LHC exploitation

Electroweak, QCD and Top Physics

KATE SHAW
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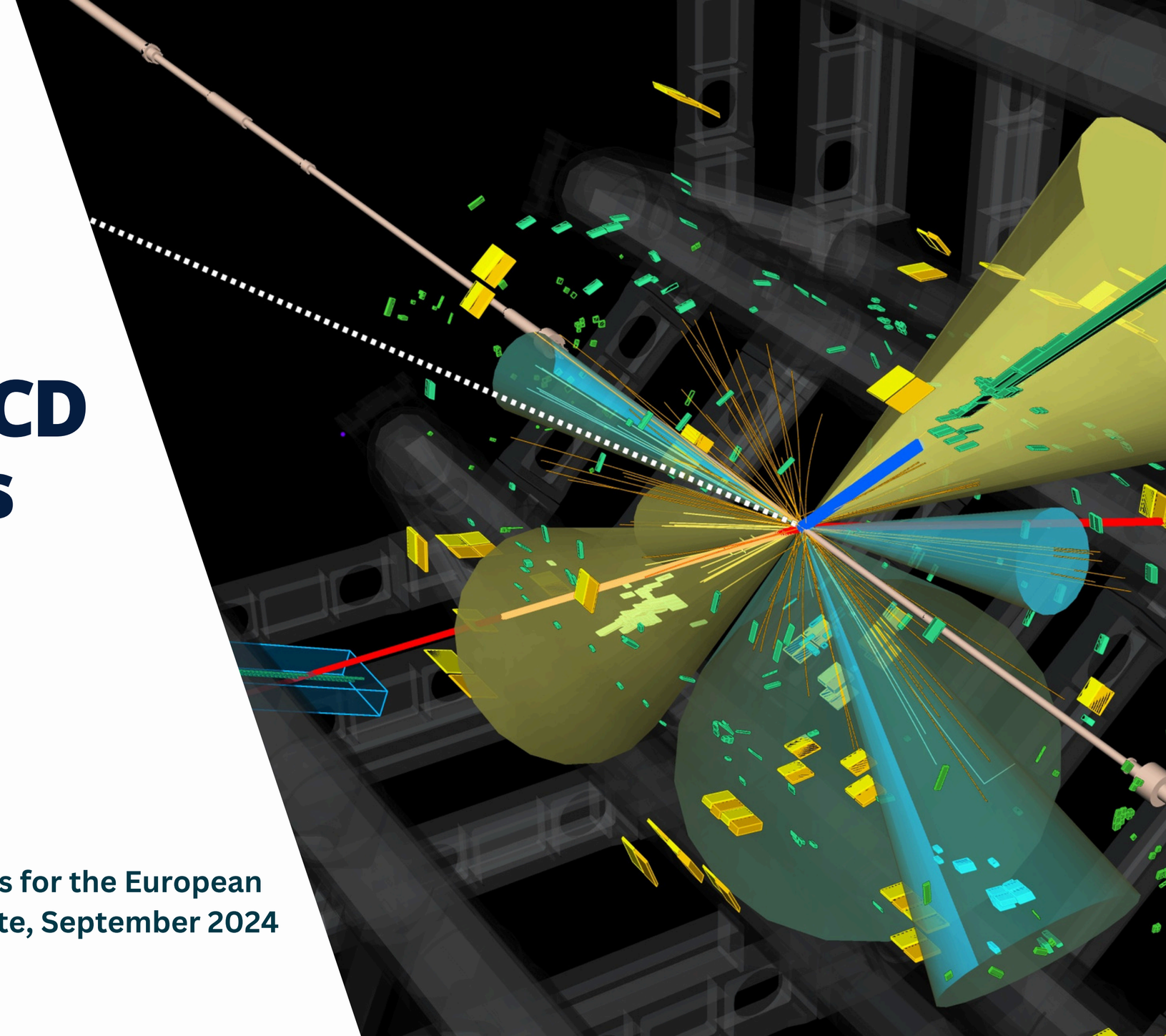

ECFA-UK Meeting on UK studies for the European Strategy Particle Physics Update, September 2024

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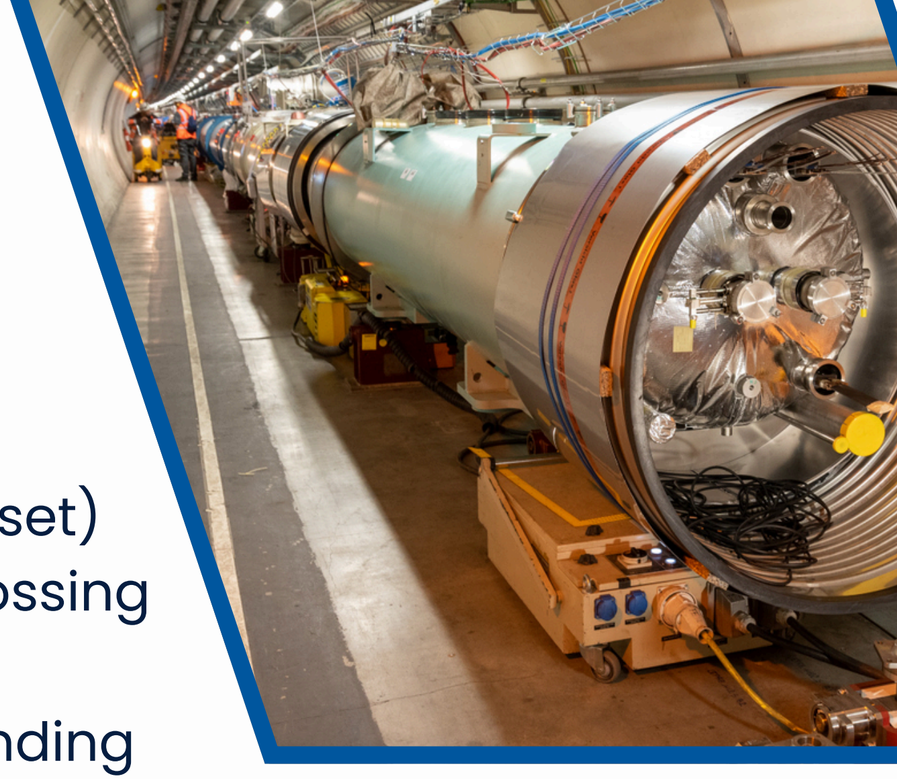
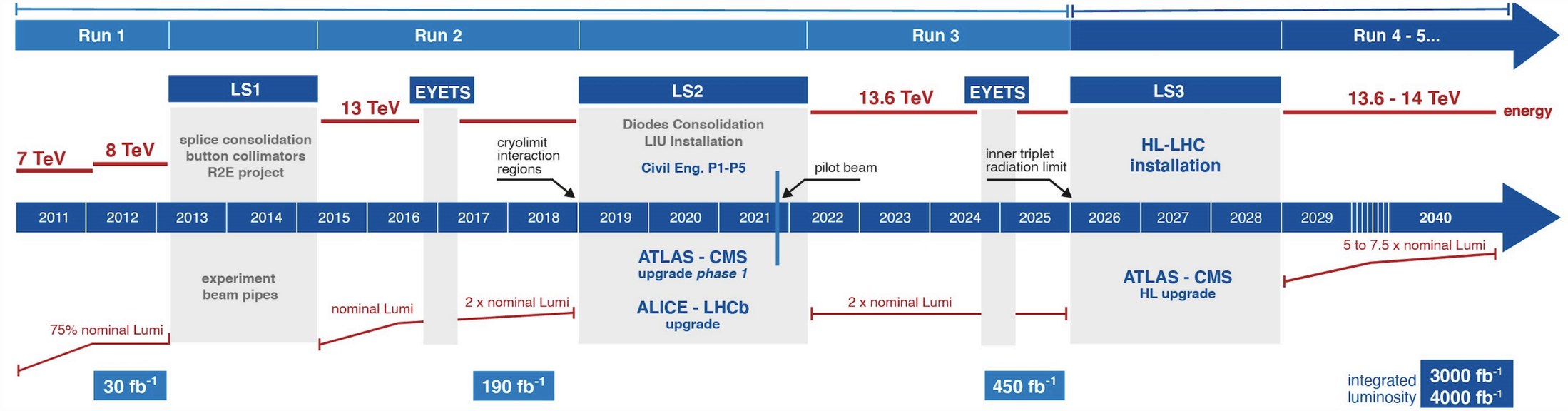
ATL-PHYS-PUB-2022-018
CMS PAS FTR-22-001
CERN-LPCC-2018-03



LHC exploitation

- **HL-LHC** upgraded LHC
  - pp @ 14TeV, L=5-7.5 10^34 cm-2s-1
  - Integrated luminosity ~ 3000fb (~ x 10 larger data set)
  - Expected pile-up 140-200 collisions per bunch crossing
- **Upgraded** ATLAS, CMS, LHCb detectors
- Expected **improvements** in the theoretical understanding



