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LHC PHYSICS EXPECTATIONS AT RUN3 AND HL-LHC

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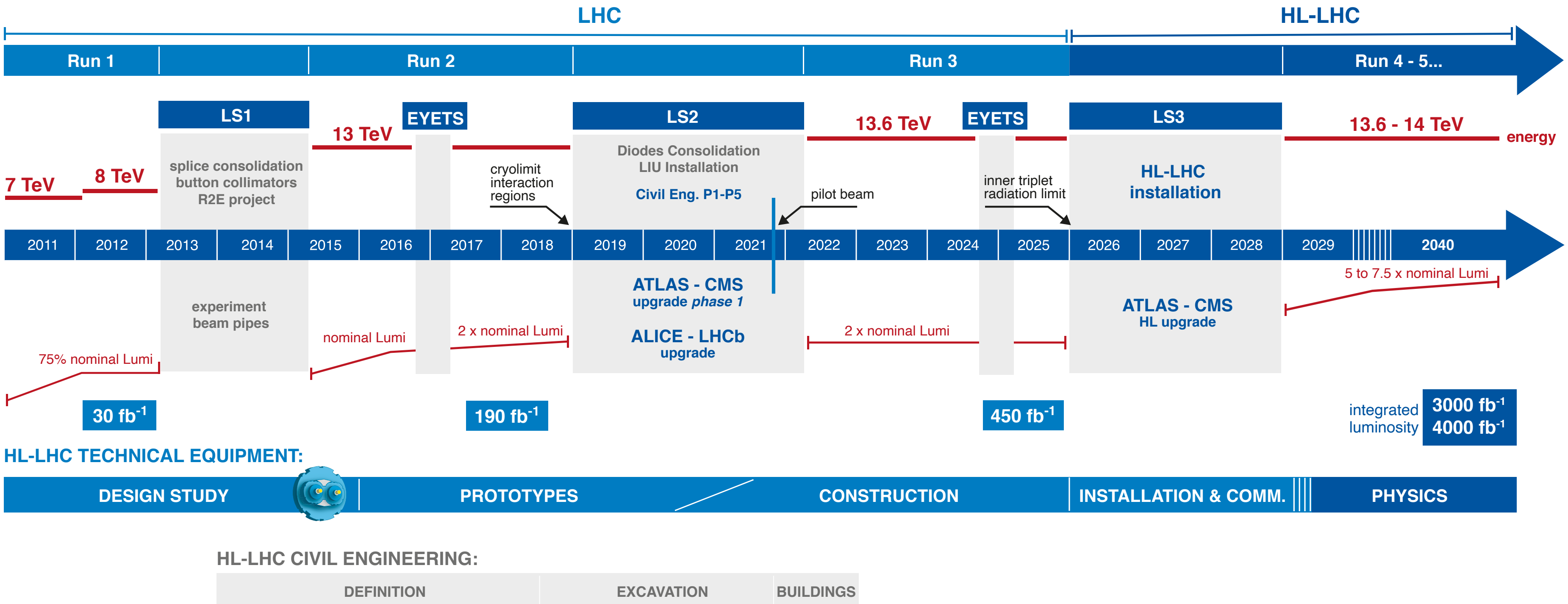
On behalf of the ATLAS,ALICE,CMS and LHCb collaborations

LHC Days, Sept 30-Oct 4 2024, Hvar,Kroatia

Overview

- Sensitivity improvements from luminosity and upgrades
- Physics expectations
  - Precision physics
  - Higgs and the Higgs potential
  - New physics and supersymmetry reaches
- ALICE upgrades and expectations
- LHCb upgrades and the CKM matrix
- New analysis techniques

LHC / HL-LHC Plan

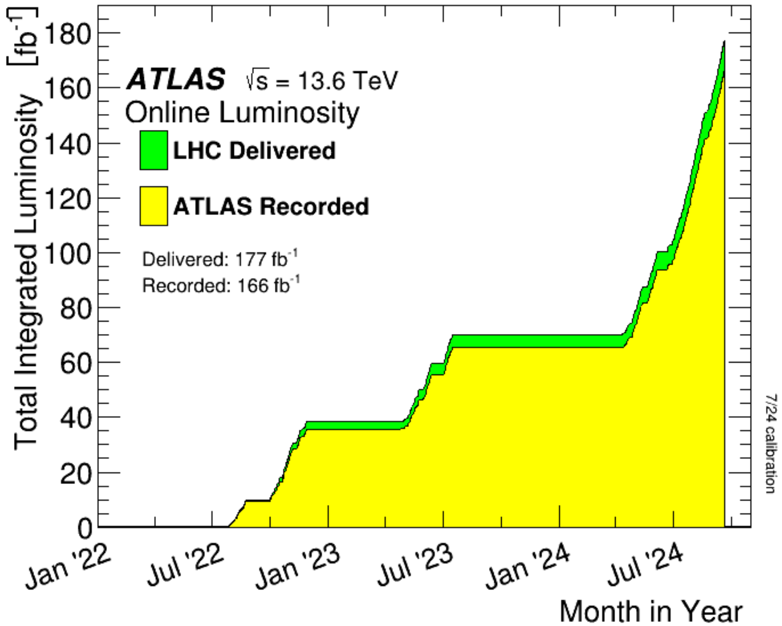


Schedule Update

O. Brüning @ Higgs Hunting Workshop, Paris, 25th September 2024

Luminosity expectations

- LHC 'Nominal Luminosity': $L_{nom} = 10^{34}\ cm^{-2}s^{-1}$
- Run3: $2xL_{nom}$ →Expected grand total: 450 fb^{-1}
  - LHC is delivering as scheduled, at 13.6 TeV

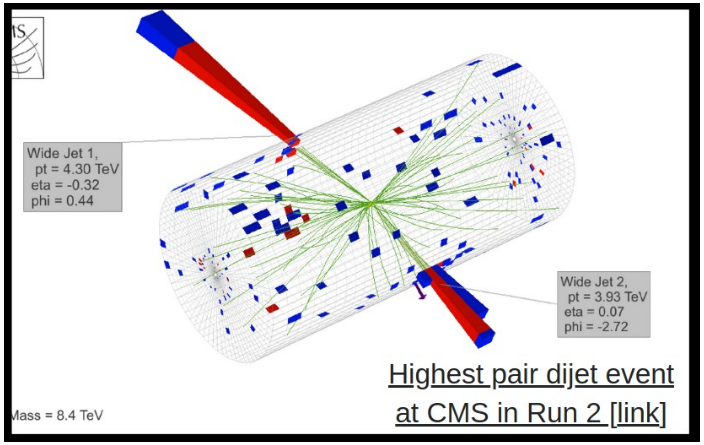


- HL-LHC 5-7xL_{nom} → 3000-4000 fb^{-1}

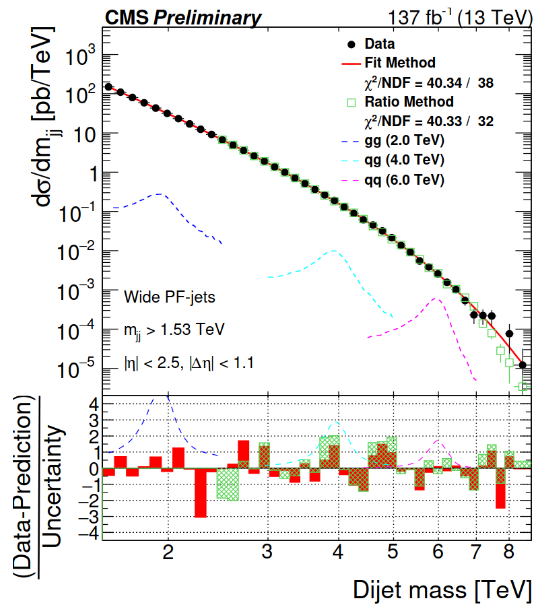
Some interesting hints in current data

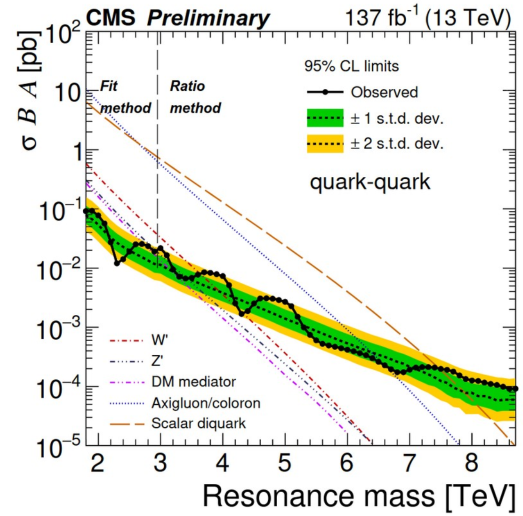
Example: CMS dijet spectrum

(CMS PAS EXO-12-012-19)



Highest pair dijet event at CMS in Run 2 [link]

