Standard Model Physics at LHC

International Conference on High Energy Physics & Astroparticle Physics

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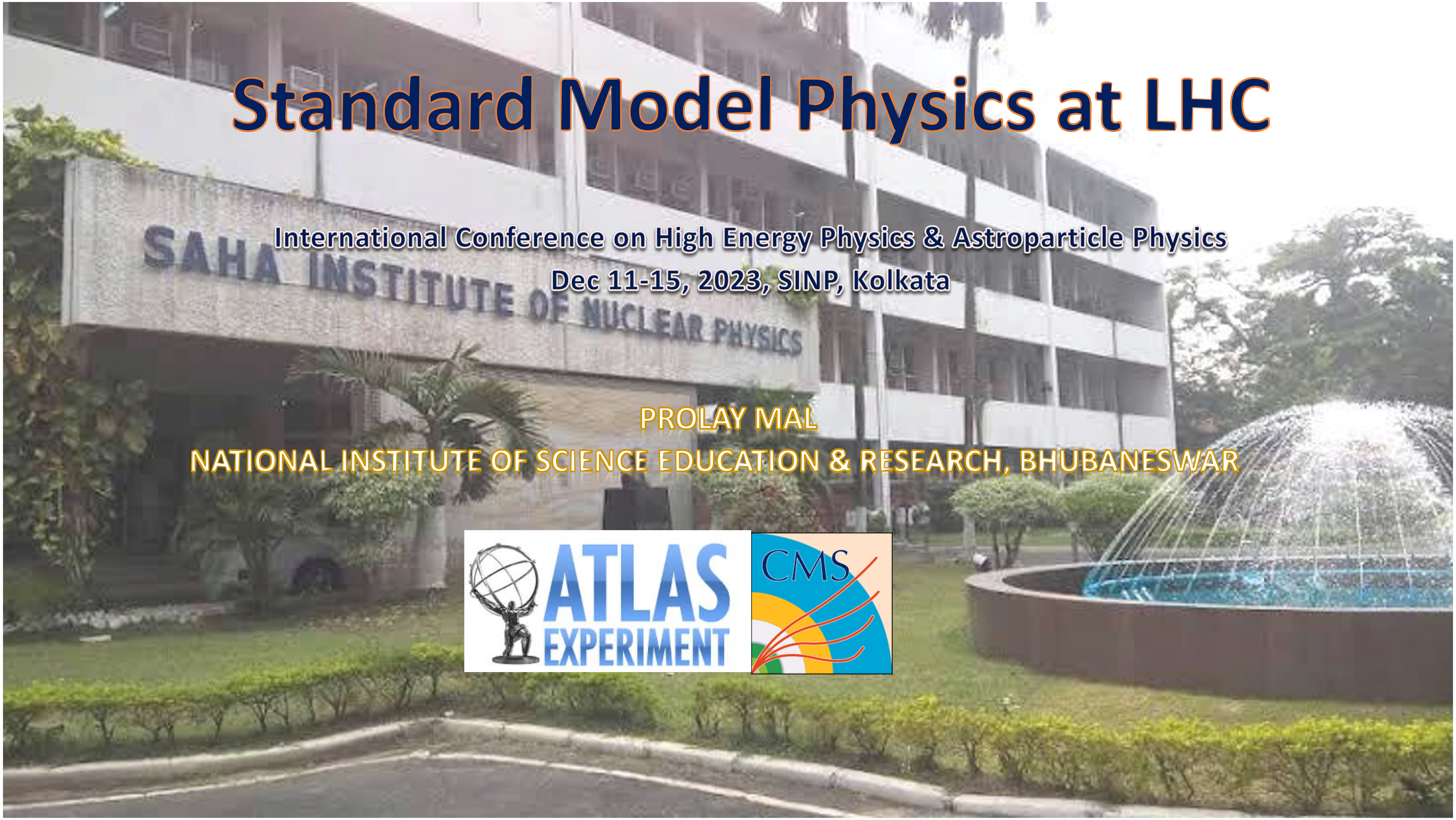
PROLAY MAL

