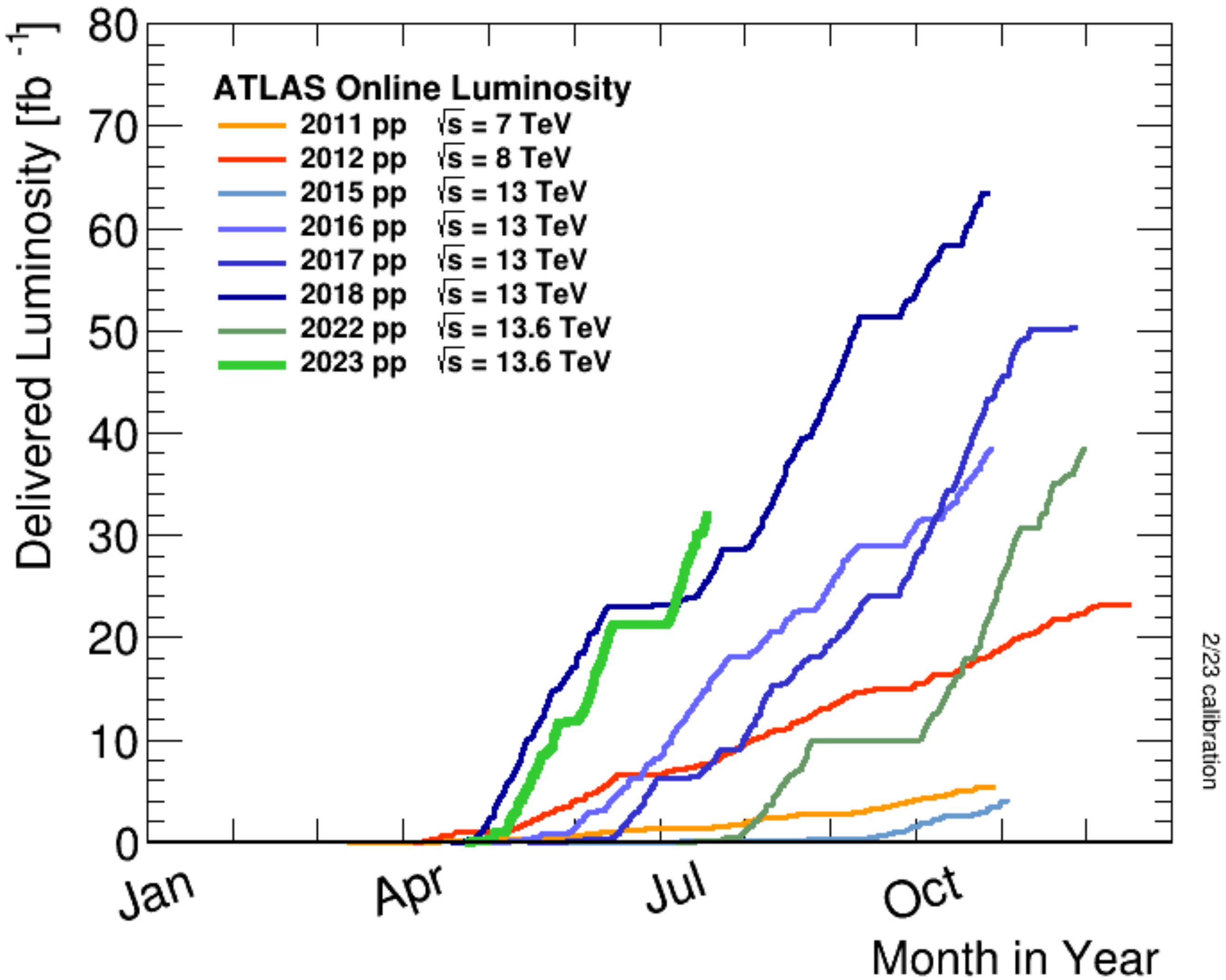
- Transverse momentum $p_T = \sqrt{p_x^2 + p_y^2}$
- Rapidity $y = \frac{1}{2} ln \frac{E + p_z}{E - p_z}$, or pseudorapidity $\eta = -\, ln(tan\frac{\theta}{2})$

Operation Parameters

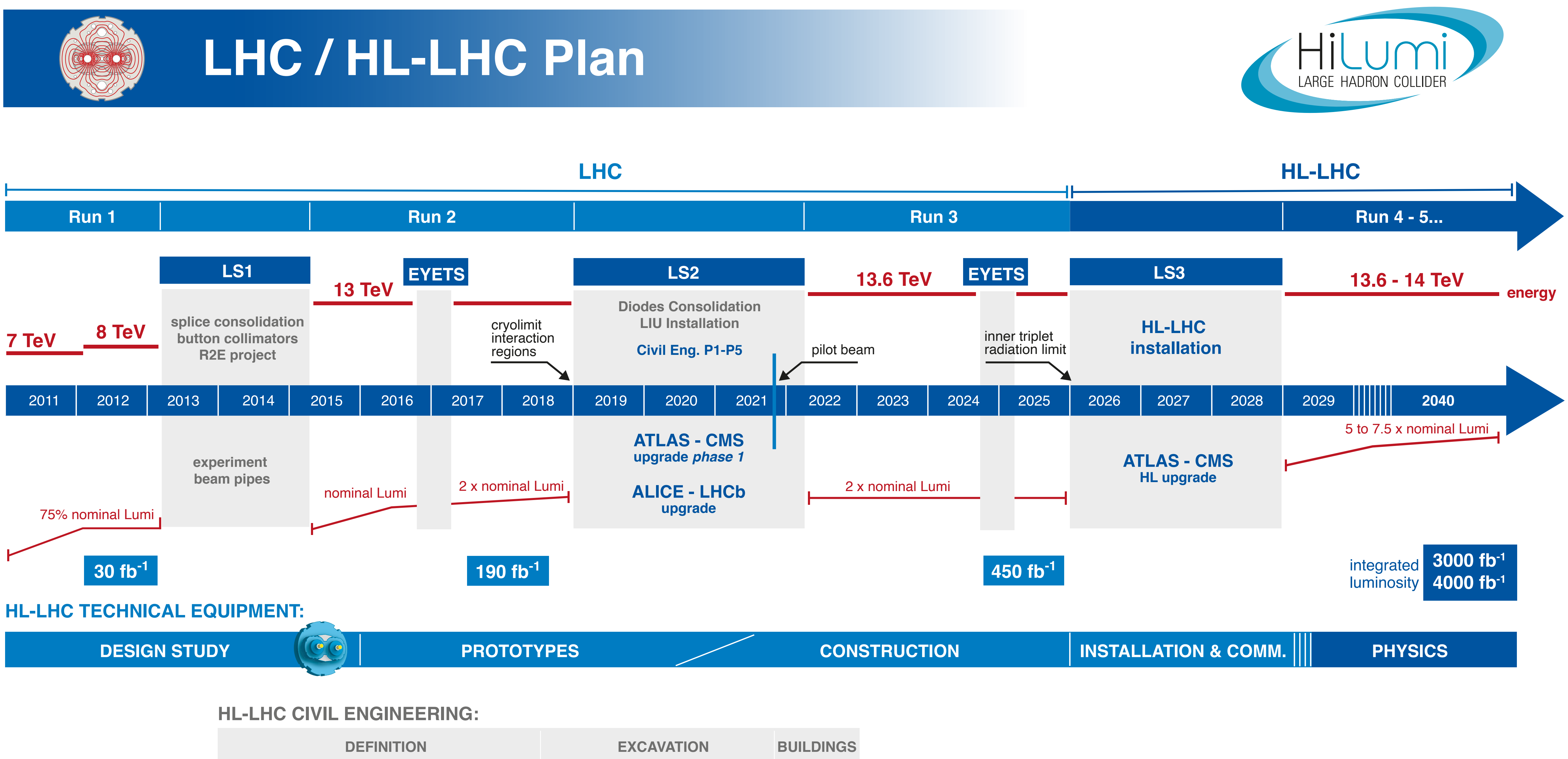
$$N_{events} = L \times \sigma(\sqrt{s})$$

- **Integrated luminosity** L: number of collisions per unit cross-section area

- **Centre-of-mass energy** $\sqrt{s}$: total energy for collisions



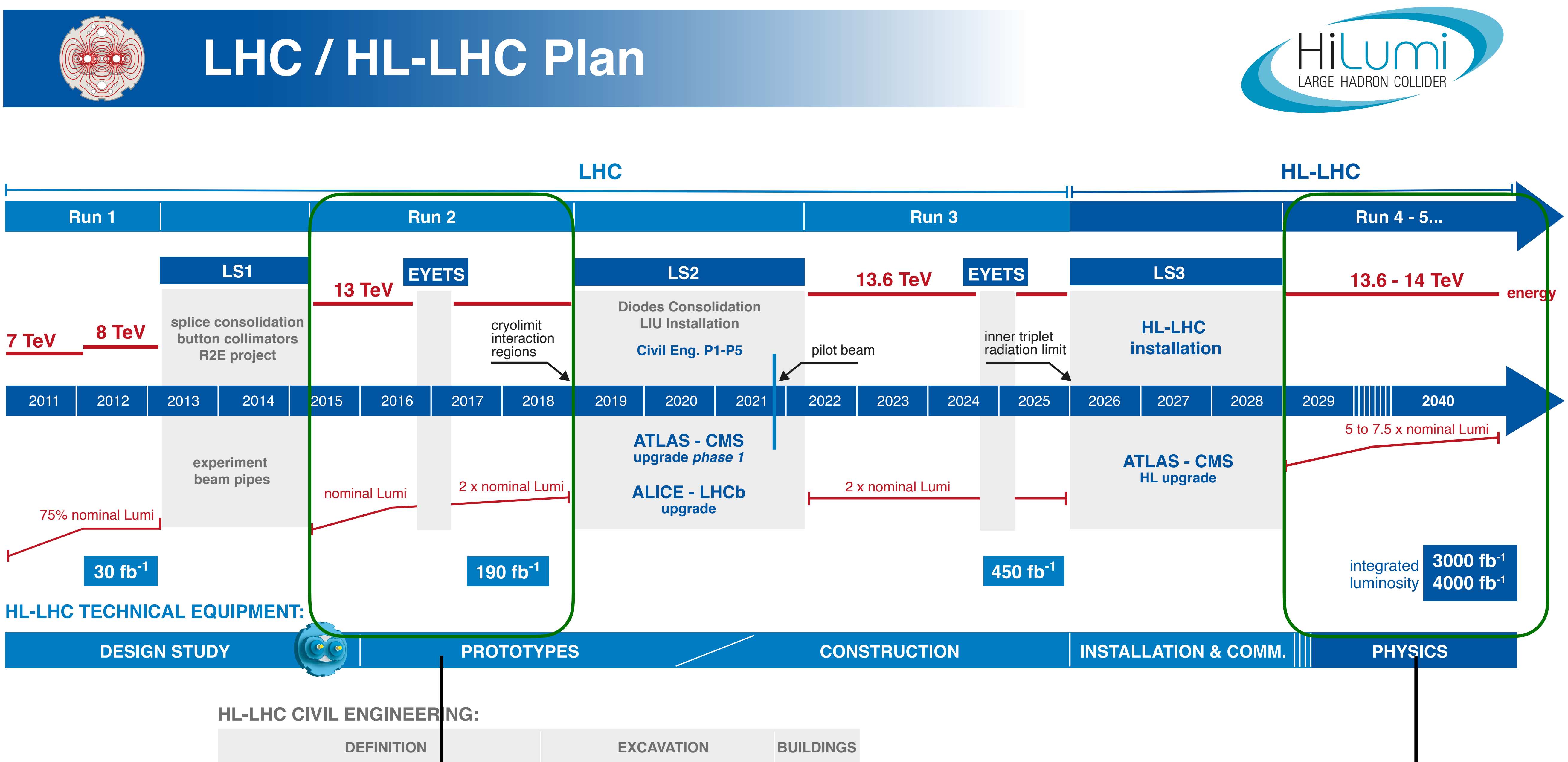
Operation Timeline



Higher number of collisions in HL-LHC → high expected radiation doses

ATLAS detector upgrade needed!

PhD Project Timeline



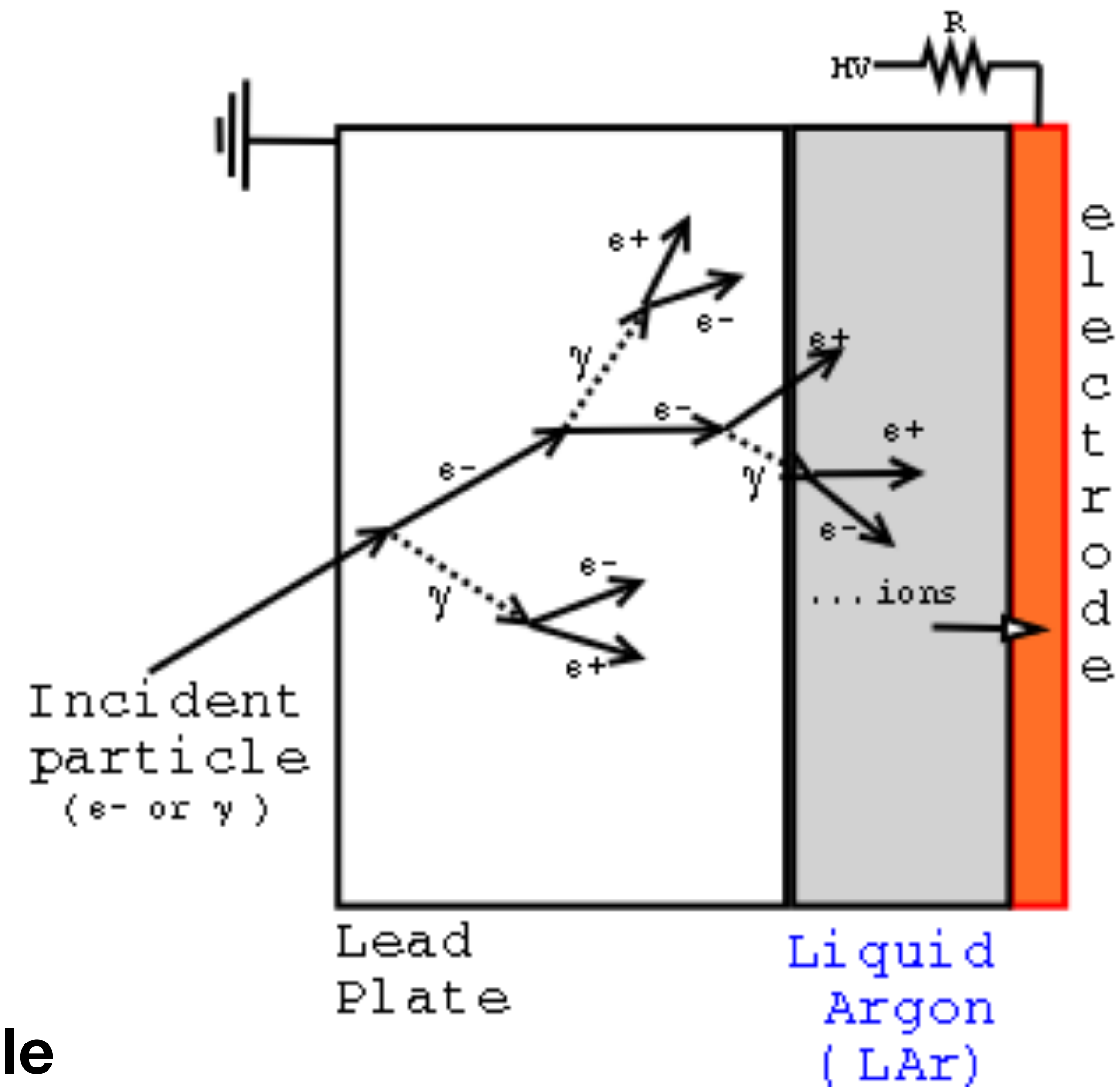
Study of Vector Boson Scattering as Probe of New Physics

ATLAS Calorimeter Upgrade

Upgrade of Liquid Argon Calorimeter Electronic Calibration Board (HL-LHC)

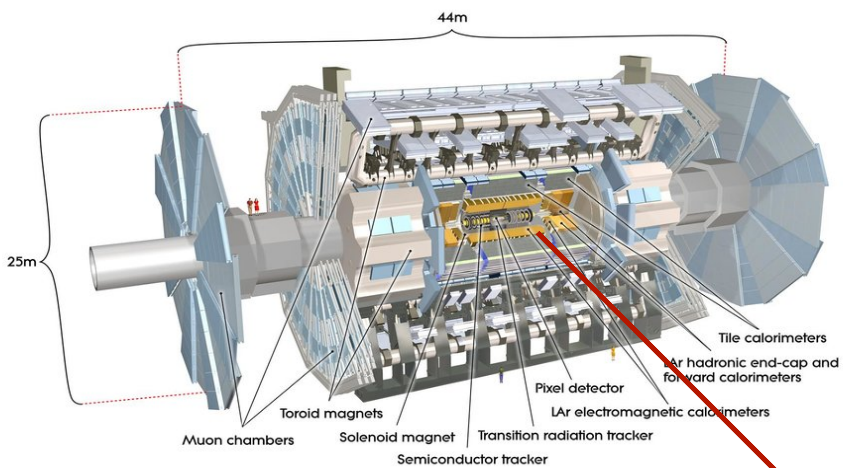
Liquid Argon Calorimeter: Principle

- **Sampling calorimeter**
  - Absorber: Lead, copper or tungsten
    - Particle shower
  - Active Medium: Liquid argon (LAr)
    - Drifting ionisation electrons induce signal on electrode
- **Peak of signal ∝ energy of incident particle**

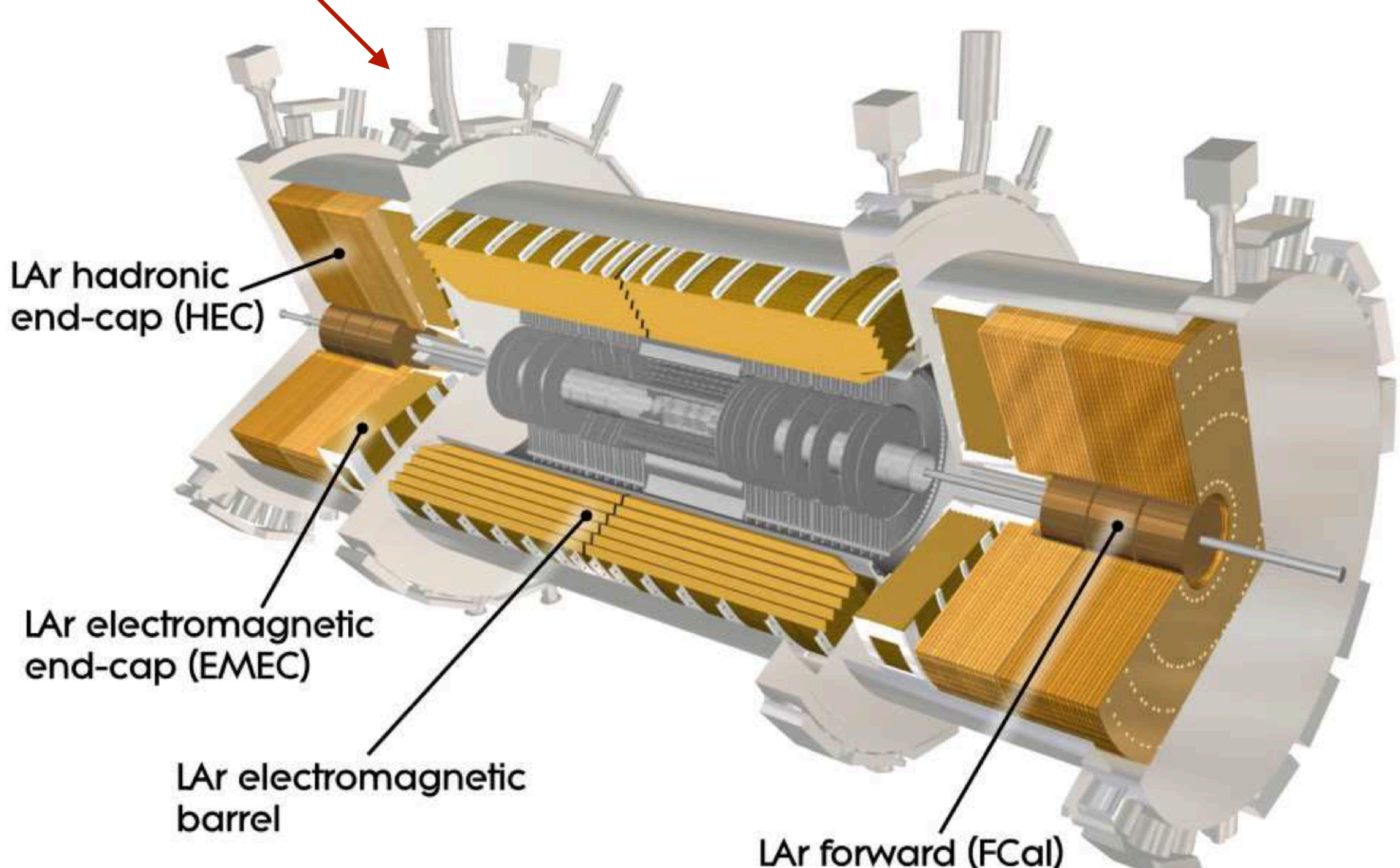


Detector Cell

ATLAS LAr Calorimeter



- EM and hadronic calorimeters
- ~180,000 detector cells
- Records energies from ~50 MeV* to 3 TeV



*energy deposited by Minimum Ionising Particle (MIP)

LAr Electronic Calibration: Motivation

Resolution $$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

dominant at high energies

- a: statistical fluctuations
- b: electronic noise
- c: response non-uniformities

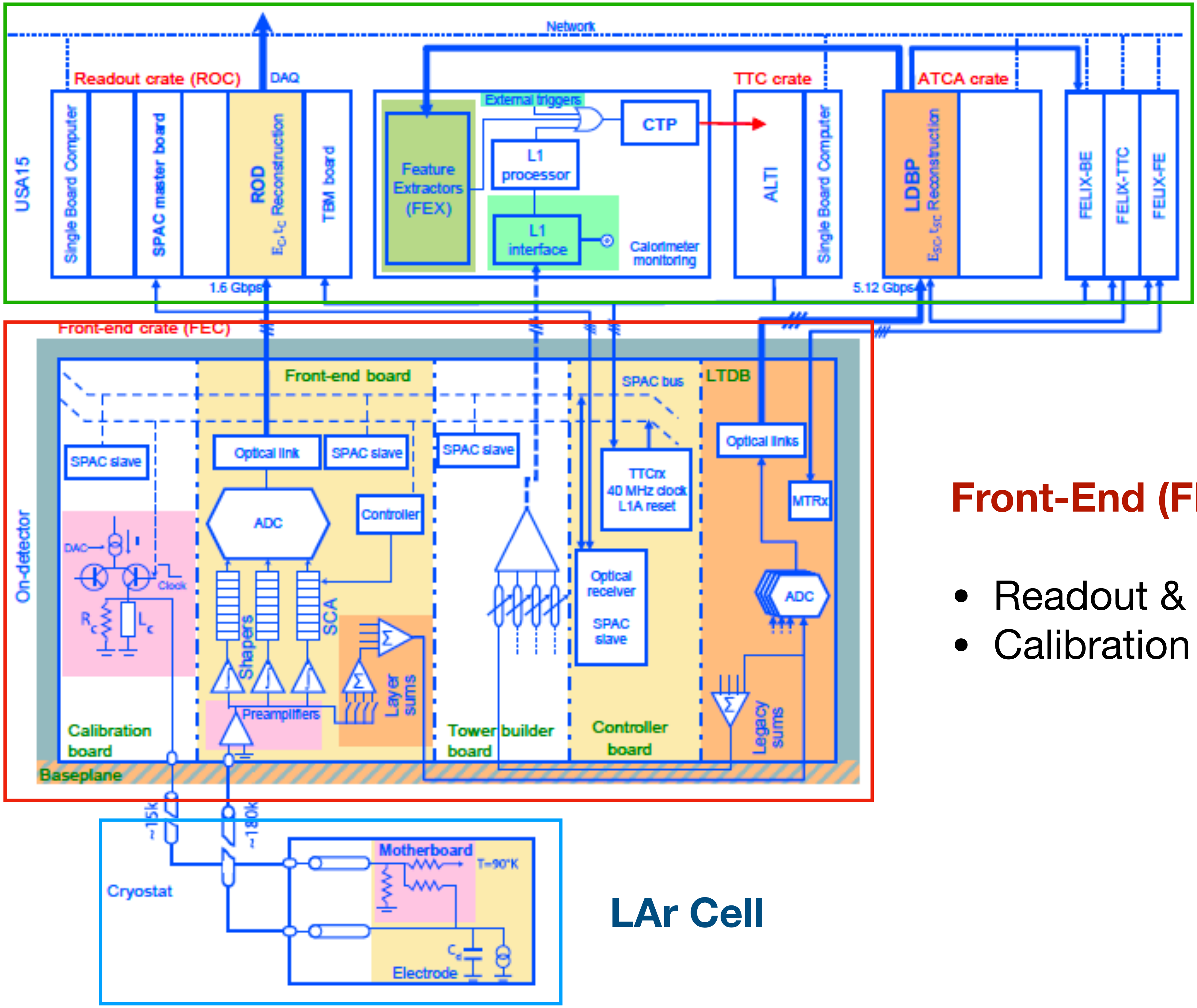
Good detector resolution → minimise c → **electronic calibration**

- Equalise cell-to-cell output signals to obtain a uniform detector response

ATLAS LAr EM calorimeter: c = 0.7%

→ **uniformity among calibration channels < 0.25%**

LAr Readout Electronics



Back-End (BE):

Reconstruction of Energy and Timing

Front-End (FE):