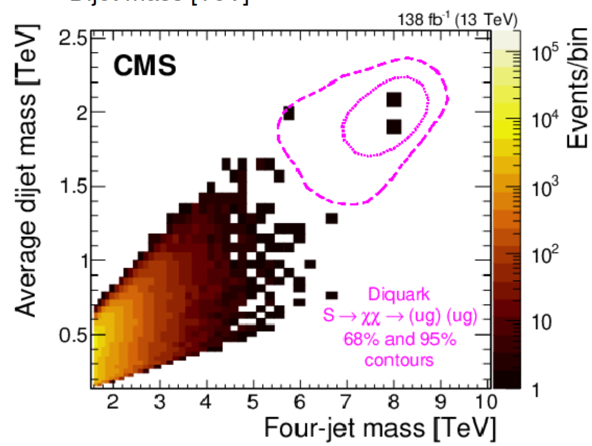




From Livia Soff ICHEP2024

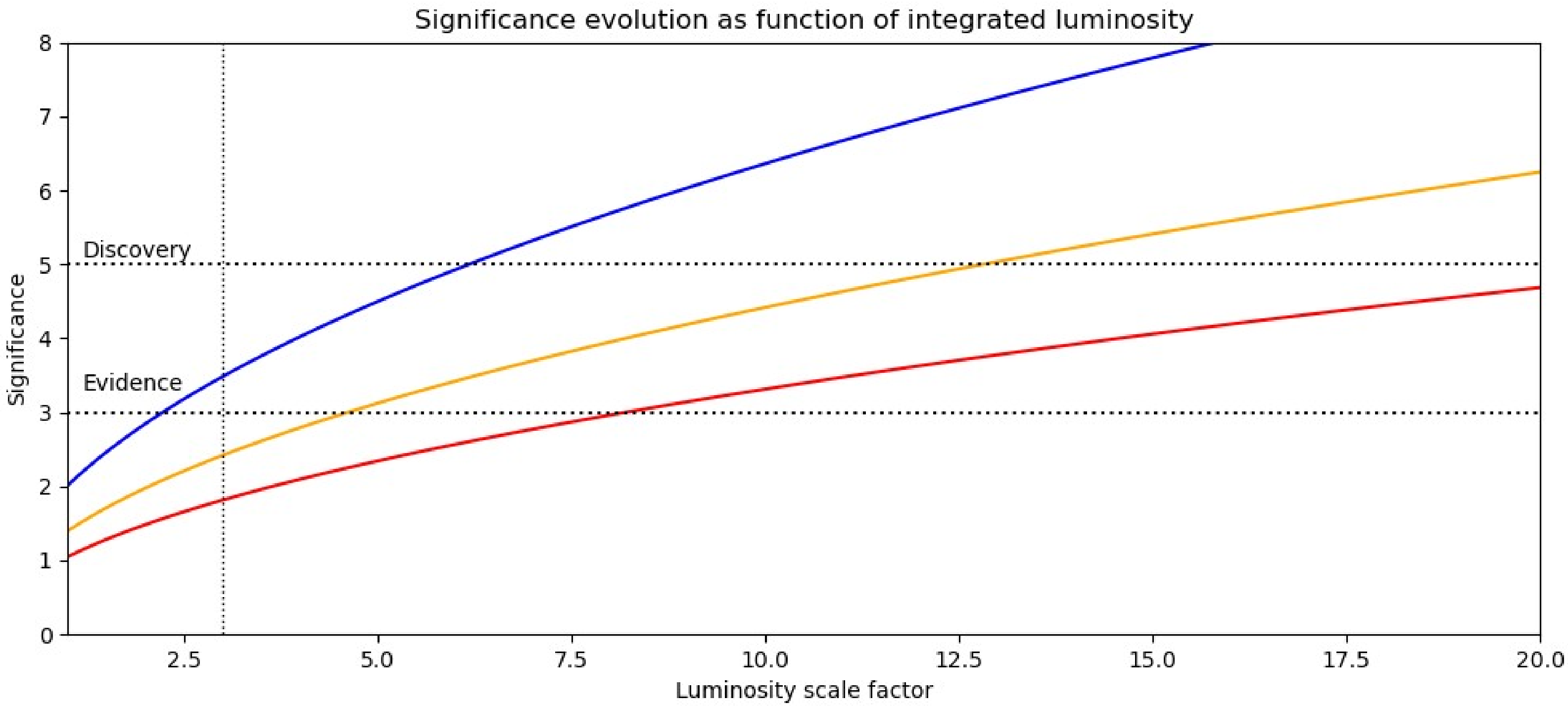
...and a 2.5 σ 4-jet excess

CMS-EXO-21-010



Less that 10% of expected dataset is collected so far! And just 5% fully analyzed (about 140 fb^{-1})

Significance evolution of present fluctuations of 1, 1.5 and 2 σ

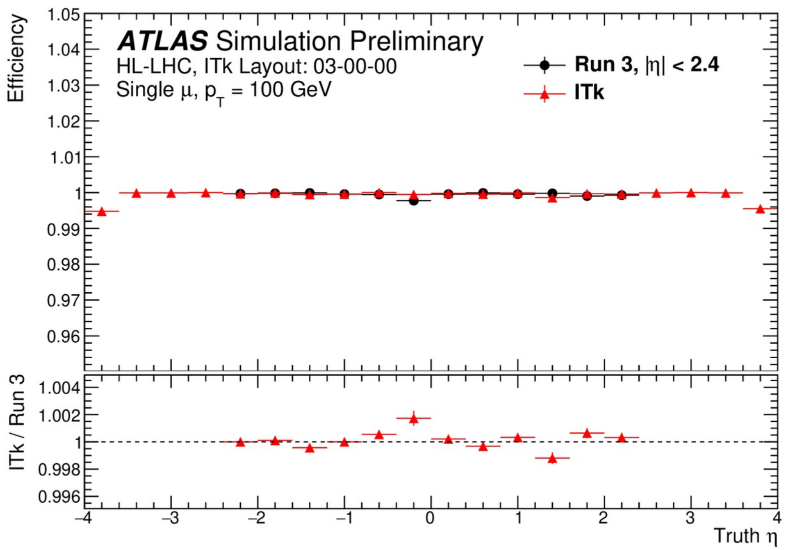


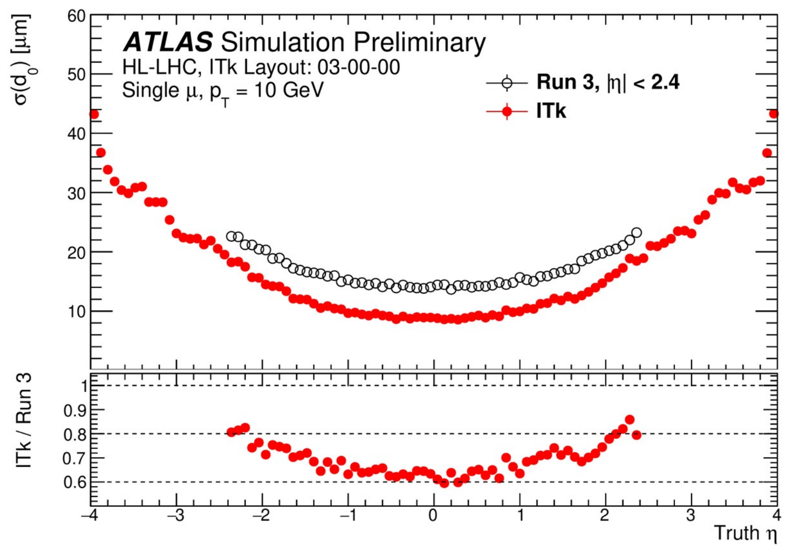
Own plot

Cowan et al. Eur.Phys. J.C. (2011) 71 $Z = \sqrt{2(s+b)\ln\left(1+s/b\right) - s}$

Detector and software upgrades should result in **MUCH** better sensitivity than inferred from simple luminosity scaling!

- Energy 13.6 - 14 TeV
- Detector upgrades (previous two talks cover ATLAS and CMS)
  - e.g. increased solid angle and improved vertexing





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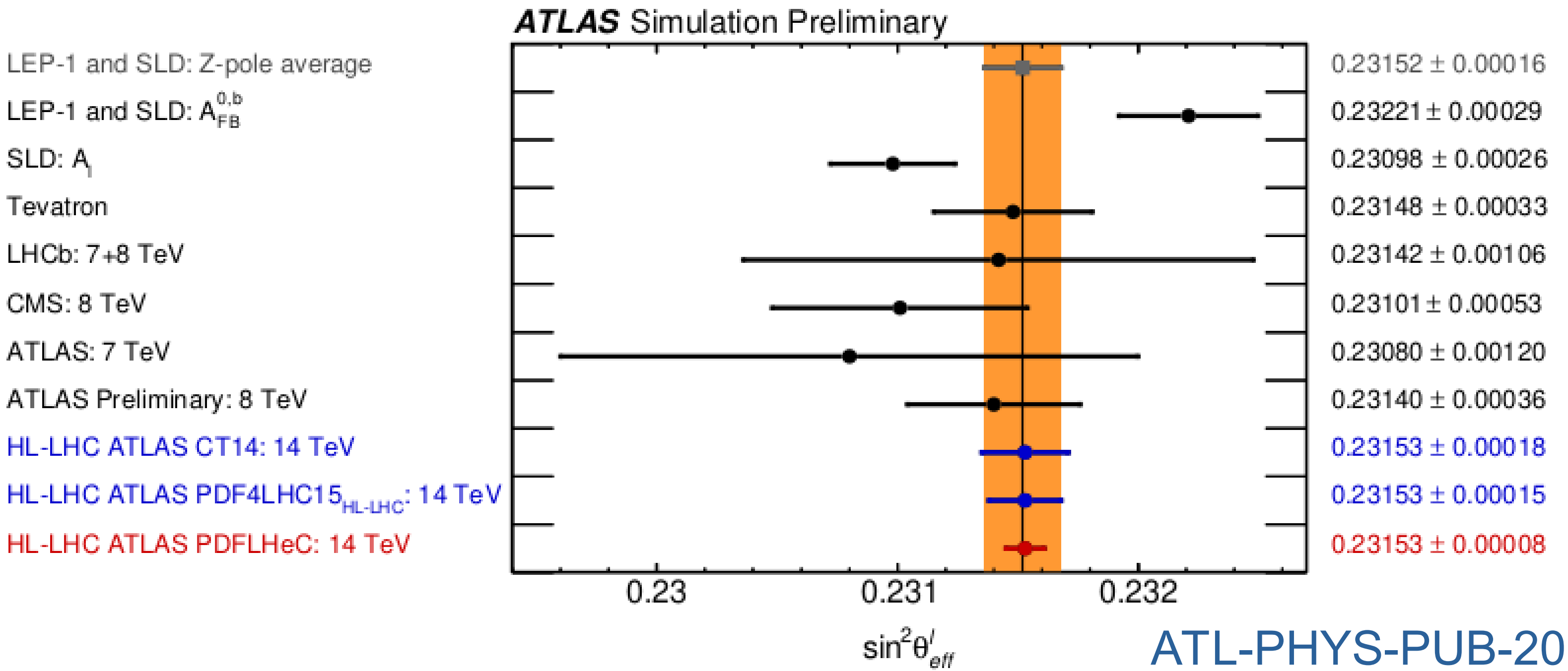
Precision measurements of the electroweak mixing angle

Measuring $\sin^2 \theta_{ew}$ using forward-backward asymmetry in Drell-Yan dileptons benefits from statistics, **improved forward electron reconstruction (including timing information for isolation)** where sensitivity to $\sin^2 \theta_{ew}$ highest.