NATIONAL INSTITUTE OF SCIENCE EDUCATION & RESEARCH, BHUBANESWAR

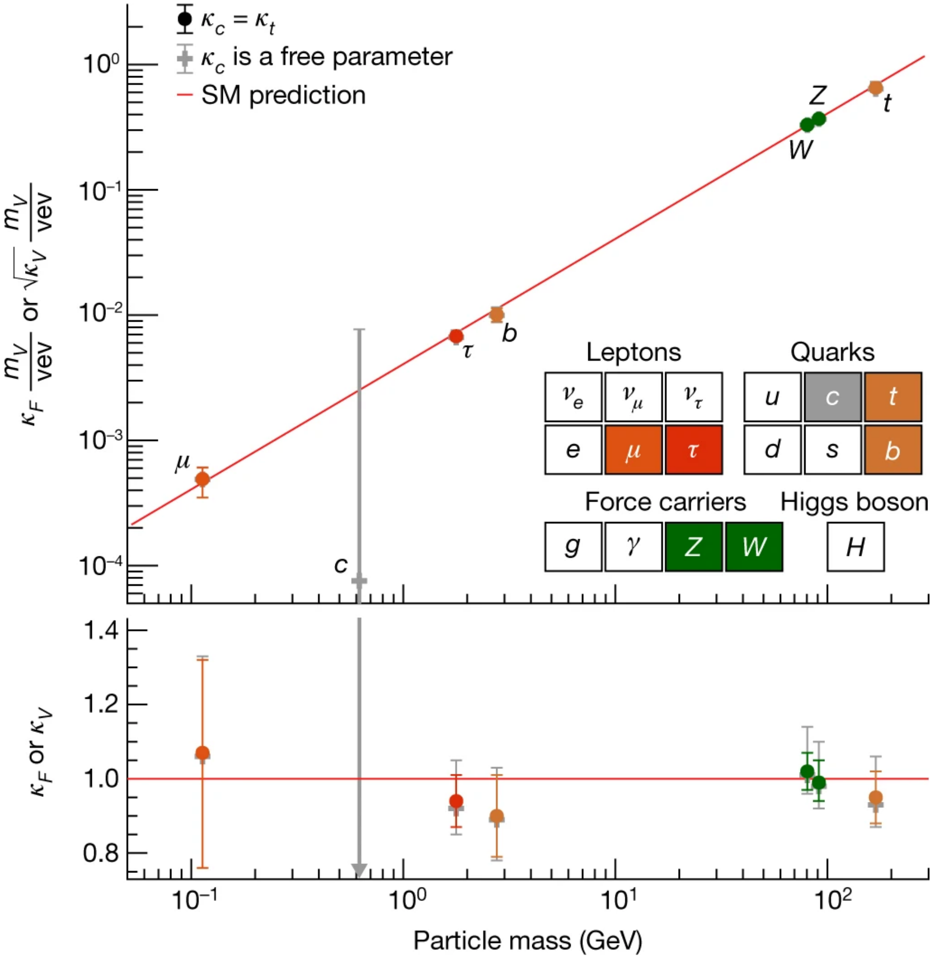


Standard Model of Particle Physics

- ✓ Consists of all the known elementary particles till date (with masses ranging over 14 orders of magnitude!) encapsulating everything we know so far about the nature
- ✓ Remarkably successful in predicting phenomena involving wide range of cross-sections [10^{-3}-10^{11} pb] and withstood many detailed scrutiny over the past few decades of terrestrial experiments!
- ✓ Discovery of the Higgs boson in 2012 of course opened up the possibility for its property measurements; (so far) no deviations from the SM observed – see Vivek Sharma's presentation
- ✓ Yes, the SM is regarded an "effective theory"

Not predicted/answered by the SM

- ➢ Hierarchy problem – new physics at TeV scale or extremely fine-tuned Higgs mass?
- ➢ Dark matter – Universe has larger mass than visible! (see presentations by A. Roy & B. Gomber on collider searches)
- ➢ Many more puzzling questions
  - ➢ Matter/antimatter asymmetry
  - ➢ Non-zero neutrino mass

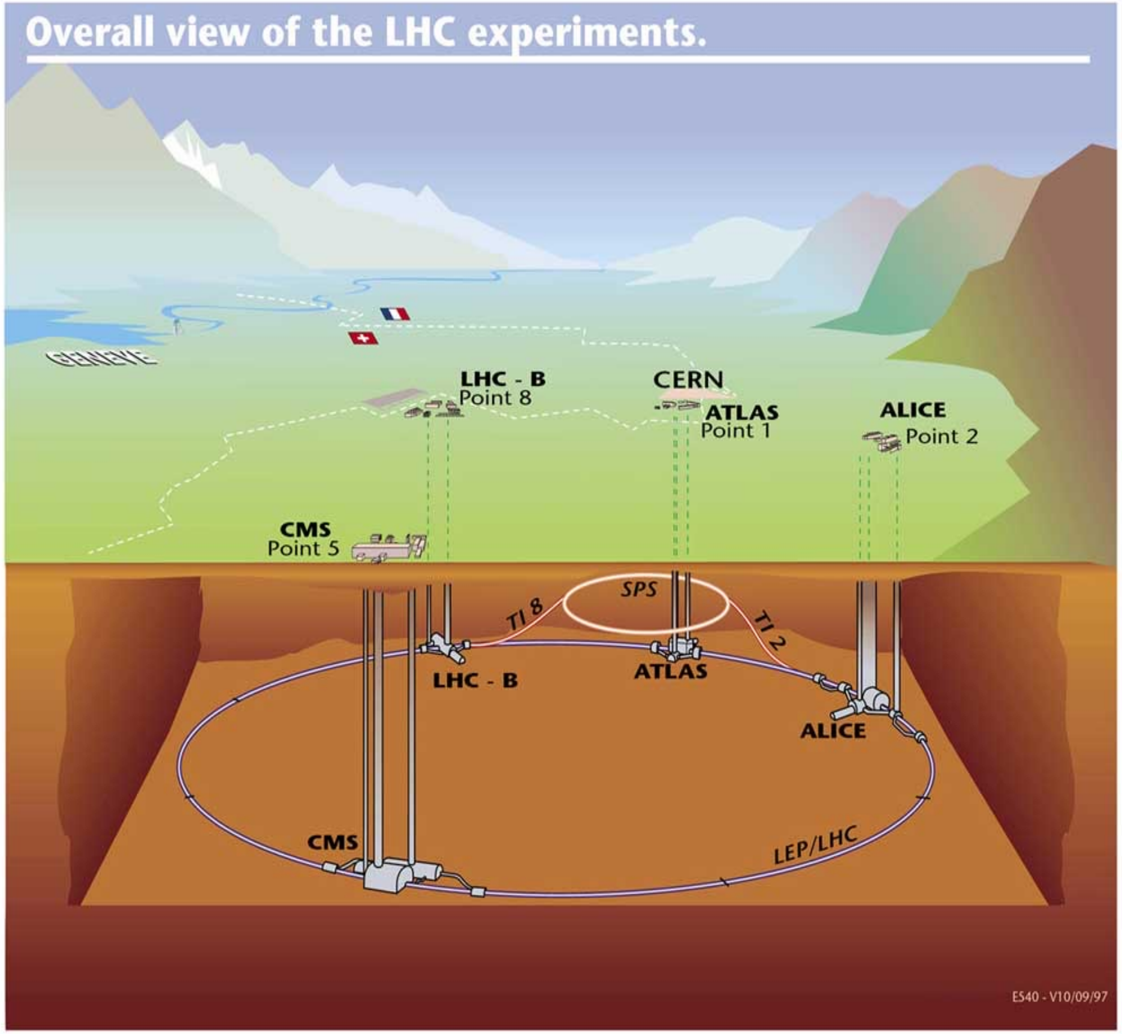


The Large Hadron Collider (LHC)

One of the largest and the most complex scientific instrument ever conceived & built by humankind

- Magnetic field at 7 TeV: 8.33 Tesla; operating temperature: 1.9 K
- Magnets: ~9300 (1232 dipole, 858 quadrupole, 6208 corrector)
- RF cavities: 8 per beam; field at top energy ≈ 5 MV/m
- Maximum number of bunches: 2808
- Peak luminosity: 2.5 x $10^{34}cm^{-2}s^{-1}$
- Collision frequency at 40 MHz
- Power consumption: ~180 MW