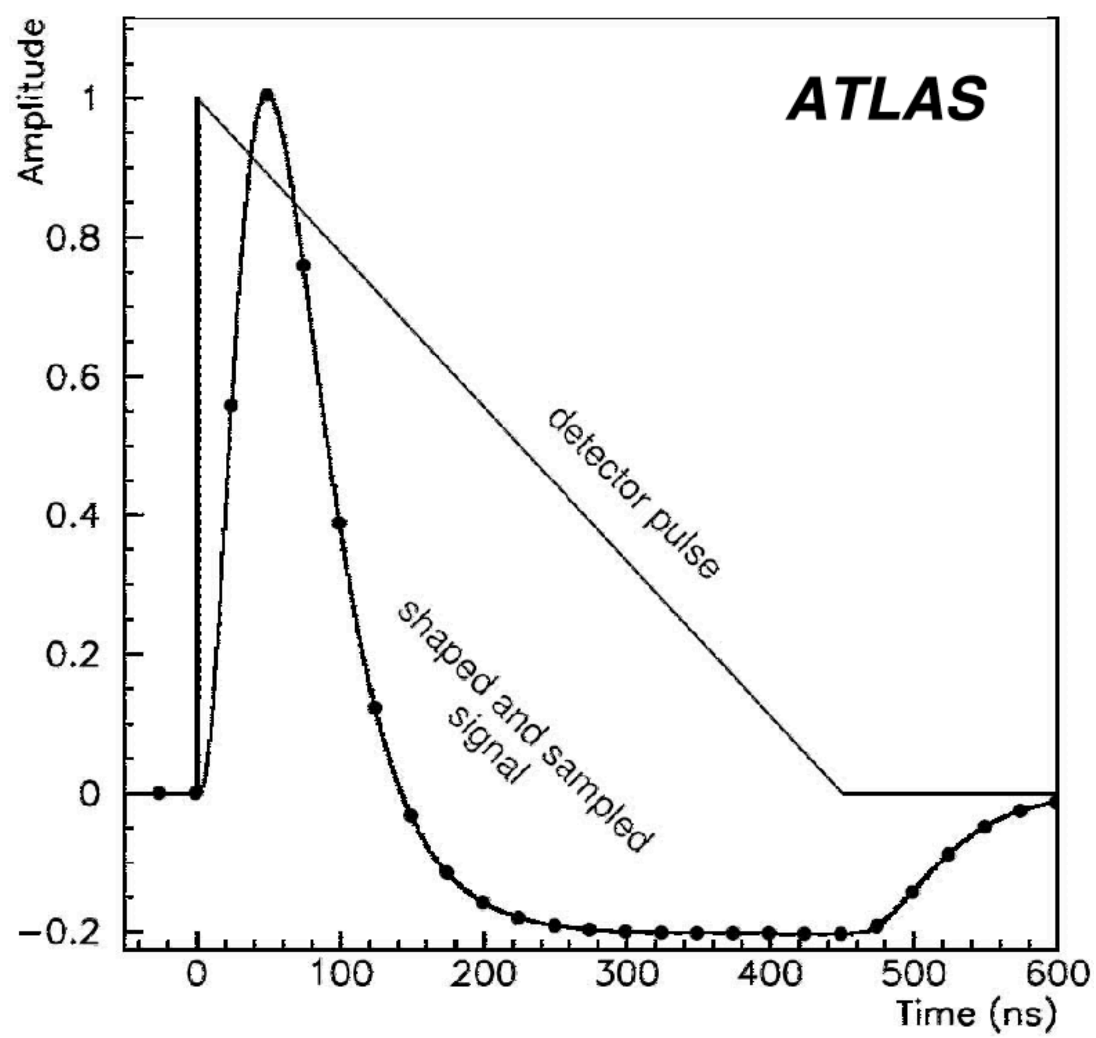
- Readout & Digitisation
- Calibration

LAr Cell

*Run-2 schematic

LAr Signal Readout

LAr Cell → **Triangular** Signal → **FE**: Readout and digitisation → Shaped & Sampled Signal → **BE**



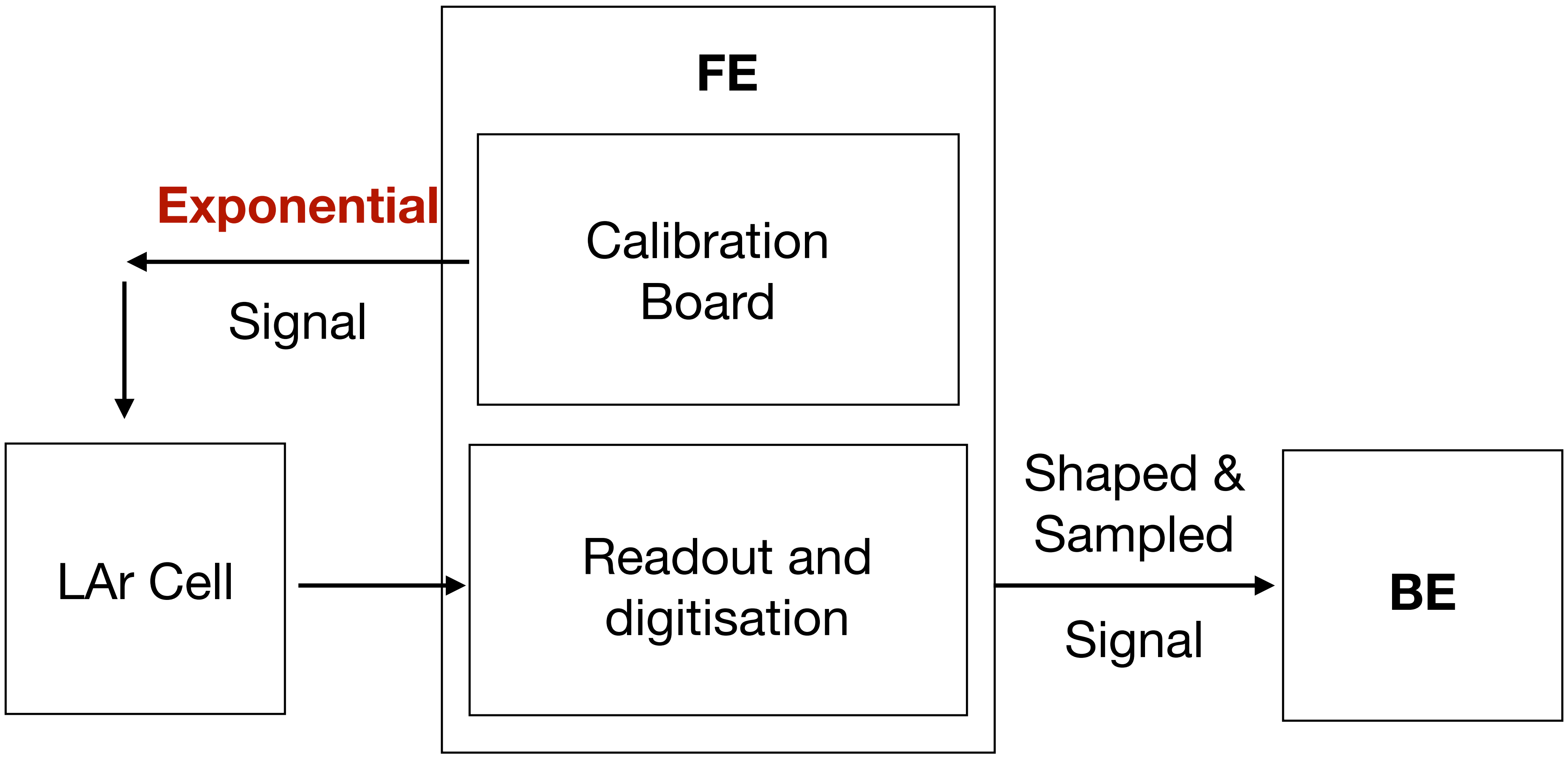
Triangular Signal: characterised by typical drift time in LAr gap

Shaped and Sampled Signal: for optimal signal-to-noise ratio, sampled at 40 MHz

Reminder
FE: Front-end, BE: Back-end

LAr Electronic Calibration

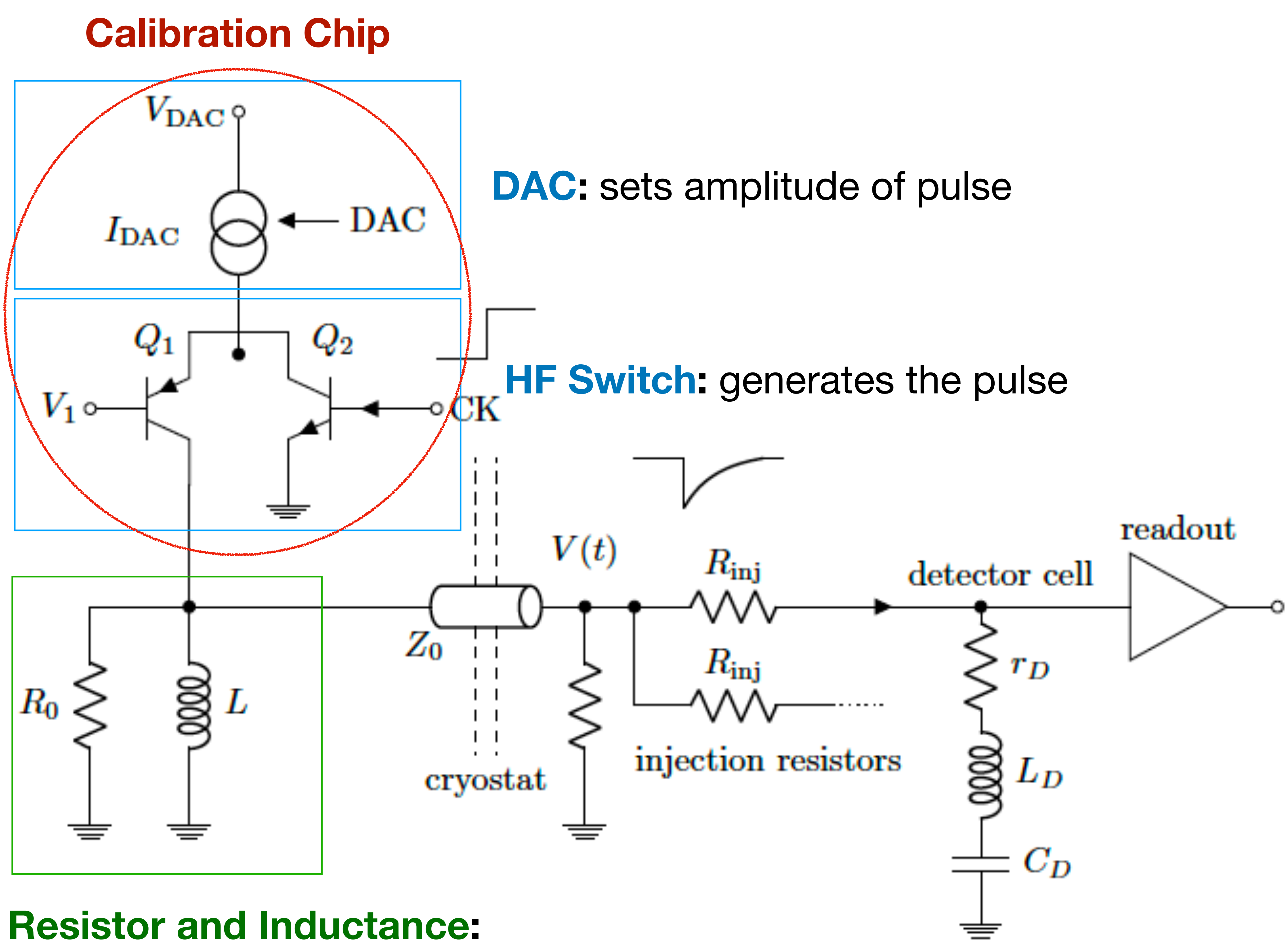
Inject calibration pulses, that mimic physics pulse, of known amplitude on detector cell to **probe electronic response**



Exponential Signal: due to difficulty in reproducing triangular physics pulse

Reminder
FE: Front-end, BE: Back-end

LAr Electronic Calibration Schematic



DAC: sets amplitude of pulse

HF Switch: generates the pulse

Resistor and Inductance:
sets shape of pulse

LAr Energy Reconstruction

Back-End:

conversion factors

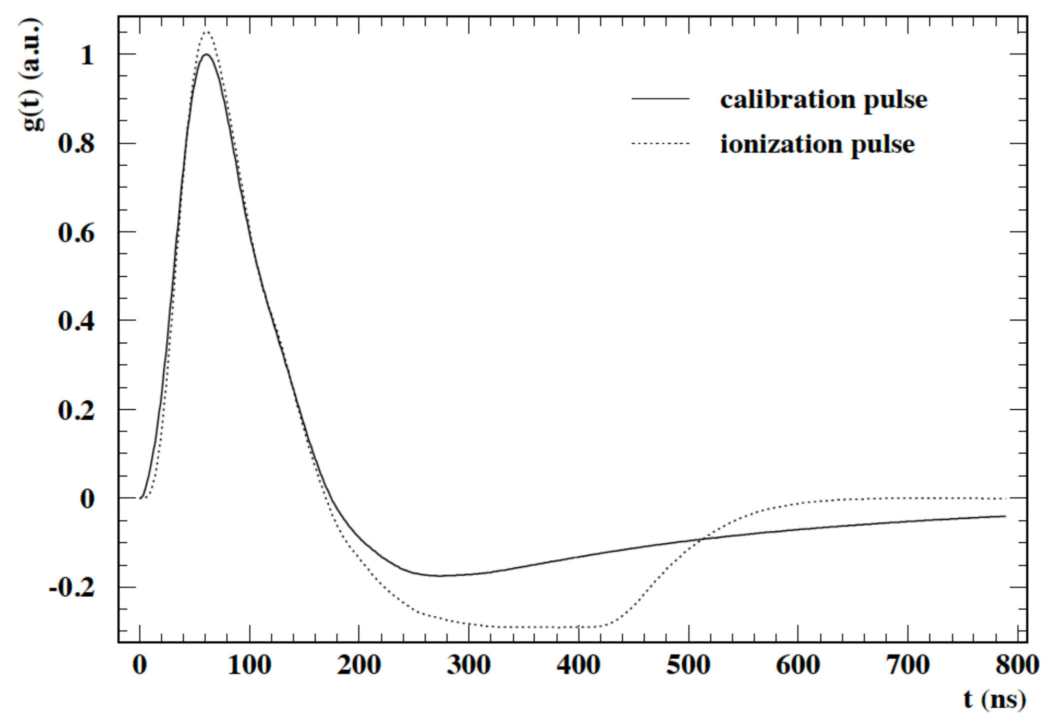
determined via calibration runs

$$E^{cell}_{MeV} = F_{\mu A \rightarrow MeV} \times F_{DAC \rightarrow \mu A} \times \boxed{\frac{M_{cali}}{M_{phys}} \times G \times A}$$

- M_{cali}/M_{phys}: correction factor for difference in shape between calibration and physics pulses

- G [DAC/ADC] : electronic cell gain

- A [ADC]: pulse amplitude, corrected for baseline level noise



LAr Electronic Calibration Upgrade: Motivation

- HL-LHC: 5-7.5 × nominal LHC luminosity
- Physical detectors do not change → electronic calibration boards need to be replaced:
    - Increased radiation exposure
    - Incompatible with communication and power upgrades
    - Technological advancements

Calibration Chip Upgrade

Reminder
DAC sets amplitude of pulse
HF switch generates pulse

Key Specifications

- Dynamic range of 16 bits
  → least significant bit: 50 MeV and maximum energy: 3 TeV

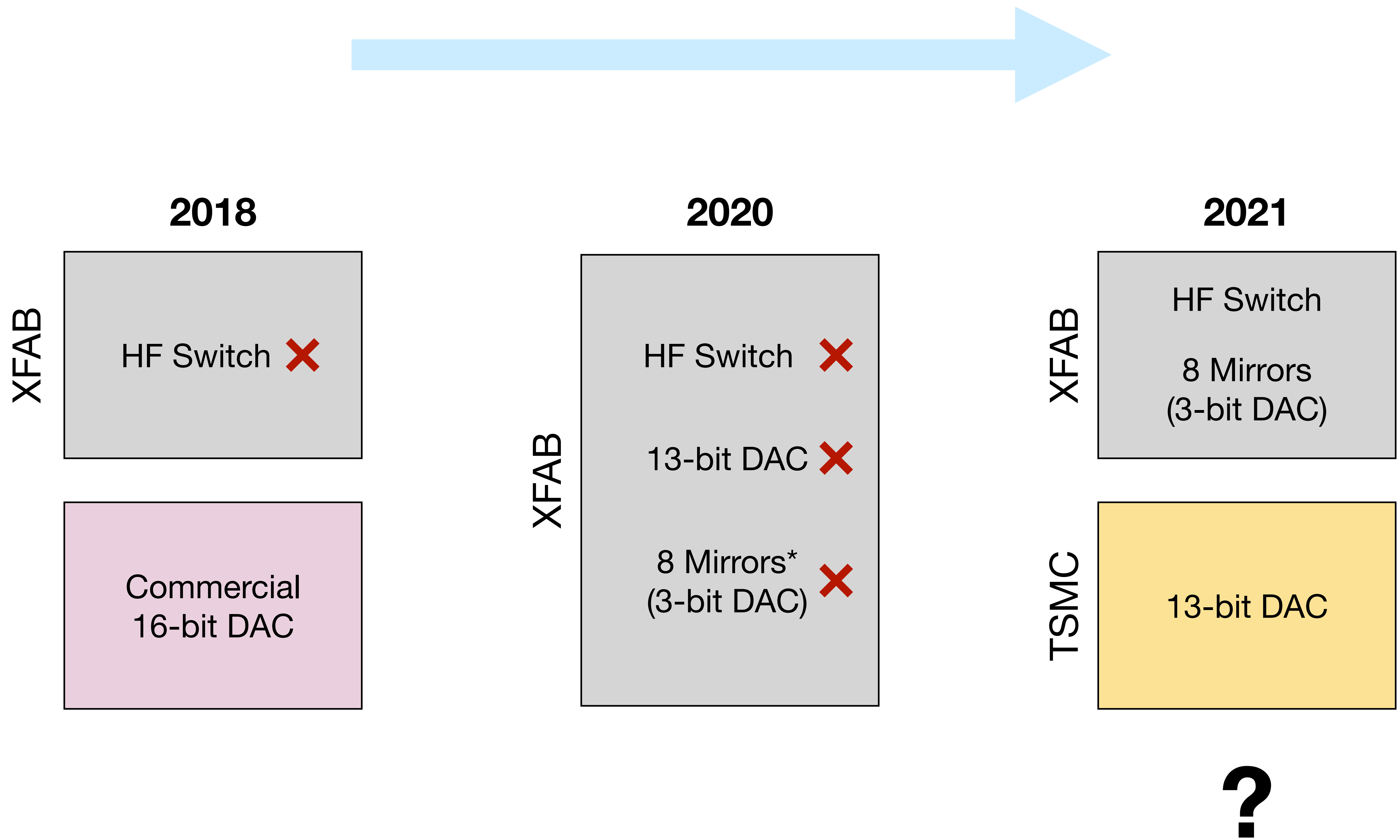
- Each chip has 1 DAC + 4 HF switches → efficient routing on board

- Radiation tolerant for HL-LHC

	Cumulative long-term degradation	Atomic displacements	Changes due to single, energetic particle
Position	TID [Gy]	NIEL [n_{eq}/cm^2]	SEE [h/cm^2]
FEC (barrel)	1400 (1.5)	4.1×10^{13} (2)	1.0×10^{13} (3)
FEC (endcap)	210 (1.5)	6.0×10^{12} (2)	1.2×10^{12} (3)

- Chip integral non-linearity (INL) < 0.1%
  → to interpolate calibration DAC values

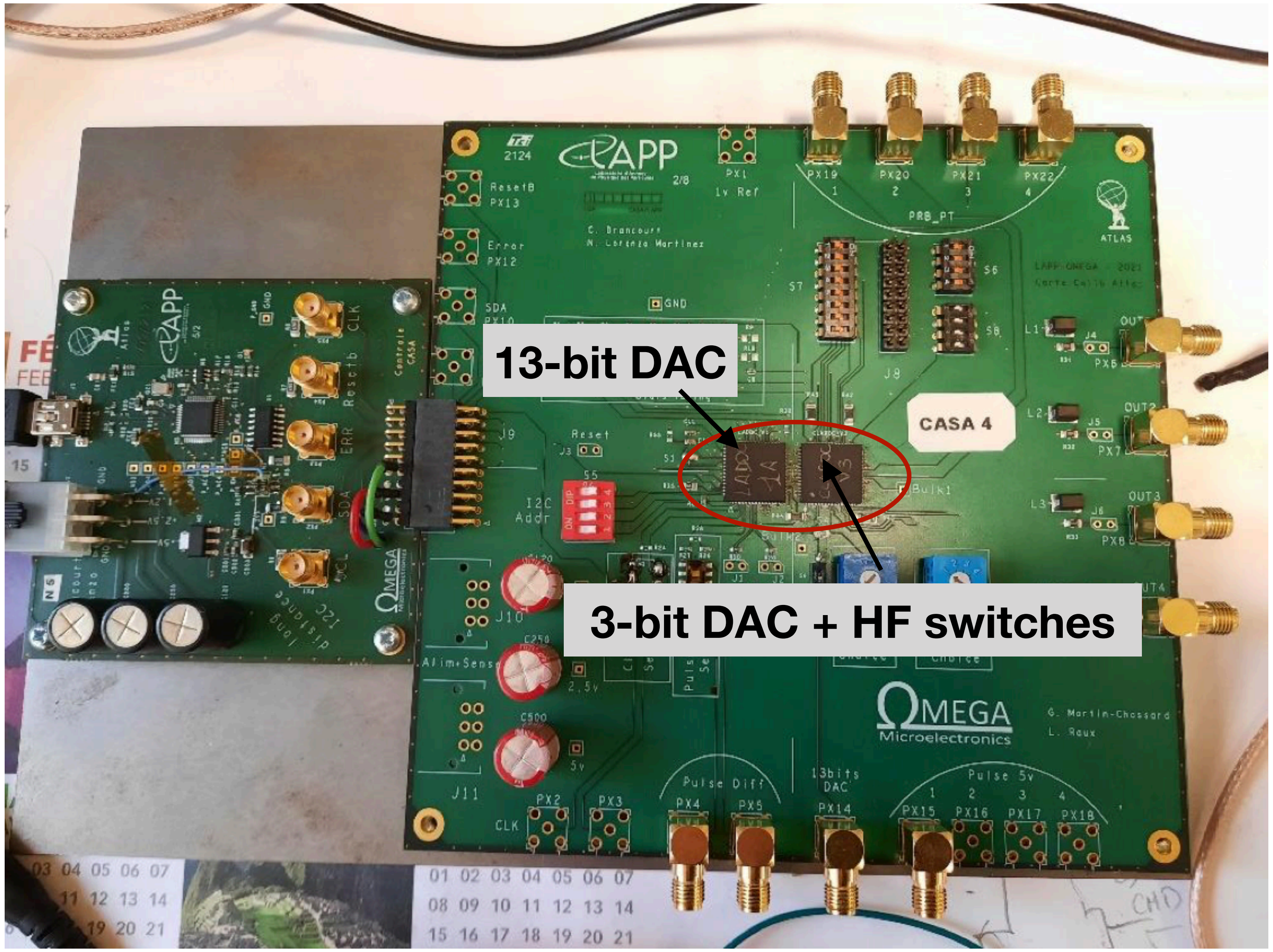
Development of Prototypes



*circuit block that copies current

Calibration Chip Prototype

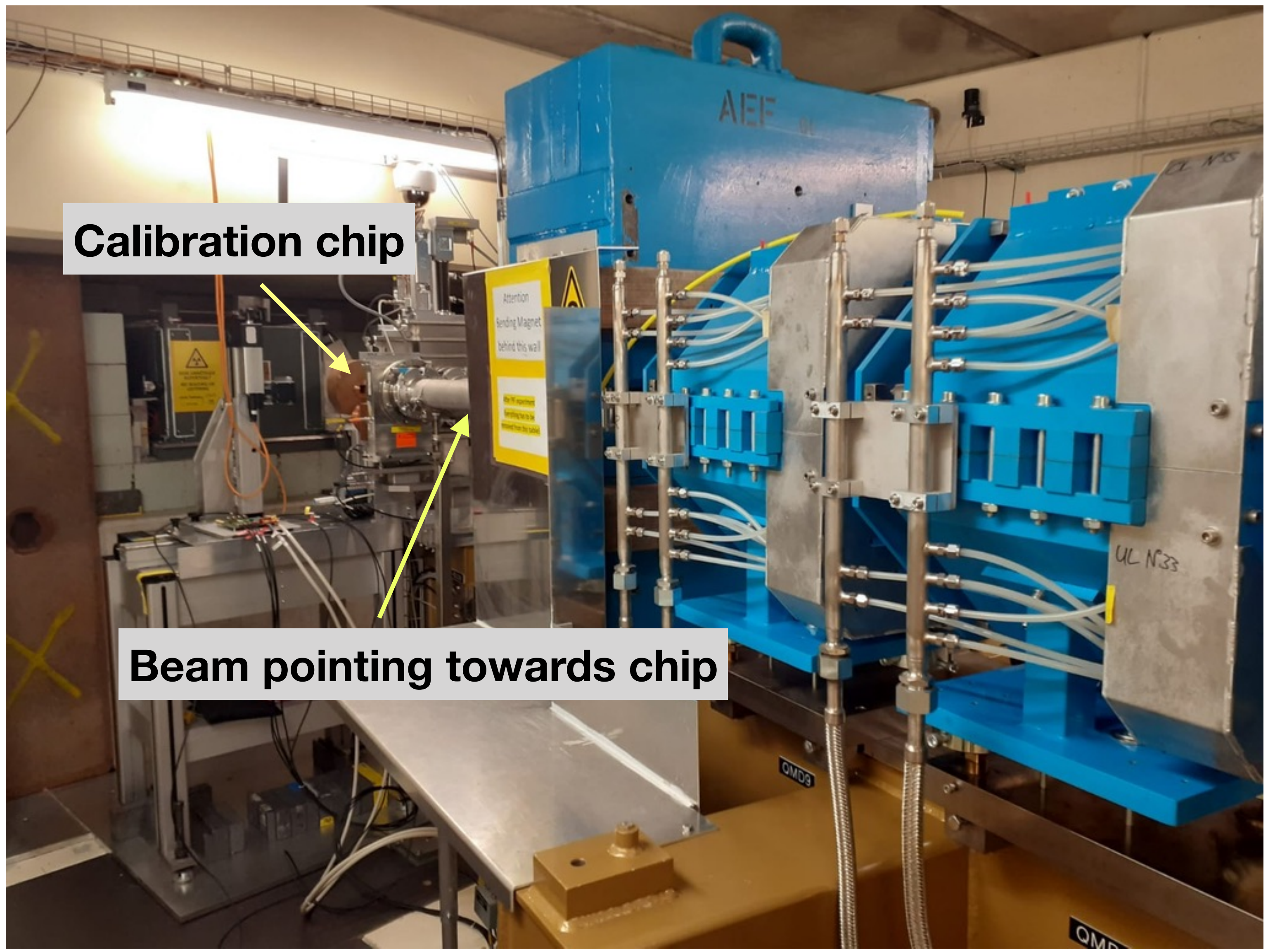
Specification: 16-bit dynamic range + 4 HF switches