Should settle LEP-1 – SLD discrepancy

Uncertainty is dominated by Parton Density Function uncertainty



ATL-PHYS-PUB-2018-037

Higgs: the last piece in the SM puzzle. Does it fit?

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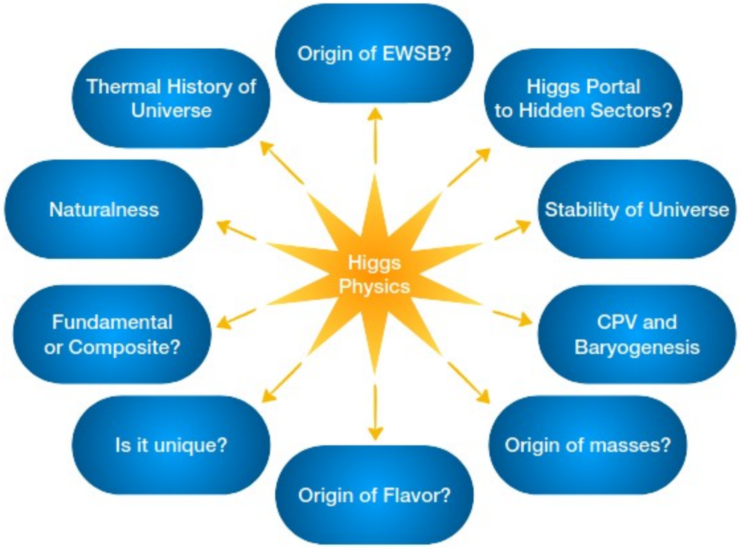
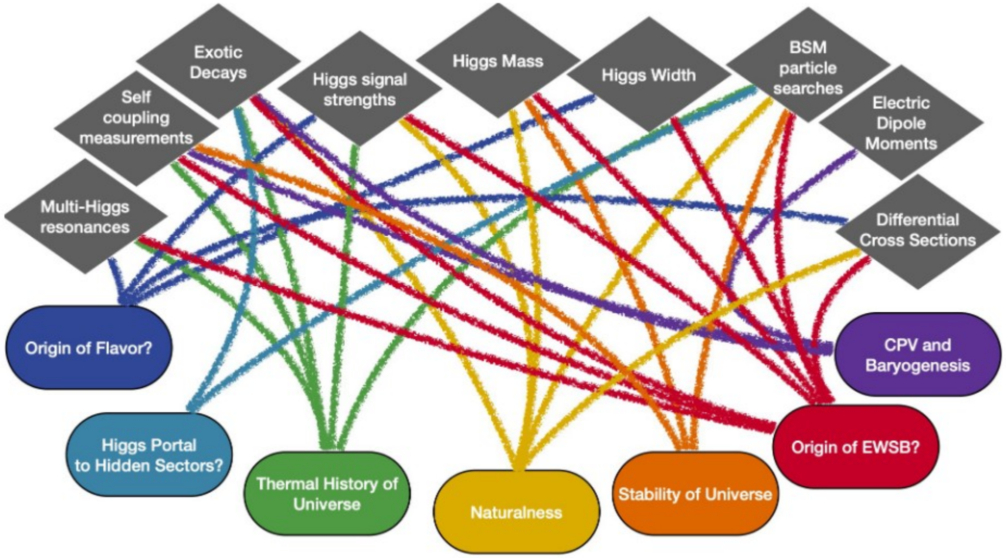
Higgs: the last piece in the SM puzzle. Does it fit?

Or a gateway to a new puzzle?
(Dark matter/Energy etc.)

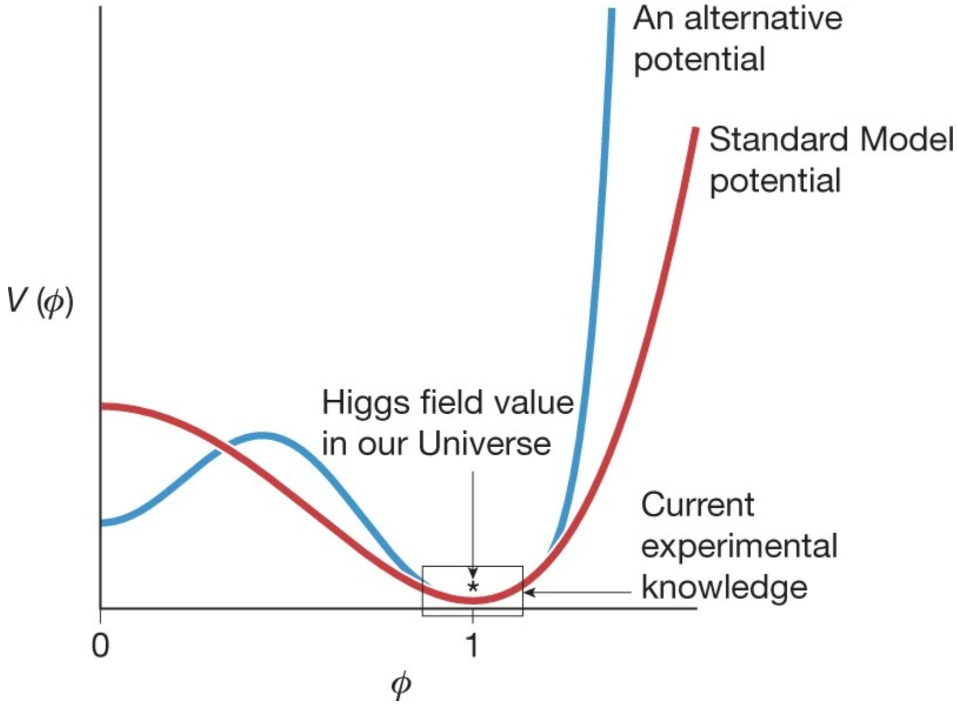
Higgs properties and BSM physics have many implications



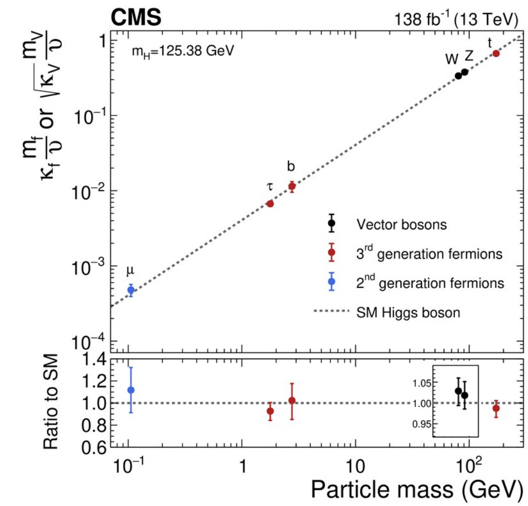


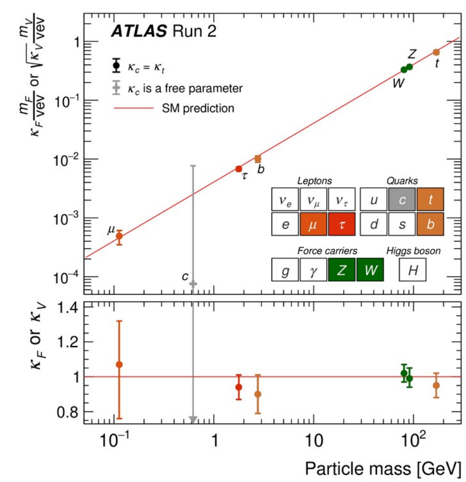
From ’Snowmass 2021’: ArXiv:2209.07510

Current knowledge:



Salam,Wang,Zanderighi Nature 607,41(2022)





..mainly about couplings to 3rd. generation fermions and heavy bosons

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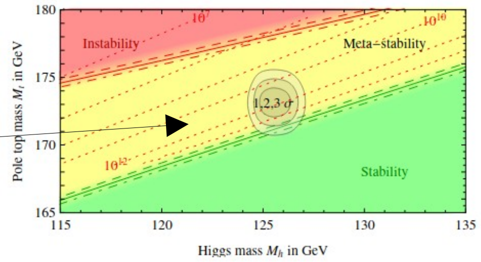
Higgs mass and width

- Mass uncertainty dominated by systematics
  - Expected σ_{stat} = 22 MeV on mass (0.02%!)
  - Width upper limits 177 MeV
  - Width inferred from off-shell can be **measured** at some 4 MeV with σ ≈2-3 MeV

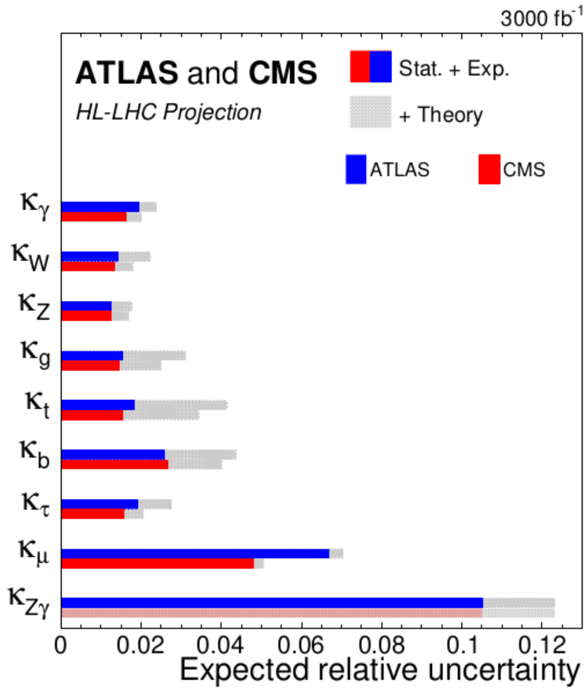
(Nisati&Sharma, ch15 of 'The Future of the LHC', World Scientific, 2023)