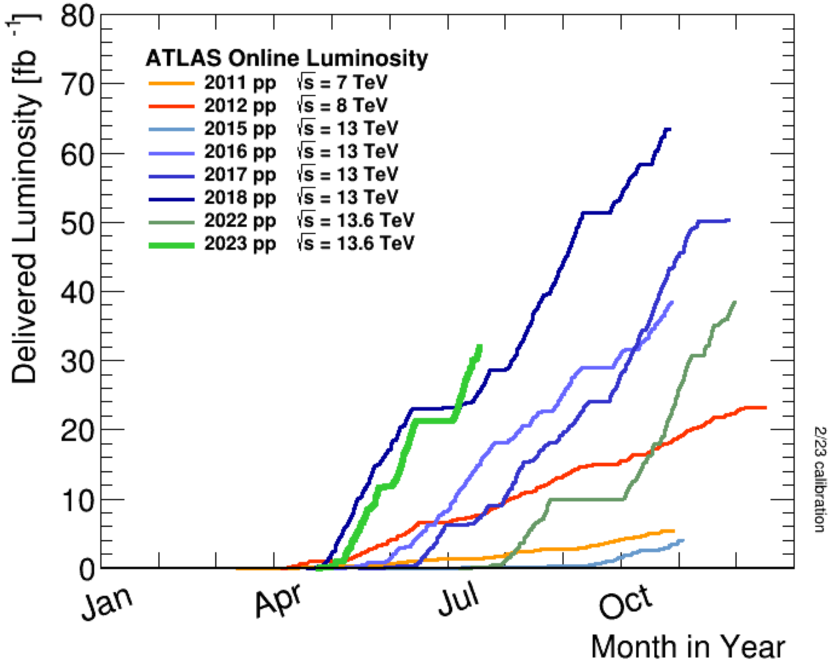
The LHC

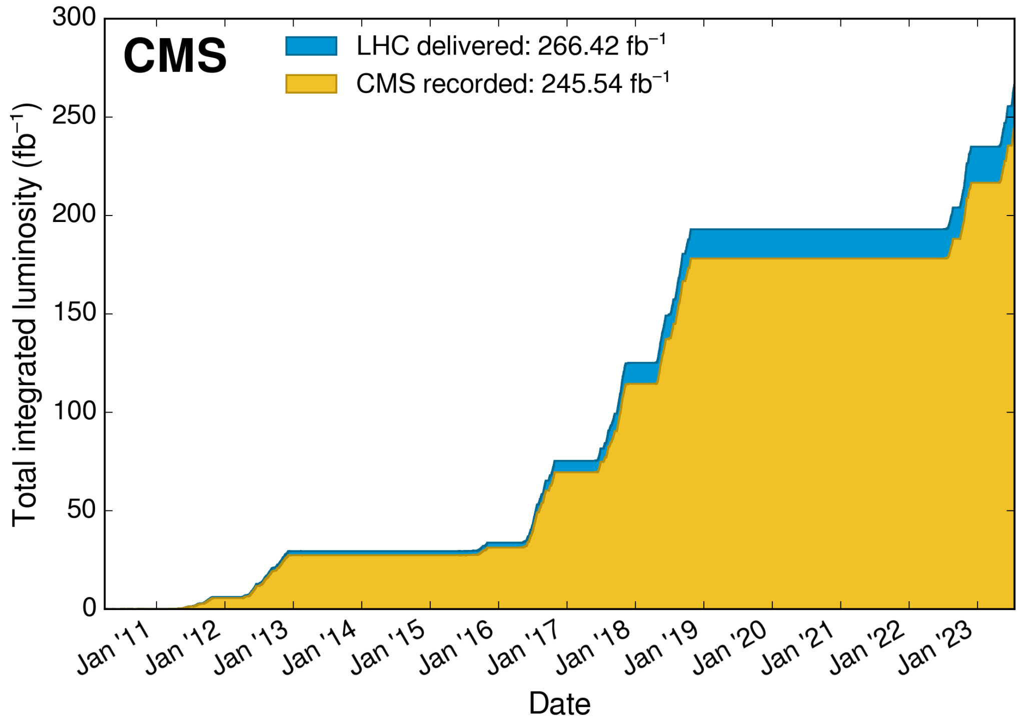


- Proton-proton (pp) collisions at √s=7-8 TeV (2010-12, Run 1); √s=13 TeV (2015-18, Run 2); presently operational at √s=13.6 TeV (Run 3 since 2022)
- ATLAS & CMS are the two general purpose particle physics experiments.