Calibration Chip Test Board

Irradiation Test on Calibration Chip

Specification: Total Ionising Dose- 1.4 kGy
→ irradiated up to 50 kGy*



Proton Irradiation at Paul Scherrer Institut, Switzerland

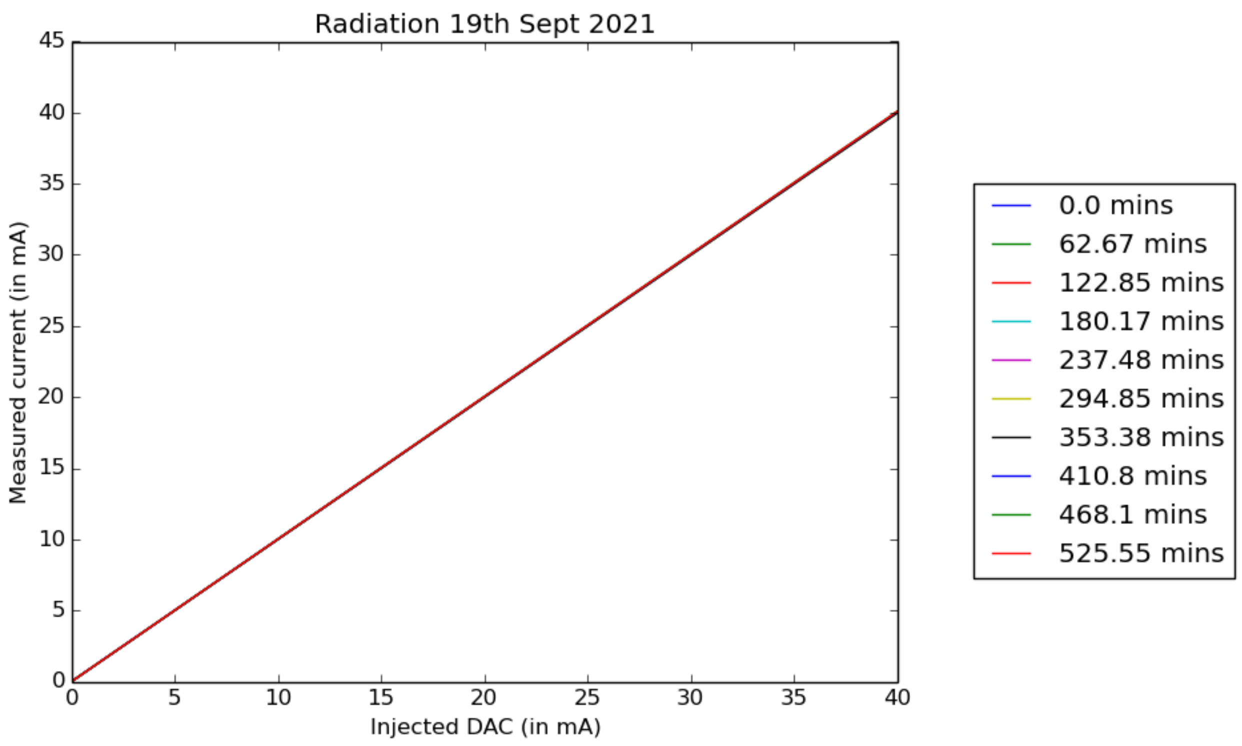
*to meet NIEL and SEE requirement

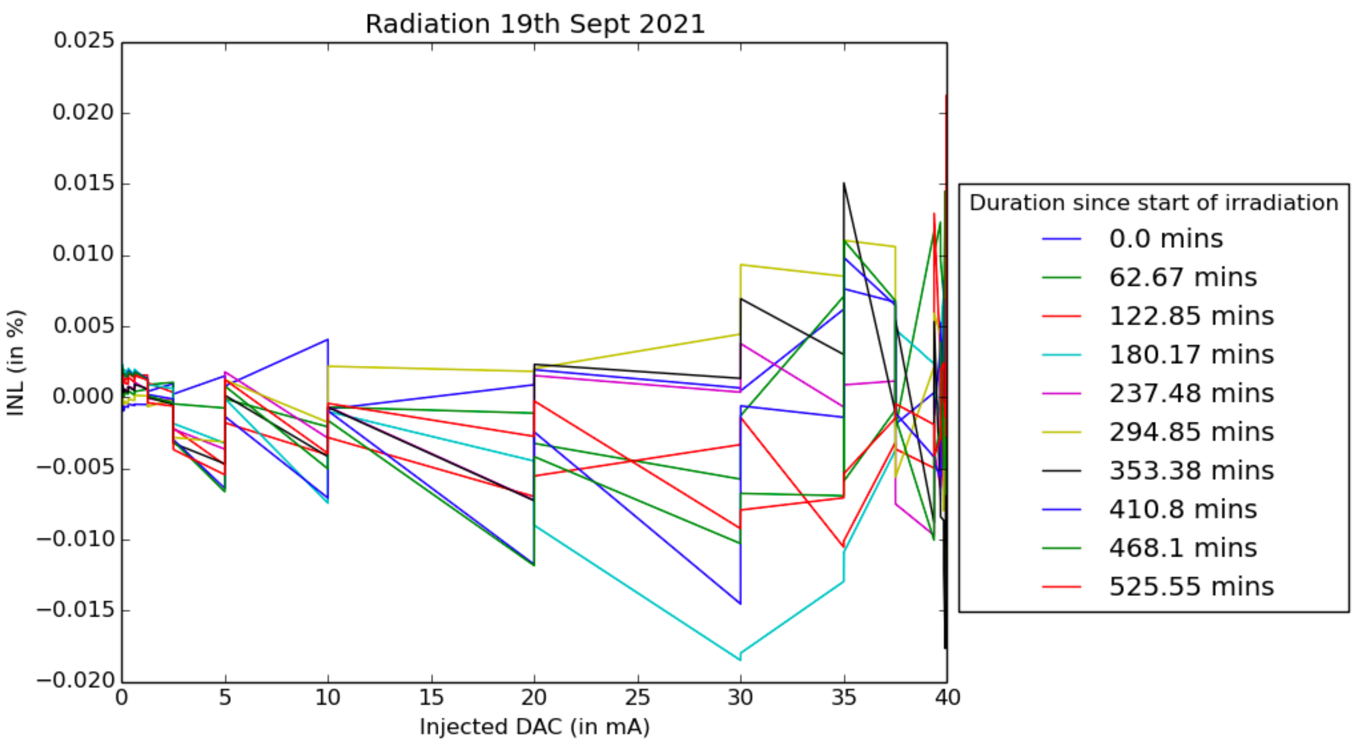
My work

Irradiation Test Results: 13-bit DAC

Specification: DAC INL < 0.1% under irradiation

$$\text{INL (\%)} = \frac{\text{measured-bestfit}}{\text{max(measured)}} \times 100$$



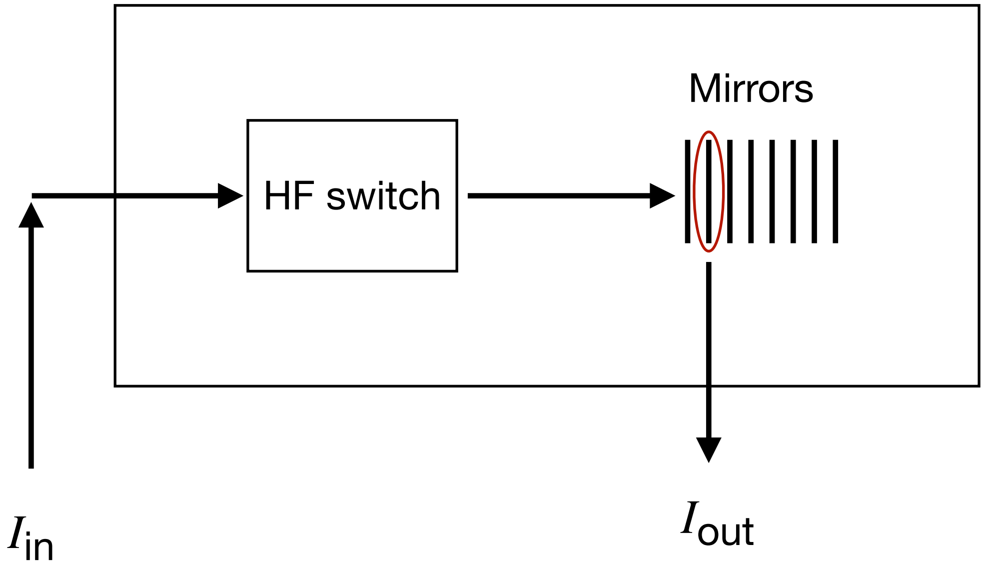


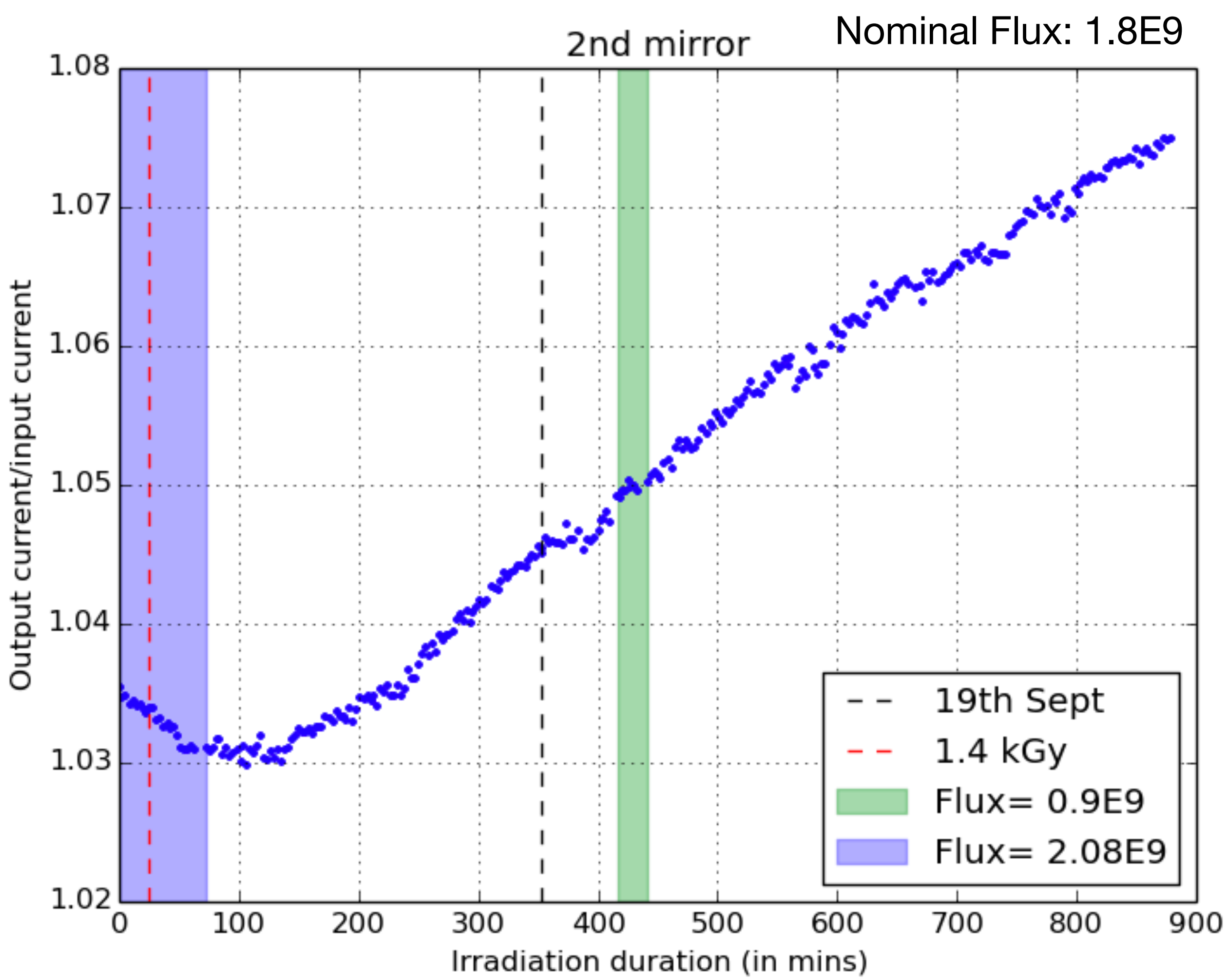
Each hour of irradiation corresponds to ~3.5 kGy → **TID specification met!**

Irradiation Test Results: 3-bit DAC + HF Switch

Specification: chip stable under irradiation

8 current mirrors → 3-bit DAC





- < 1.4 kGy: Shift in transistor voltage of HF switch under irradiation → decrease in I_{in}
  TID specification not met → new chip prototype needed!
- > 1.4 kGy: Degradation of mirrors due to irradiation → increase in I_{out}

Reminder
HF switch composed of transistors Q_1 and Q_2

Current Status

	2021	2022
XFAB	HF Switch ✗ 8 Mirrors (3-bit DAC) ✗	HF Switch with amplifier* 1 mirror with constant gain
TSMC	13-bit DAC ✓	16-bit DAC

?

Next: irradiation tests for new chip prototype

*to compensate for transistor voltage shift

Calibration Board Upgrade

Reminder

Chip $\begin{cases} \text{DAC sets amplitude of pulse} \\ \text{HF switch generates pulse} \end{cases}$

RL sets shape of pulse

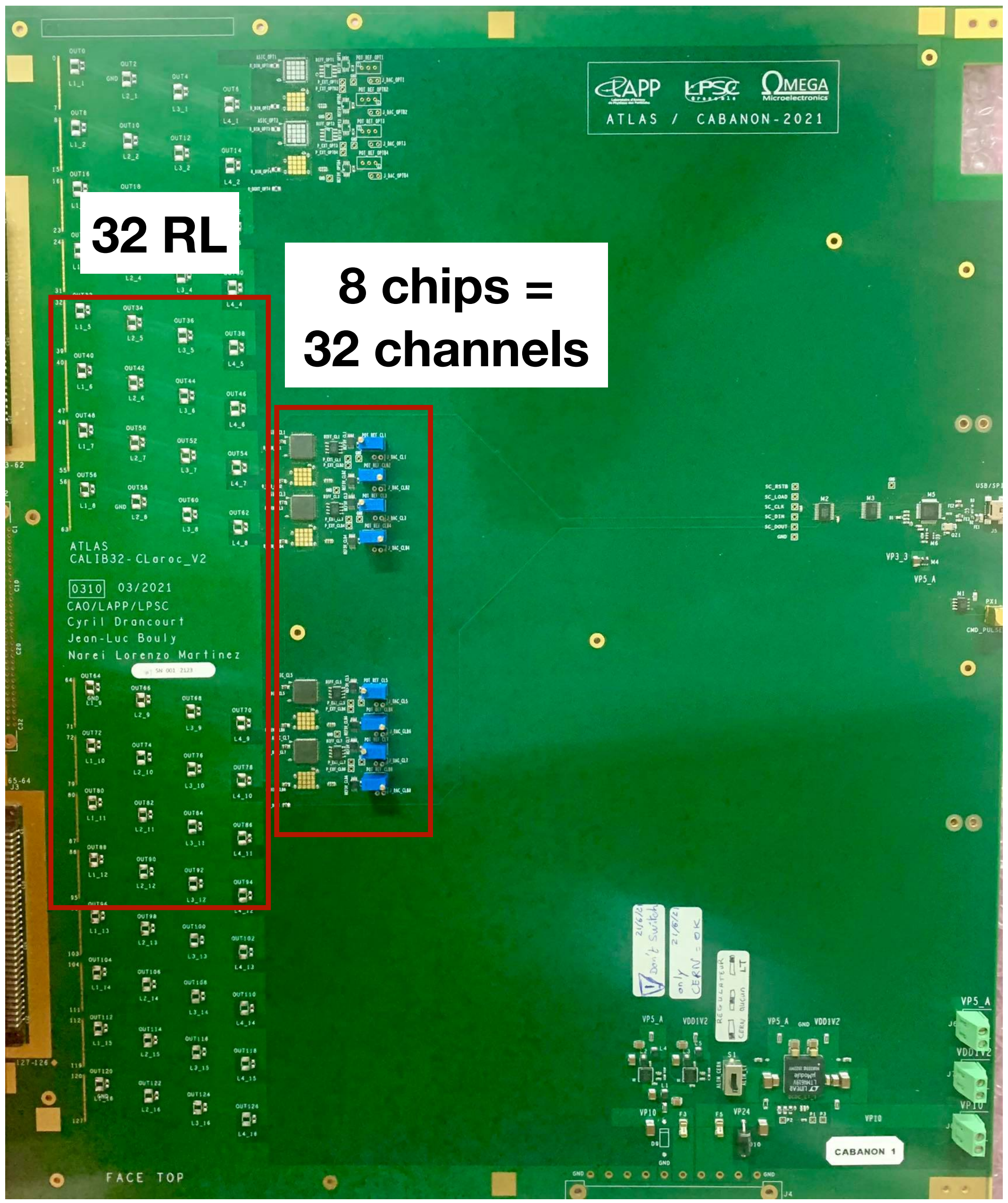
Key Specifications

- 128 calibration channels per board
  - Each channel calibrates 1-32 detector cells → ~150 calibration boards
- Uniformity among channels $< 0.25\%$ → to maintain c of LAr EM calorimeters at 0.7%
  - Crosstalk, i.e. undesired signal in a channel different from the one that was pulsed $< 0.1\%$

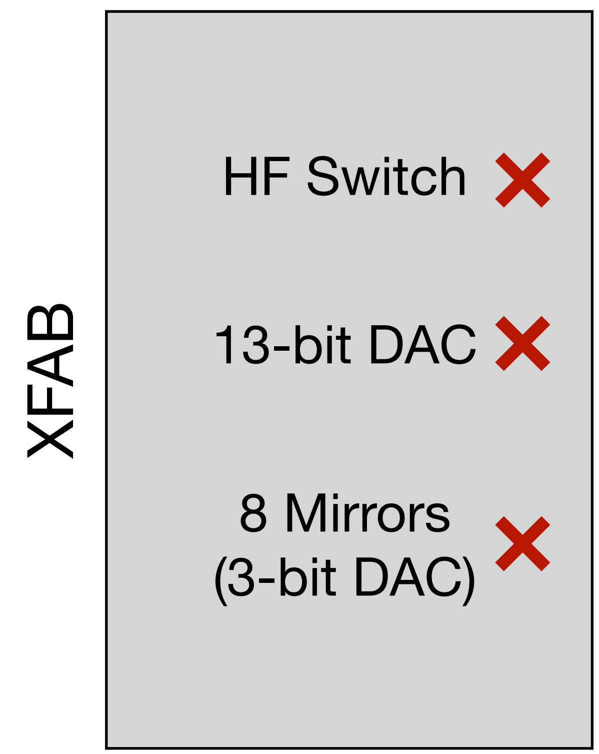
Calibration Board Prototype

Specification: 128 channels

→ test with 32 channel board, with 16 channels on top and 16 on bottom



2021: First Calibration Board Prototype for HL-LHC!



2020 chip prototype incorporated

→ parallel development of board needed

Reminder

chip = 1 DAC + 4 HF switches

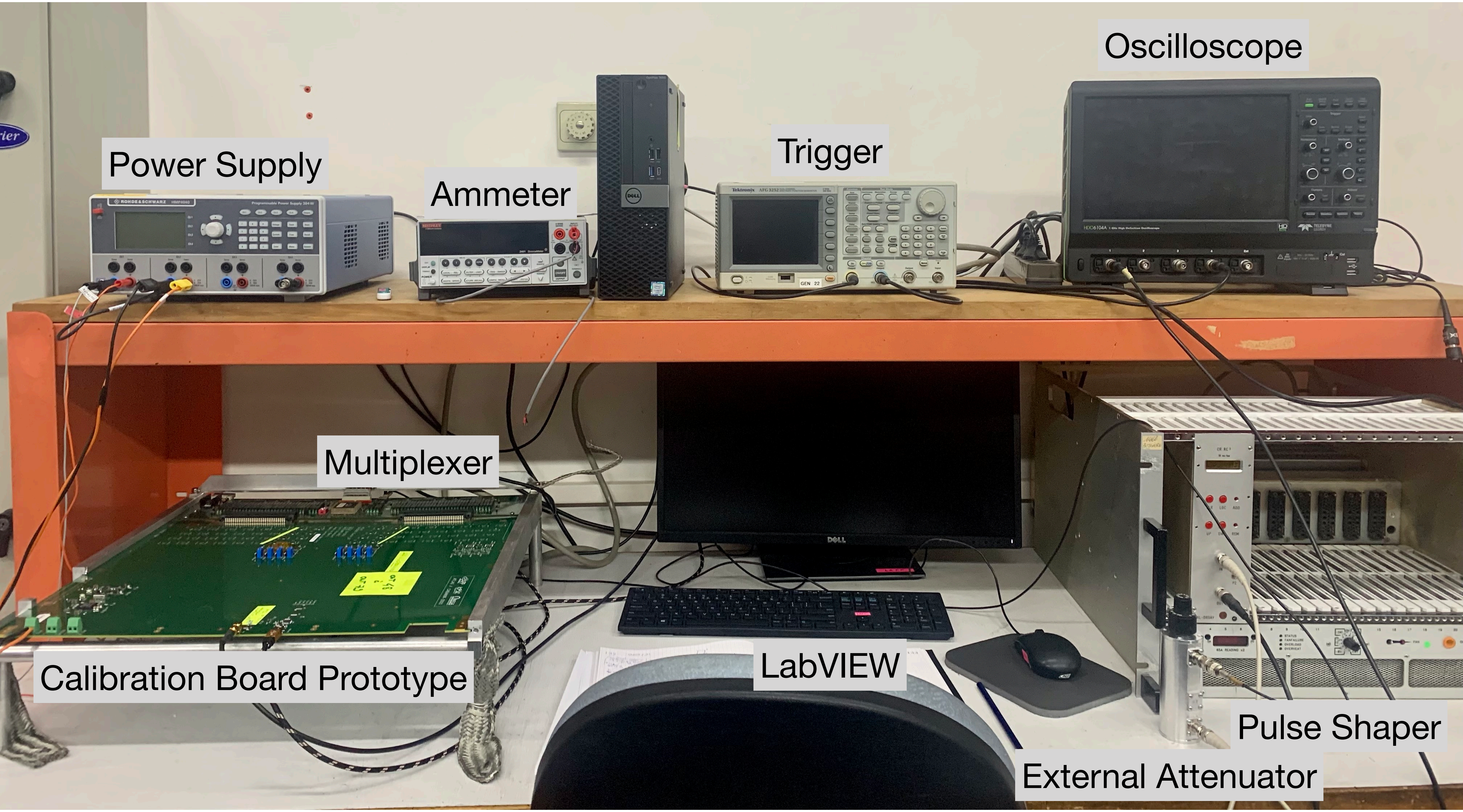
Calibration Board Prototype (II)

3 board prototypes developed:

- Inductance → to assess most suitable component in magnetic environment
  - ISC1210ER120J: 5% tolerance, used in existing calibration boards
  - S1812R-123G: 2% tolerance, new type under study
- Position of Chips → to ensure consistent results across the board