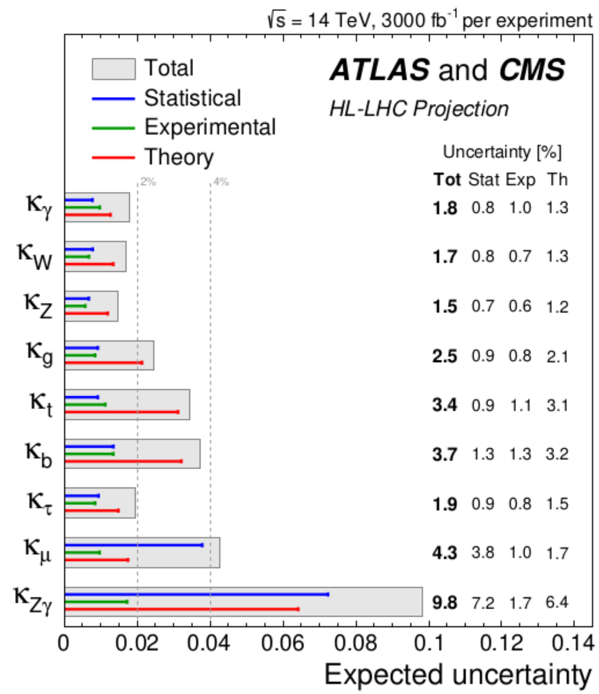
Higgs and top masses impact the stability of our universe:
Degrassi et al.: JHEP08 (2012) 098

Meta-stable region



Expected precision of signal strength parameters
CERN Yellow report 2019-007



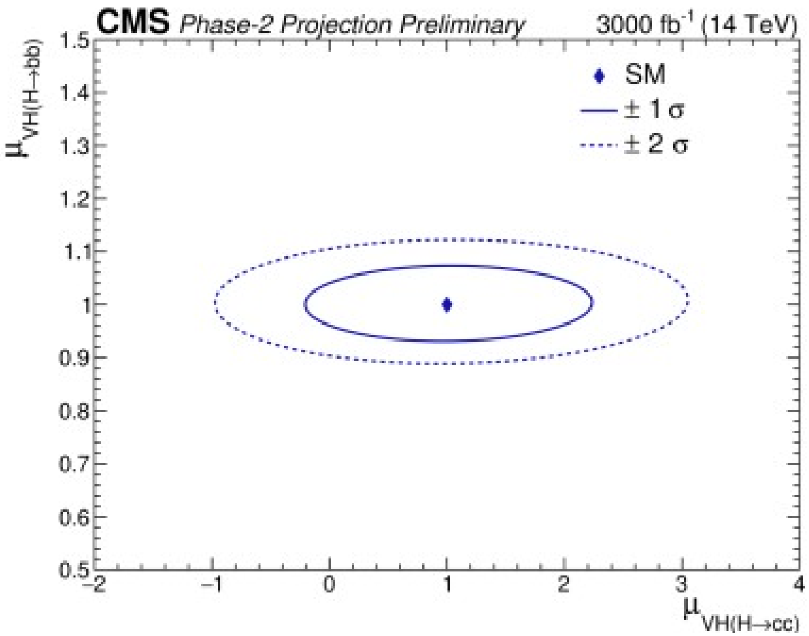


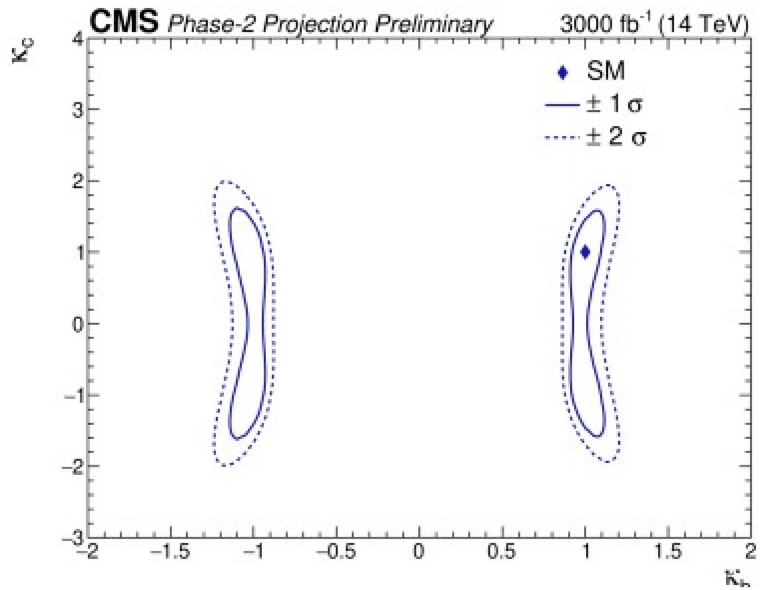
Improved reconstruction techniques:

We should expect to do better than 2018 projections!

There is now a result addressing H → $c\bar{c}$

This permits a sensible projection for a κ_{cc} couplings constraint after HL-LHC





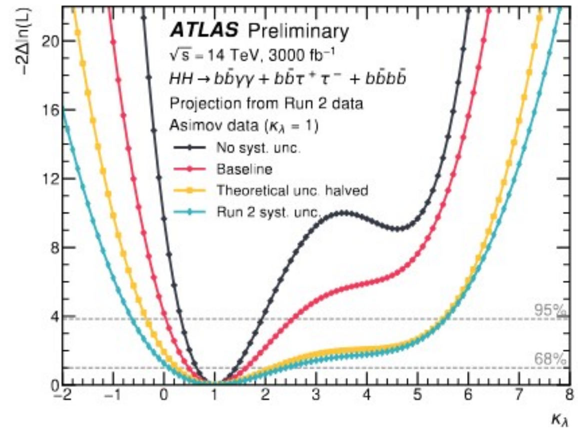
Higgs pair production and self coupling:

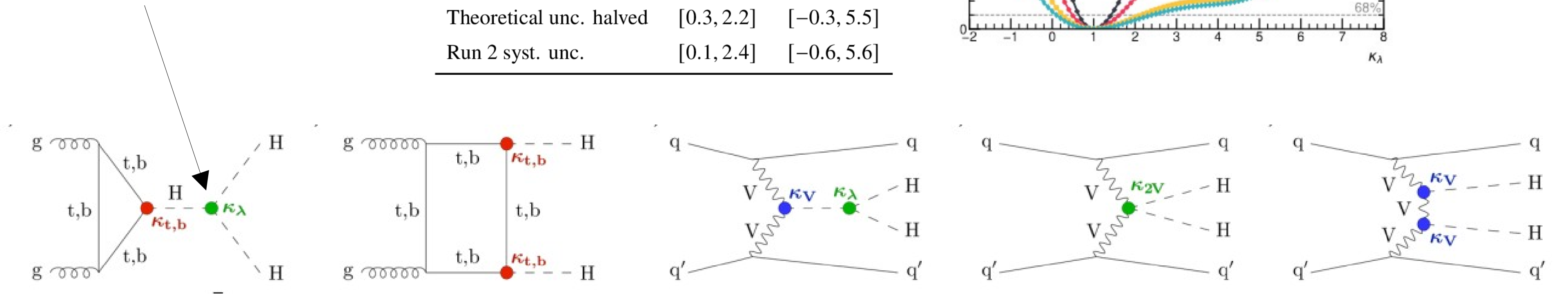
Self coupling probes the shape of the higgs potential

$$\lambda_{HHH}^{SM} = \frac{m_H^2}{2v^2}$$

$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$$

Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
No syst. unc.	[0.7, 1.4]	[0.3, 1.9]
Baseline	[0.5, 1.6]	[0.0, 2.5]
Theoretical unc. halved	[0.3, 2.2]	[−0.3, 5.5]
Run 2 syst. unc.	[0.1, 2.4]	[−0.6, 5.6]





ATL-PHYS-PUB-2022-053:

3000 fb^{-1} HH-> $b\bar{b}b\bar{b} + b\bar{b}\tau^+\tau^- + b\bar{b}\gamma\gamma$ discovery significance 3.4 σ

Updated projections underway, ATL-PHYS-PUB-2024-016 for $b\bar{b}\tau^+\tau^-$

ATLAS EXPERIMENT

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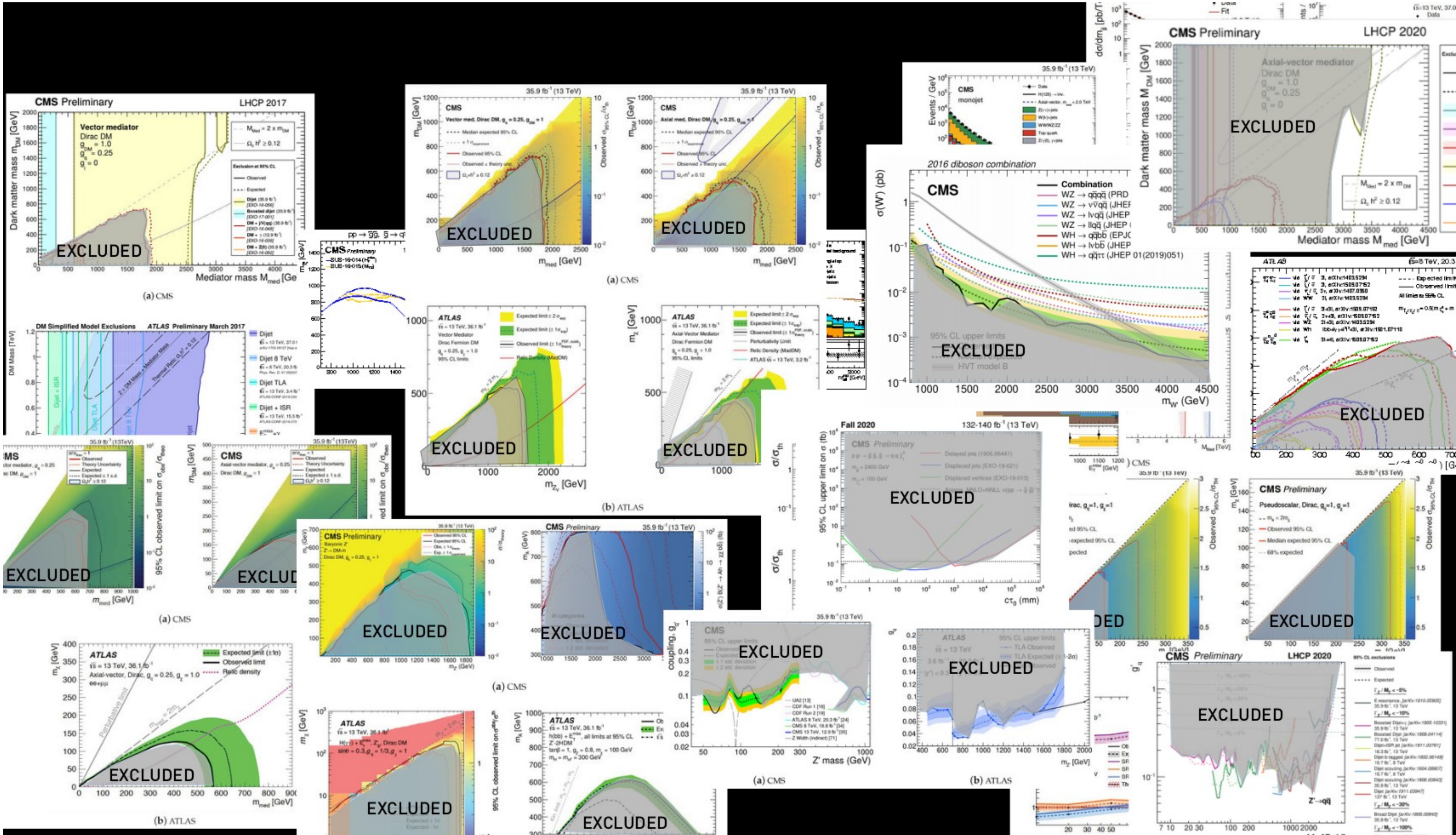
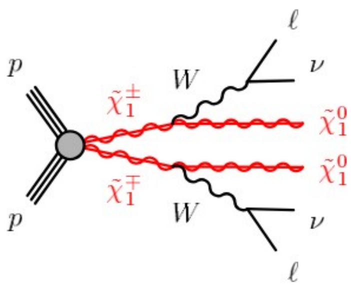
Any hope for SUSY?