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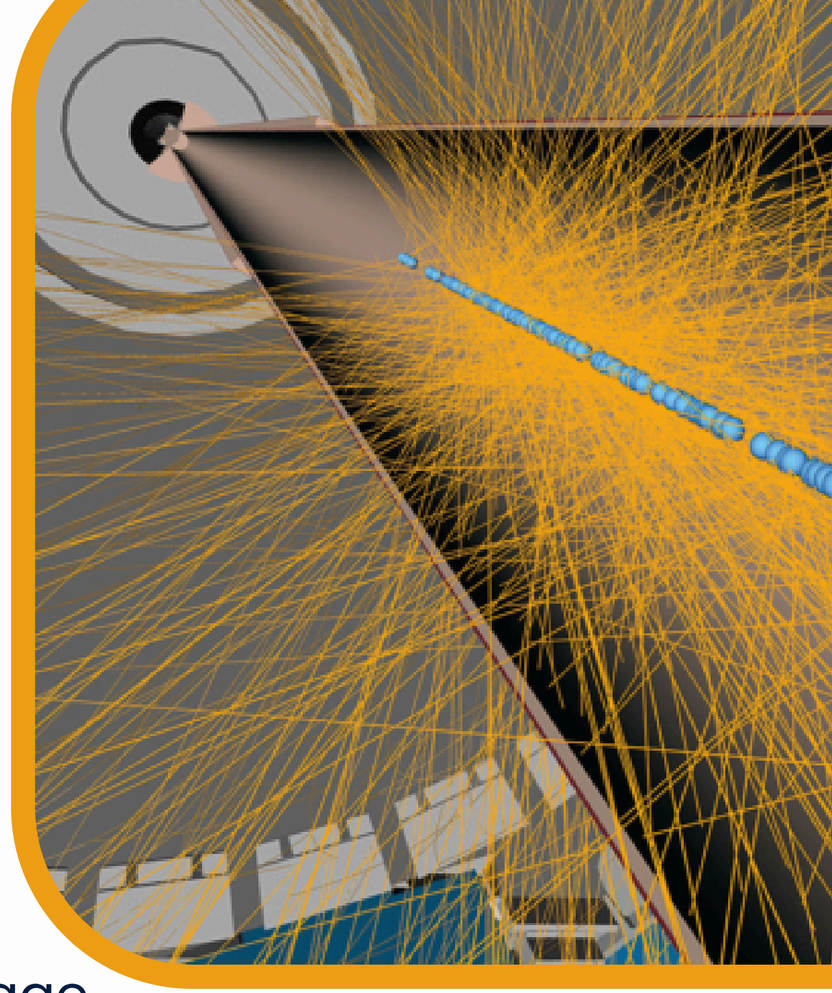
Detector Upgrades



Extensive **replacements** and **upgrades** for detectors

- to sustain increased **radiation** level
- to deal with higher data rates
- to cope with an extreme high-occupancy environment with up to 200 pp interactions per bunch crossing

Important upgrades in ATLAS and CMS

- **Tracking** extended with SI detectors up to $|\eta|=4.0$
- Increased L1 and HL **trigger rates** with tracks at early stage
- **Timing detectors** with high timing resolution (30ps) for charged particles and primary vertex reconstruction

LHCb will upgrade its electromagnetic **calorimeter** and equip its ring-imaging Cherenkov detectors with very **fast electronics**

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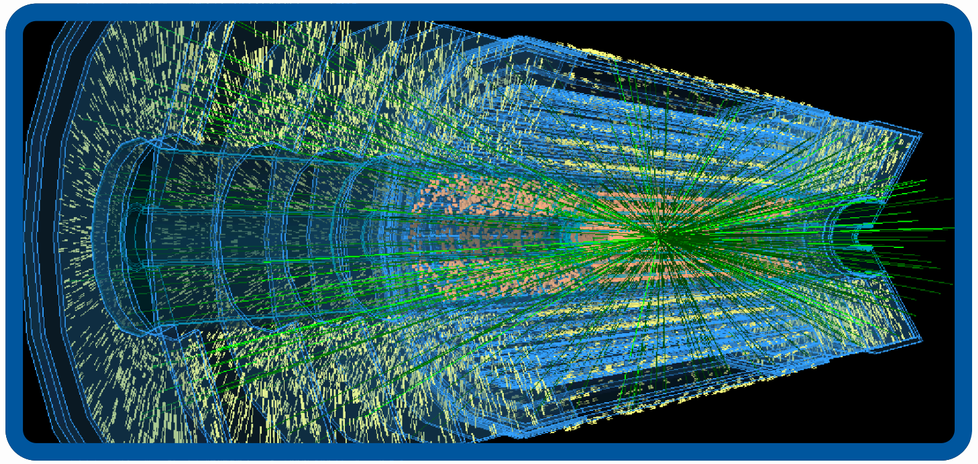
HL-LHC SM Physics Outcomes



- **Improved precision measurements!**
  - Also as backgrounds to searches

- Global PDF fits of Standard Model measurements will significantly improve **PDF uncertainties** and **SM parameters** (weak mixing angle, W boson mass)

- Extend the **sensitivity to new physics** in direct and indirect searches for **rare** processes and **harder** signatures, insights to new physics effects from **higher energy scales**

- Luminosity uncertainty has been set at 1% , (ATLAS already achieved 0.83%!)

- Presenting a **tiny few examples of SM** physics we can do at HL-LHC!!

We are already achieving more than expected a few years ago (4tops, W mass!!)

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Electroweak physics

Important physics for:

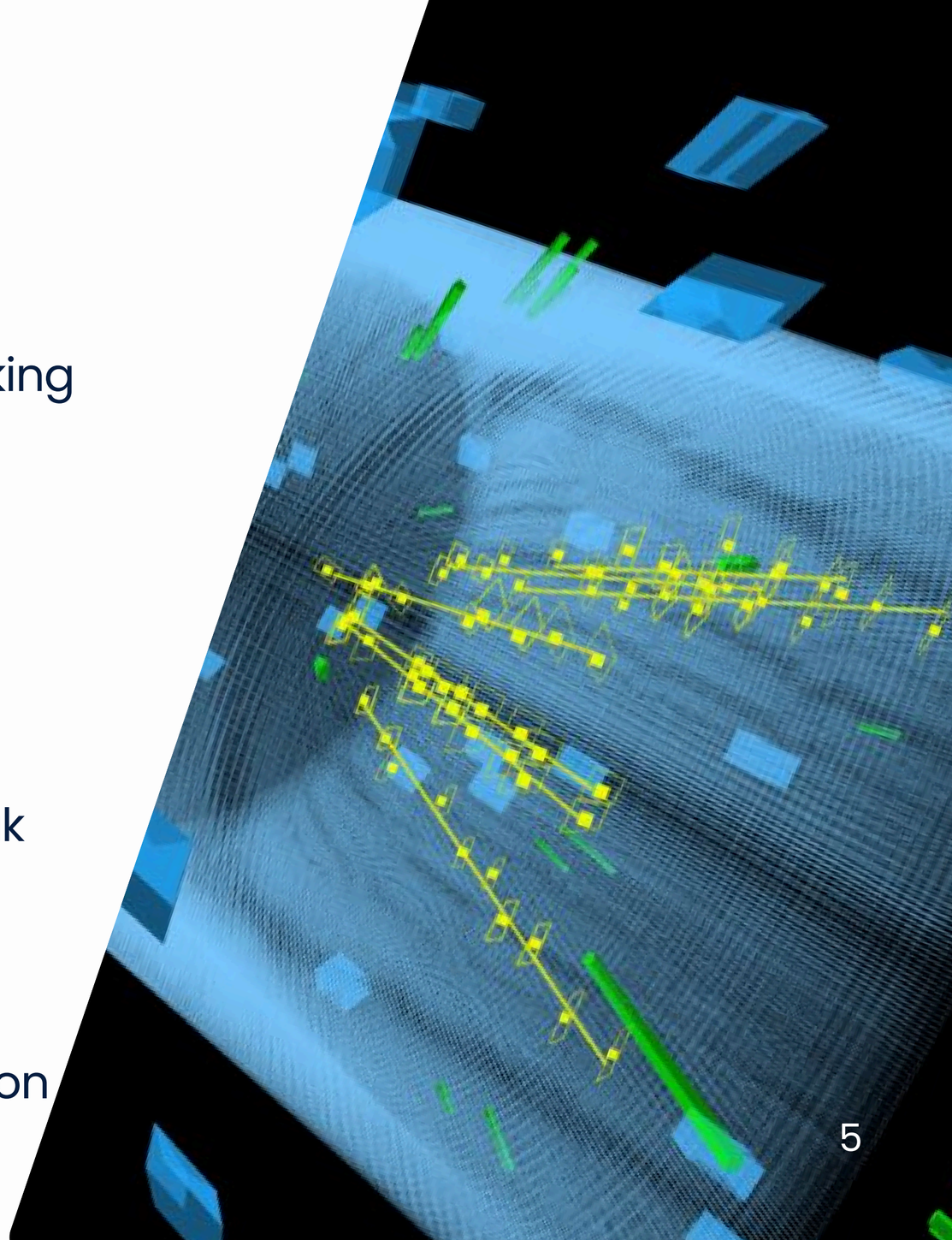
- Understanding electroweak symmetry breaking
  - Probing Vector Boson Scattering (VBS)
- Measurement of electroweak parameters
  - Measurements of the weak mixing angle
- Constraining PDFs

Improvements due to x10 luminosity

-> Many precision measurements of electroweak processes are statistically limited