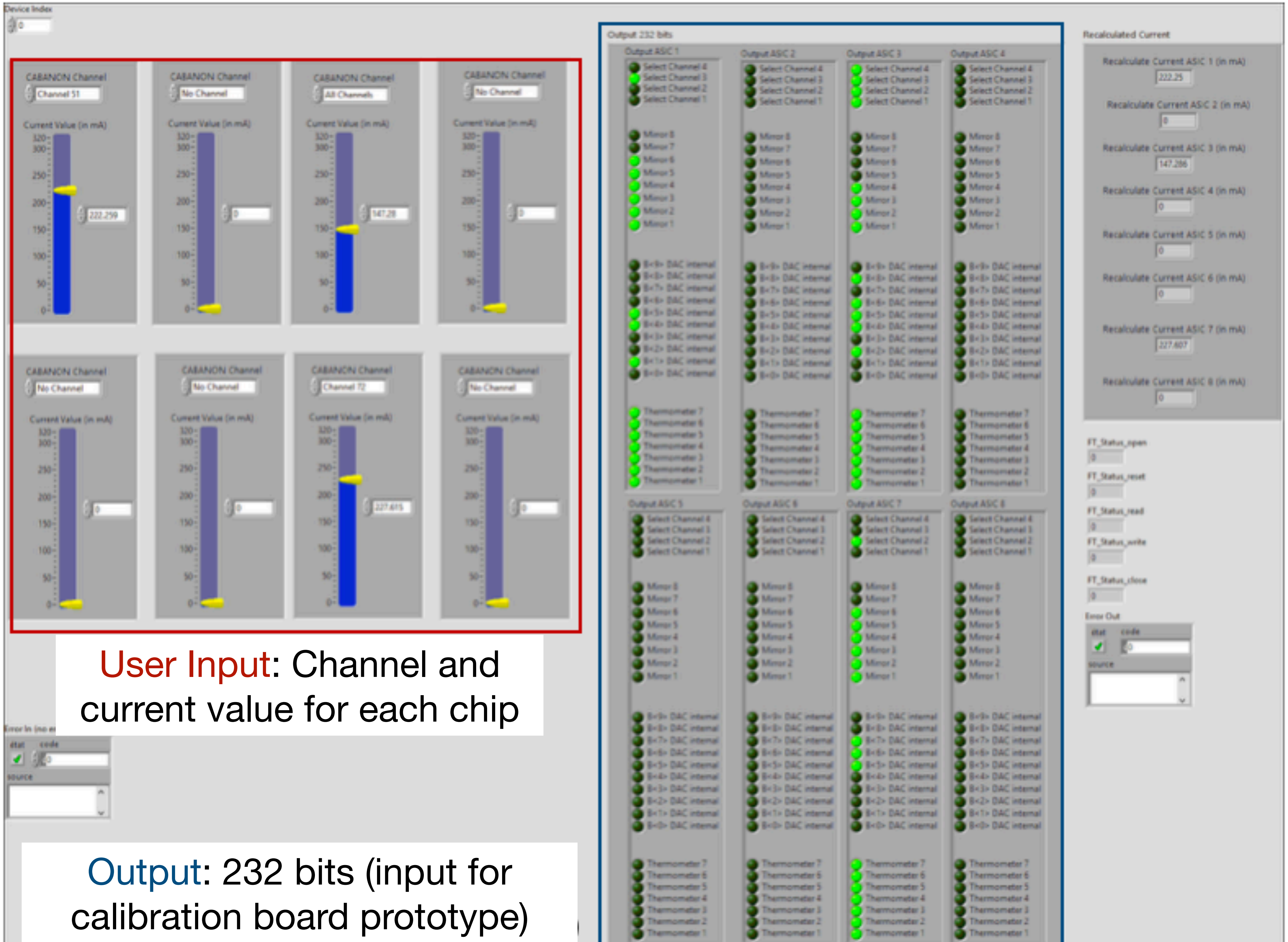
Board Prototype	**Inductance**	**Position of Chips**
Board 1	ISC1210ER120J	Middle Sector
Board 2	S1812R-123G	Middle Sector
Board 3	ISC1210ER120J	Top Sector

Test Bench Setup



My work

Test Bench Setup: LabVIEW

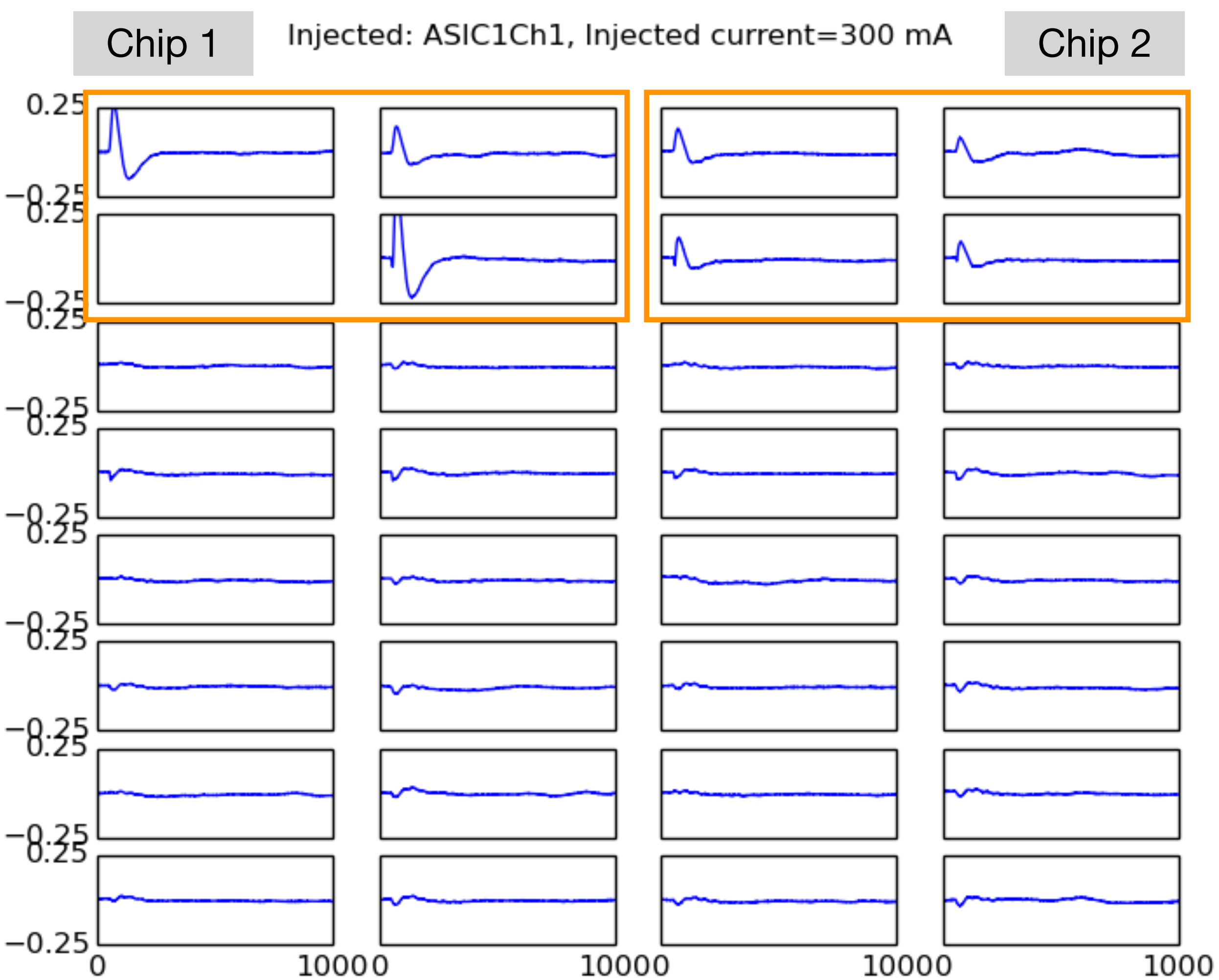


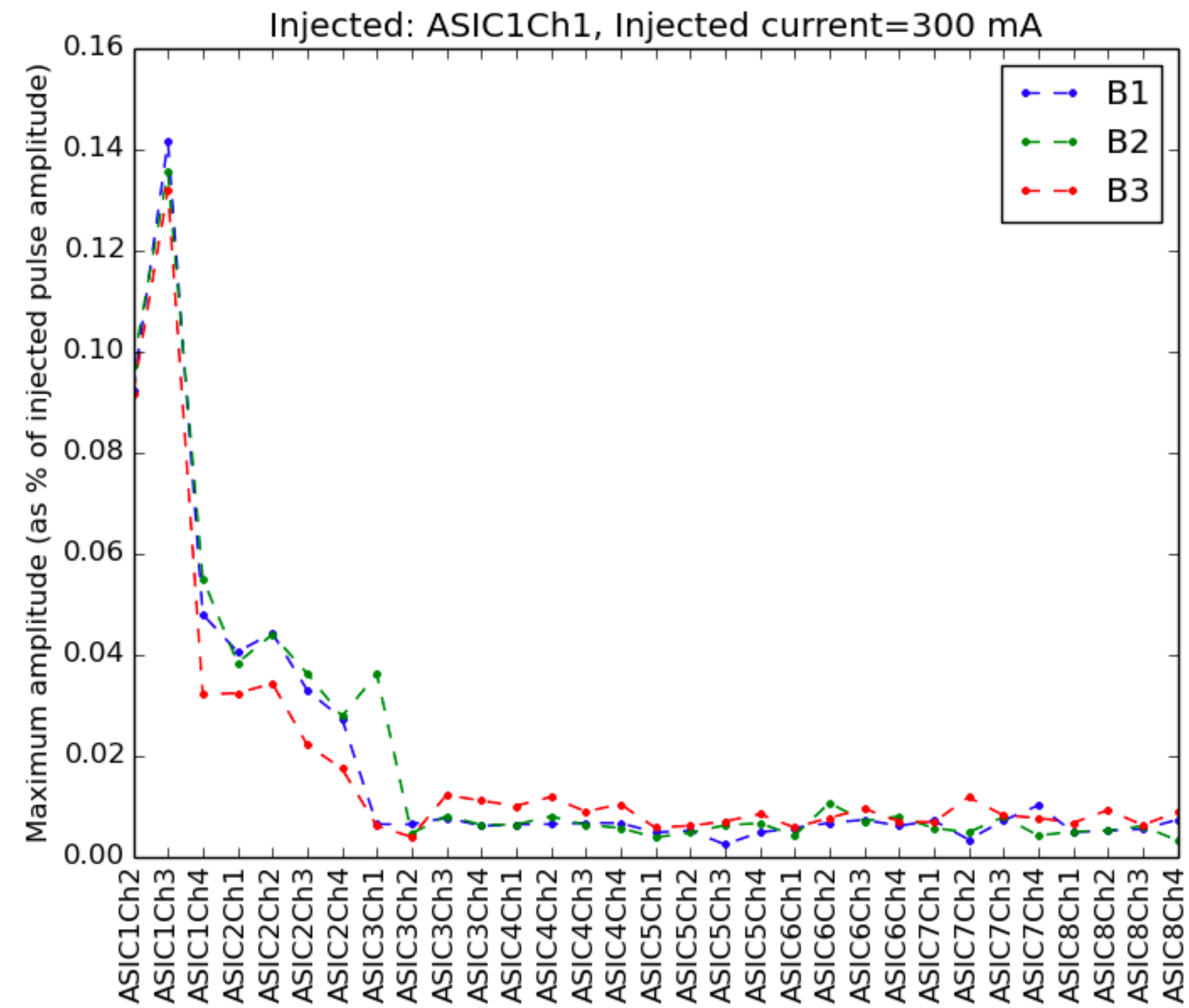
User Input: Channel and current value for each chip

Output: 232 bits (input for calibration board prototype)

Uniformity Studies: Crosstalk

Specification: maximum crosstalk < 0.1% of injected pulse amplitude
→ **specification met!**





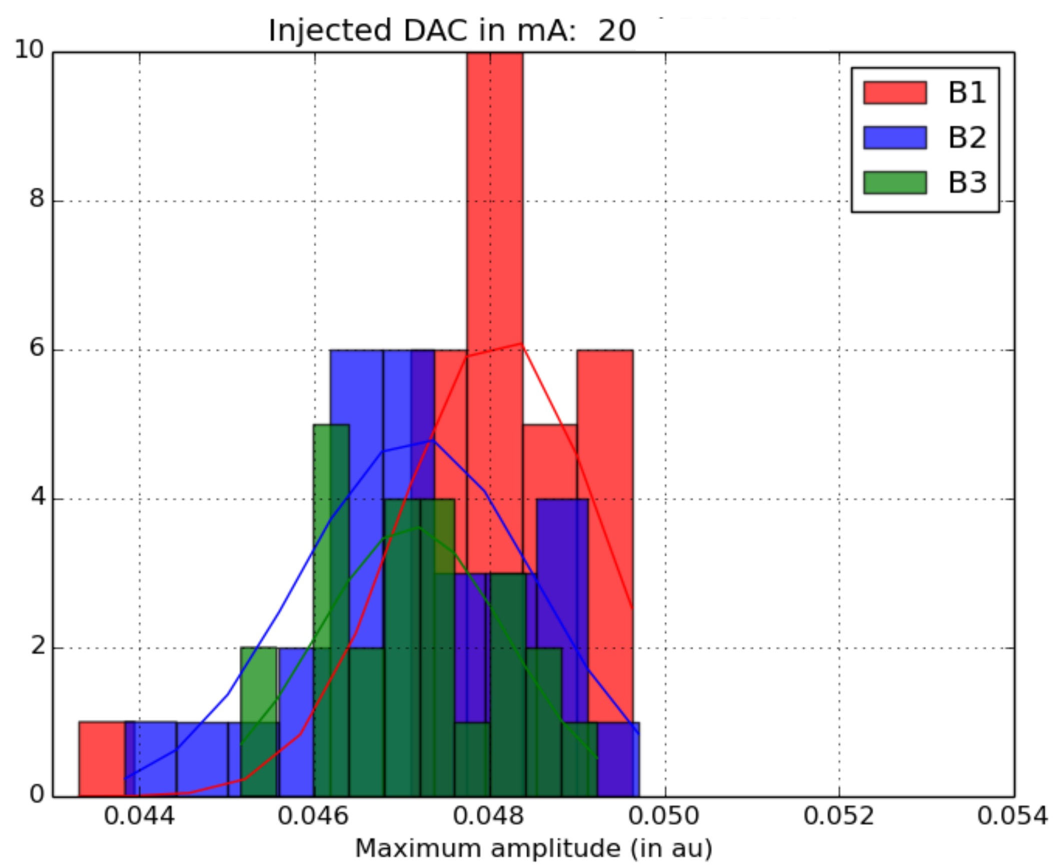
1) No dependence on position of chips → consistent results across board
2) No dependence on type of inductance → magnetic tests needed

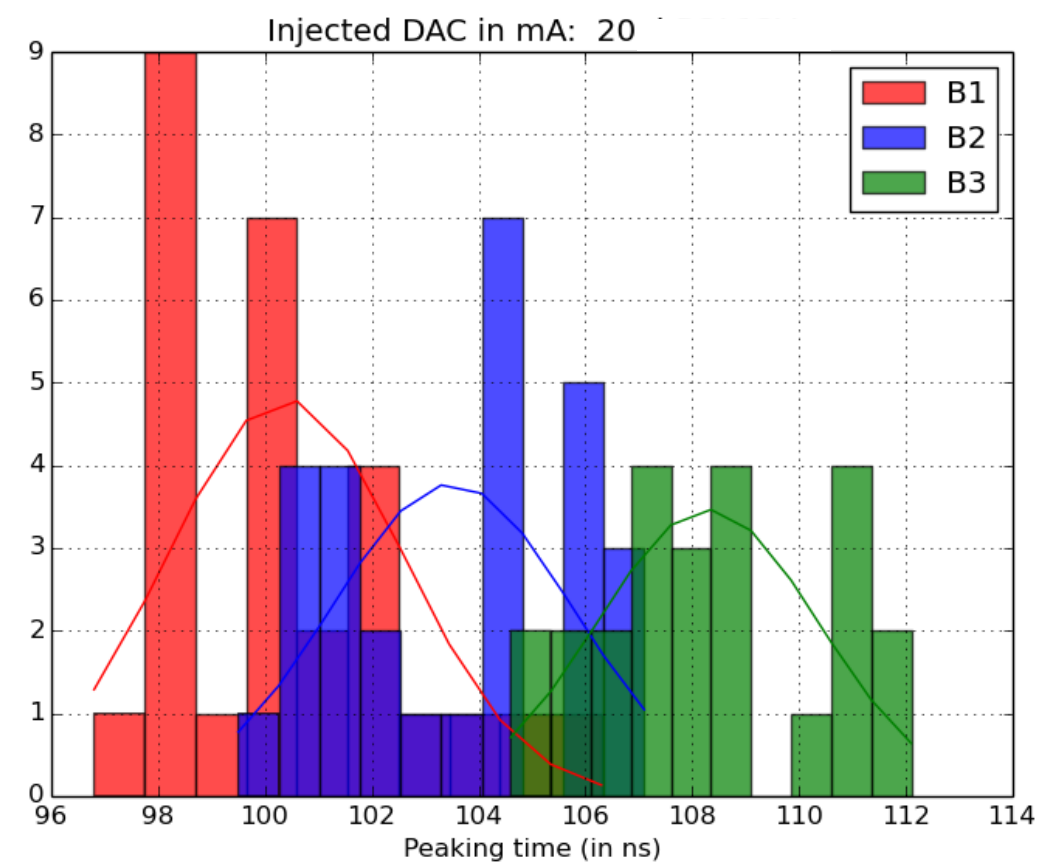
My work

Uniformity Studies: Pulse Shape

Specification: uniformity among channels < 0.25%

→ measure maximum amplitude and peaking time of pulse



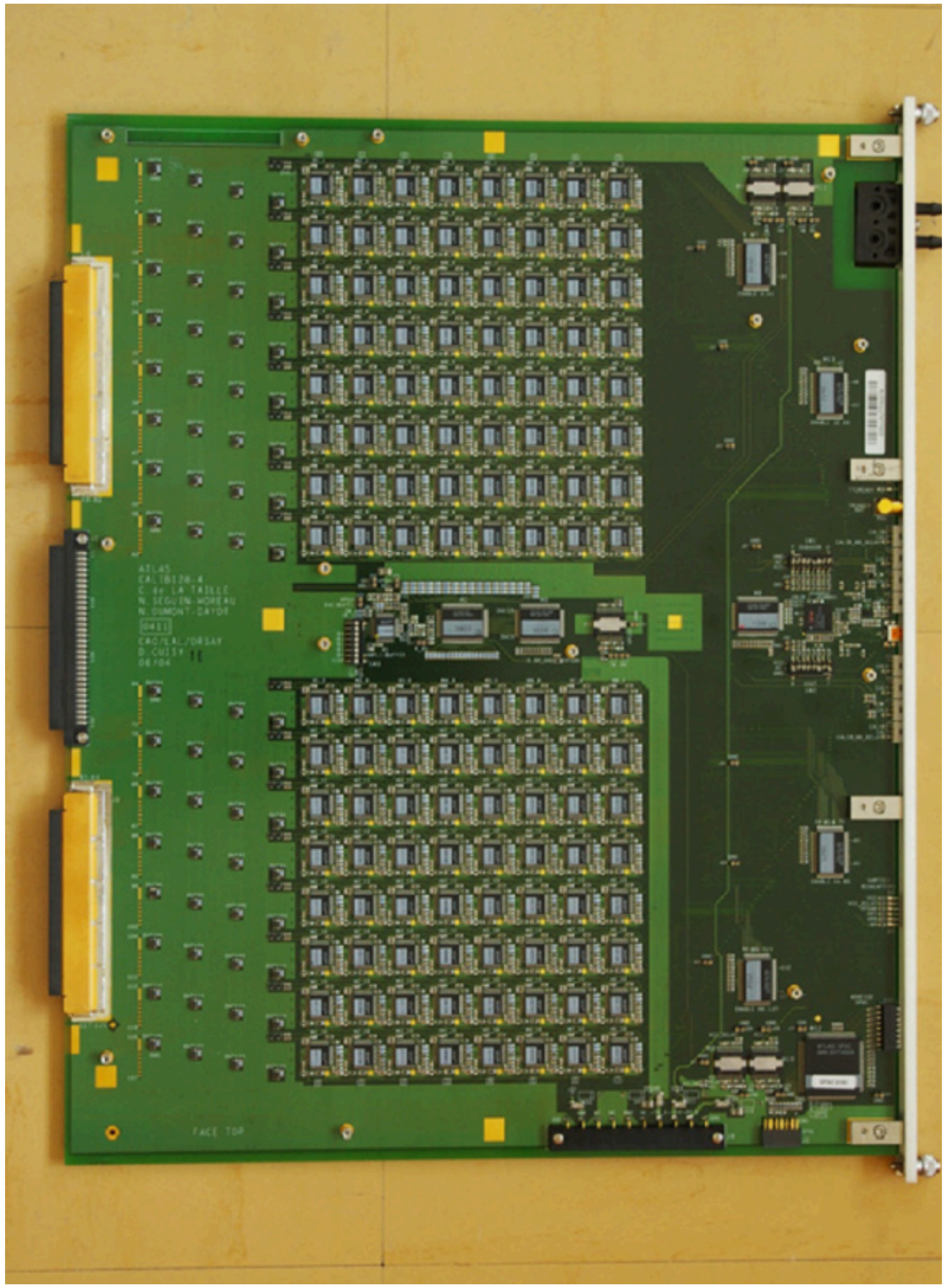


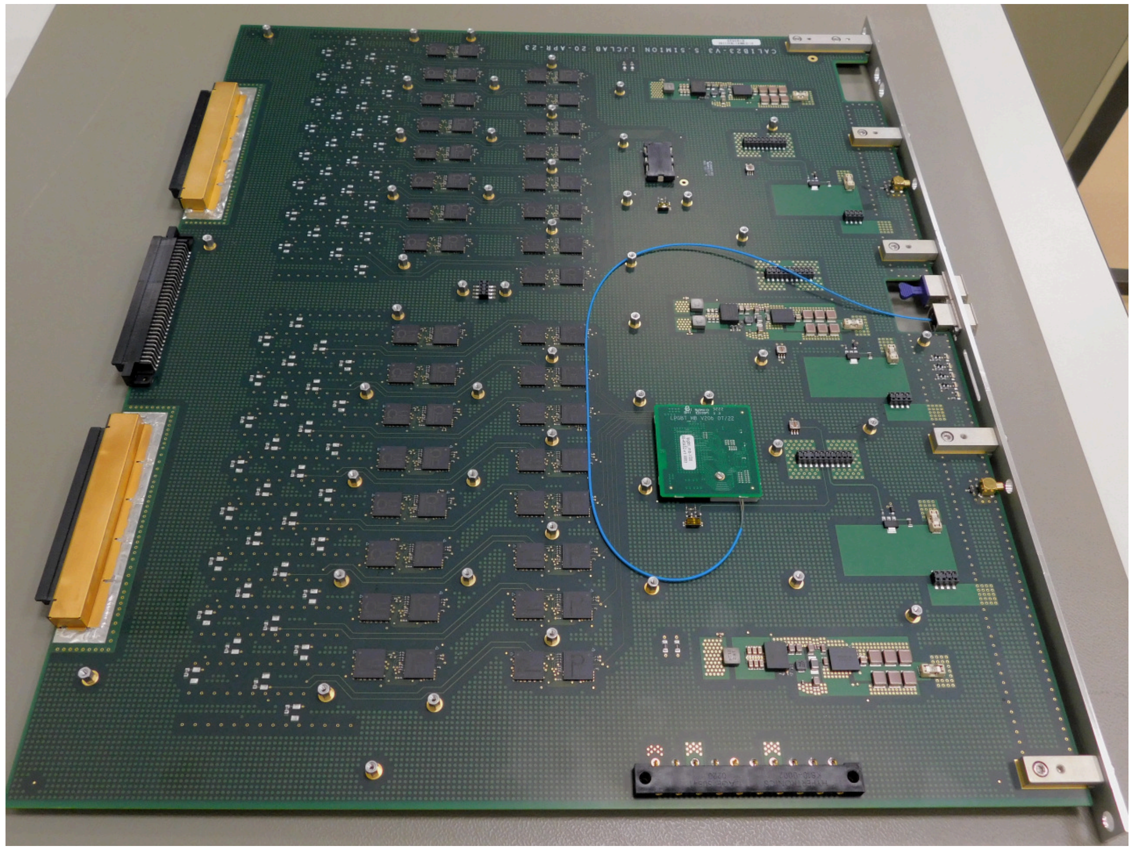
1) Relative standard deviation > 0.25% → mainly due to non-uniform chips

Specification not met → new board prototype needed!