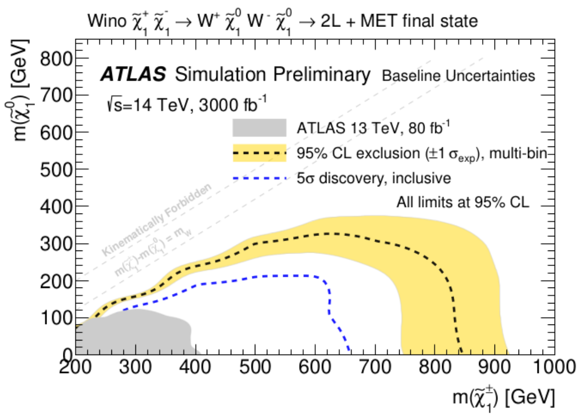


(Thea Aarrestad, CERN-70 symposium, Bergen 13/9-24)

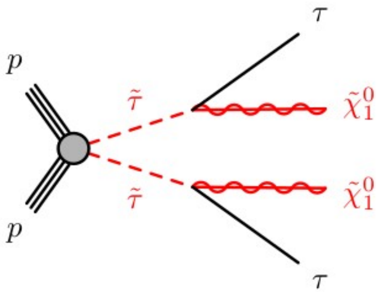
Examples of improved SUSY mass reach:

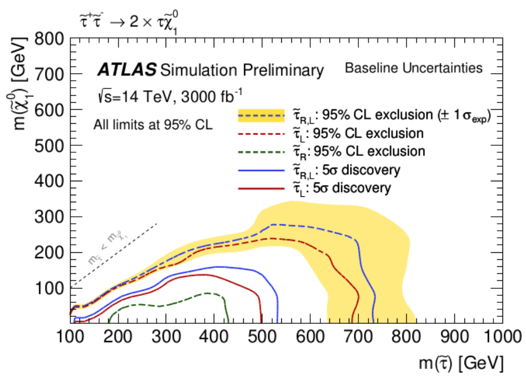
Chargino pairs





stau pairs

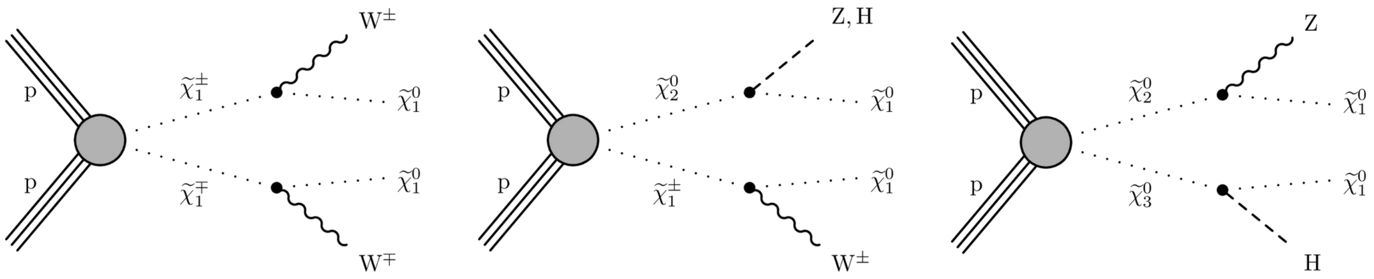


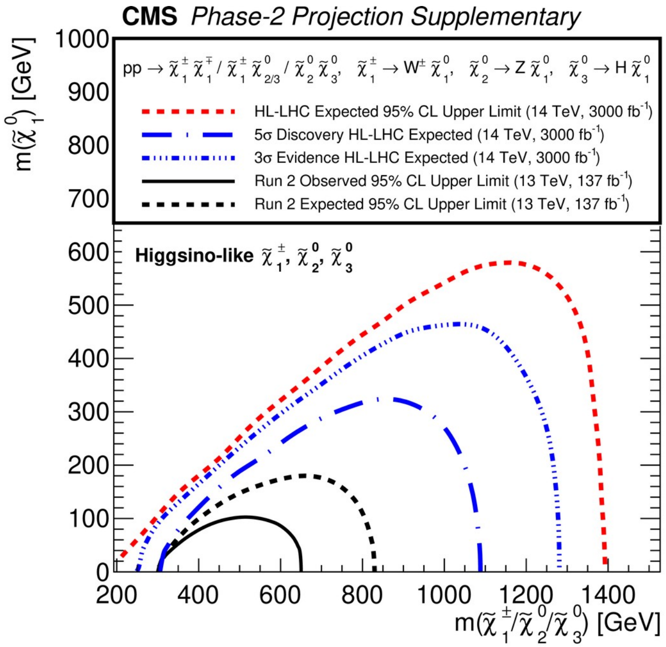


CERN Yellow report: CERN-2019-007

SUSY mass reach in a more specific pair production scenario

Projections from a recent run2 analysis (CMS Phys.Lett. B842 (2023) 137460)





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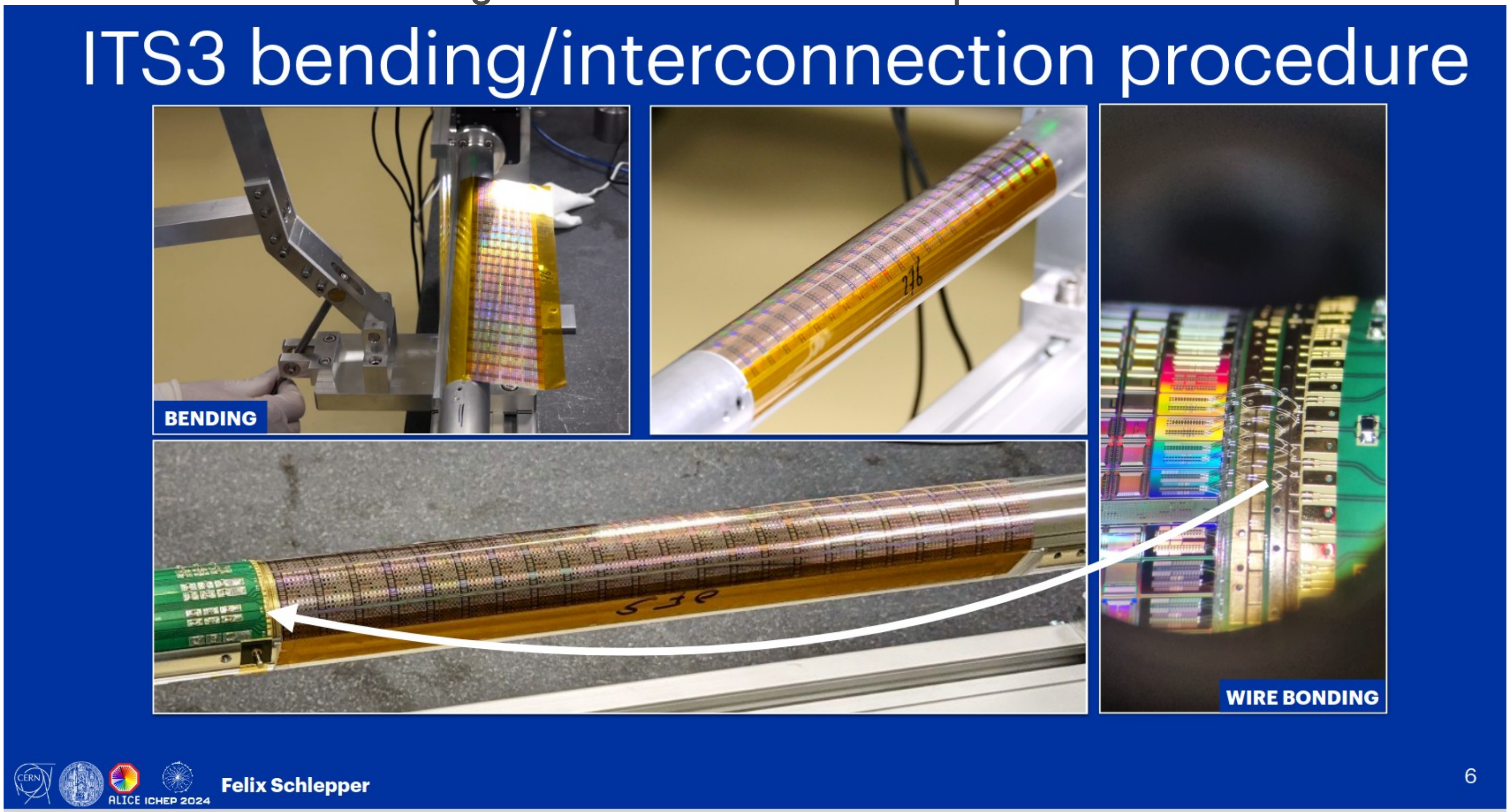
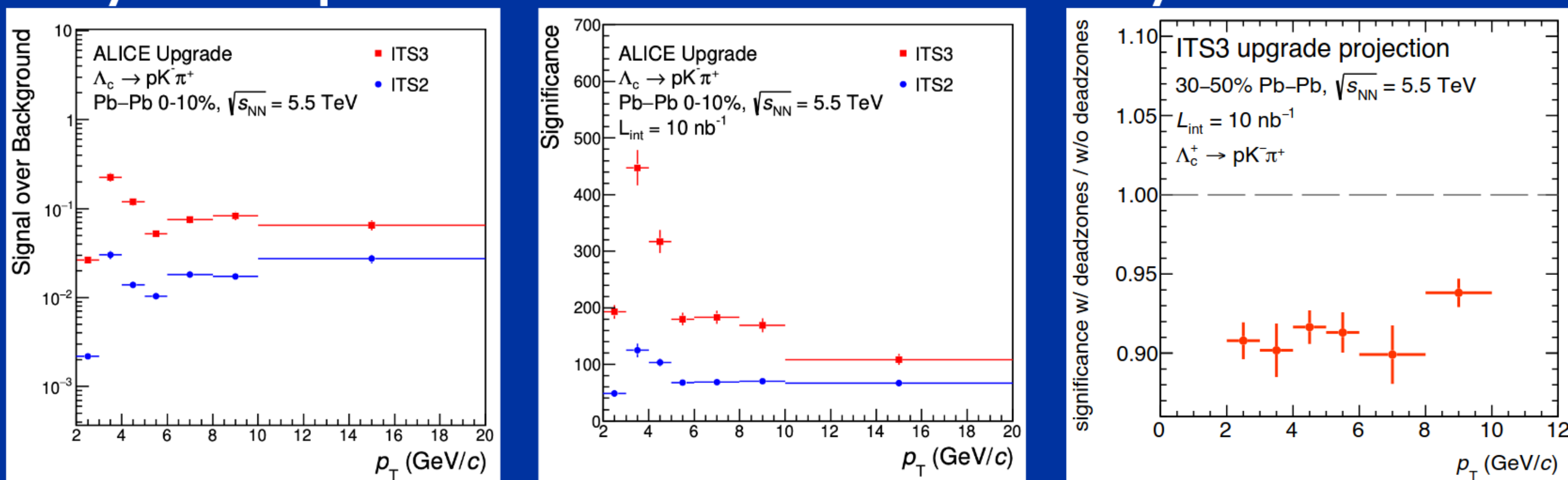
ALICE: The amazing ultrathin monolithic Alpide sensor