Improvements due to detector upgrades

-> Improved forward jet and lepton reconstruction



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CMS-PAS-FTR-18-005

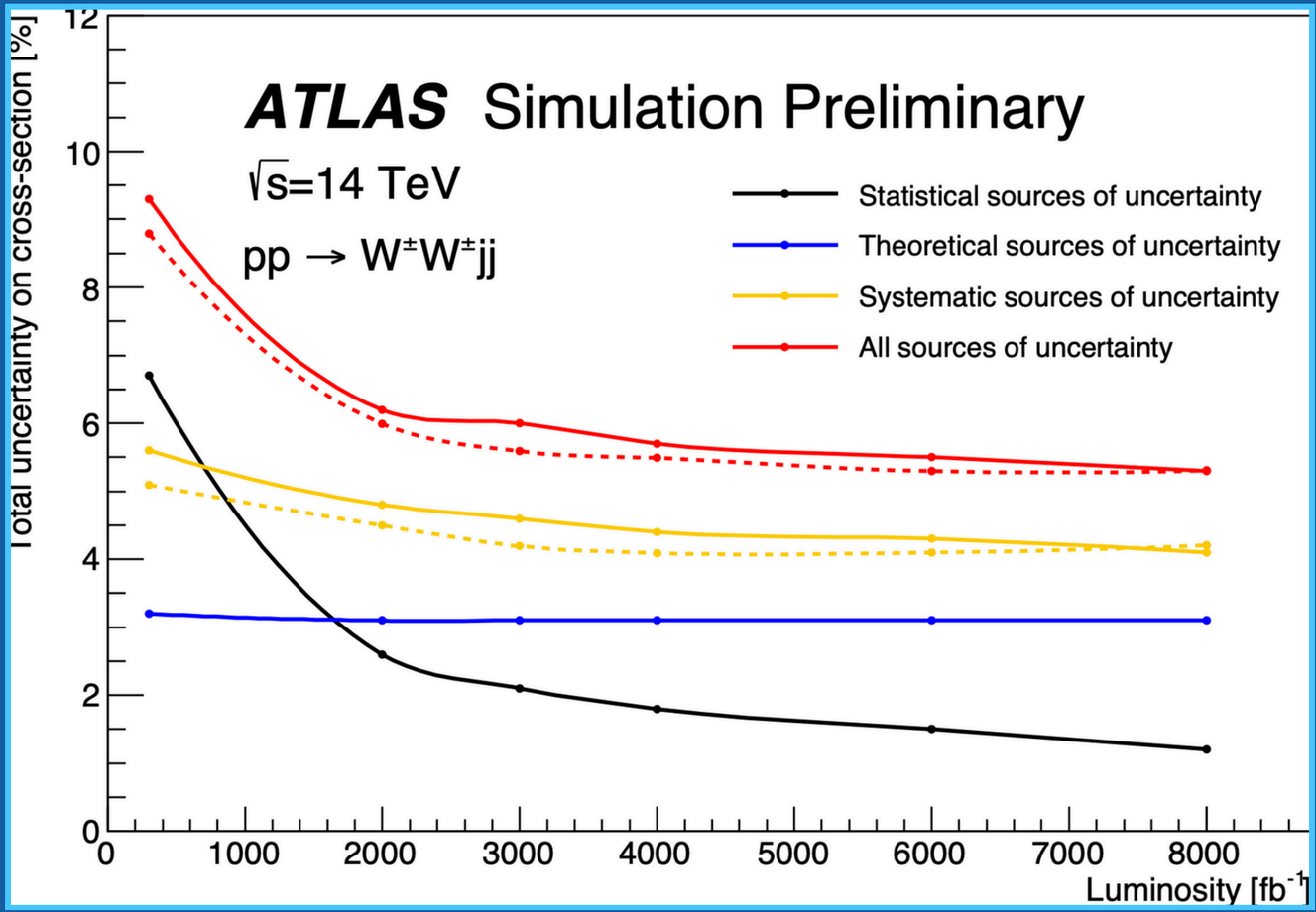
ATL-PHYS-PUB-2018-052

Electroweak physics

Precision measurements of VBS scattering processes

Ultimate test of Higgs mechanism in electroweak symmetry breaking lies in VBS process

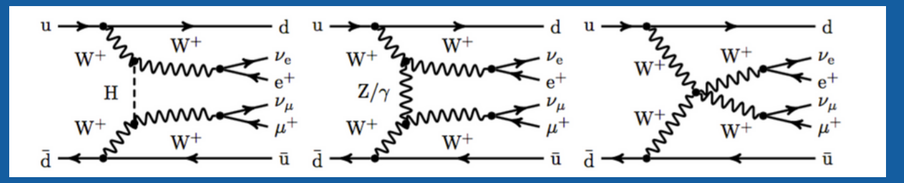
13 TeV Observation of W±W± (diagrams bottom right) ZZ, W±Z, Zγ



Cross-section measurements at HL-LHC of leptonic decays of electroweak production of VBS processes

- **W±W±** ATLAS 6%, CMS 3 %
- **W±Z** ATLAS & CMS 3-5%
- **ZZ** - depends on the theoretical modelling

Benefits from large dataset, forward lepton reconstruction, improving PU jet rejection for forward jets.



t-channel Higgs exchange

t-channel Z/γ exchange with triple gauge couplings

Quartic gauge coupling

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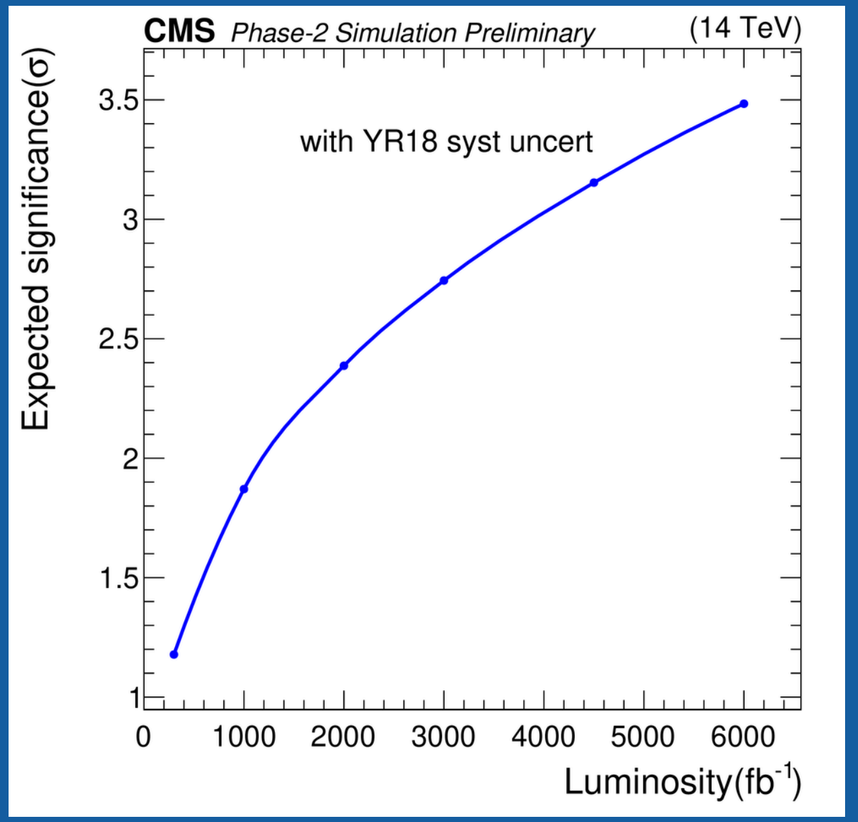
Electroweak physics

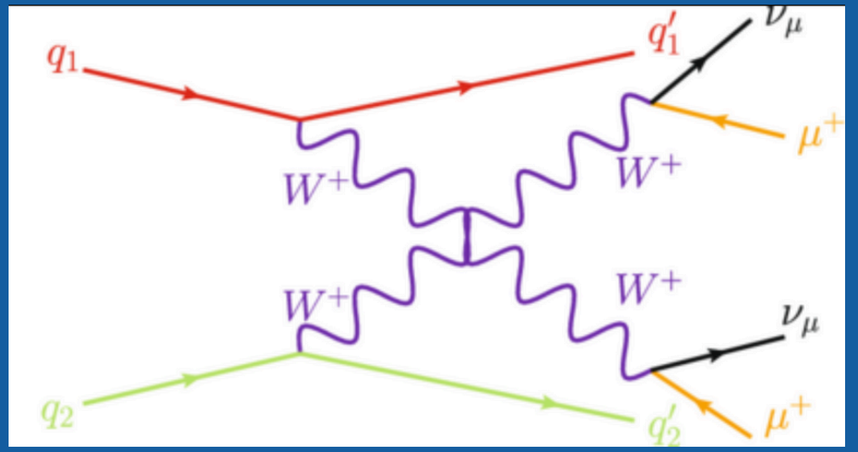
Precision measurements of VBS scattering processes

A challenging but important part of HL-LHC physics program is to measure **polarised same-sign WW scattering**

- Both bosons are longitudinally polarized (VL VL), 6–7% of the total cross-section (~1fb)
- Process is **unitarized** due to Higgs contribution, deviations may indicate presence of BSM physics
- Measured using **difference in phi** between the two tagging jets
  - WLWL expected significance ~ 2.7 sigma
  - WLZL expected significance < 1 sigma
  - ZLZL expected significance ~ 4 Sigma