2) Board 3 → larger peaking time → probably due to longer length of cables

Calibration System: Current Status





Full 128-channel calibration board prototype for HL-LHC

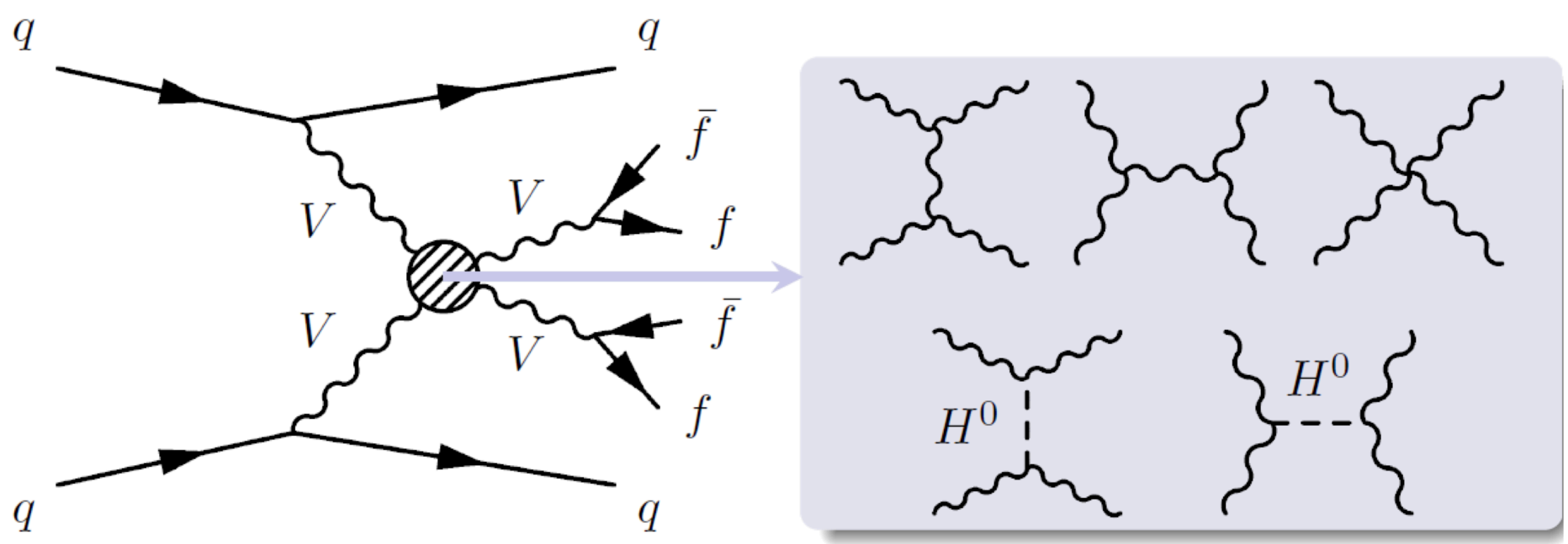
Next: All tests

Existing calibration board

Goal: 150 boards in 2027

$Z\gamma$ Vector Boson Scattering (LHC Run 2)

Vector Boson Scattering at LHC

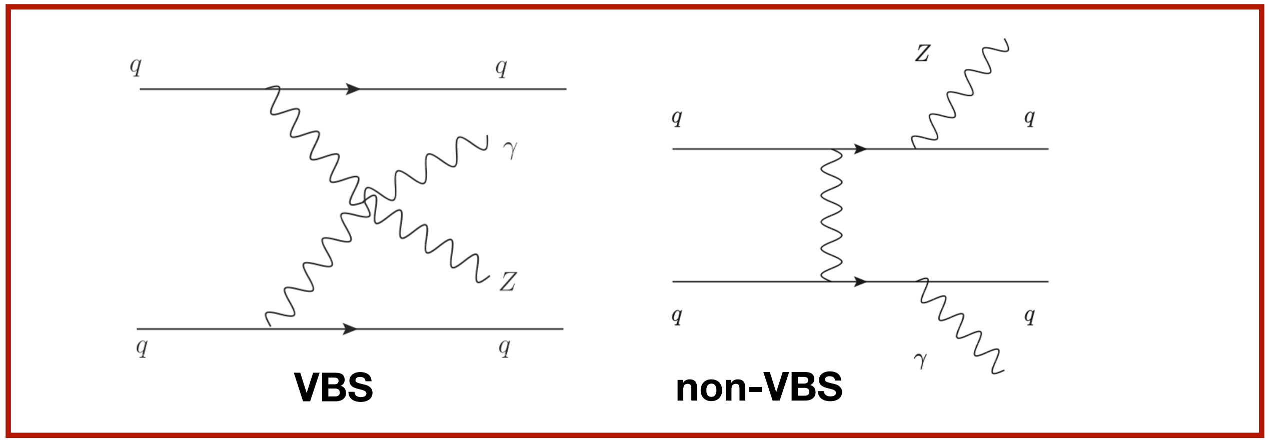


$$V = W, Z, \gamma$$

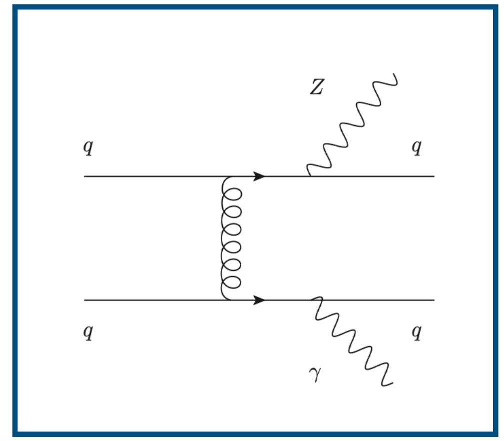
- Probe the electroweak sector → **precision test of SM**
- Sensitive to anomalous couplings → **good platform for new physics**

Electroweak Production of $VVjj$ (II)

EW-$VVjj\ O(\alpha_{EW}^4)$



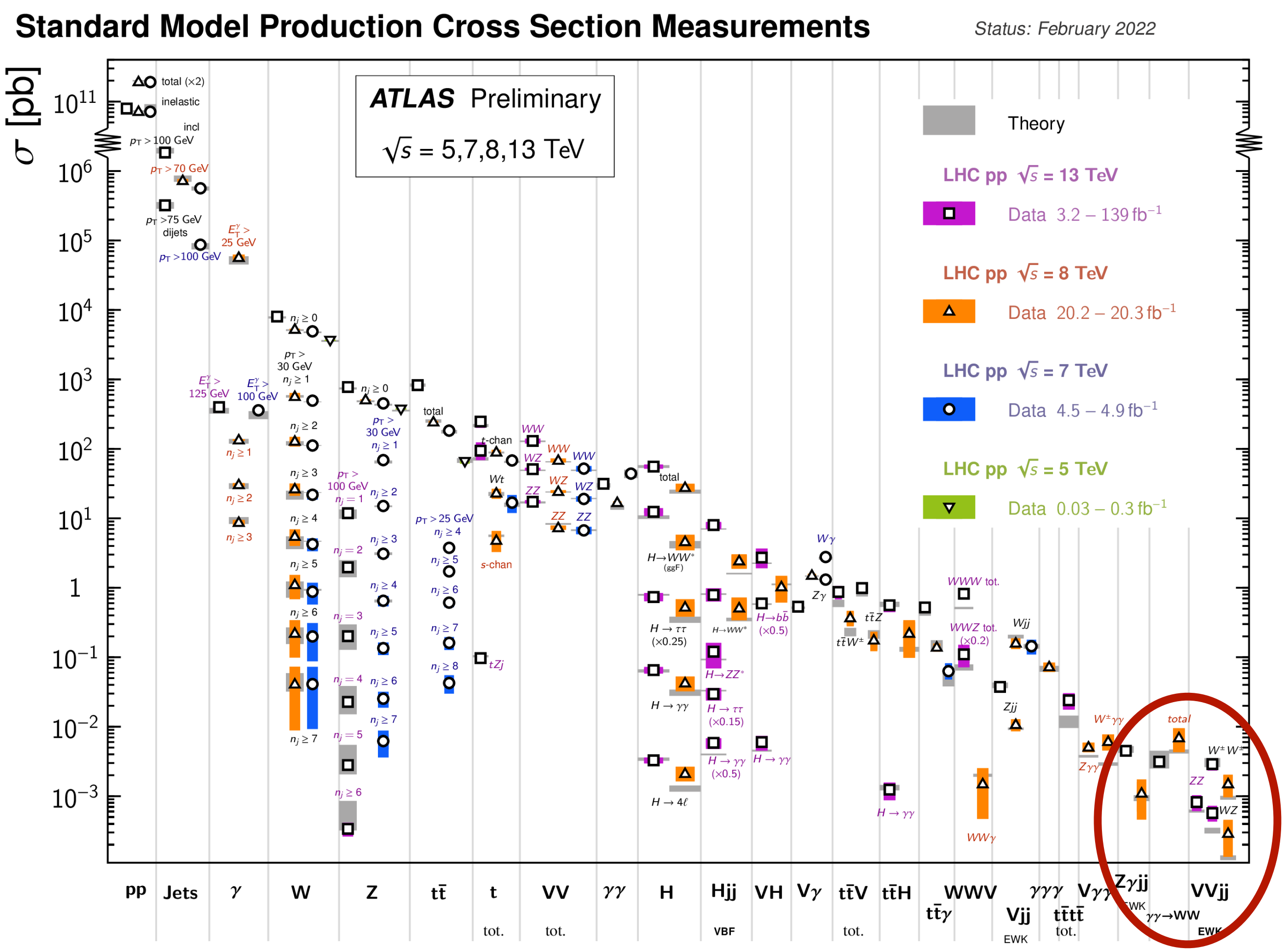
QCD-$VVjj\ O(\alpha_S^2\alpha_{EW}^2)$



+Small interference $O(\alpha_S\alpha_{EW}^3)$

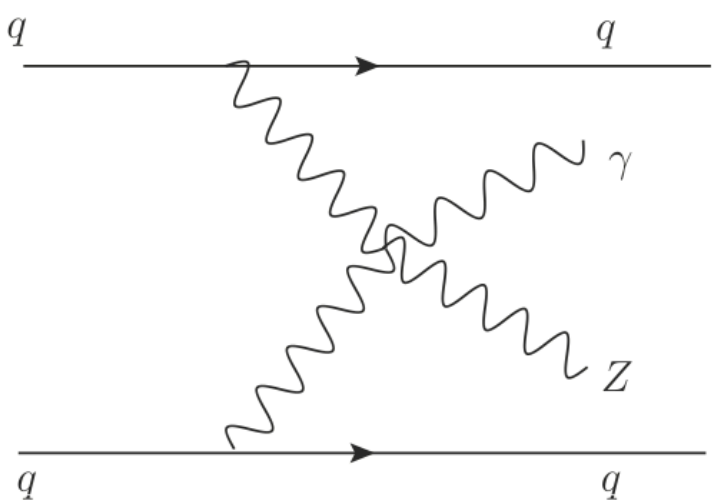
Signal: process of interest

Background: resembles signature of signal

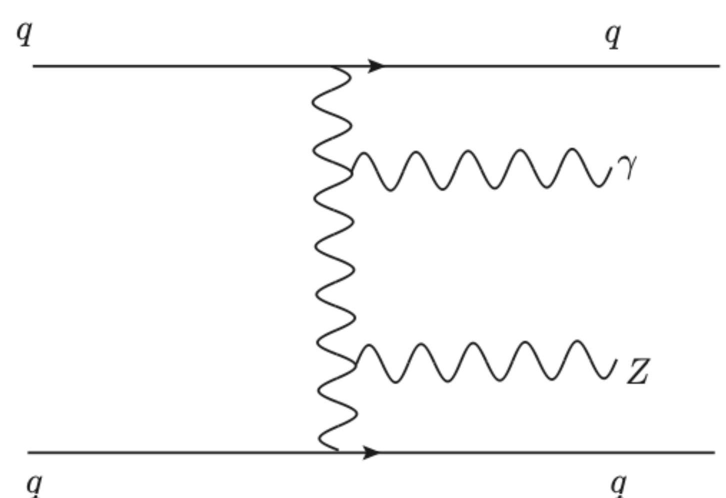


very **rare processes** → only accessible in recent years with Run 2 data

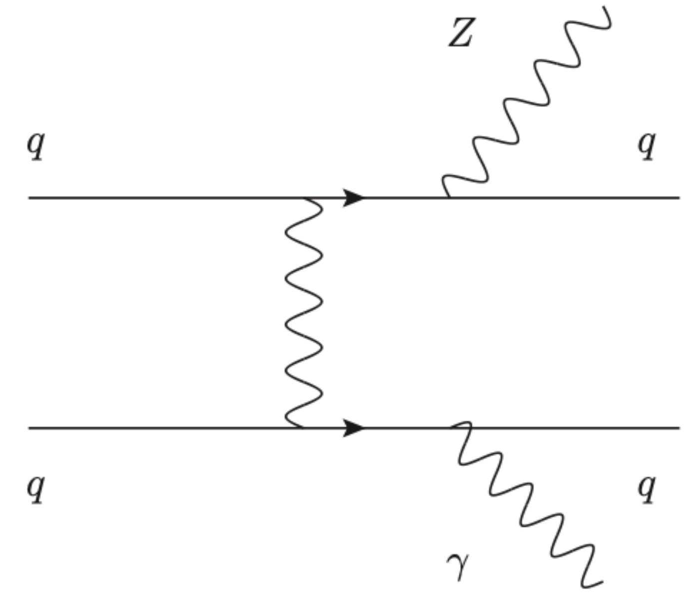
Electroweak Production of $Z\gamma jj$



VBS via quartic gauge coupling (QGC)



VBS via triple gauge coupling (TGC)



EW non-VBS

Final state: $Z\gamma \rightarrow l^+l^-\gamma$, where $l = e, \mu$ (τ has negligible contribution)

- $Z\gamma \rightarrow 2q\gamma$: large hadronic backgrounds*
- $Z\gamma \rightarrow 2\nu\gamma$: neutrinos escape without a detectable signal

*LHC is a QCD factory

Electroweak Production of $Z\gamma jj$: Motivation

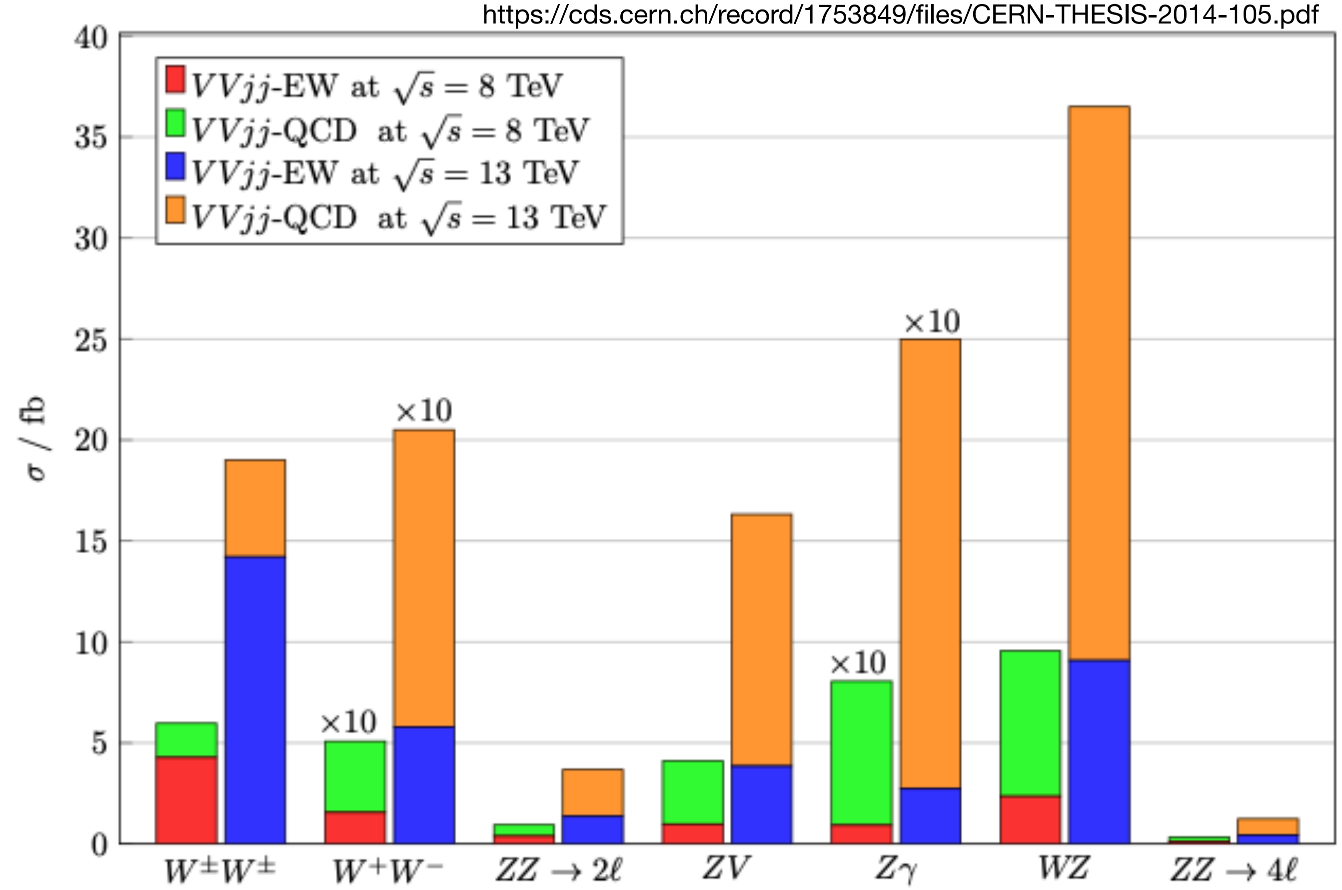
Best channel to **probe neutral quartic gauge coupling** that is forbidden by SM

- ZZ
  - $\rightarrow 4l$ or $\rightarrow 2l2\nu$: low cross section
  - $\rightarrow 4q$ or $\rightarrow 2l2q$: large hadronic backgrounds
  - $\rightarrow 4\nu$: neutrinos escape without a detectable signal
- $\gamma\gamma$: large background from mis-identified photons

P. Anger

https://cds.cern.ch/record/1753849/files/CERN-THESIS-2014-105.pdf

Estimated $VVjj$ (with at least 2 leptons in final state) cross sections in typical VBS region:



Studies on EW-$Z(\to ll)\gamma jj$ with ATLAS

2017: https://arxiv.org/pdf/1705.01966.pdf

- 2012 data $\to L = 20.2\ \text{fb}^{-1}$
- No evidence of EW-$Z\gamma jj \to 2\sigma$

2020: https://arxiv.org/pdf/1910.09503.pdf

- 2015-2016 data $\to L = 36\ \text{fb}^{-1}$
- Evidence of EW-$Z\gamma jj \to 4.1\sigma$

2023 (this analysis): https://arxiv.org/pdf/2305.19142.pdf

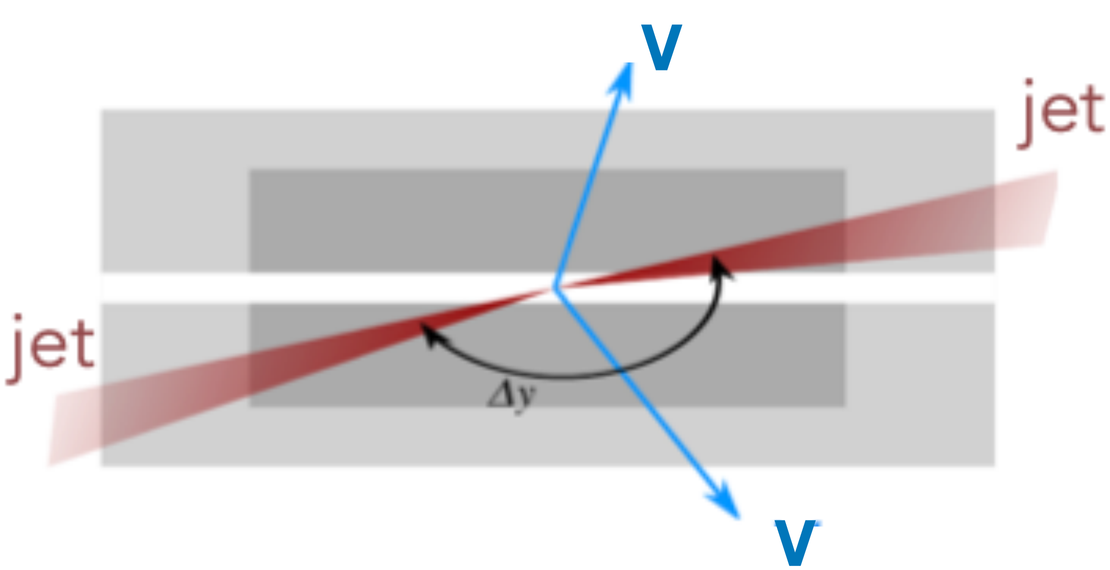
- 2015-2018 data $\to L = 140\ \text{fb}^{-1}$
- **Goals:**
    - Observation of EW-$Z\gamma jj$
    - First differential cross section measurements of EW-$Z\gamma jj$

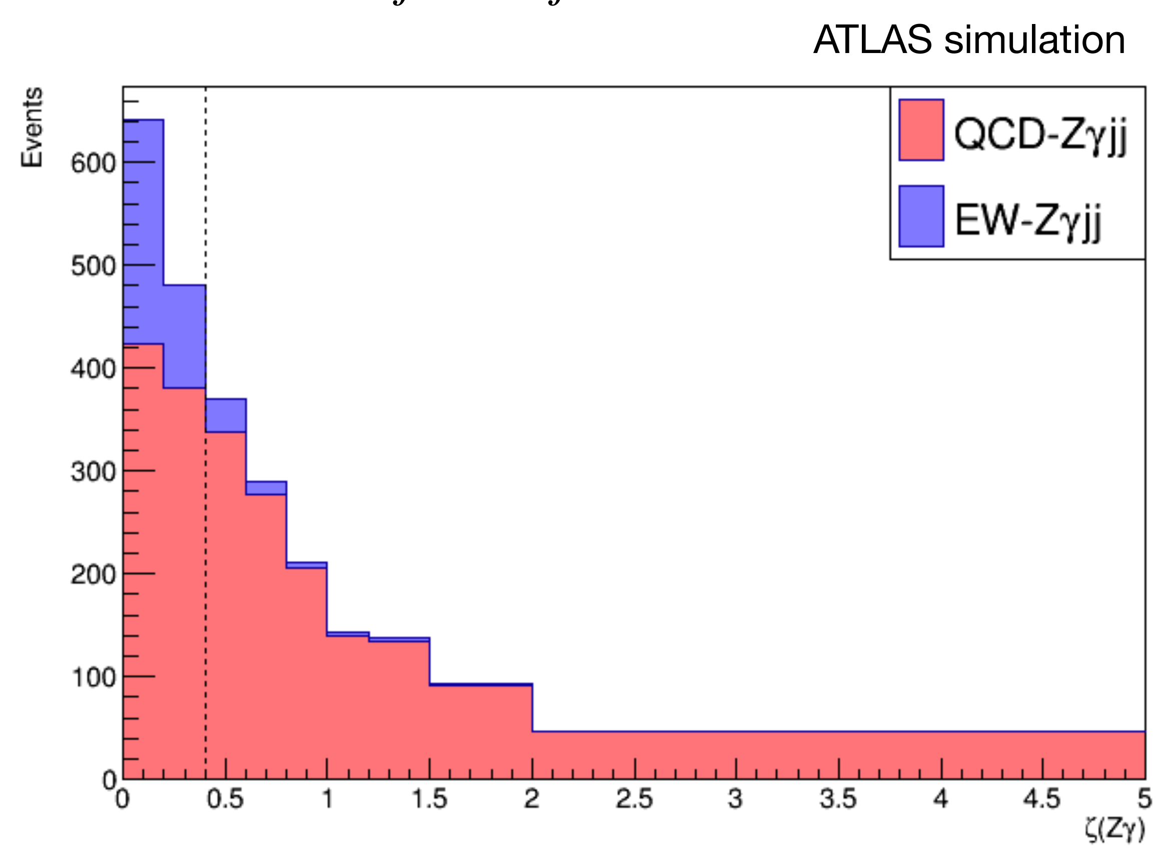
Analysis Strategy

EW-$Z\gamma jj$: Event Selection

Based on **typical VBS topology**

- Two high energy forward jets (*tagging jets*): $m_{jj} > 150$ GeV, $|\Delta y| > 1$
- Hadronic activity suppressed between jets: $N_{gap}^{jets} = 0$
- Centrally produced vector bosons: $\zeta(Z\gamma) = \left|\frac{y_{Z\gamma} - (y_{j1} + y_{j2})/2}{y_{j1} - y_{j2}}\right| < 0.4$



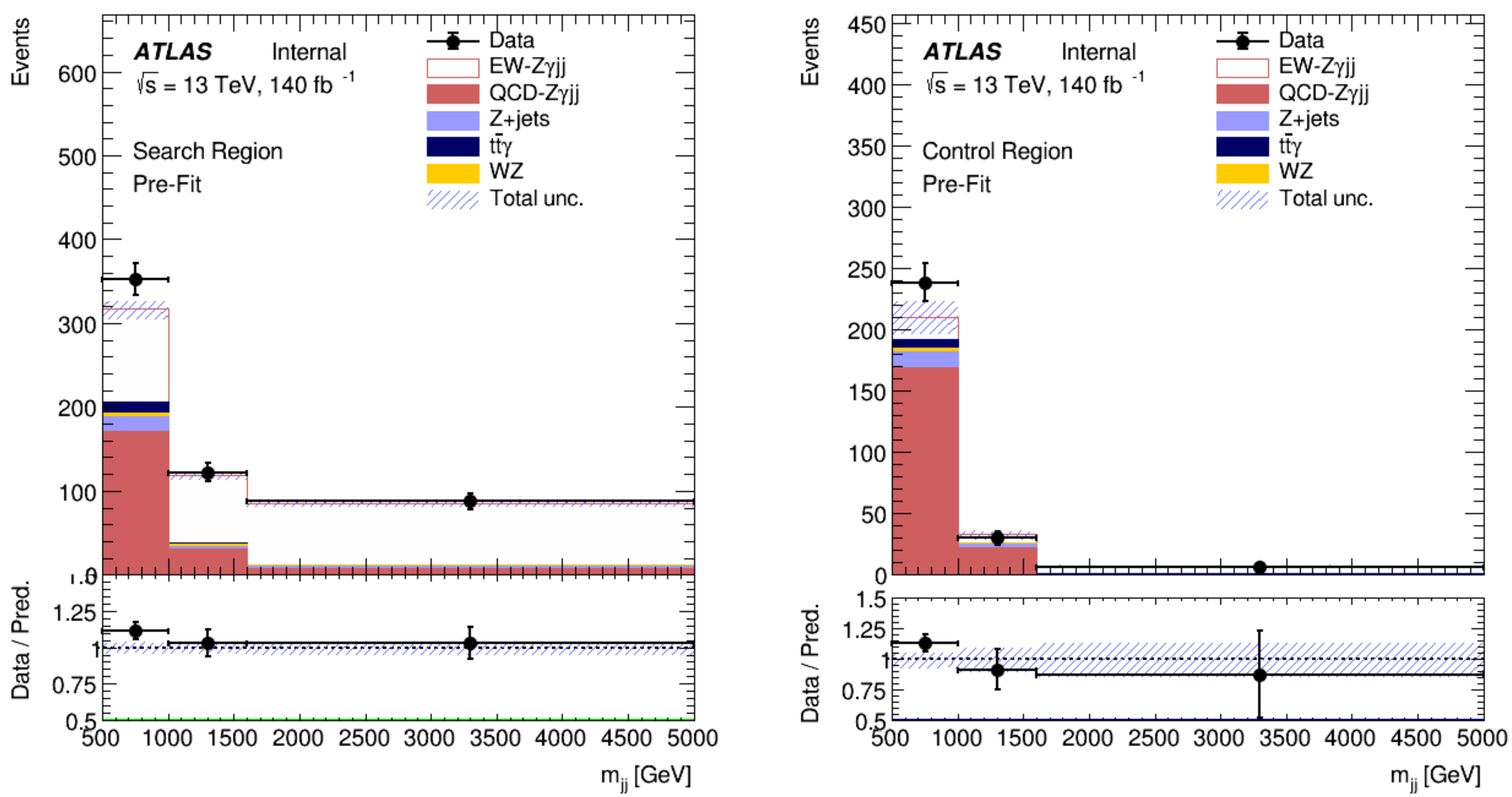


EW-$Z\gamma jj$: Measurement Strategy

- **Search Region**: $\zeta(Z\gamma) < 0.4$
- **Control Region**: $\zeta(Z\gamma) > 0.4$
    - To constrain QCD-$Z\gamma jj$ background