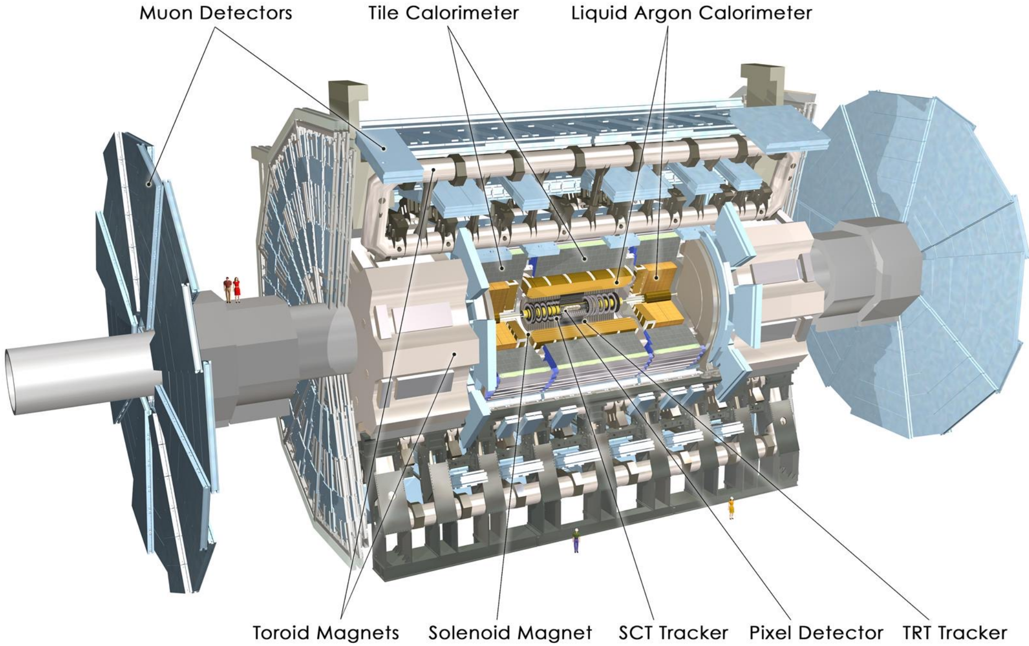
LHC Luminosity Accumulation

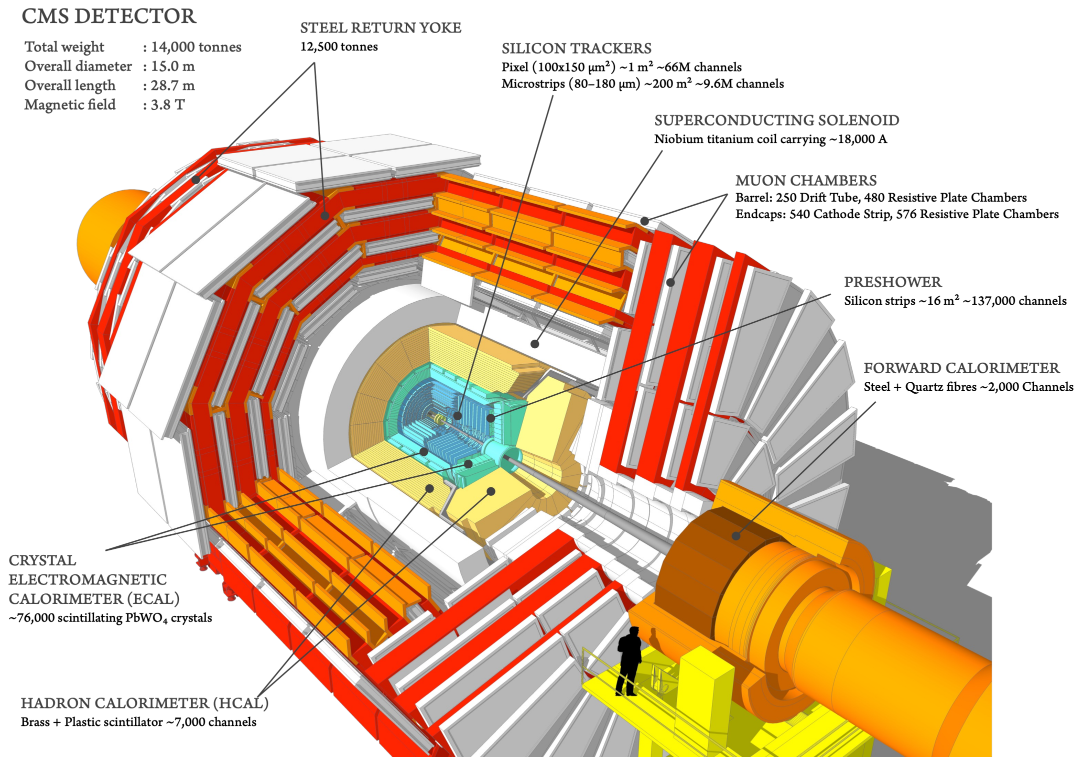
- Ongoing Run 3 started in 2022 at √s=13.6 TeV and LHC has been setting new record-breaking luminosity
- Exceedingly well performance by the LHC with delivered luminosities increasing rapidly
- Many precision measurements and rare processes studies have been plausible mostly due to the LHC performance “beyond the design goal”.