Phys. Lett. B 812 (2021) 136018
CMS-PAS-FTR-18-005





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ATL-PHYS-PUB-2018-037

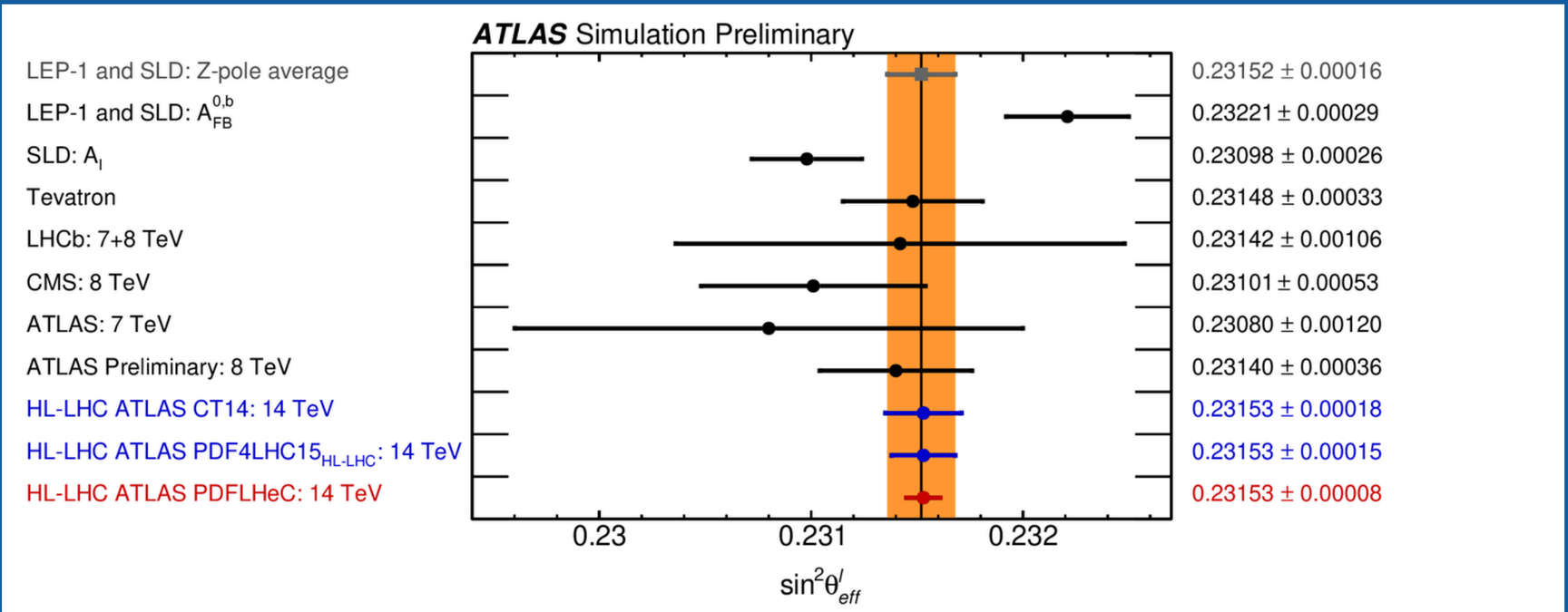
Electroweak physics

Precision measurements of electroweak parameters

The weak mixing angle is a key SM parameter

- Describing the vector & axial-vector components of the coupling of the Z boson
- Related to other SM parameters such as the W boson mass

Current precision of 1.6 x 10-4, (LEP, SLD) 3 sigma tension



The two most precise measurements of the angle to date, made at LEP and SLD disagree at a level of approximately **3 standard deviations**

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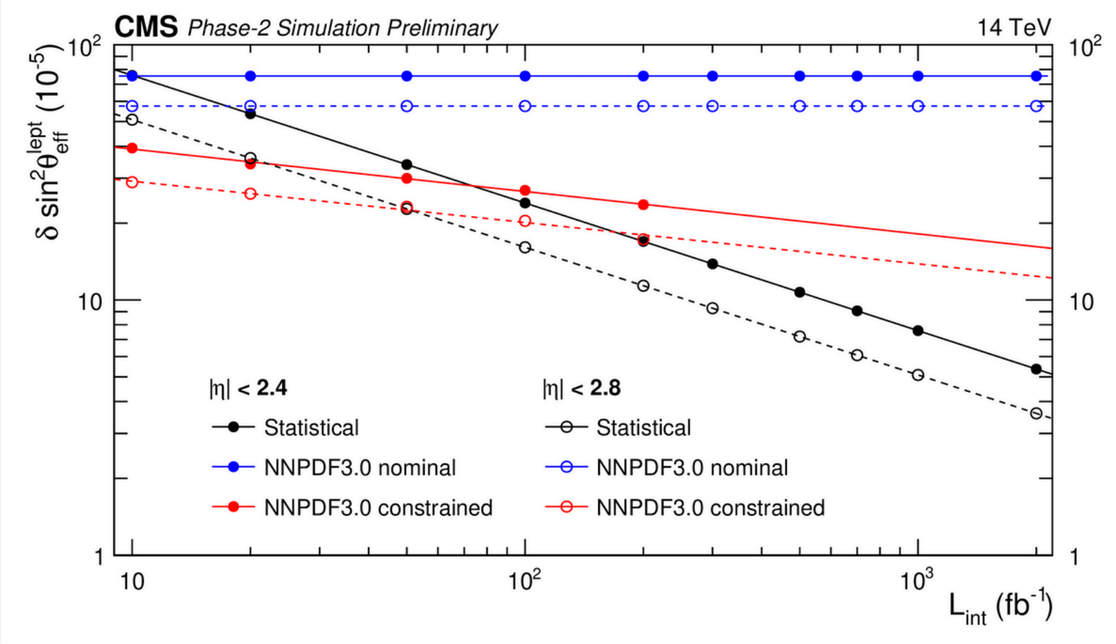
CMS-PAS-FTR-17-001
ATL-PHYS-PUB-2018-037
LHCb-PUB-2018-013

Electroweak physics

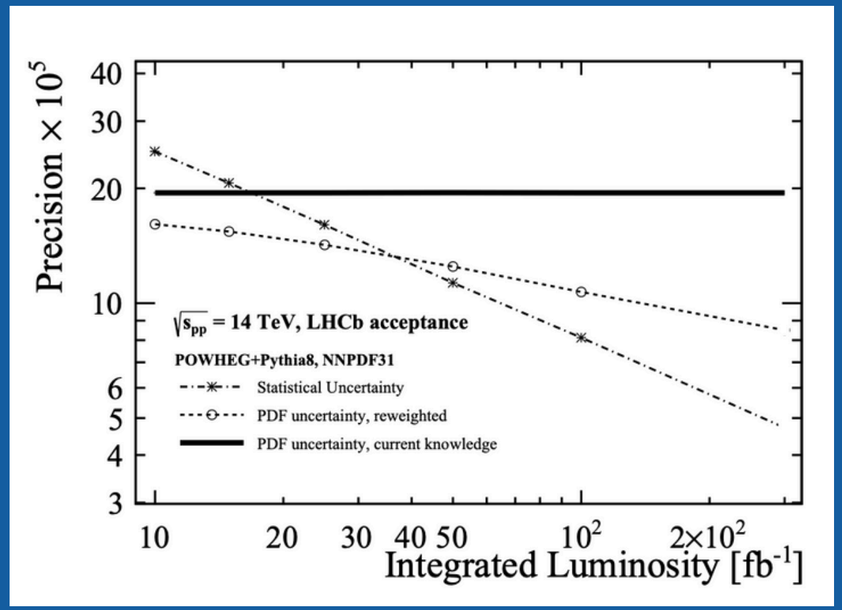
Precision measurements of electroweak parameters

$$A_{FB} = \frac{N(\cos\theta^* > 0) - N(\cos\theta^* < 0)}{N(\cos\theta^* > 0) + N(\cos\theta^* < 0)}$$

Weak mixing angle measured using AFB of Drell-Yan dilepton events at HL-LHC



LHCb with 300 fb-1 benefits from forward coverage



Stat uncert reduced by ~ 30%

PDF uncert reduced by ~ 20%

ATLAS benefit from ITk upgrade, resulting in better forward lepton reconstruction

CMS benefit from muon system upgrade extending pseudorapidity coverage

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Electroweak physics

Precision measurements of W mass

At HL-LHC we expect ~ 2 million W boson events in 1 week!