Also: Focal, prompt photons, excellent π^0-γ separation
Semiconductor sensing pads & pixels
QCD probed at extremely low momentum fractions

ALICE performance improvements on heavy meson/baryon reconstruction

Physics performance — Heavy flavour



Signal and Background yields estimated in $\pm 3\sigma$ interval around Λ_c^+ mass

Public Note on ITS3 Physics Performance ALICE-PUBLIC-2023-002

Λ_c^+ reconstruction as an example for possible improvement

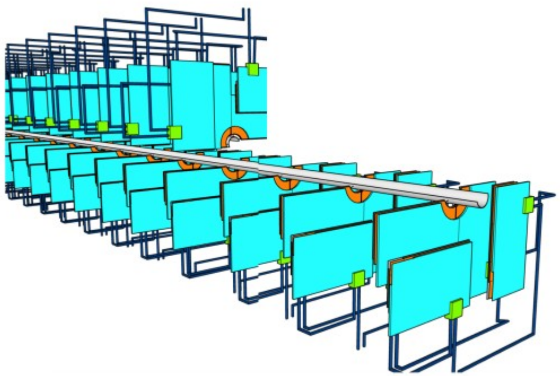
- ➡ Large three-prong combinatorial background
- ➡ Can be better suppressed with improved primary and secondary vertex reconstruction

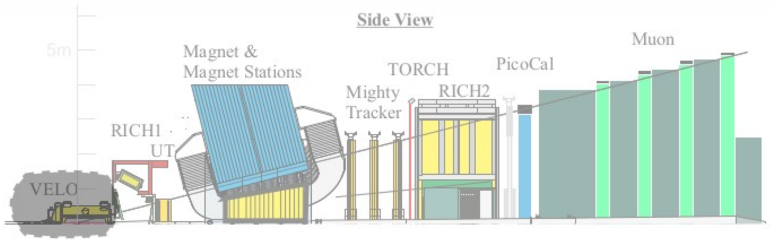
Factor 10 improvement for S/B
Factor 4 improvement for the significance
Impact of deadzones negligible compared to the improvement over ITS2

ALICE ICHEP 2024 **Felix Schlepper** 17

LHCb upgrades -> record every event, software 'triggering'. Tracking with high precision timing. Vertex separation through timing.

Tracking system : Velo UpgradeII



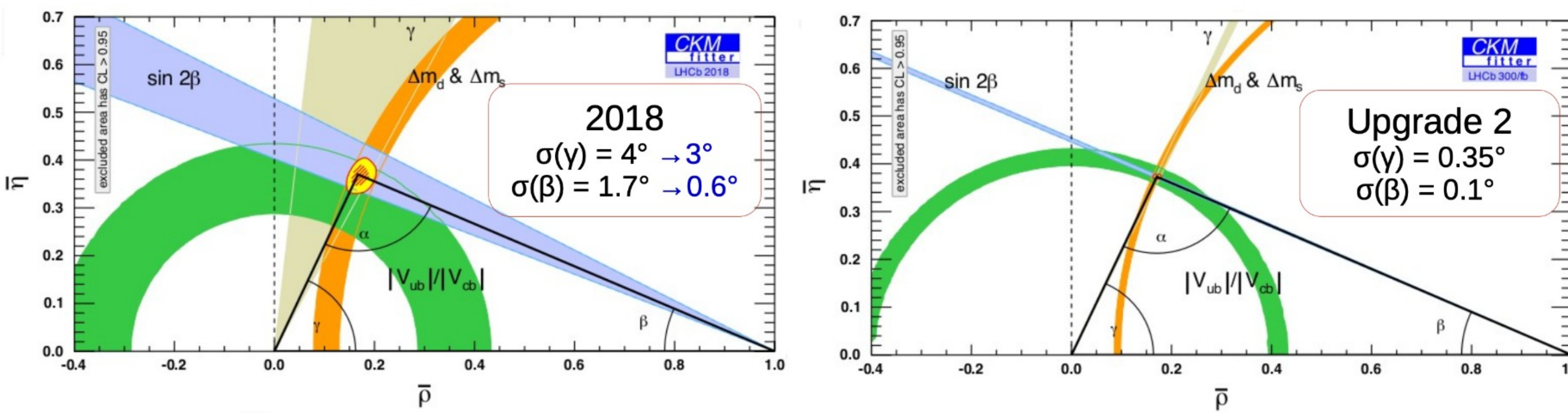


- Goal: achieve full 4D reconstruction delivering same performance as Run 3
  - Hybrid pixels 3D-sensors
  - Per-hit σ_t : 50 ps $\rightarrow$ 20ps/track
  - 7.1 mm from beam pipe , $Pitch \sim 55 \times 55 \mu m^2$
  - Rad hard (max ~ 6 x 10^{16} neq/cm-2) [6x wrt Run3 Velo]
  - Low material budget (RF-foil + Sensors)
- R&D on 28 nm technology: PixoPix, IGNITE
  - Replaceable modules, thinner or no RF foil, robust 3D printed Ti cooling substrate....
- Technological challenge(s) to match requirements, R&D critical for future facilities

More on Maria Domenica Galati 'The LHCb VELO detector: operation, performance and future upgrades'' (Talk, 18 July)

LHCB projections on the CKM matrix

- LHCb has outperformed expected Run 2 sensitivities for both β and γ
- Many other BSM searches rely on these benchmarks



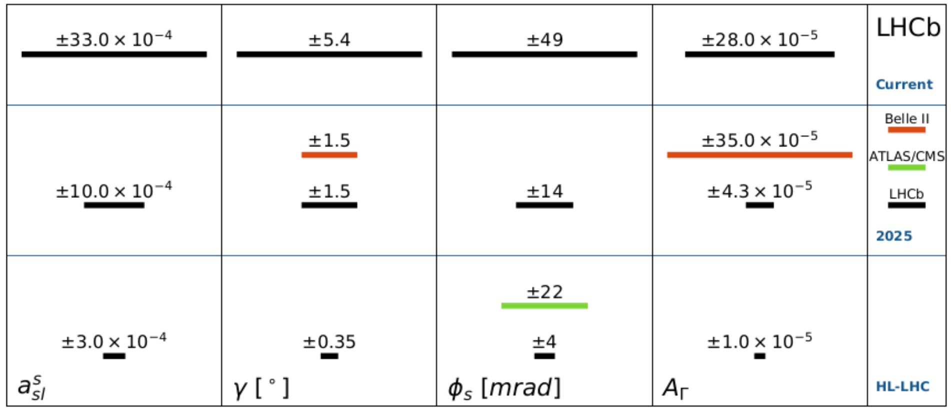
LHCb Upgrade II will make the most precise measurement of all of the 5 key CP violation parameters $(\beta, \gamma, \phi_s, A^s_{sl}, A^d_{sl})$ in the B system