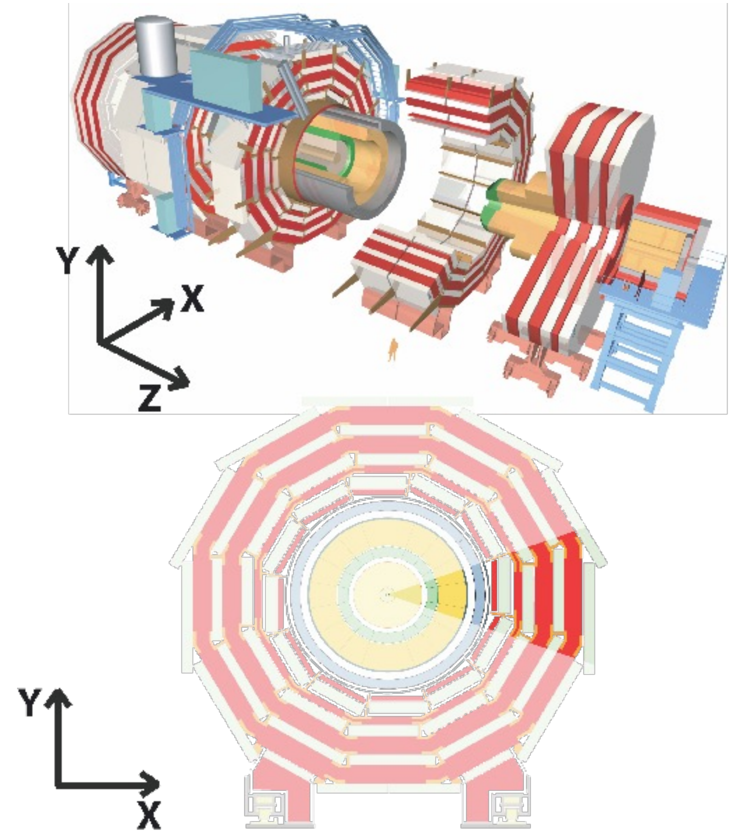
ATLAS & CMS detectors

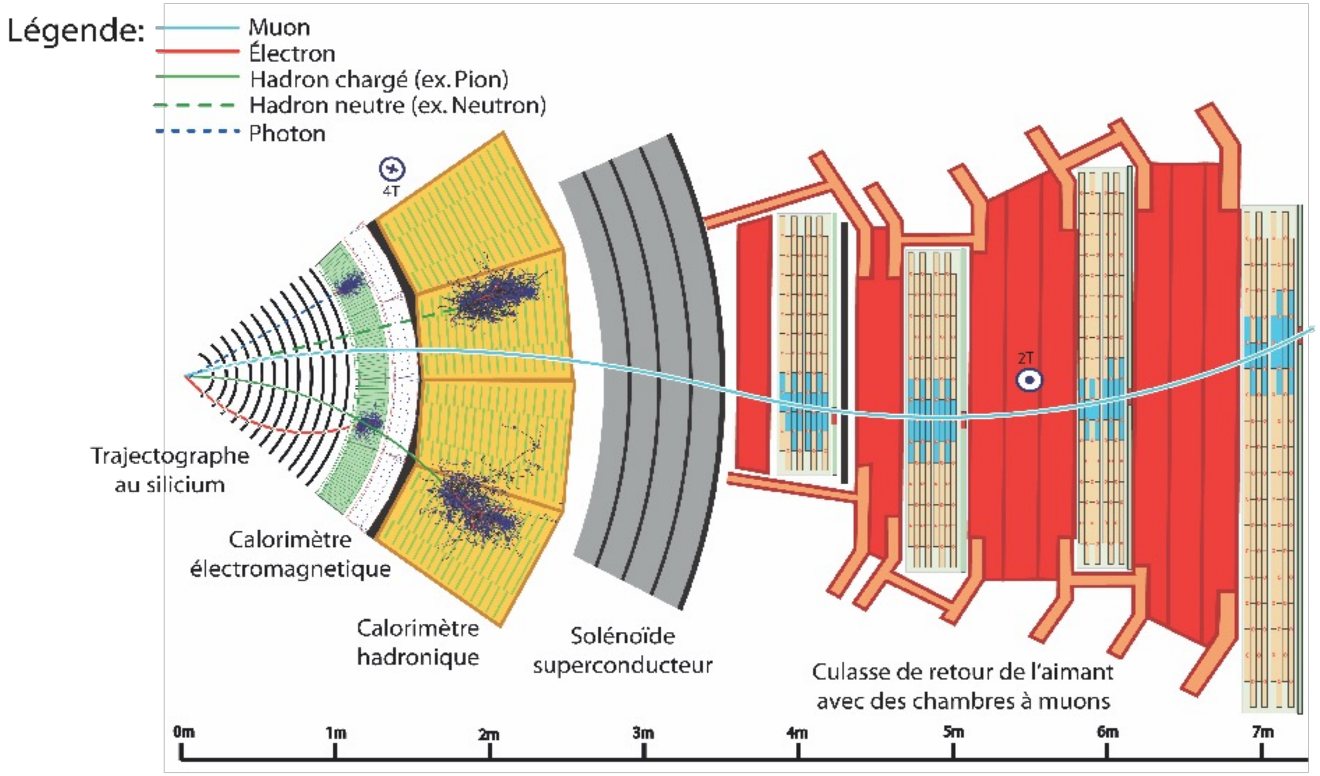




- **multi-purpose detectors with tracker, calorimeter and muon systems with hermatic coverage**
  - **Both have undergone upgrades during the Long shutdown 1 (LS1) 1 and LS2 already**
  - **Major detector upgrade (Phase 2) to follow for the High-Luminosity operations (HL-LHC)**

Particle Detection/Identification (CMS)

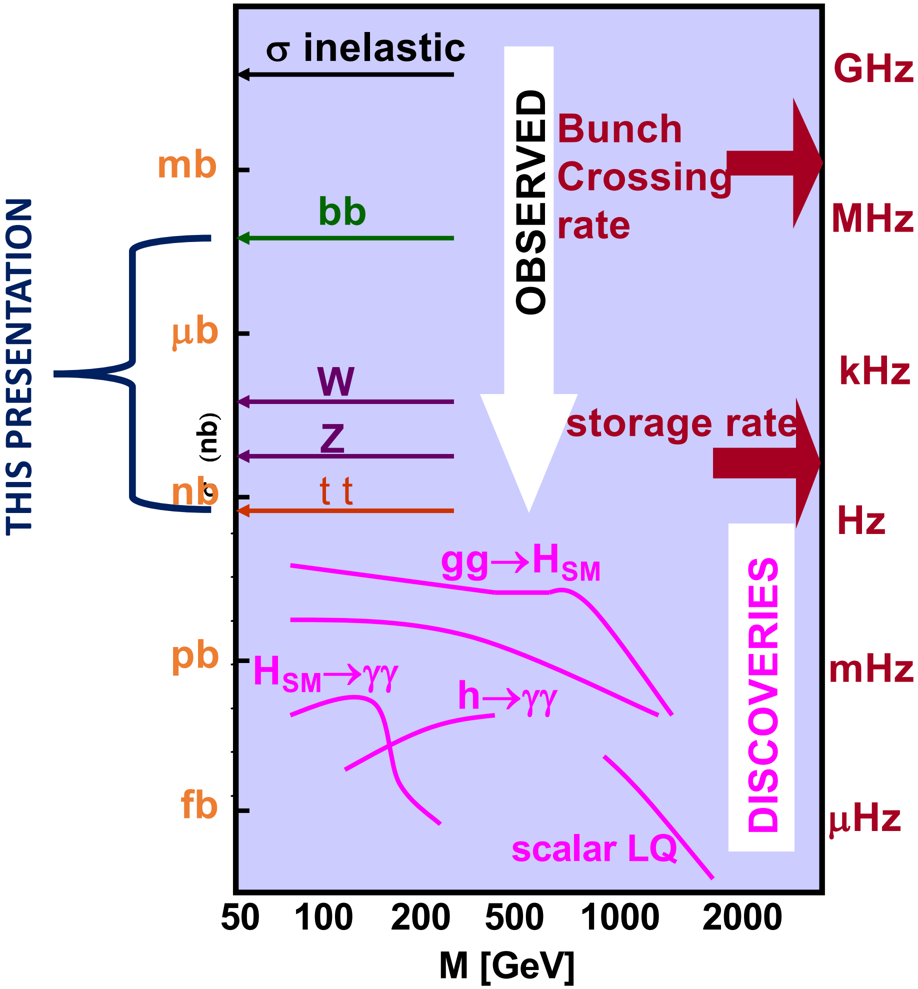




Muon **Electron** **Charged hadron (e.g. pion)**

Neutral hadron (e.g. neutron) **Photon**

The challenge @LHC



At the "standard" LHC luminosity:

$L=10^{34}\ cm^{-2}s^{-1} = 10^{10}\ Hz/b$

$\sigma_{inelastic}(pp) \sim 70\ mb$

$\Rightarrow 7 \times 10^{8}$ interactions

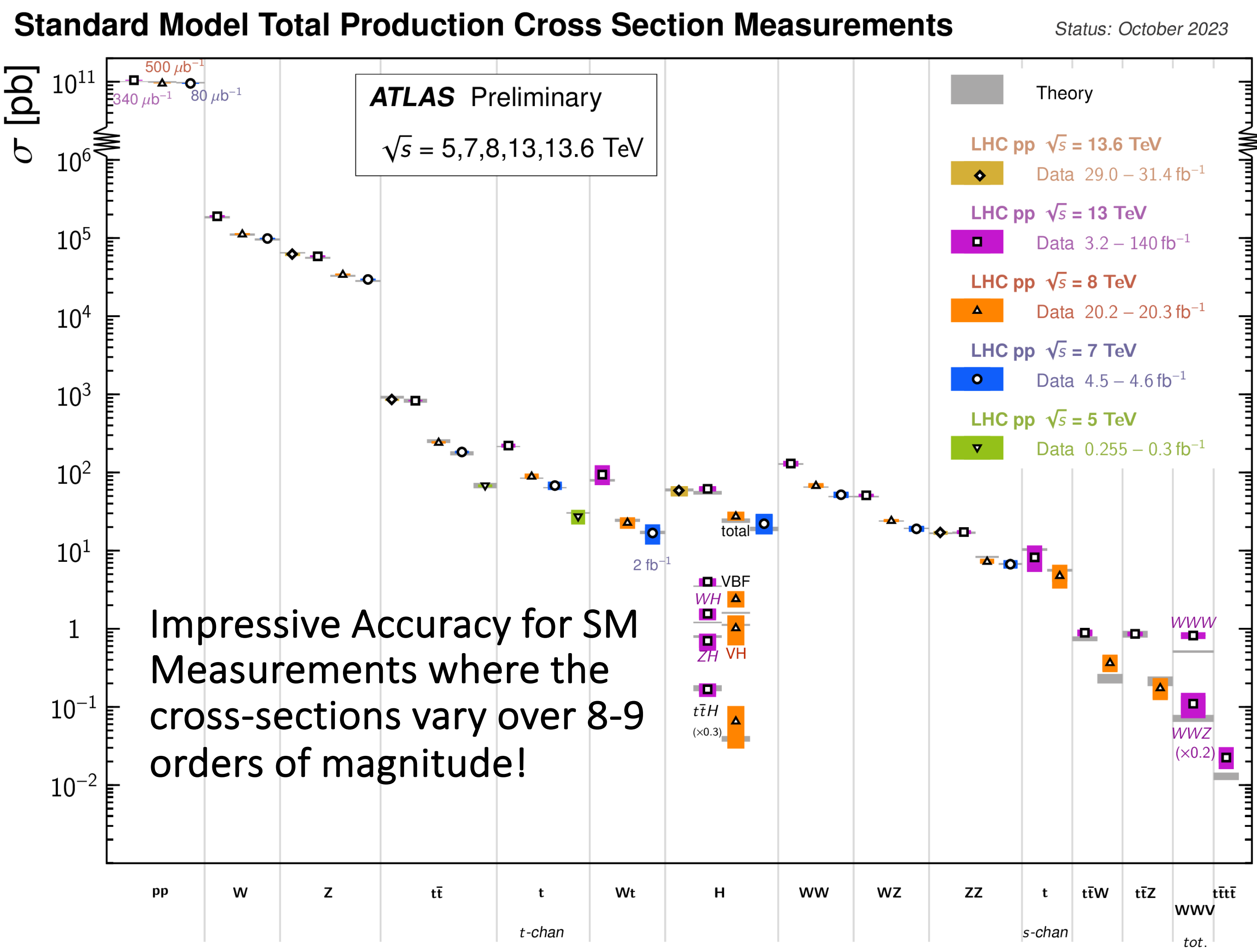
Bunch crossing frequency: 40MHz

Storage rate ~ 1000 Hz

→ online rejection: > 99.99%

→ crucial impact on physics reach

Events discarded by the trigger system are lost forever



Impressive Accuracy for SM Measurements where the cross-sections vary over 8-9 orders of magnitude!

✧ Number of produced events for 137 fb^{-1}

✧ W bosons 2.7×10^{10}

✧ Z bosons 8×10^{9}

✧ Top quarks 1.3×10^{8}

✧ Higgs 8×10^{6}

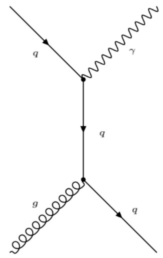
Recent QCD results

Inclusive Photon Production

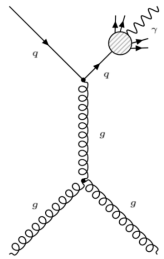
Measurement of inclusive isolated-photon cross section in ATLAS (full Run 2)

- Important measurement for test of pQCD
  - SHERPA 2.2.2: γ + 0,1,2j @NLO + 3,4j@LO
  - Fixed order predictions: JETPHOX (NLO) and NNLOJET (NNLO)
- Constraints on PDF (especially gluon)