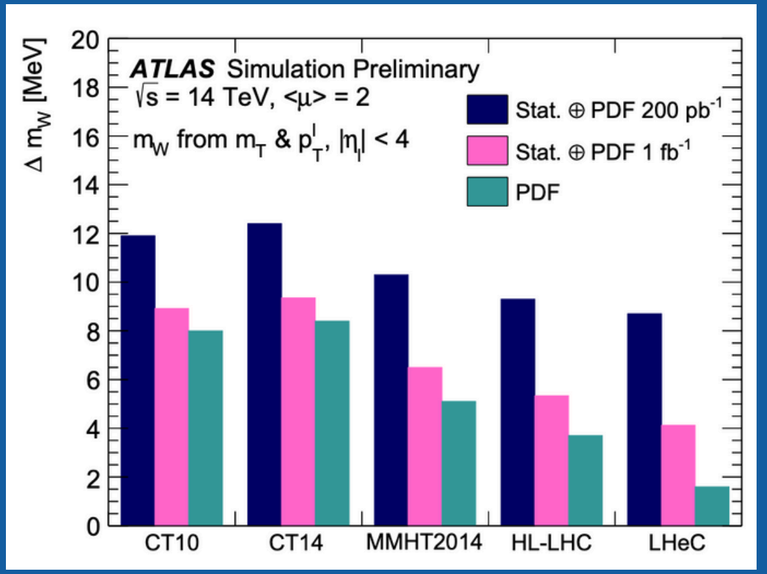
CMS-PAS-SMP-23-002
ATL-PHYS-PUB-2018-026

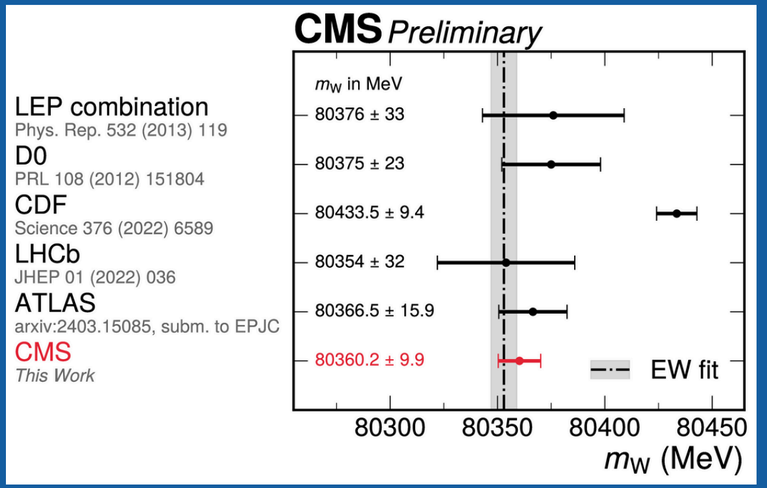
Precise measurement W mass important test of SM

- Dedicated low mu dataset required (mu ~2)
- Expected uncertainties with different PDF sets
  - ~10 MeV (200 pb-1)
  - ~6 MeV (1 fb-1)

Compare with most recent, and senstive W mass measurement from CMS with uncertainty 9.9 MeV!

- **Precision** comparable to that of the CDF (9.4 MeV) measurement
- In line with all previous measurements **except** the CDF result.





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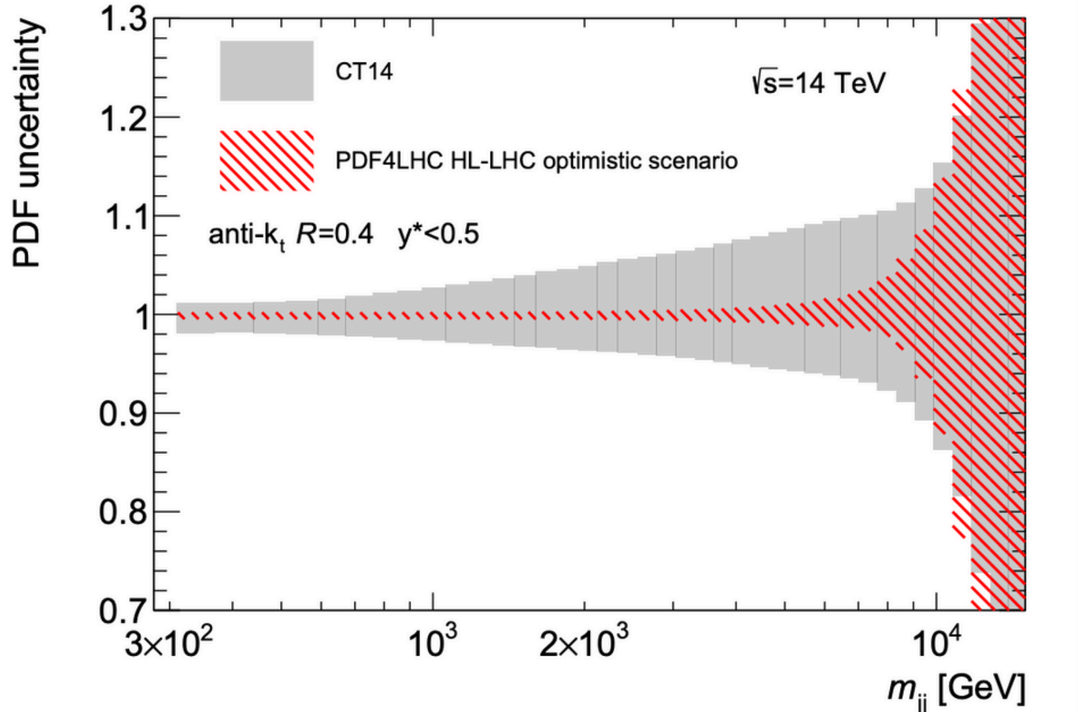
ATL-PHYS-PUB-2018-051
CMS-PAS-FTR-18-032
Eur. Phys. J. C 78 (2018) 962,

QCD physics

Precision jet and photon cross-section measurements & jet energy correlators and jet substructure measurements

- Provide information about the proton and constrain PDFs
- Used to measure the running of the strong coupling
- Improve understanding of QCD matrix elements and parton showers

See Mrinal Dasgupta Talk on Monday



Studies show including HL-LHC measurements in PDF fits results in a significant reduction in the PDF uncertainties compared to the CT14 PDF set

Jet cross-section measurements are crucial for these improvements due to sensitivity to the gluon density

Dijet cross-sections calculated using the CT14 PDF and PDF4LHC HL-LHC sets at √ = 14 TeV with 3000 fb−1

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Top physics

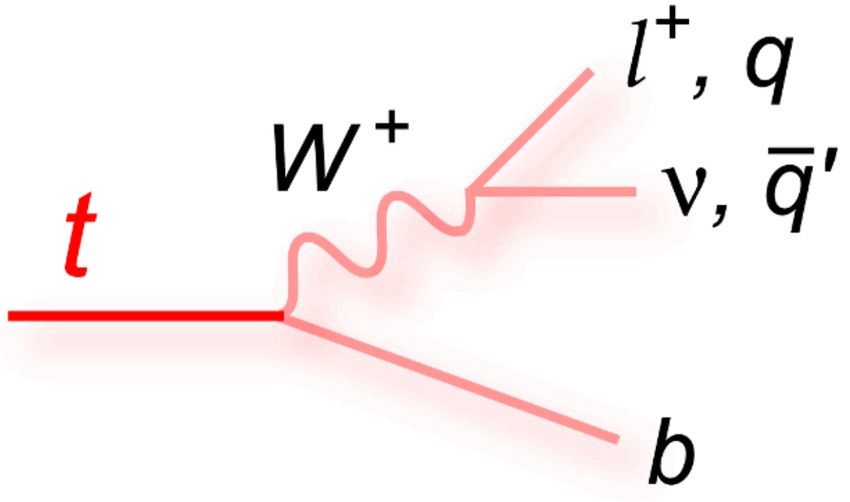
HL-LHC is a top quark factory!
3 x 10^9 ttbar, 800x10^6 single top, 3x10^6 tt+X

Important physics for:

- Providing a stringent test of **perturbative QCD** and electroweak theory
- Gateway to search for **New Physics**
- Providing inputs to **Global PDFs fits**
- Allows extraction of aS, mtop, Yukawa Coupling yt

Precision measurements

- Inclusive & differential top quark production
- **Properties** including spin correlation, mass
- Probing top couplings, strong & EW theories, **rare decays**
- **BSM** physics with top quarks, **asymmetries**, modified vertex properties, resonances or couplings to new particles



- **Heaviest known Fundamental particle m ~ 173 GeV**
- **Mass is of order of the electroweak (EW) symmetry breaking scale**
- **Short lifetime allowing the study of the bare quark and its spin**