LHCb: Expect 5-10 fold increase in precision on CP-violating parameters

LHCb in 2018

2025

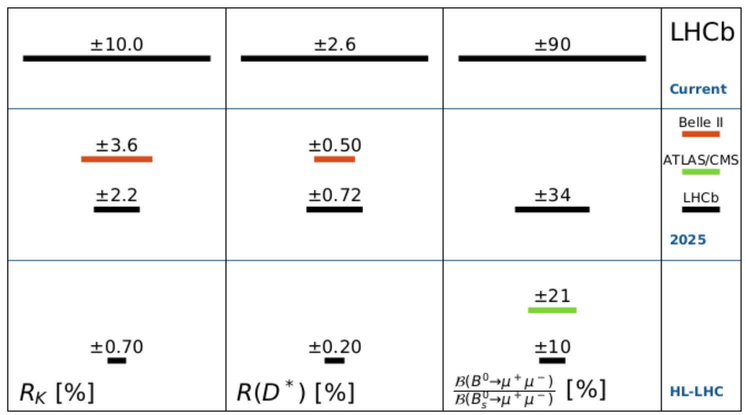
HL-LHC



LHCb in 2018

2025

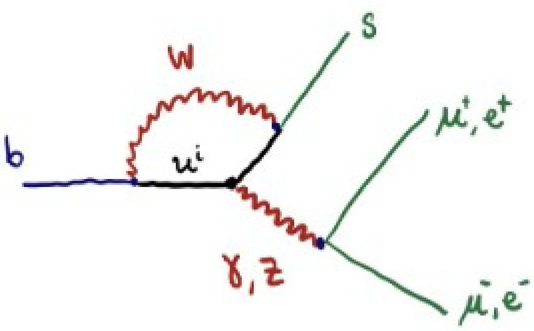
HL-LHC

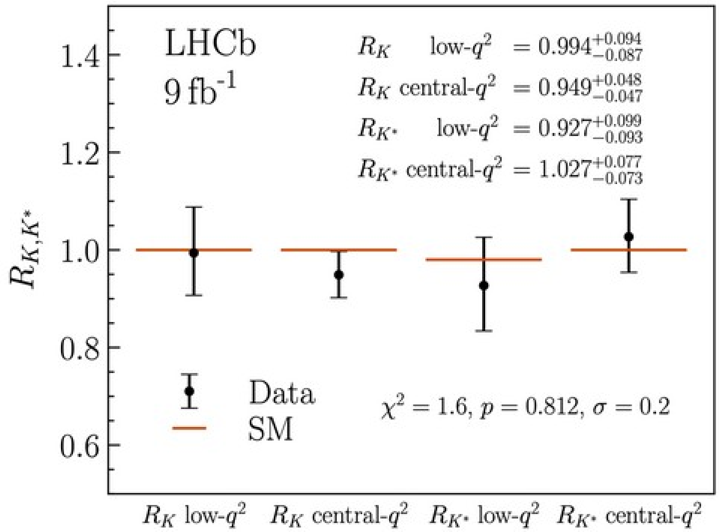


From CERN-LHCC-2018-027

The B-anomalies: Possible violation of lepton unversality

$$R_{X_s} = \frac{\mathcal{B}(B \to X_s\, \mu\bar{\mu})}{\mathcal{B}(B \to X_s\, e\bar{e})}$$



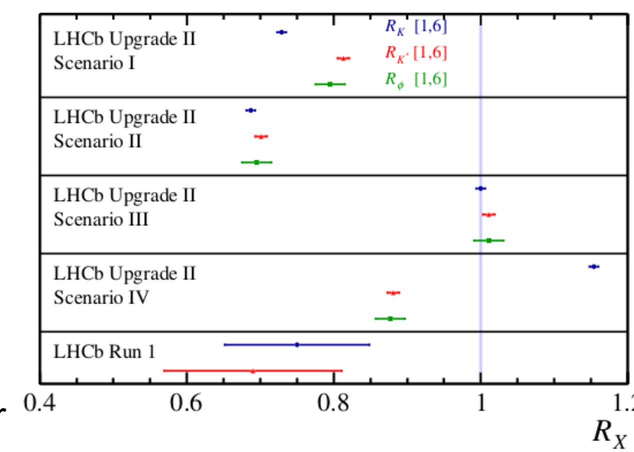


LHCb: Phys Rev D 108.032002

Recent LHCb results resolves a lot,
The current precision is still poor

RUN3 and HL-LHC
should result in large improvements

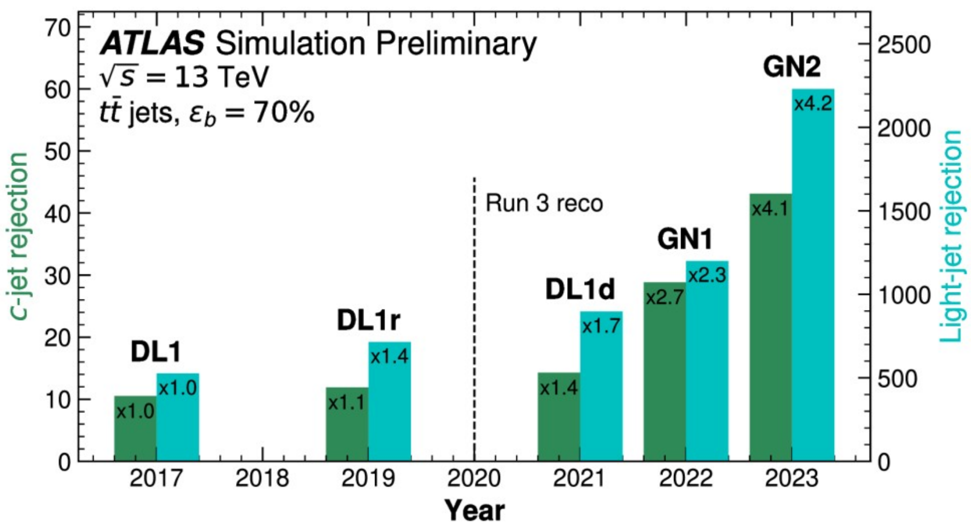
CERN/LHCC-2018-027



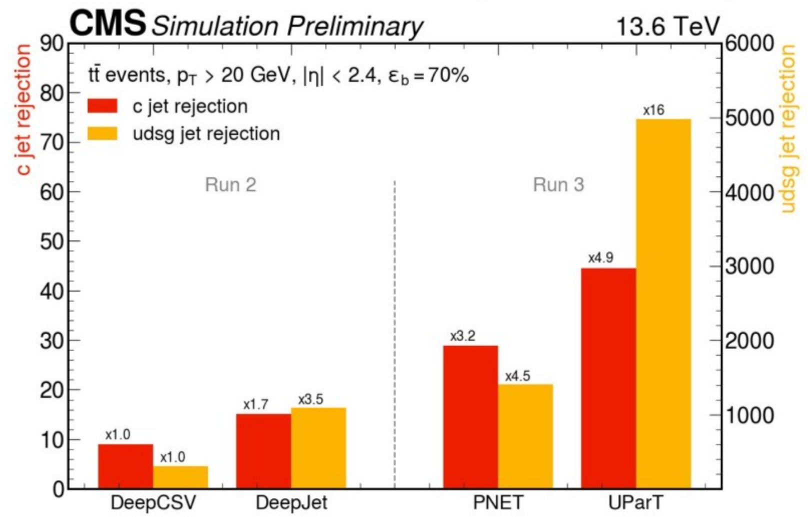
Improved algoritms and analysis techniques can make a big impact

Machine Learning algoriths improve light flavor rejection factors dramatically for given b-jet efficiency!

Eur. Phys. J. C 83 (2023) 681   FTAG-2023-01

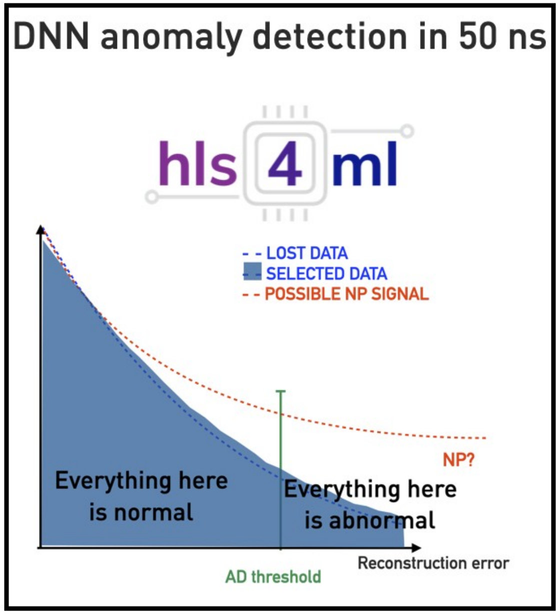


CMS-DP-2024-066

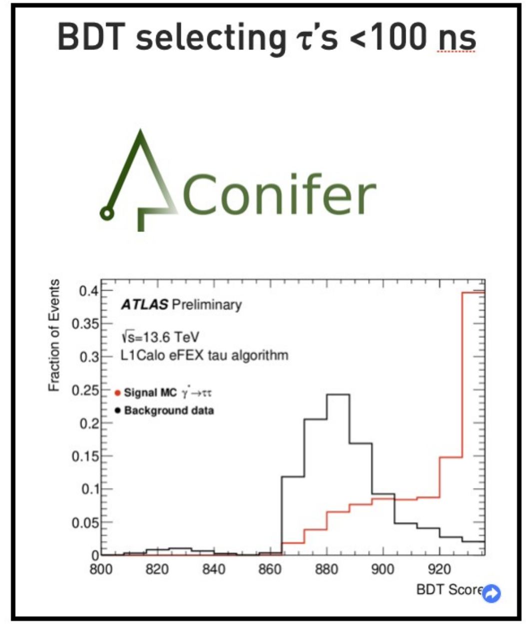


Triggering based on Machine Learning techniques

First ML triggers in ATLAS and in CMS in 2024



CMS DP2023_079



L1CaloTriggerPublicResults

Slide from Thea Aarrestad, ETH Zürich /CMS

More information at https://fastmachinelearning.org

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Do we overlook something? Trends of AI:

- **Model ’agnostic’** searches for anomalies

  (Javier Duarte ICHEP 2024, and: B. Nachman https://indico.cern.ch/event/1188153/)

  – ML algoriths to look for any out of the ordinary event
  – No MC training samples, so less sensitivity than targeted searches
  – **Reward:** find the unexpected
  – Drawback: Use some data to find anomalies in the ’same’ data samples..