Variable: m_{jj}

$\rightarrow$ uncorrelated with $\zeta(Z\gamma)$

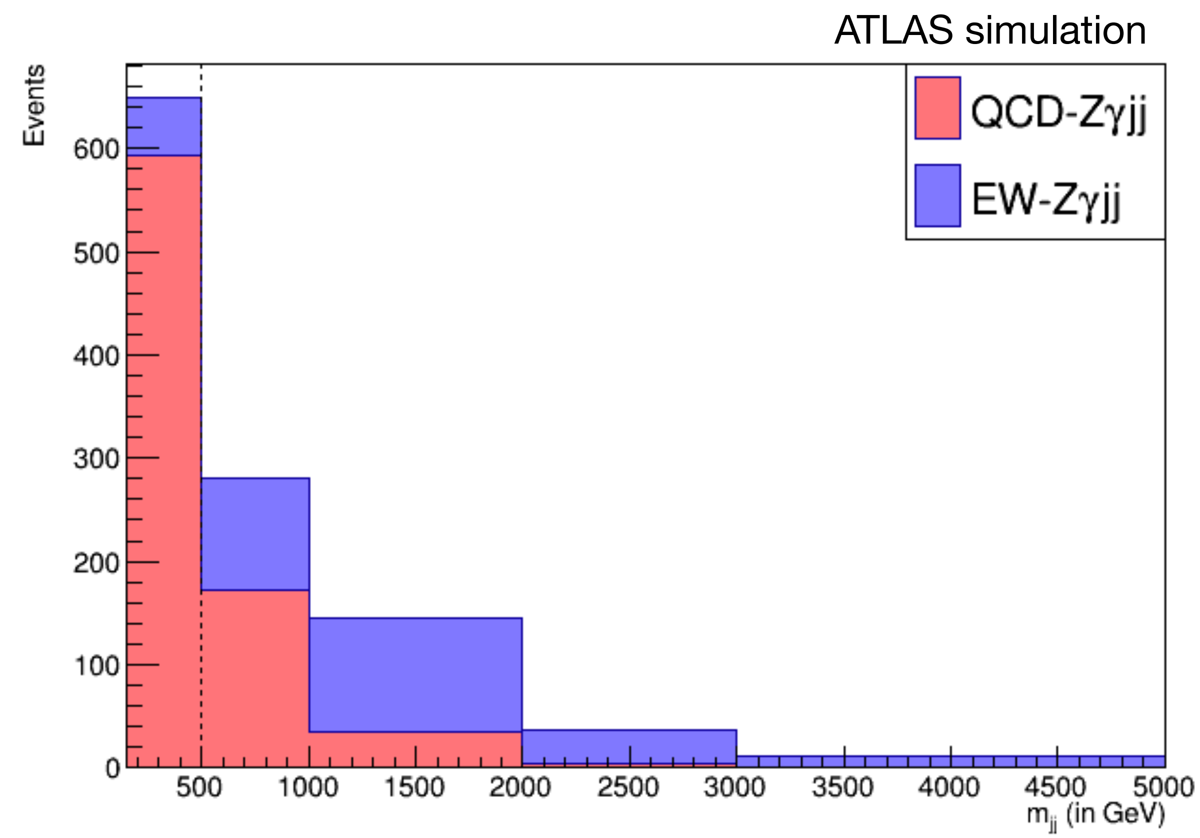


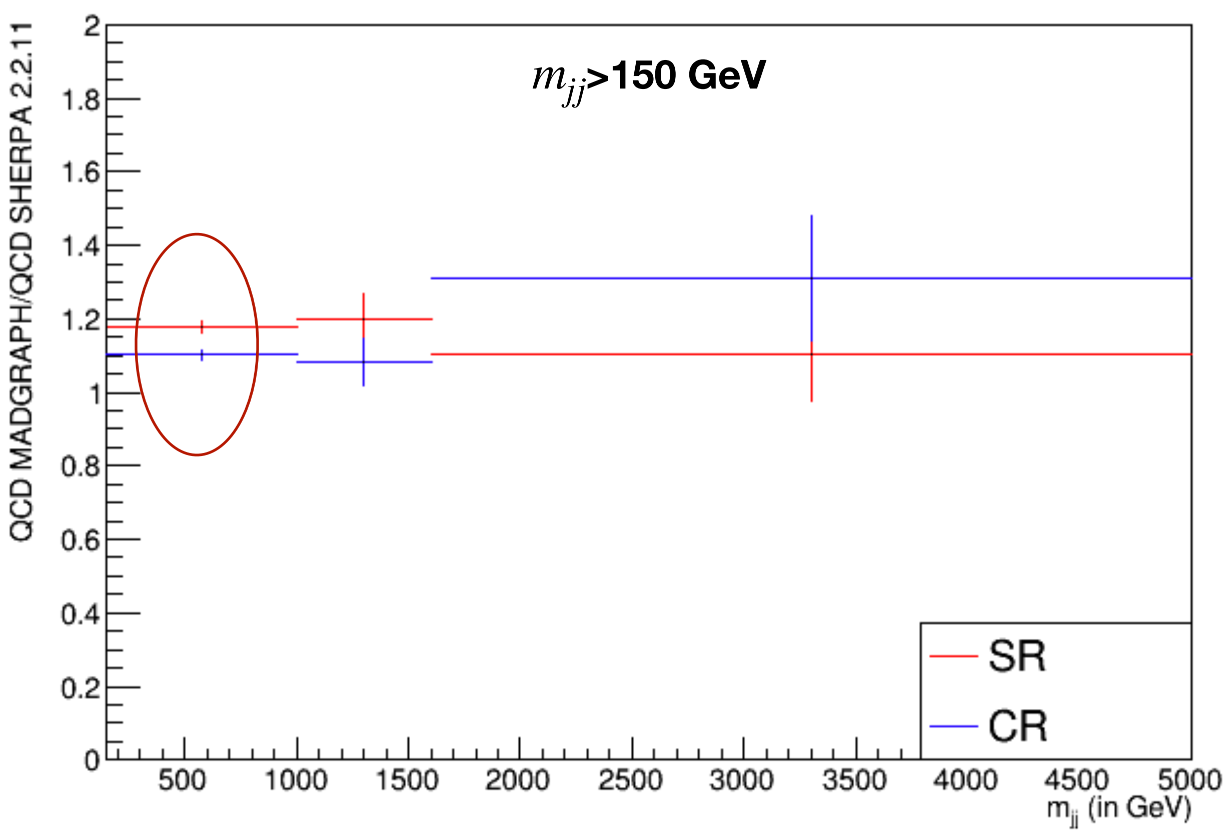
My work

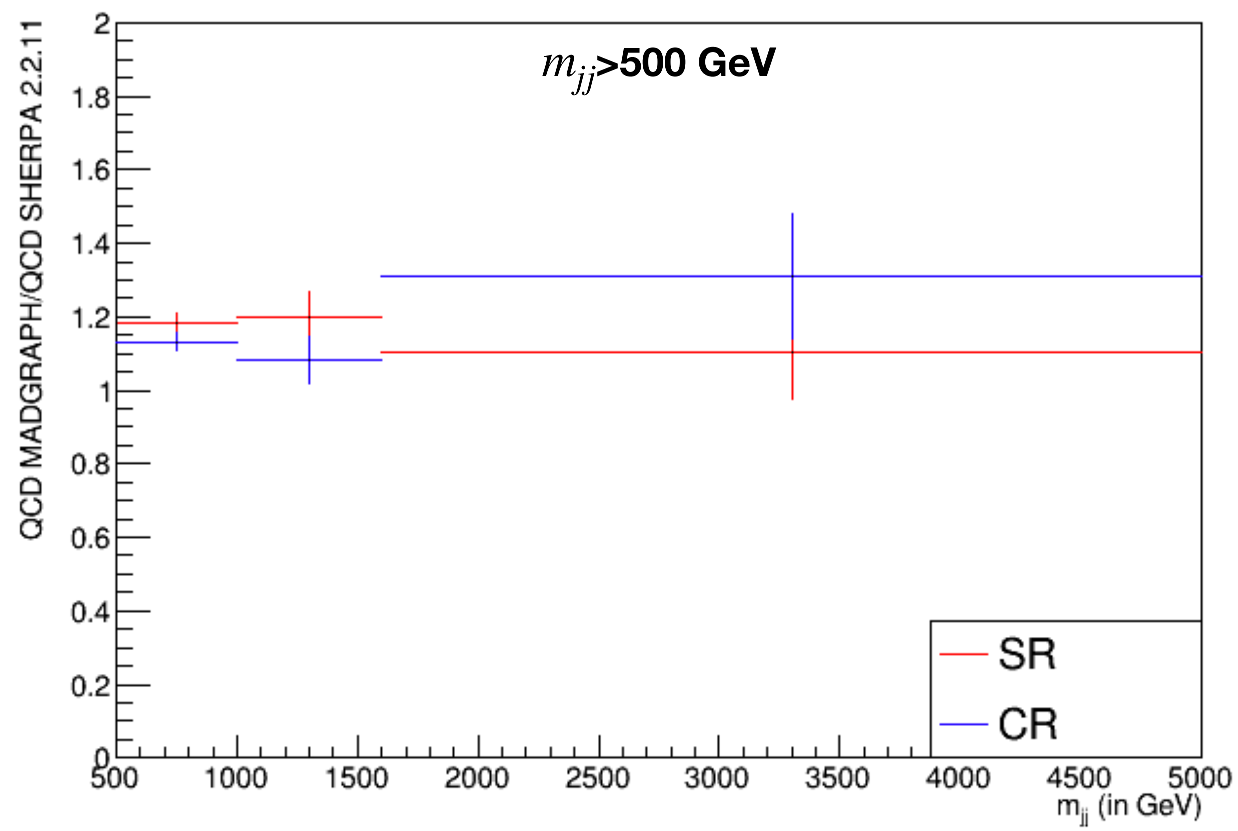
EW-$Z\gamma jj$: Measurement Region

m_{jj} > 500 GeV:

- Improve signal/background
- Shape of QCD-$Z\gamma jj$ consistent in SR and CR → extrapolate shape from CR to SR in data

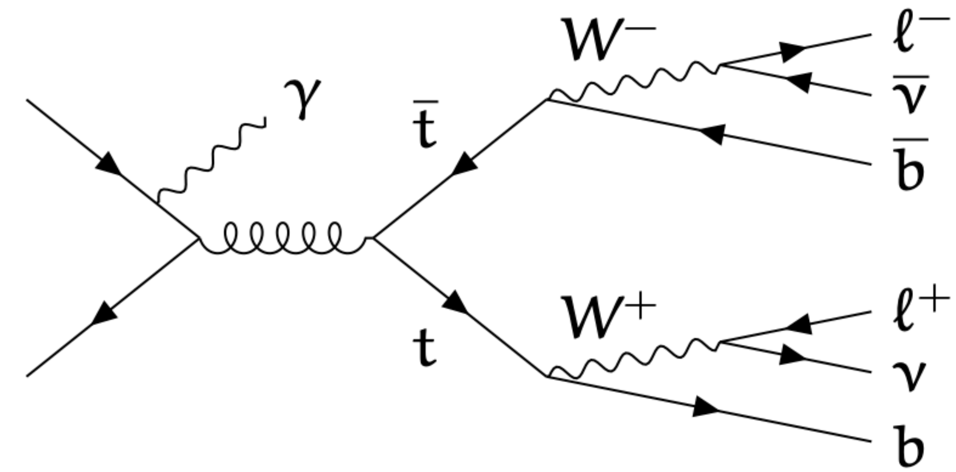






EW-$Z\gamma jj$: Background

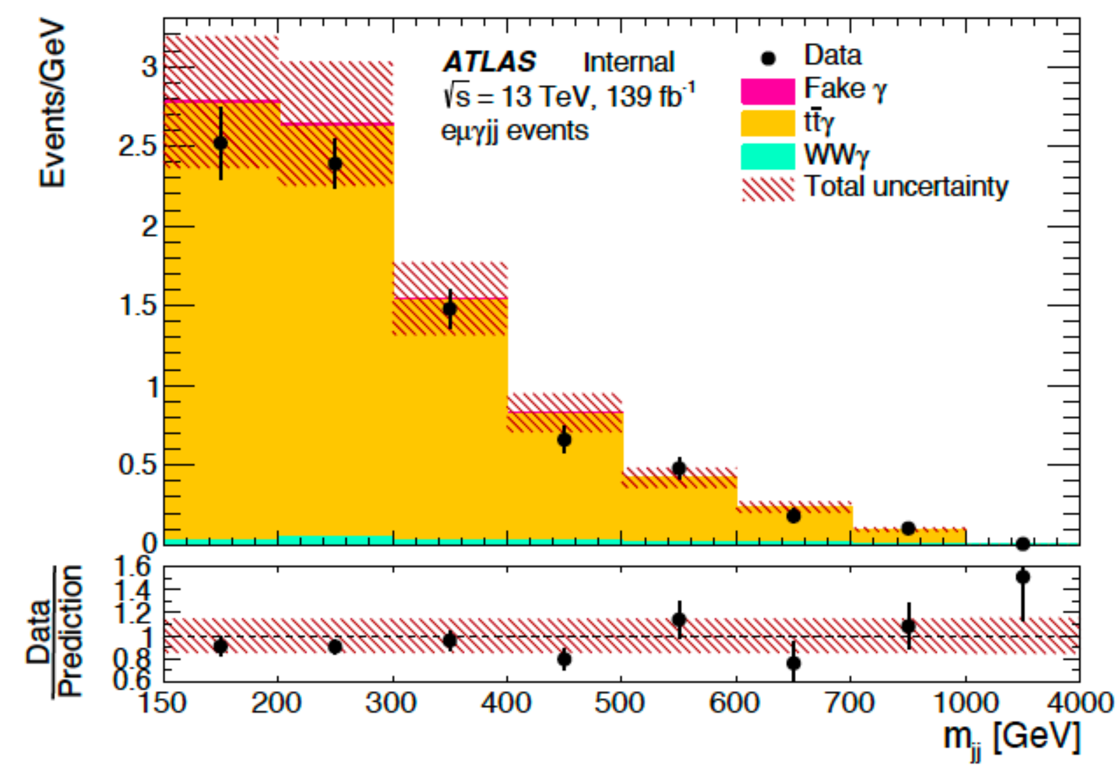
1. QCD-$Z\gamma jj$:
   - Dominant background
   - Constrained in QCD-$Z\gamma jj$ enriched control region



$t\bar{t}\gamma$

2. Z+jets:
   - Obtained from data-driven methods

3. $t\bar{t}\gamma$:
   - Estimated from simulation, validated in $e\mu\gamma$ control region



4. $WZjj$:
   - Estimated from simulation

Systematic Uncertainty: Experimental

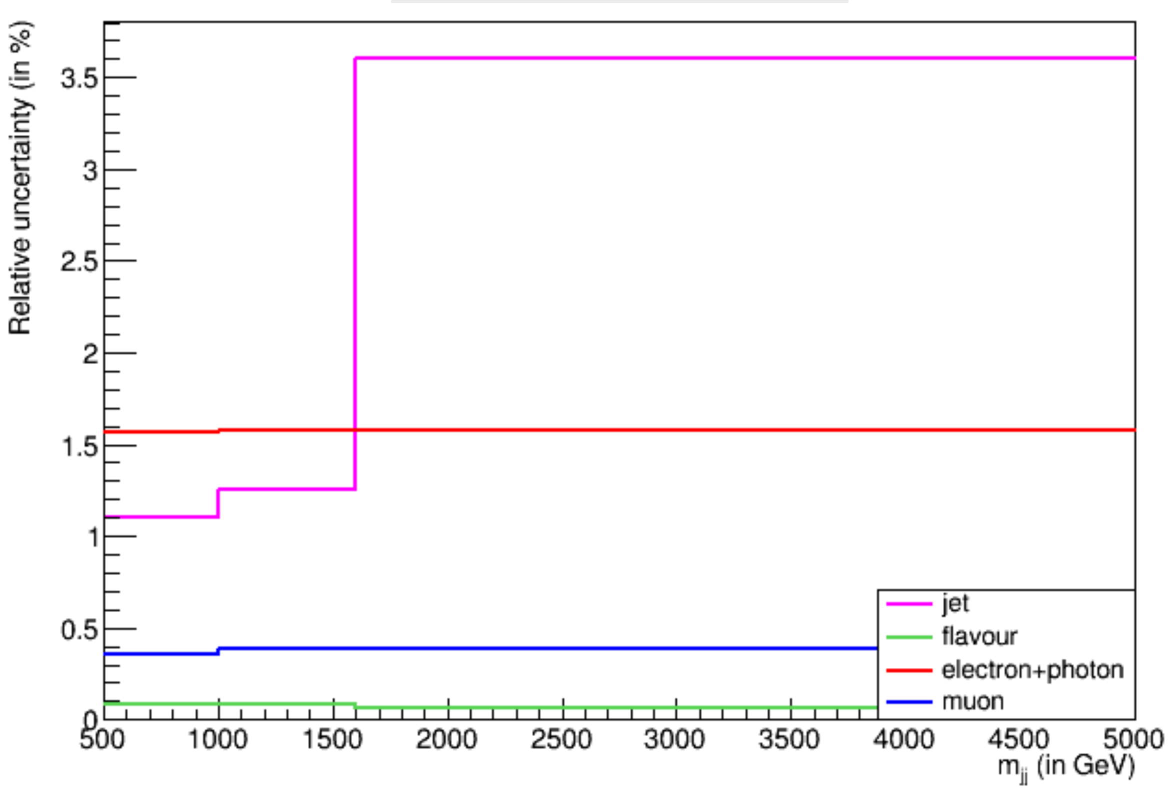
Reconstructed

- $Z\gamma jj$:
  - detector reconstruction of photons, leptons and jets
  - pileup* re-weighting: ~2%
- All samples:
  - luminosity: 0.83%

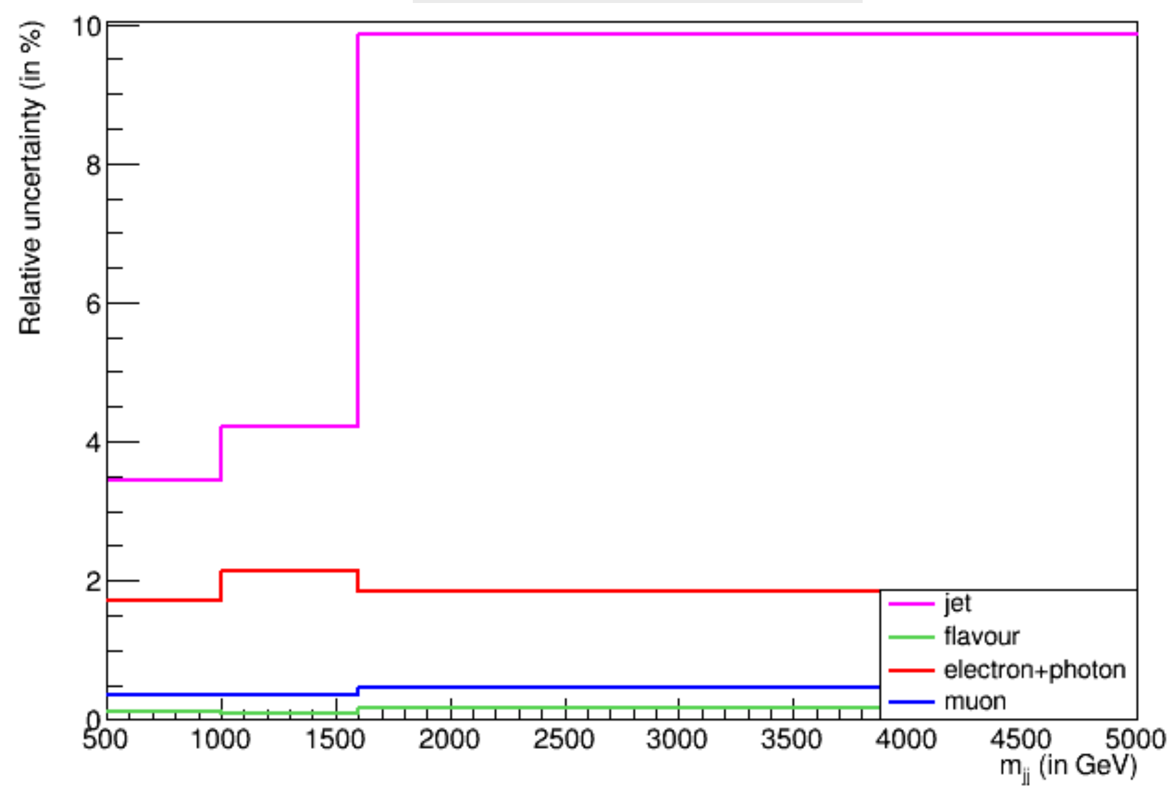
Background

- Z+jets:
  SR: 32% (stat.) and 21% (syst.)
  CR: 26% (stat.) and 18% (syst.)
- $t\bar{t}\gamma$: 15%
- $WZjj$: 20%

EW-$Z\gamma jj$, SR



QCD-$Z\gamma jj$, SR

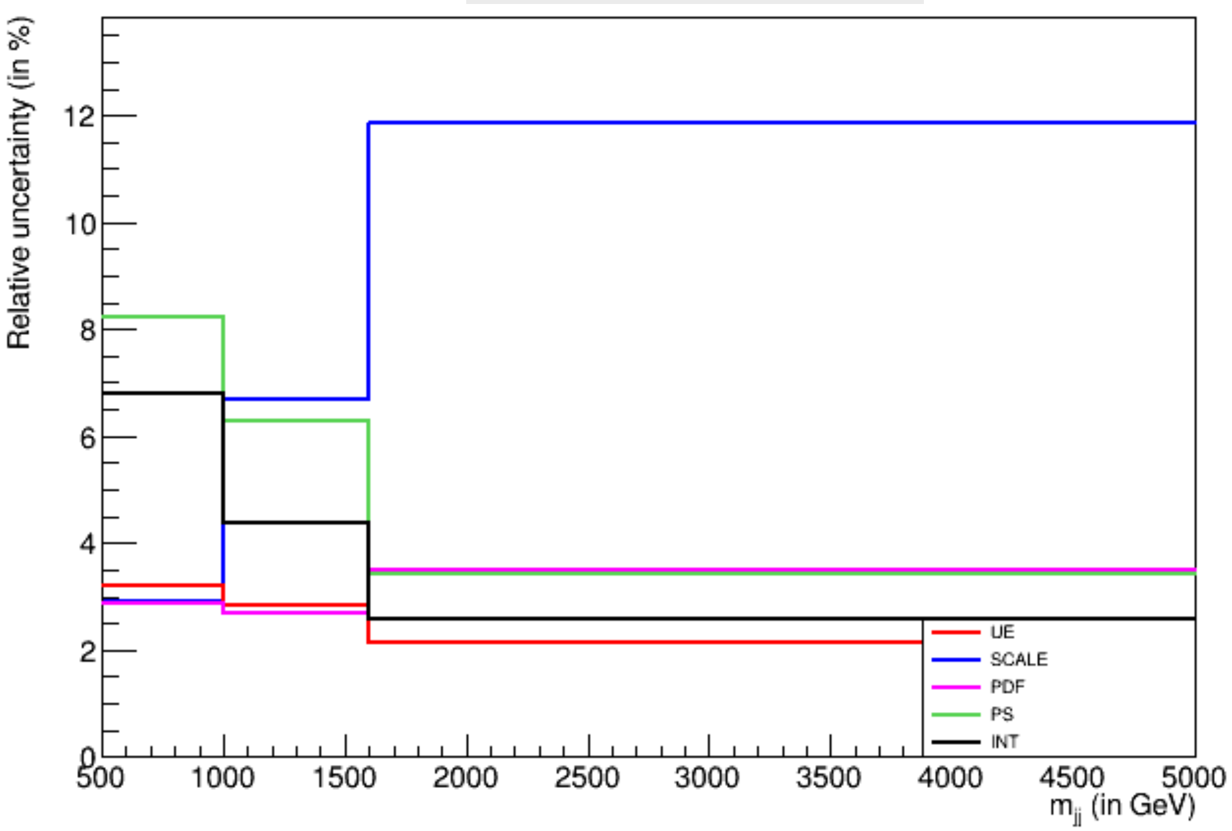


*additional pp collisions

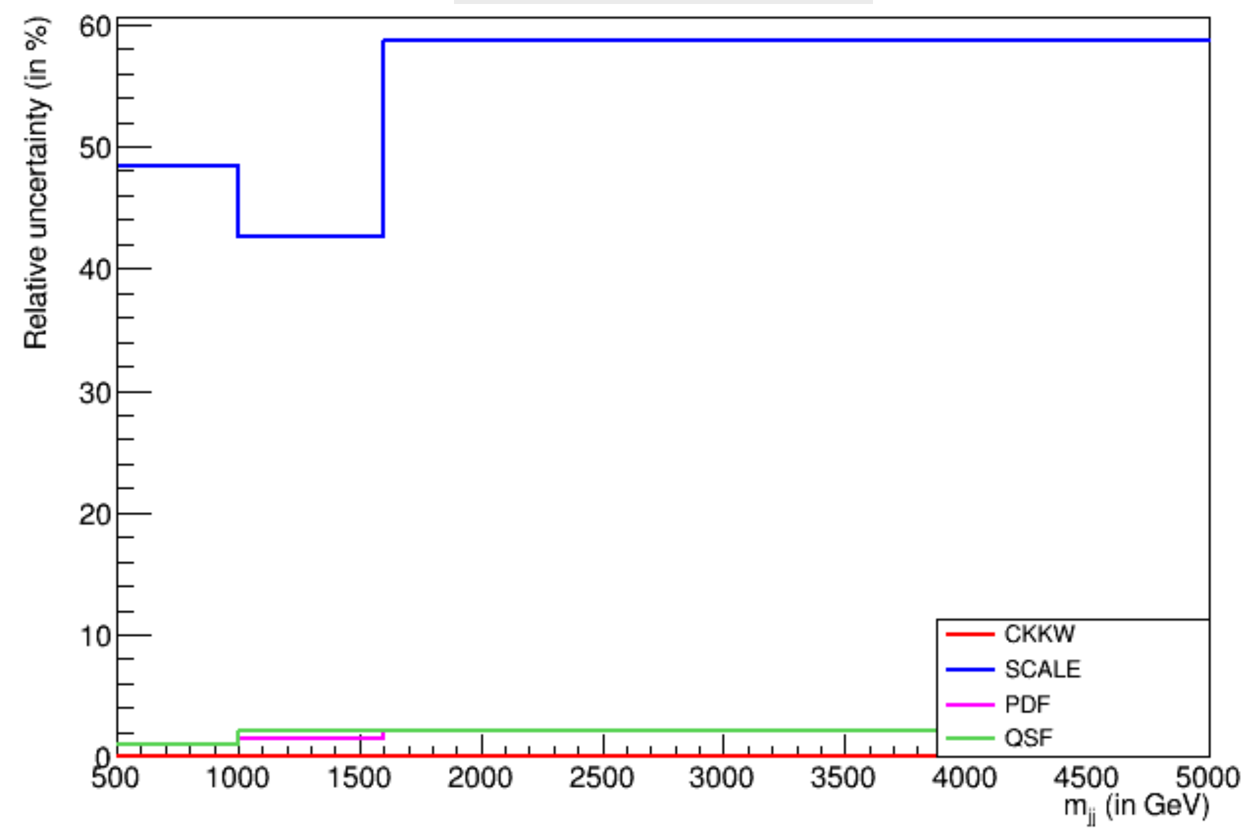
Systematic Uncertainty: Theoretical

- EW-$Z\gamma jj$:
    - interference between EW and QCD $Z\gamma jj$
    - theoretical modelling (parton shower, underlying event, scale, pdf)
- QCD-$Z\gamma jj$:
    - theoretical modelling (scale, pdf, merging scale CKKW, resummation scale QSF)