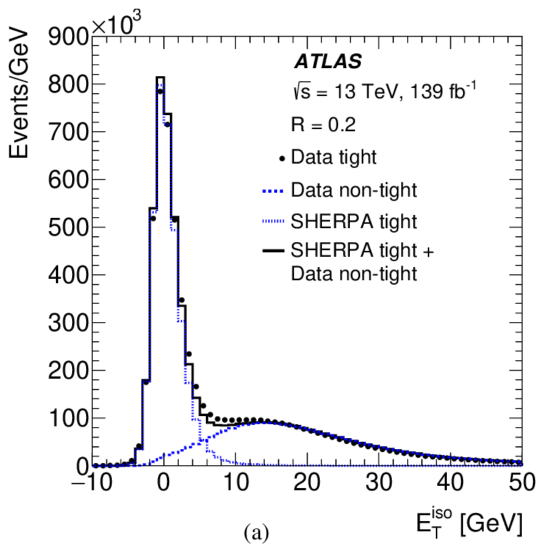
Direct process



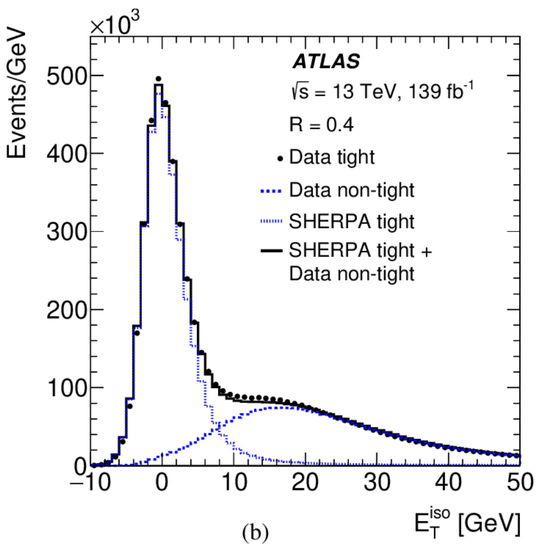
Fragmentation process



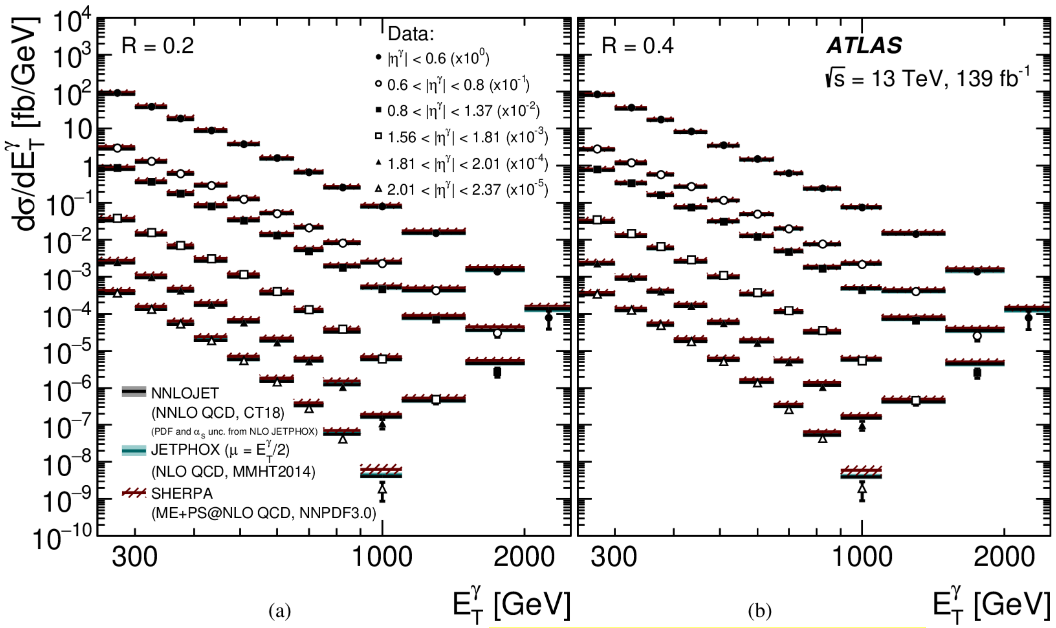
- Select isolated photons to remove photons from jets
  - Cone-based isolation: R=0.2/0.4



(a)



(b)



(a) (b)

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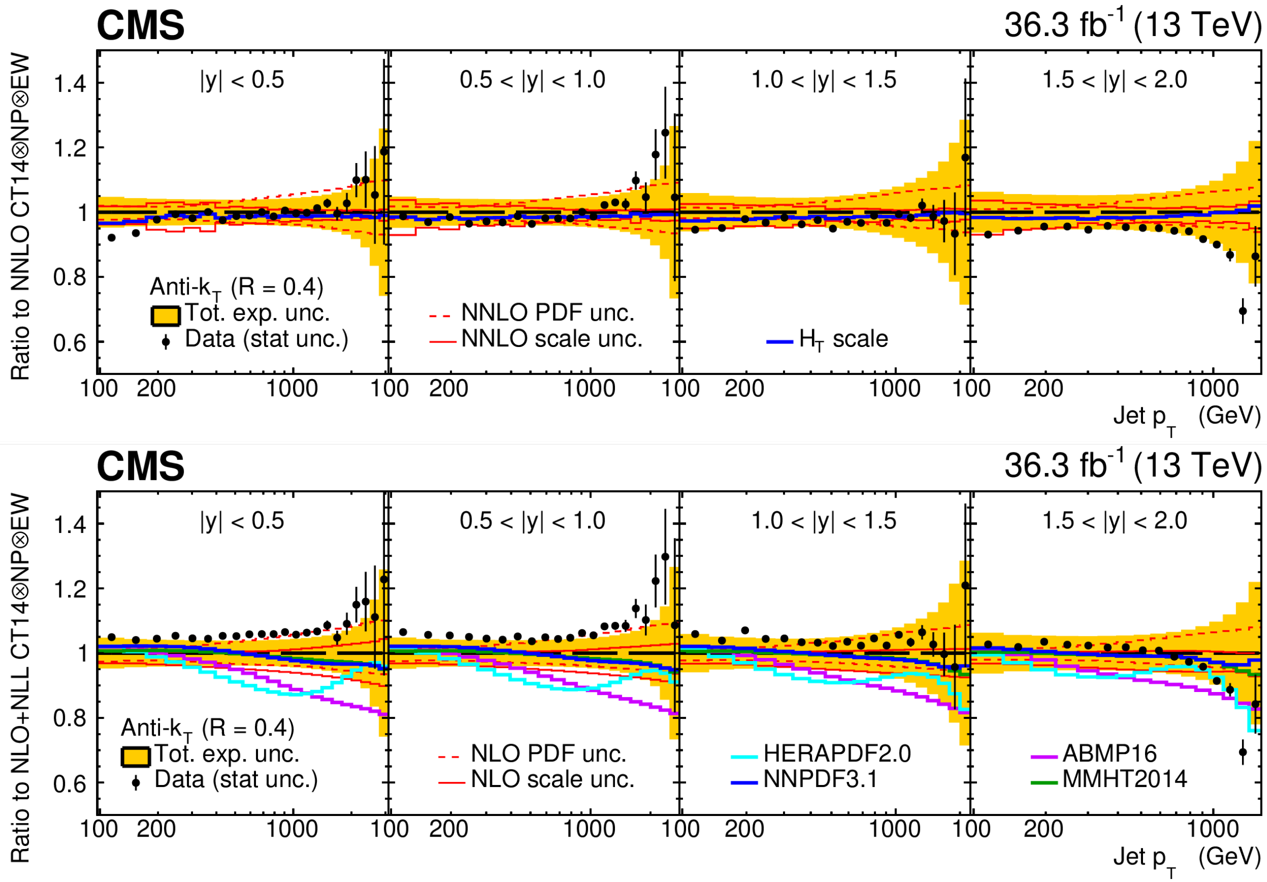
QCD Strong Coupling constant (α_S)

- ❖ α_S uncertainty is ~1%

  PDG: $\alpha_s\left(m_z\right) = 0.1179 \pm 0.0009$
- ❖ Inclusive jets measurements to obtain/extract PDF and α_S simultaneously

- ❖ 13 TeV dataset with AK4/AK7 jets with pT>97 GeV and |y|<2.0
  - ❖ Improved precision of the gluon at high x-values (NNL0)