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Top quark physics

Top mass measurements

CMS-PAS-FTR-16-006
ATL-PHYS-PUB-2018-042

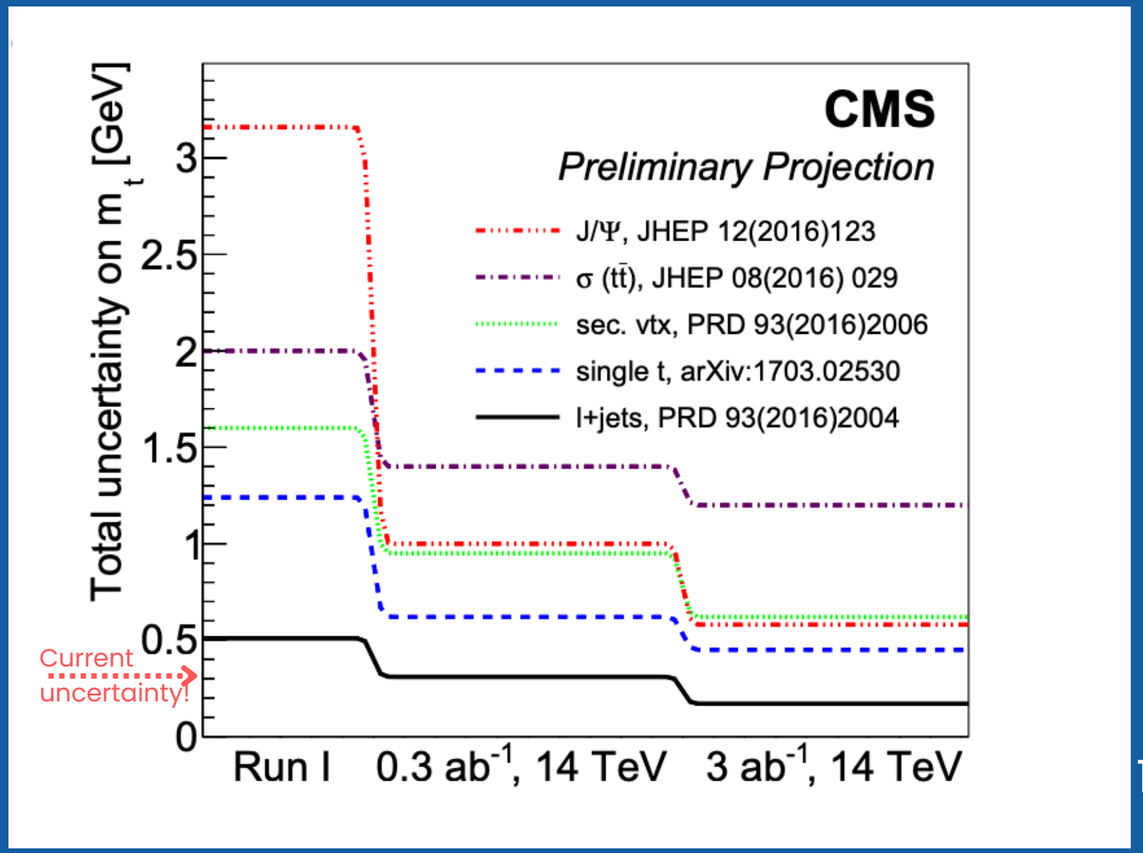
The uncertainties on the latest mass measurements are on the order of 500 to 600 MeV, and at the HL-LHC this is projected to be reduced to 200 MeV

Direct measurement in ttbar or single top
- jet systematics dominate

Indirect measurement from cross sections
- theory & luminosity uncertainties dominate

ATLAS and CMS studied top quark mass in the lepton + jets channel with a J/Psi decaying into a muon-antimuon pair

Expected to yield an ultimate relative precision below ~ **0.1% at the HL-LHC**



Run 1 combination: 0.33 GeV
Best run-2 single measurement: 0.37 GeV

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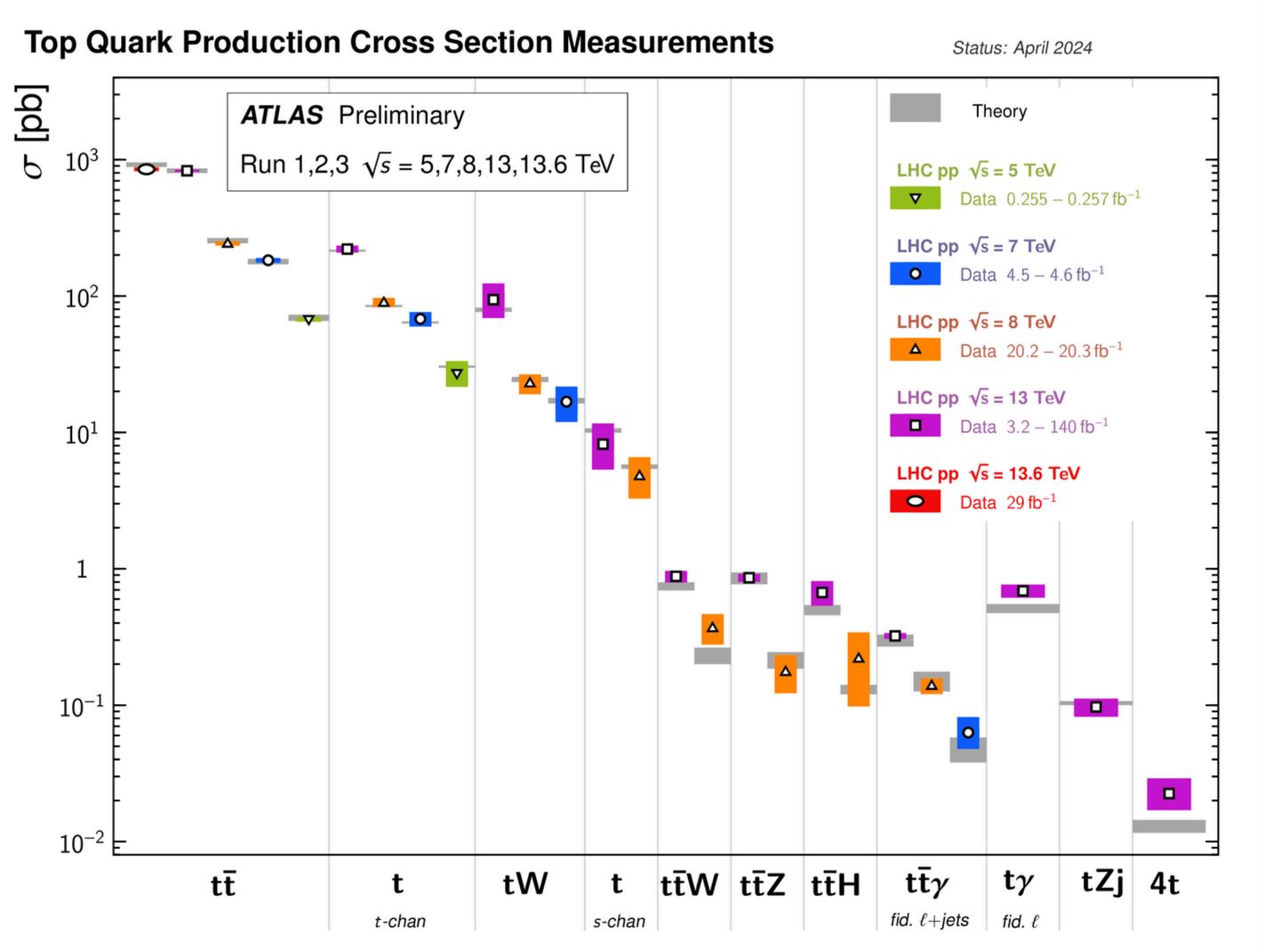
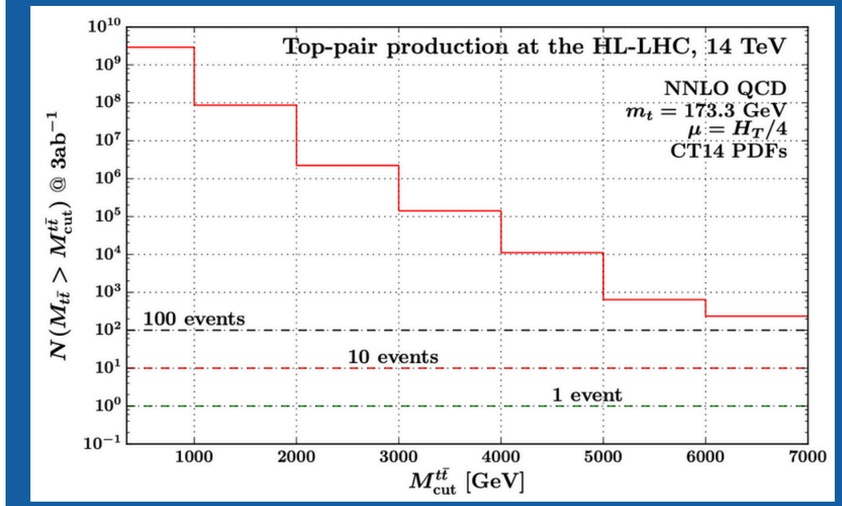
Top quark physics

Studies of rare top processes

Eur. Phys. J. C 83 (2023) 496
CMS-PAS-TOP-22-013



At HL-LHC, cross sections for tt, tt+X will increase by a factor of 1.2 (tttt by a factor 1.3)



HL-LHC allows detailed studies of top quark pair production with mtt of up to about 7 TeV.
The region > 7 TeV provides a low SM background for searches