EW-$Z\gamma jj$, SR



QCD-$Z\gamma jj$, SR



Event Counts

	Signal Region	Control Region
EW $- Z\gamma jj$	262 ± 23	27 ± 7
QCD $- Z\gamma jj$	211 ± 15	196 ± 14
$Z +$ **jets**	22 ± 9	16 ± 6
$t\bar{t}\gamma$	16 ± 3	7 ± 1
$WZjj$	9 ± 2	4 ± 1
Total	520 ± 31	250 ± 17
Data	562 ± 24	274 ± 17

Pre-fit yields

Observation of EW-$Z\gamma jj$

Profile Likelihood Fit

Data

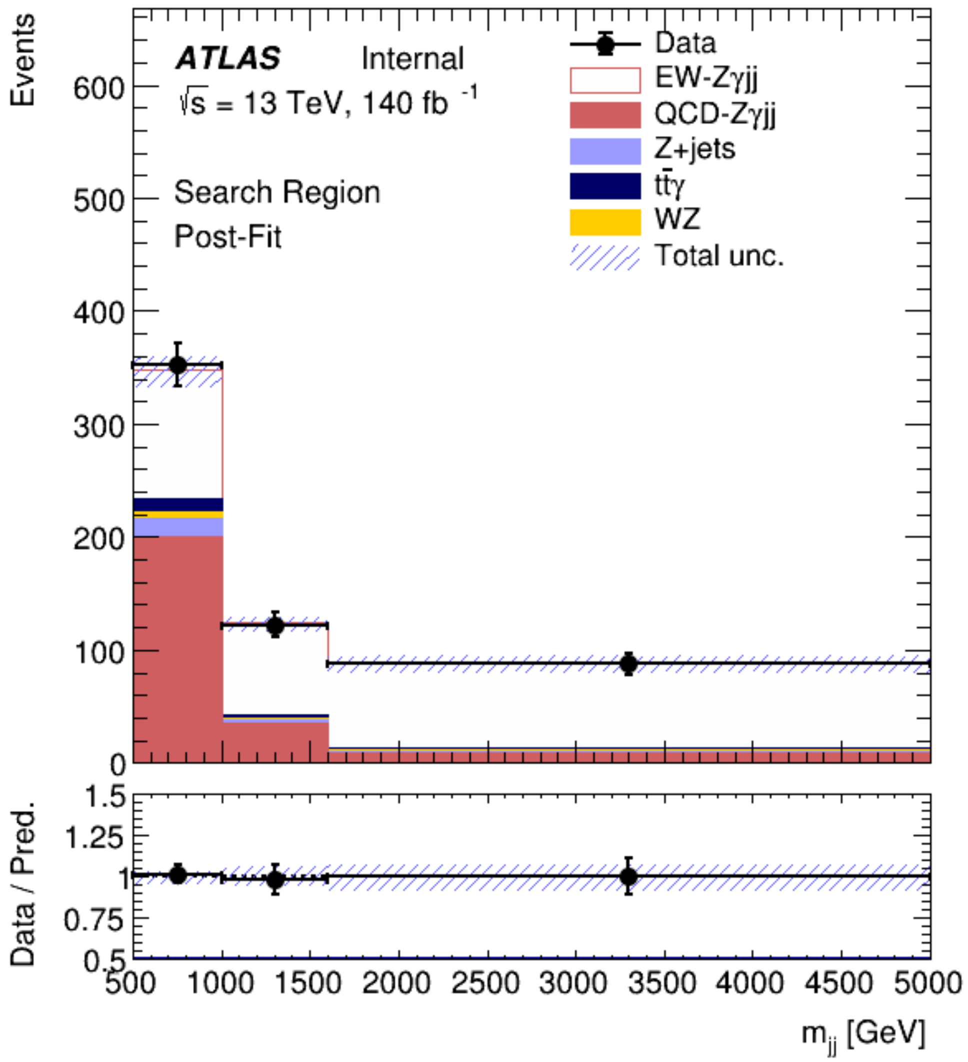
$$L(\mu, \vec{k}, \vec{\theta}, \vec{\gamma}) = \prod_{i \in \text{bins}} \text{Pois}(n_i | (\mu s_i(\vec{\theta}) + k b_i(\vec{\theta}))\gamma_i) \times \prod_{j \in \text{syst}} C(\theta_j | 0, 1) \times \prod_{i \in \text{bins}} C(\gamma_i | 1, \sigma_{\gamma_i})$$

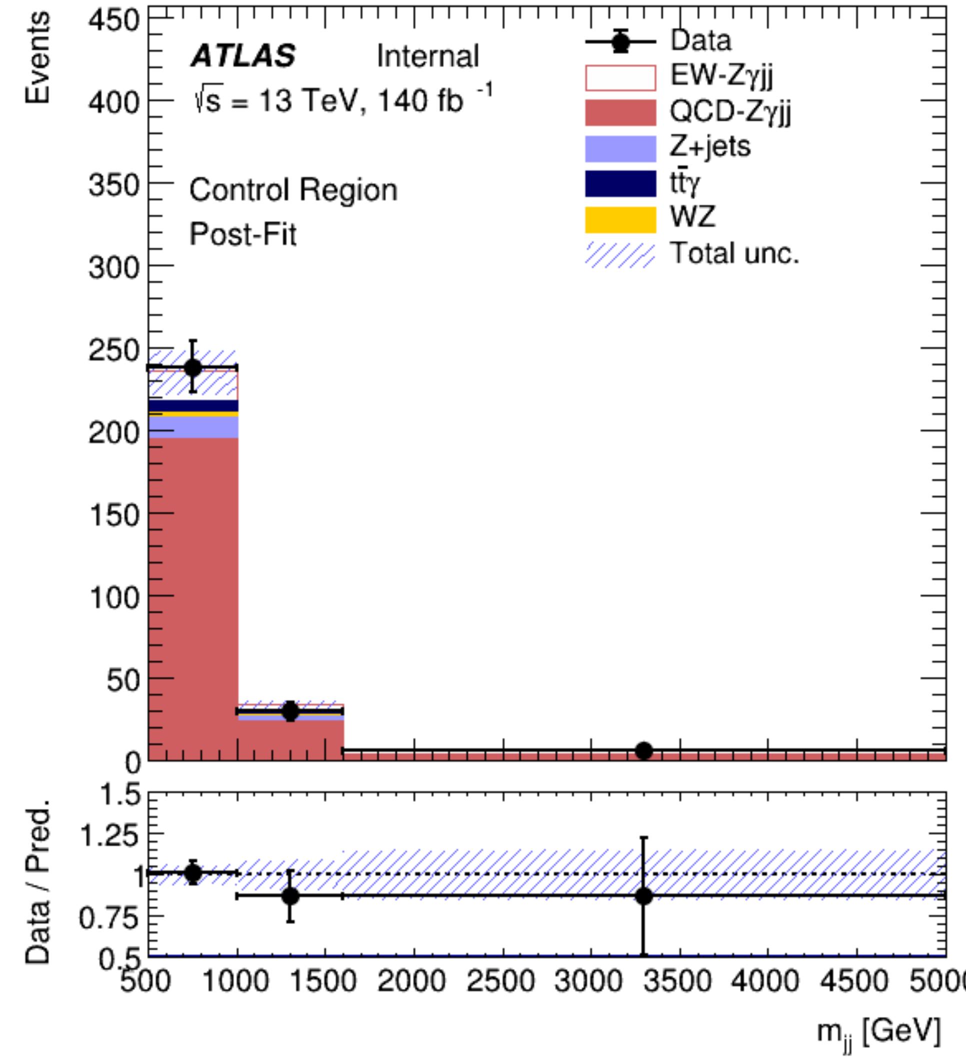
Prediction
(Signal+Background)

Goal: maximise L to estimate its parameters

- **Parameter of Interest:**
  - Unconstrained $\mu_{EW} = \sigma^{EW-Z\gamma jj}_{measured} / \sigma^{EW-Z\gamma jj}_{predicted}$
- **Nuisance Parameters:**
  - Unconstrained k: normalisation of QCD-$Z\gamma jj$
  - Constrained θ: experimental and theoretical systematic uncertainties
  - Constrained γ: systematic uncertainty due to finite size of simulation

Results





$$\mu_{EW} = 1.02^{+0.13}_{-0.12}$$
$$= 1.02 \pm 0.09(stat.) \pm 0.09(syst.)$$

Dominant systematics: EW-$Z\gamma jj$ modelling

$$\boxed{\sigma_{EW} = 3.6 \pm 0.5 \text{ fb}}$$

$$\mu_{QCD} = 1.18^{+0.10}_{-0.10}$$

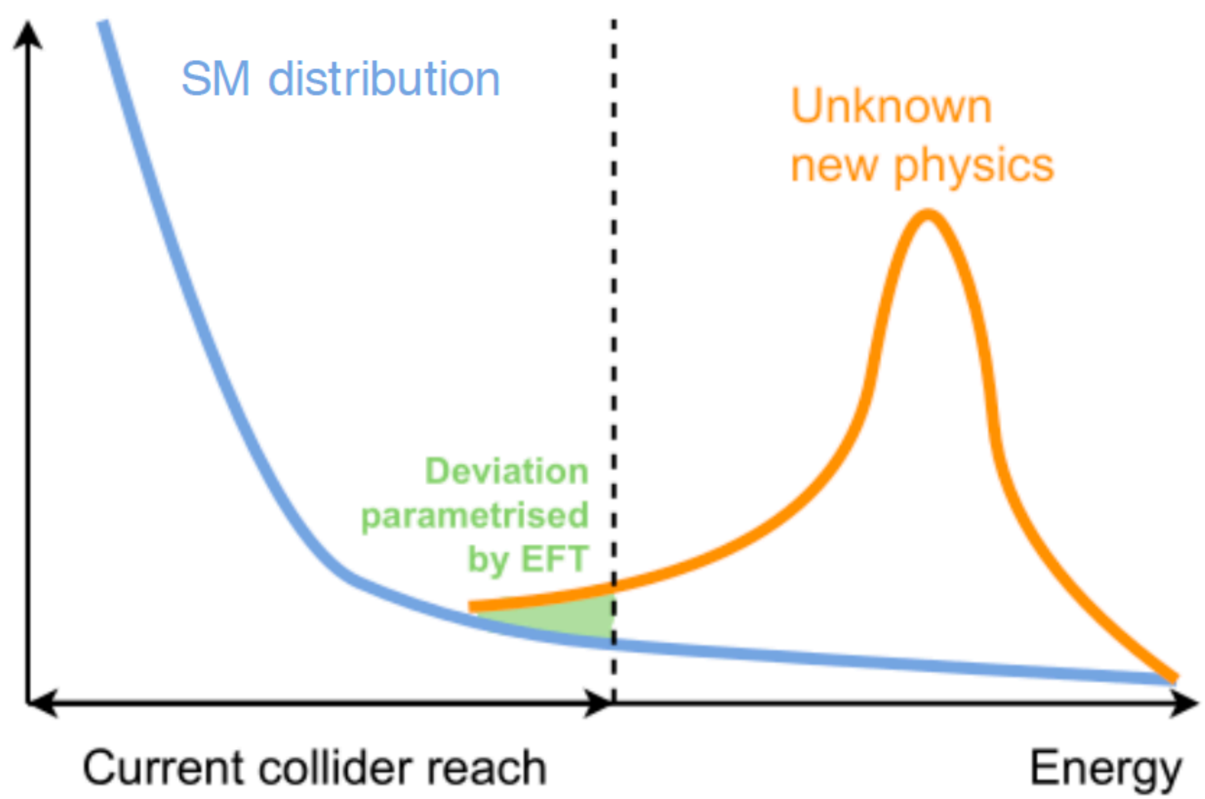
$$\sigma^{pred}_{EW} = 3.5 \pm 0.2 \text{ fb}$$

First observation of EW-$Z\gamma jj$ with ATLAS

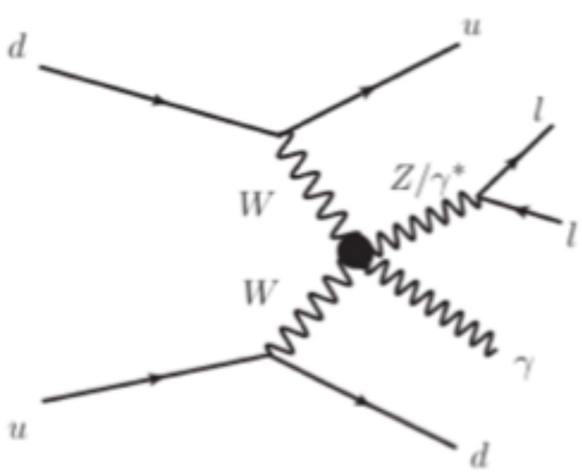
Differential Measurements of EW-$Z\gamma jj$

Motivation

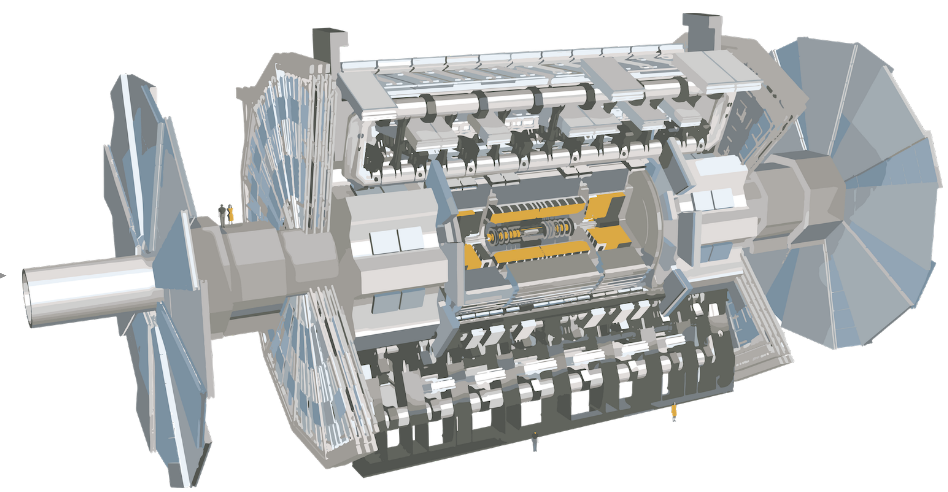
- sensitive to Effective Field Theory (EFT) studies
- improve modelling of EW-$Z\gamma jj$



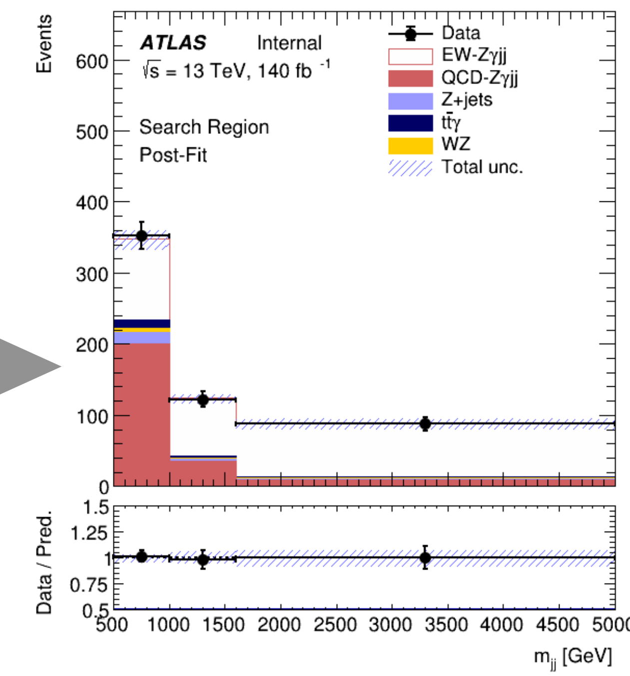
Unfolding



Particle level



Detector



Measured distribution

?

Correcting the measured distribution for detector effects

- Direct comparison to theoretical predictions
- Enables comparison of measurement of various experiments with different detector effects

Goal: to perform EW-$Z\gamma jj$ unfolding and measure differential cross sections

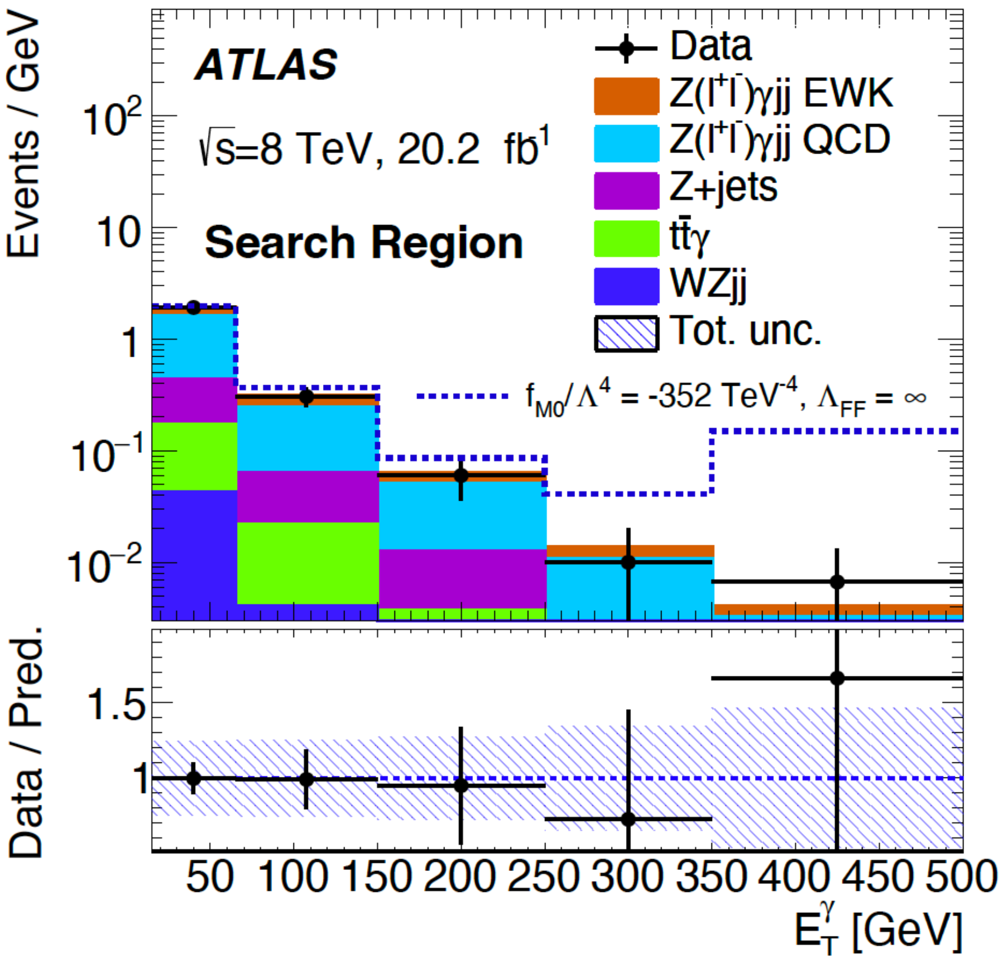
EW-$Z\gamma jj$: Unfolding Variables

Focus of talk!

- Modelling studies: m_{jj}, $|\Delta y_{jj}|$, p_T^l, p_T^j

Typical VBS variables

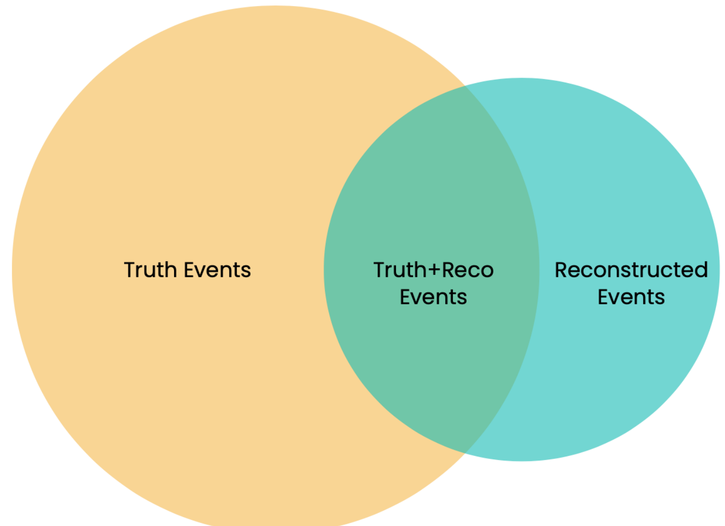
- Sensitive to EFT studies: $p_T^{Z\gamma}$, E_T^{γ}, $|\Delta\phi(Z\gamma, jj)|$



My work

EW-$Z\gamma jj$: Unfolding Inputs

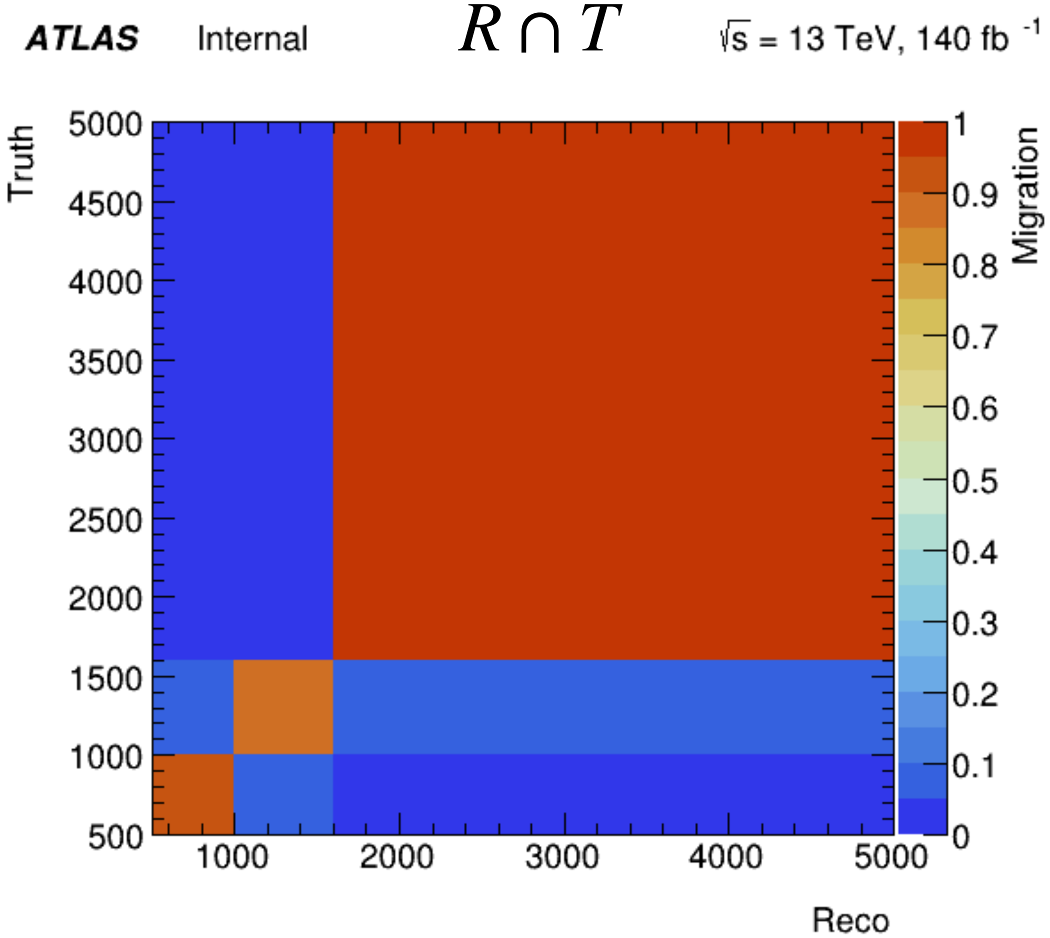
Truth: simulation of particle level physics model