CONCLUSIONS AND OUTLOOK

- RUN3 and HL-LHC are extremely challenging data-taking environments, and requires many improvements from the experiments
  - Trigger & Hardware
  - Software and storage
  - Reconstruction and analysis techniques
- All 4 experiments have embarked on extensive upgrade programs
- Many clever ML and AI algorithms have been invented, and it is likely that we still are at the beginning of the AI revolution:
  - Trigger replacements by clever software/FPGA algorithms
  - Signal agnostic searches for anomalies using AI techniques

PHYSICS EXPECTATIONS

- **Higgs:** Precise determination of many Higgs couplings
  - First probing of small couplings (κ_c κ_λ ...)
  - Higgs CP-properties
- **Beyond Standard Model:**
  - Increased mass reach in many models.
  - SUSY mass and parameter space is widened further
- **Standard model:**
  - Much improved precision of the CKM parameters, hadron physics,universality trdtd.
- **Heavy-ions:**
  - Improved spectroscopy and QGP properties
  - QCD probing in new regimes (Bjorken-x down to $x \approx 10^{-6}$)
- **AND MUCH MORE**

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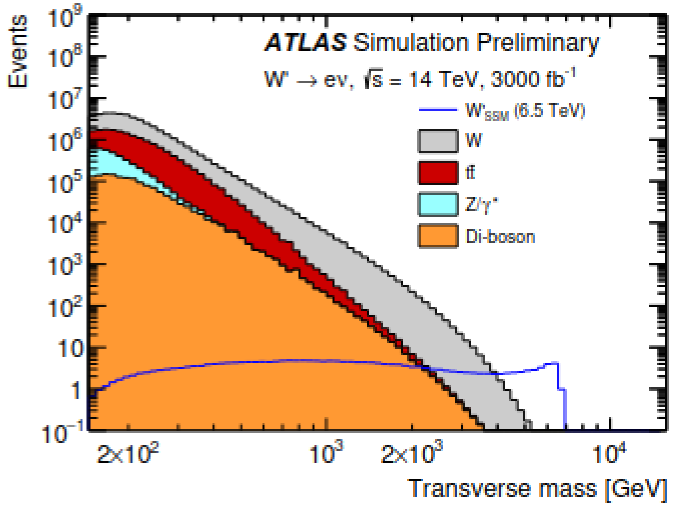
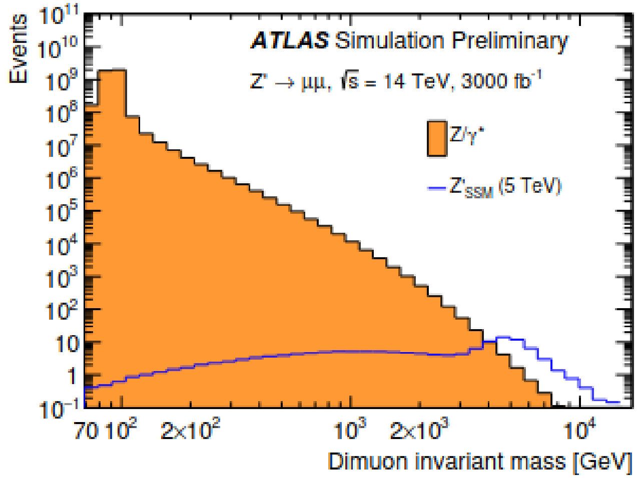
BACKUP

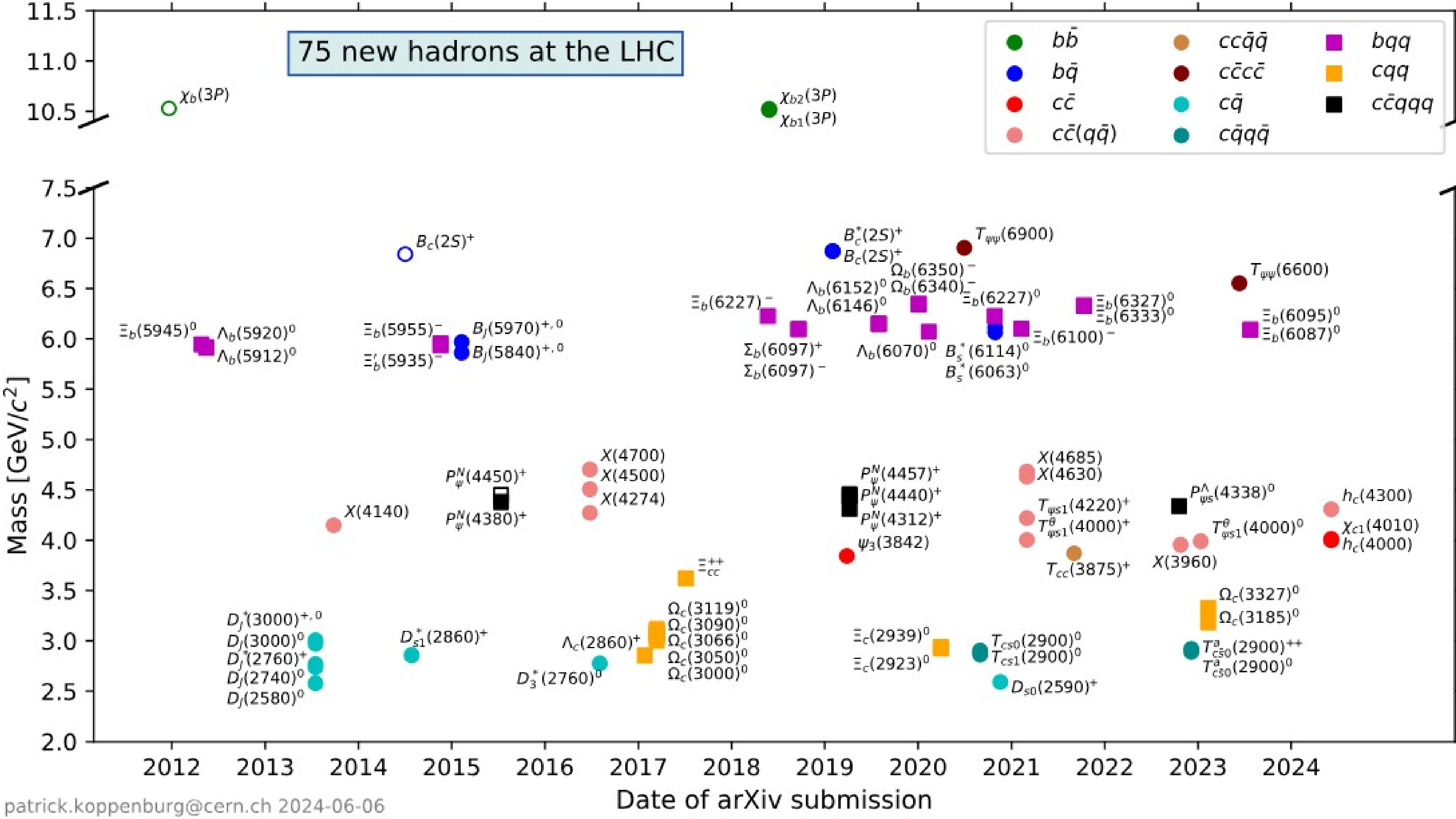
Mass reach of heavy gauge bosons





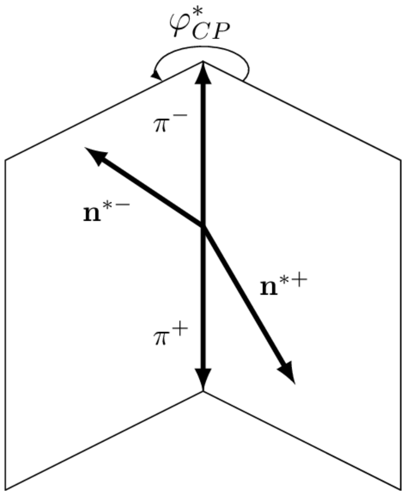
ATL-PHYS-PUB-2018-044

Model	Run 2 exclusion [TeV]	HL-LHC exclusion [TeV]
Right-handled W'	3.15	4.9
Sequential Standard Model W'	5.6	7.9
Right-handled Z'	5.4	5.8
Sequential Standard Model Z'	6.1	6.5



(from Yasmine Amhis ICHEP2024)

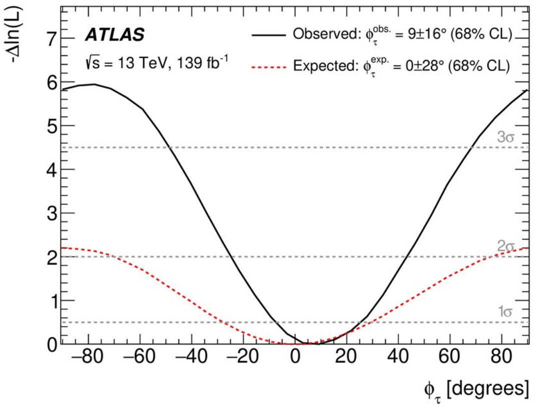
Higgs CP – properties in $H\to\tau^+\tau^-$ Asymmetries in φ^*_{CP} distributions of the differences in the τ decay planes

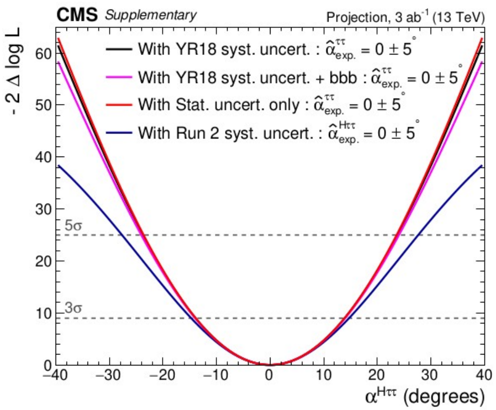


$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H,$$

$$\mathrm{d}\Gamma_{H\to\tau^+\tau^-} \approx 1 - b(E_+)b(E_-)\frac{\pi^2}{16}\cos(\varphi^*_{CP} - 2\phi_\tau),$$

Projected σ=5°





Eur.Phys.J. C 83(2023)563