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Top quark physics

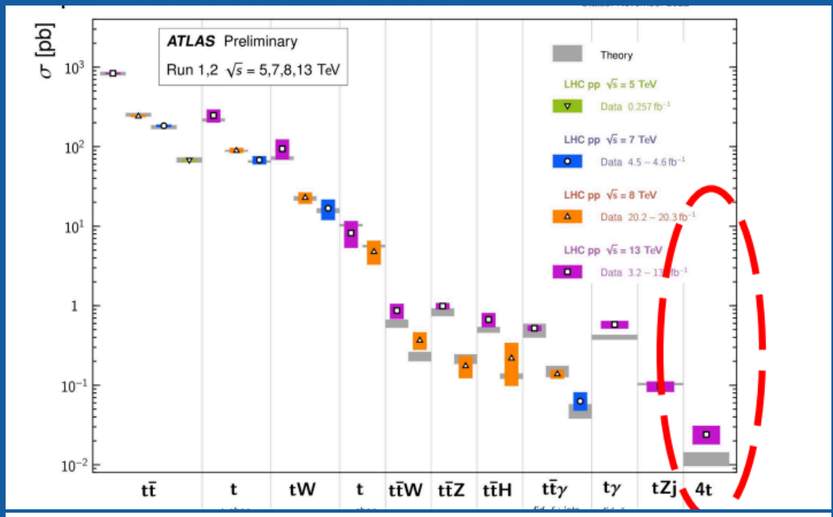
Studies of rare top processes, tttt

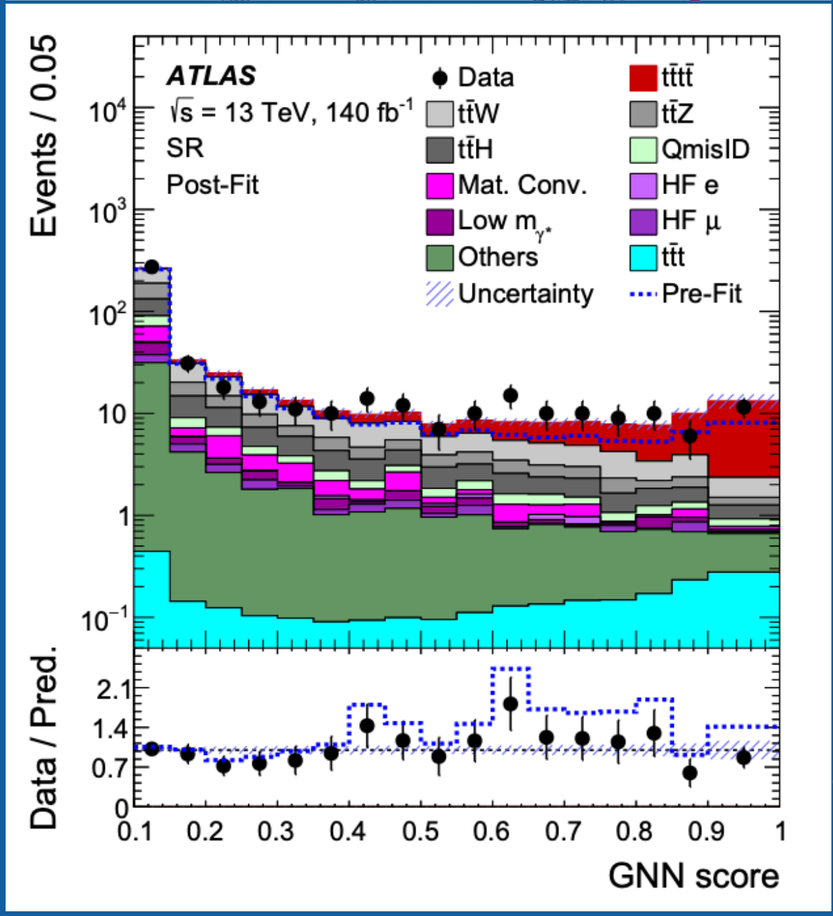
tttt is a **very rare process** with large sensitivity to NP
Its the heaviest processes ever observed at the LHC (total particle mass ~700 GeV)

Observed **earlier than expected** consistent with the 13 TeV SM prediction of 12.0 ± 2.4 fb within 1.8 standard deviations by ATLAS

Complex analysis possible due to development of **Graphic Neutral Network**

HL-LHC will result in **30%** increased production rate, allow **differential** measurements and increased **precision** results in uncertainty at **percent level**





Eur. Phys. J. C 83 (2023) 496
CMS-PAS-TOP-22-013

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ATL-PHYS-PUB-2018-049

Top quark physics

Studies of rare top processes tt+photon

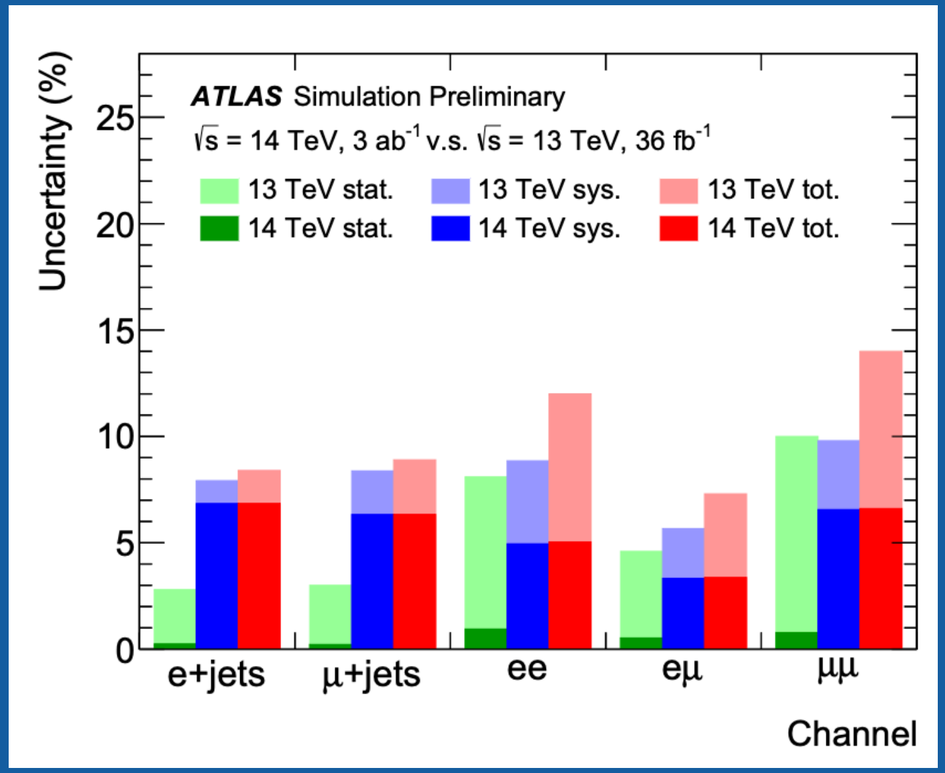
Associated production of a top quark pair with a highpT photon, probes the ty electroweak coupling

For HL-LHC fiducial cross-section uncertainty projected one (two) leptons

- 6% (3%) for pT(y)>20GeV
- 8% (12%) for pT(y)>500GeV

Expected uncertainties of differential cross-section measurements are below 5%

Measurement could effectively constrain some Wilson coefficients in top-quark EFTs



Operator	O_{tB}	O_{tG}	O_{tW}
Single lepton	[-0.5,0.3]	[-0.1,0.1]	[-0.3,0.5]
Dilepton	[-0.6,0.4]	[-0.1,0.1]	[-0.4,0.3]

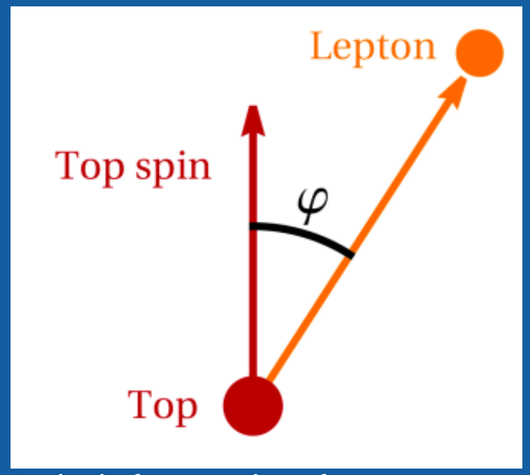
https://journals.aps.org/prd/pdf/10.1103/PhysRevD.109.115023
https://link.springer.com/article/10.1140/epjc/s10052-022-10245-9
https://arxiv.org/pdf/2110.10112
https:/arxiv.org/pdf/2102.11883

Top quark physics

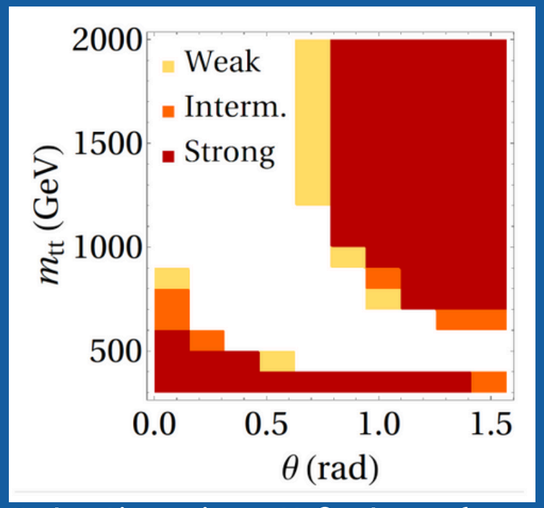
Quantum Entanglement

HL-LHC allows us to probe top quark quantum entanglement further and to assess Bell inequalities violation, which can test quantum mechanics (also with Higgs!)