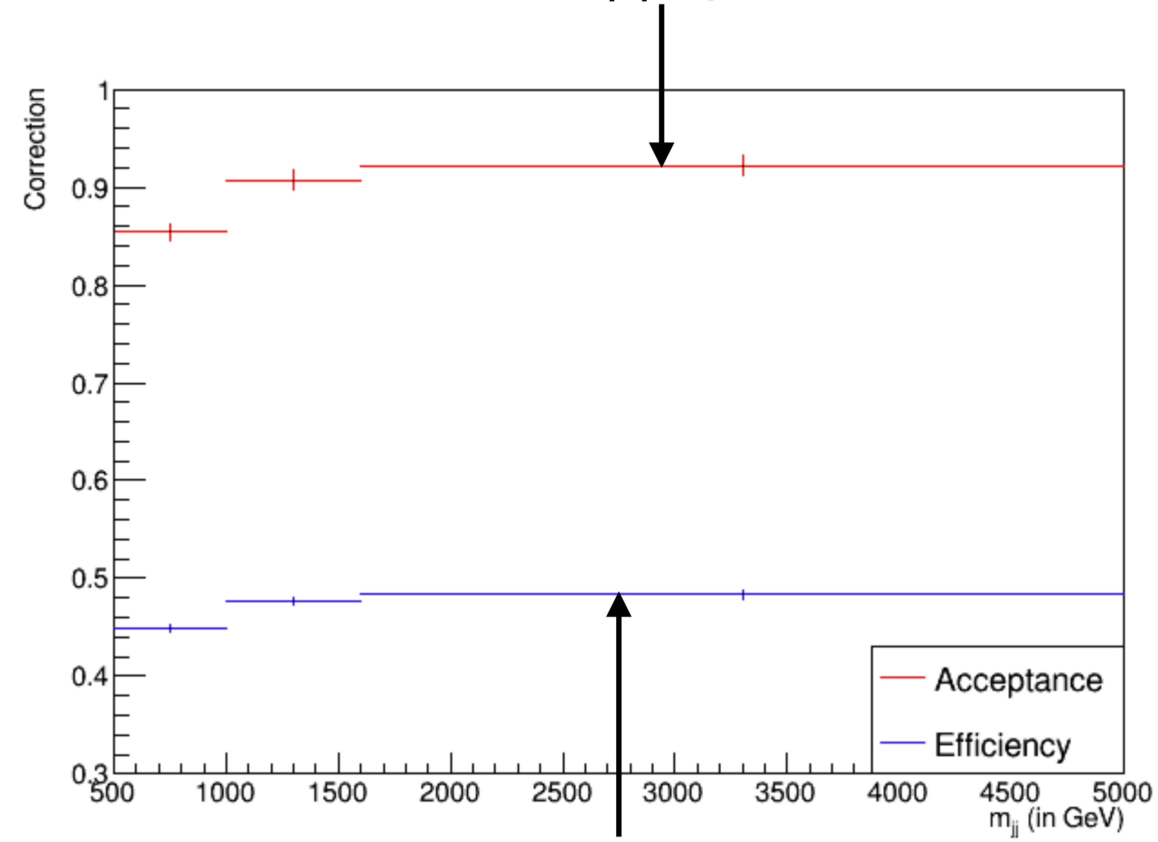
Reconstructed: simulation of measured data

Migration matrix:

$R \cap T$



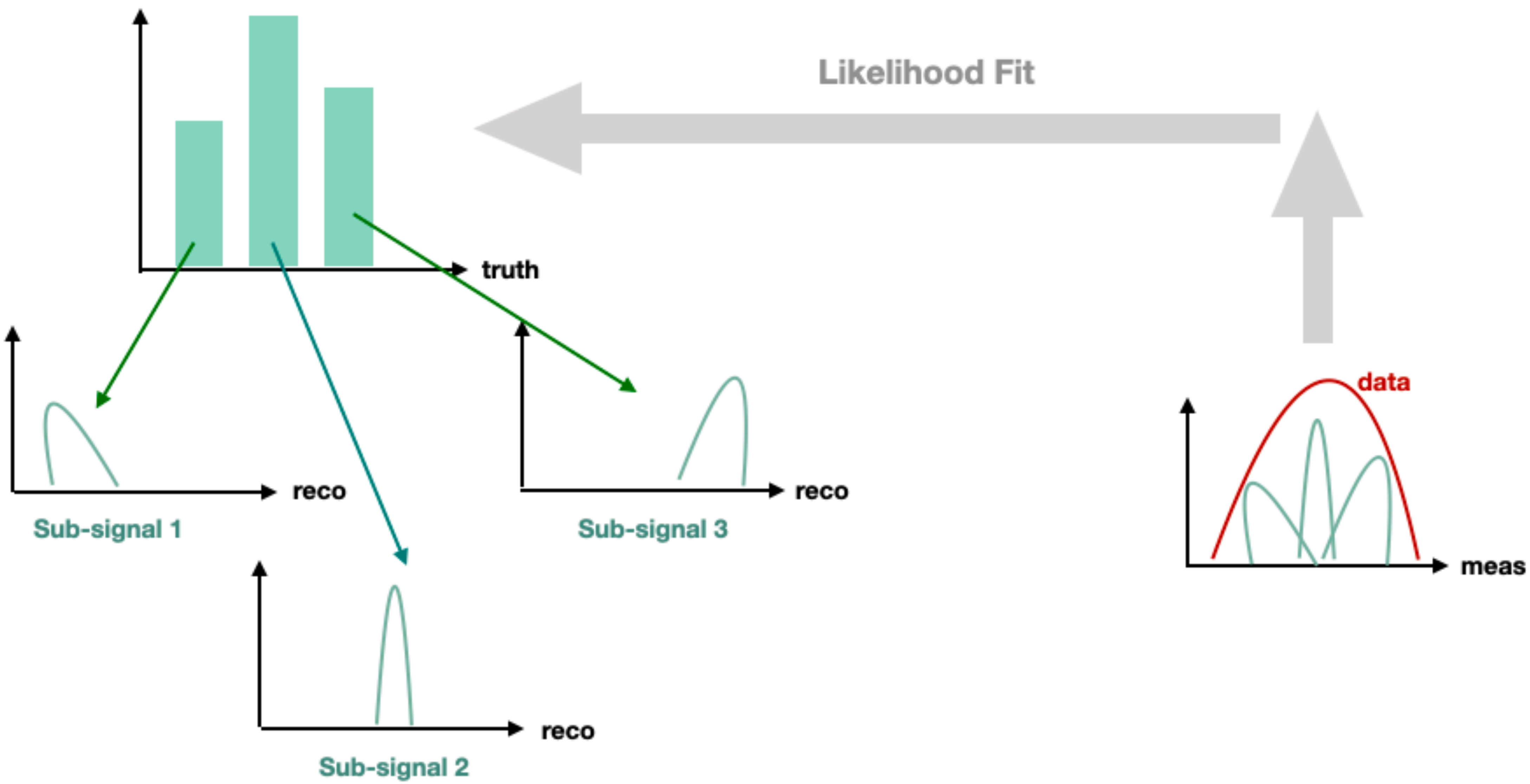
$R \cap T / R$



$R \cap T / T$

Detector response = $\dfrac{1}{acc} \cdot M \cdot eff$

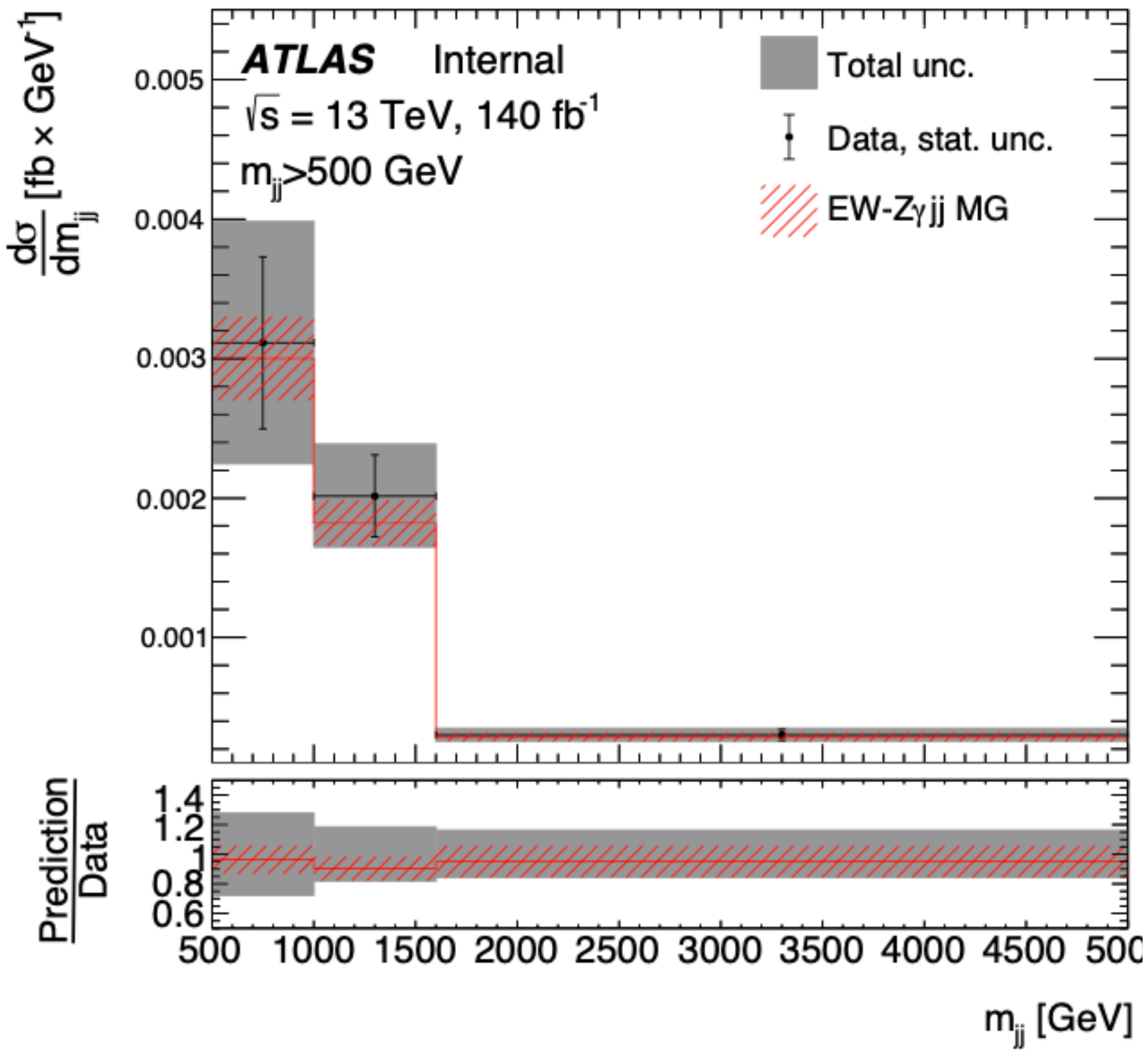
Profile Likelihood Unfolding

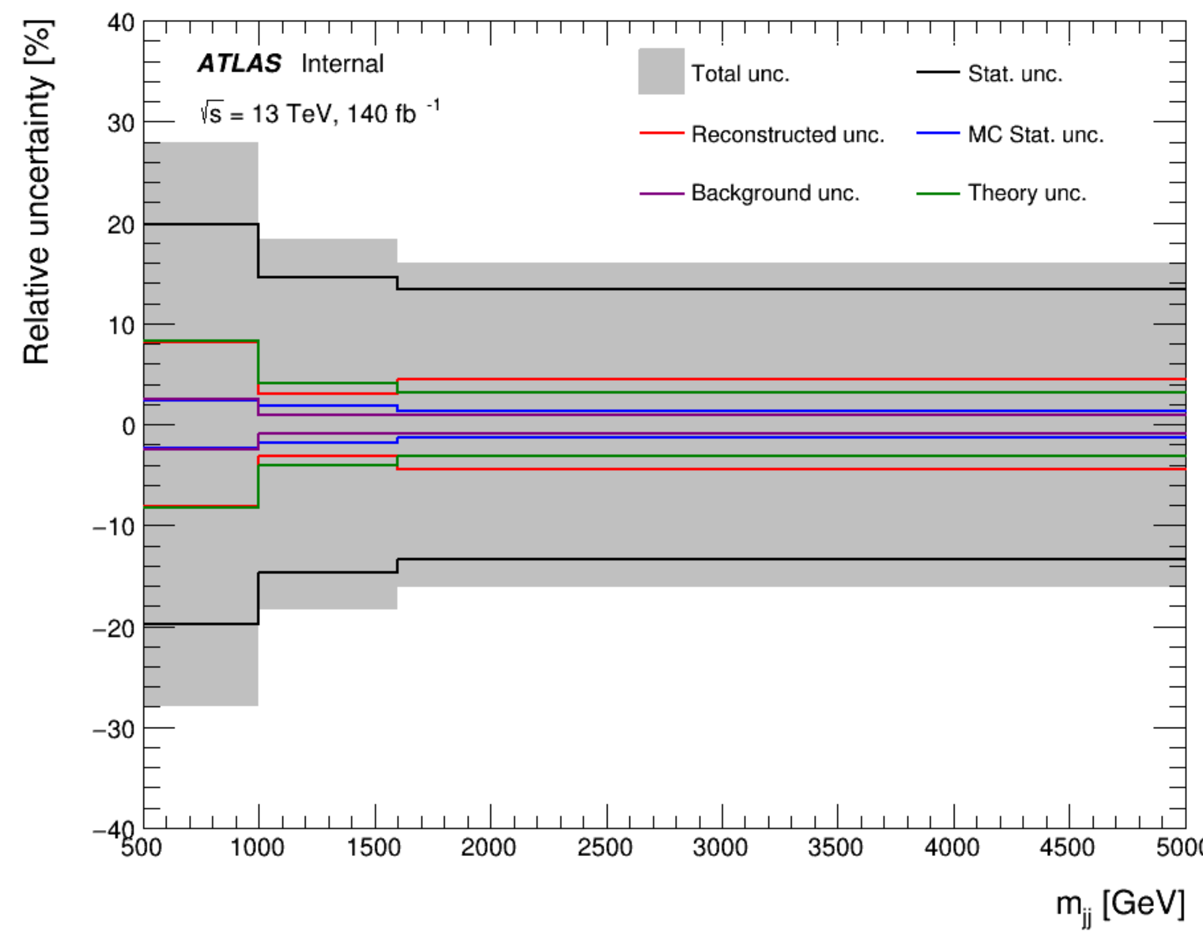


Simultaneously constrain normalisation of QCD-$Z\gamma jj$ bin-by-bin

Results

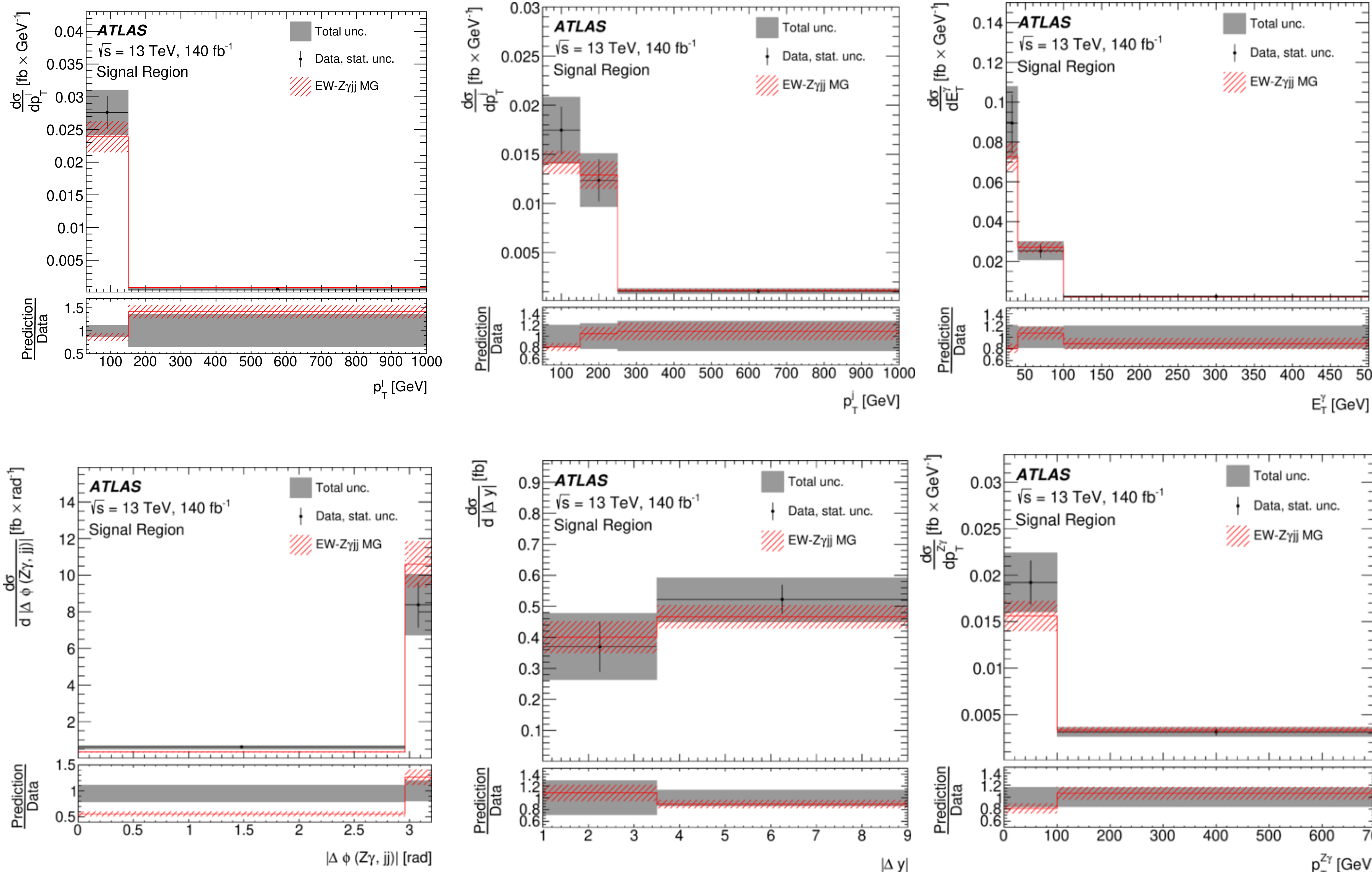
Differential measurements performed **first time for EW-$VVjj$ with ATLAS**





Statistics dominated uncertainty, results are consistent within 1σ of SM

Results (II)


ATLAS
√s = 13 TeV, 140 fb-1
Signal Region
Total unc.
Data, stat. unc.
EW-Zγjj MG
Prediction / Data
dσ/dp_T^j [fb × GeV-1]
p_T^j [GeV]
dσ/dE_T^γ [fb × GeV-1]
E_T^γ [GeV]
dσ/d|Δ φ (Zγ, jj)| [fb × rad-1]
|Δ φ (Zγ, jj)| [rad]
dσ/d|Δ y| [fb]
|Δ y|
dσ/dp_T^Zγ [fb × GeV-1]
p_T^Zγ [GeV]

Conclusion

- **HL-LHC Upgrade of Liquid Argon Electronic Calibration Board:**
  - Calibration chip: performed irradiation tests on a prototype
  - Calibration board: designed and performed uniformity tests on first prototype
  - Tests on new prototypes are underway!
- $Z\gamma$ **Vector Boson Scattering (Run 2):**
  - First observation of EW-$Z\gamma jj$ with ATLAS
  - First differential cross section measurements of EW-$VVjj$ with ATLAS
    - $p_T^{Z\gamma}$ and $|\Delta\phi(Z\gamma, jj)|$ have been measured differentially for first time at LHC
  - Next: EFT interpretation

Prospectives of EW-$Z(\rightarrow ll)\gamma jj$ with ATLAS

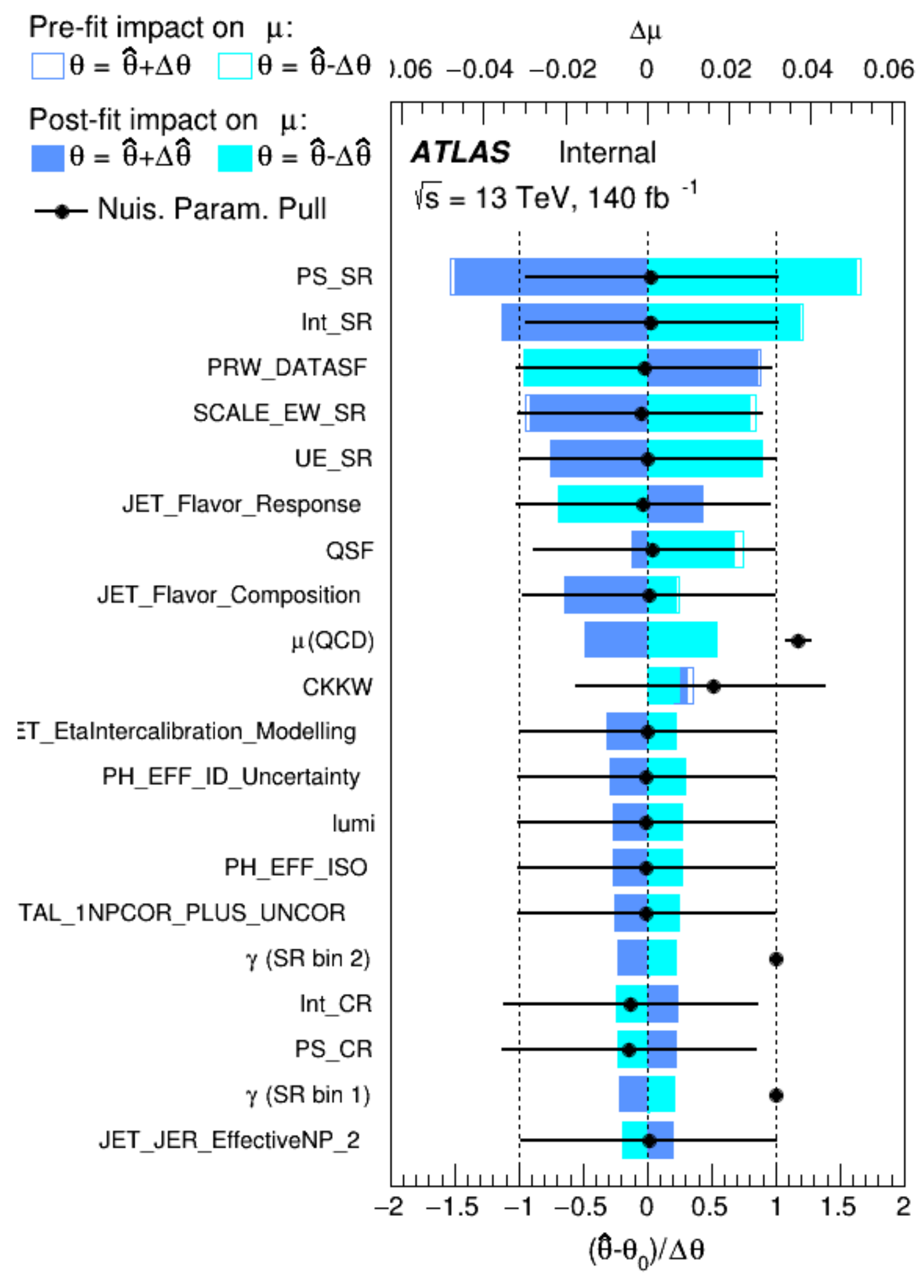
Run	Integrated Luminosity (in fb inverse)	Statistical Uncertainty (in %)
Run 2	140	0.09
Run 3	300	0.06
HL-LHC	4000	0.02

- **Run 3:**
  - Improved quark/gluon tagger
- **HL-LHC:**
  - Upgraded inner tracker (ITk): extending pseudorapidity up to $|\eta|$=4.0
  - High Granularity Timing Detector (HGTD): aid reconstruction of leptons and jets in forward region
- **Improved theory modelling and better treatment of interference**

Backup

EW-$Z\gamma jj$ Production Cross Section: Uncertainty

Uncertainty	Value
Monte Carlo Statistics	$\pm 1\%$
Background ($t\bar{t}\gamma$, $WZjj$, Z+jets) Systematics	$\pm 1\%$
Experimental Systematics	$\pm 4\%$
EW-$Z\gamma jj$ Theory Systematics	$+8/\text{-}6\%$
QCD–$Z\gamma jj$ Theory Systematics	$\pm 2\%$
Data Statistics	$\pm 9\%$
Total	$+13\%/\text{-}12\%$



ATLAS and CMS: EW-$Z(\to ll)\gamma jj$

ATLAS

- **SR**: $m_{jj} > 500$ GeV, $|\Delta y_{jj}| > 1$, $N_{jets}^{gap} = 0$, $\zeta(Z\gamma) < 0.4$
- **CR**: $\zeta(Z\gamma) > 0.4$

CMS

- **SR**: $m_{jj} > 500$ GeV, $|\Delta\eta_{jj}| > 2.5$, $\Delta\phi(Z\gamma, jj) > 1.9$, $\eta* < 2.4$
- **CR**: 150 GeV $< m_{jj} <$ 500 GeV

Production Cross Section

$$\mu_{EW}^{ATLAS} = 1.02^{+0.13}_{-0.12}$$

$$\mu_{EW}^{CMS} = 1.20^{+0.18}_{-0.17}$$

Differential variables: m_{jj}, $|\Delta y_{jj}|$, p_T^l, p_T^j, E_T^γ, $p_T^{Z\gamma}, |\Delta\phi(Z\gamma, jj)|$

Precision per bin within ~30%

Differential variables: $m_{jj} - |\Delta\eta_{jj}|$, p_T^l, p_T^j, p_T^γ

Precision per bin within ~45%

Results from both experiments are consistent with SM

$\eta* = |\eta_{Z\gamma} - (\eta_{j1} + \eta_{j2})/2|$

CMS: EW-$Z(\to ll)\gamma jj$ Differential Measurements