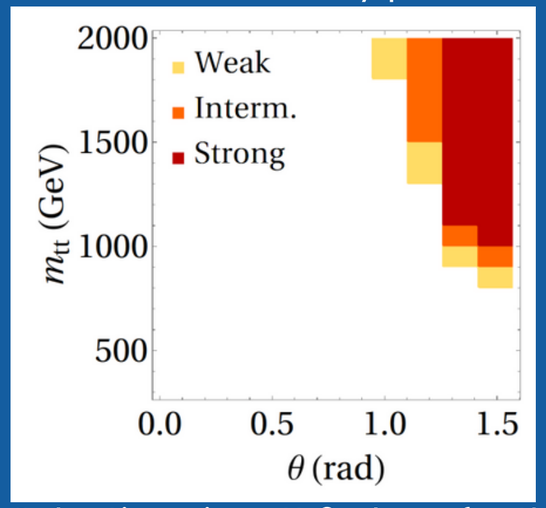
- Observed at threshold at particle level with **ATLAS** utilizing a calibration curve, and at **CMS** at parton level using a binned likelihood fit
- Regions of phase space where top spins are entangled and where they are so entangled (left) that they **violate Bell Inequalities** (right)
- This region of phase space is very very small, and **requires sufficient statistics** using boosted measurements at the **HL-LHC**



Spin information from tops transferred to decay particles



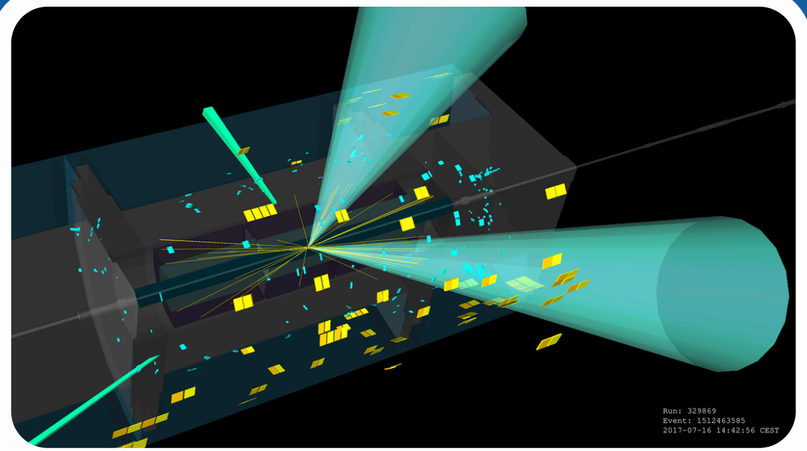
Selections in mtt θ plane for the observation of entanglement



Selections in mtt θ plane for the observation of a violation of the Bel inequality.

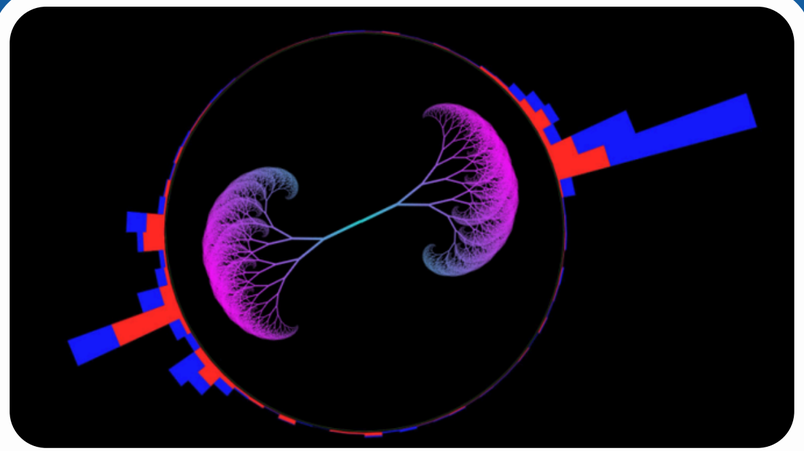
HL-LHC

MORE DATA, IMPROVED DETECTORS, ADVANCES IN ANALYSIS TECHNIQUES
REDUCED UNCERTAINTIES, PRECISION MEAUREMENTS, AND SENSITIVITY TO NEW PHYSICS



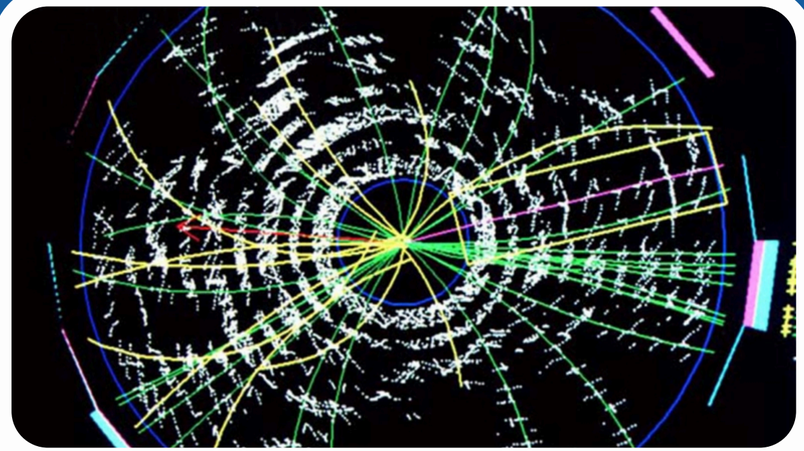
ELECTROWEAK

The large HL-LHC dataset will enable precision measurements of various electroweak processes, many of which are currently limited by statistical uncertainties.



PERTURBATIVE QCD

The HL-LHC will will provide the opportunity to test the behavior of QCD with better precision, particularly at high energies which are currently limited by statistical uncertainties

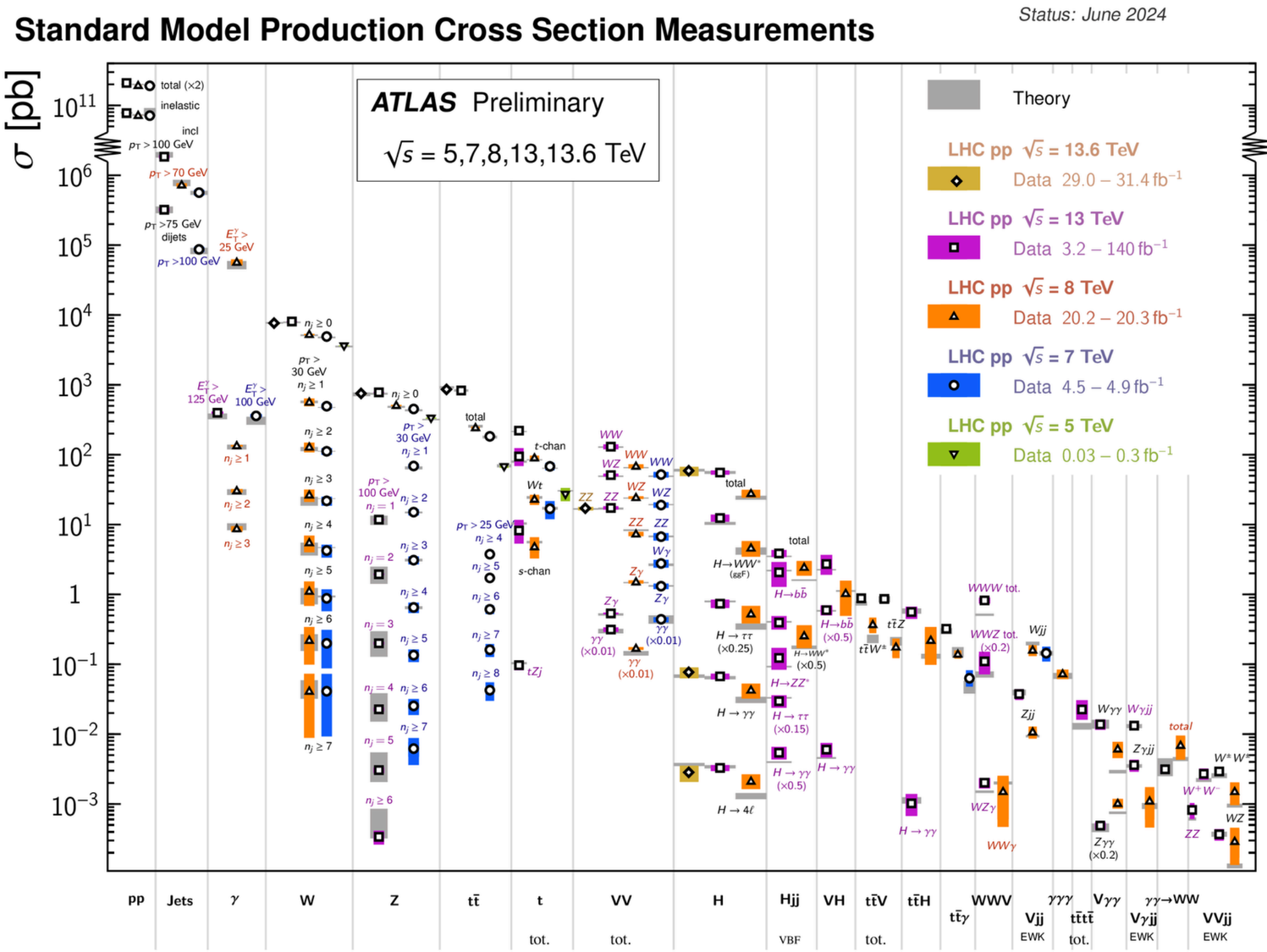


TOP PHYSICS

Top quark production physics at HL-LHC will enable precision cross-section measurements probing very rare and very high energy processes, with high sensitivity to New Physics.

Thank You

Standard Model Measurements



Opportunity to carry out staggering extent of **diverse** verifications of the Standard Model predictions

Processes with assorted final states

Spans several orders of **magnitude** in cross-section