Extracted $\alpha_S(m_Z)$= 0.1166 ± 0.0017



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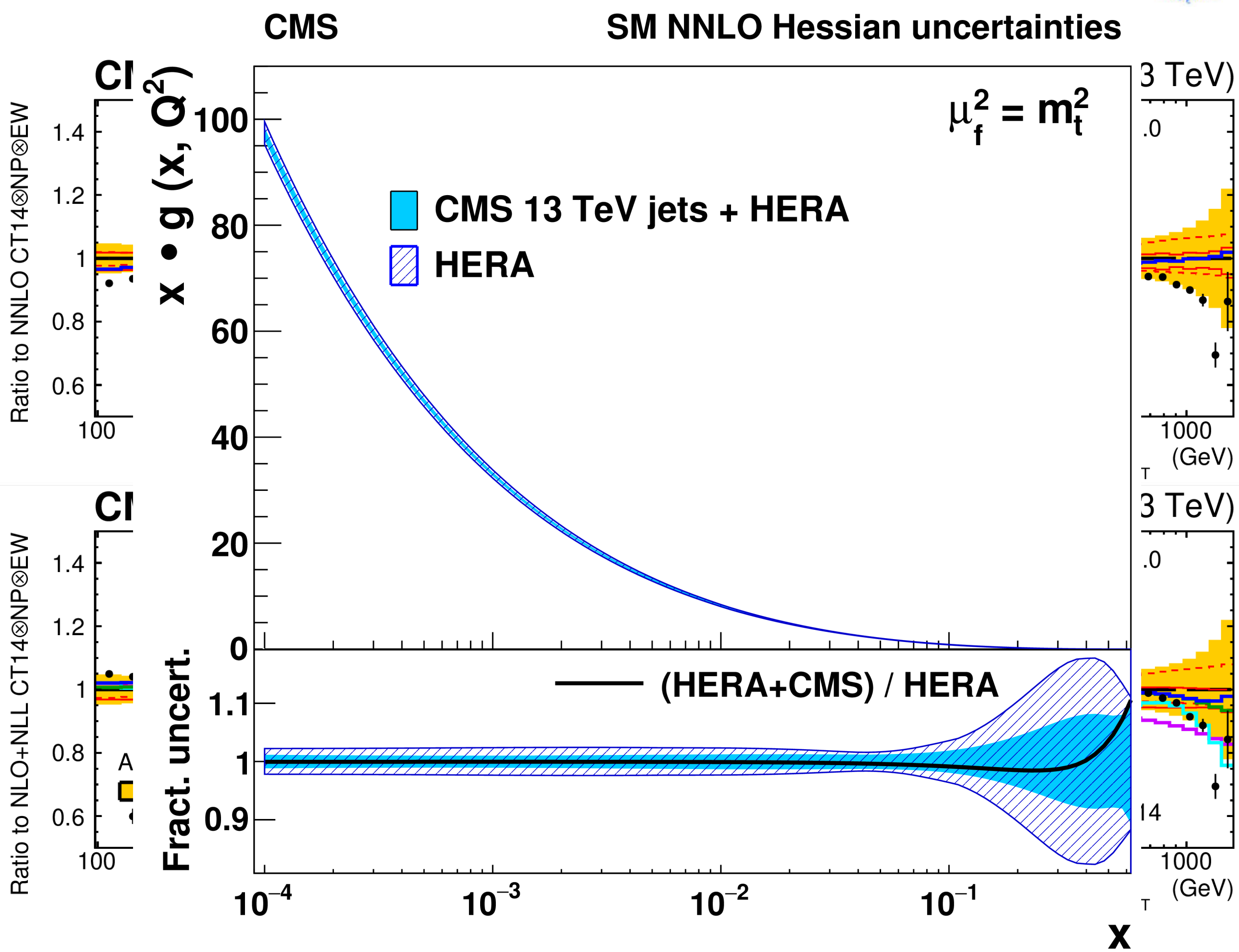

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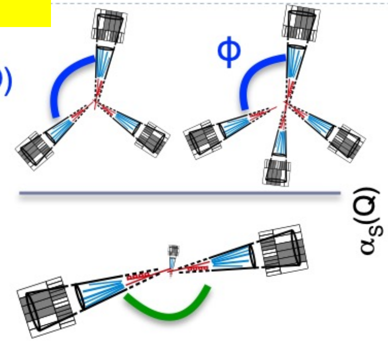
Measurement of α_S from jet azimuthal correlation

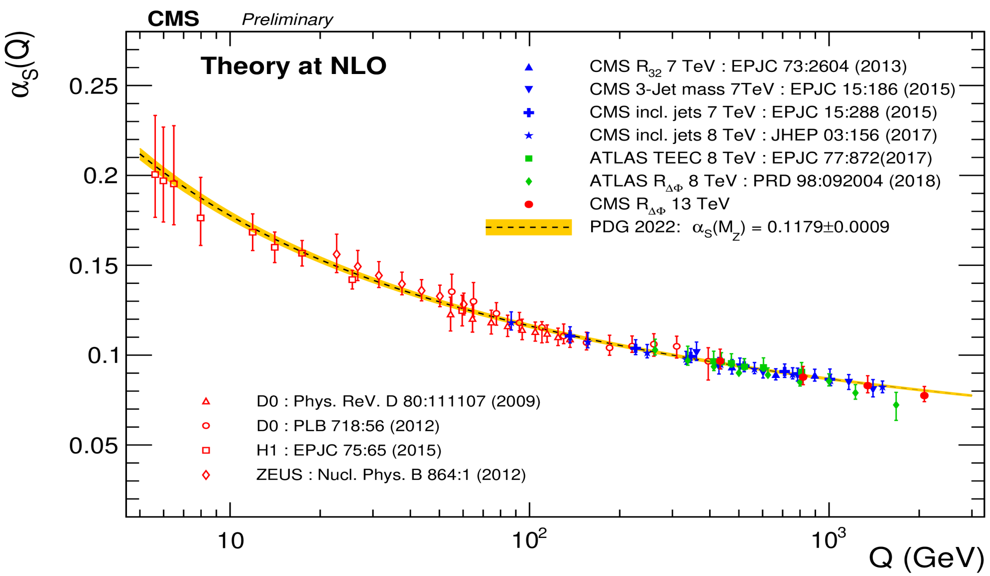
CMS-PAS-SMP-22-005

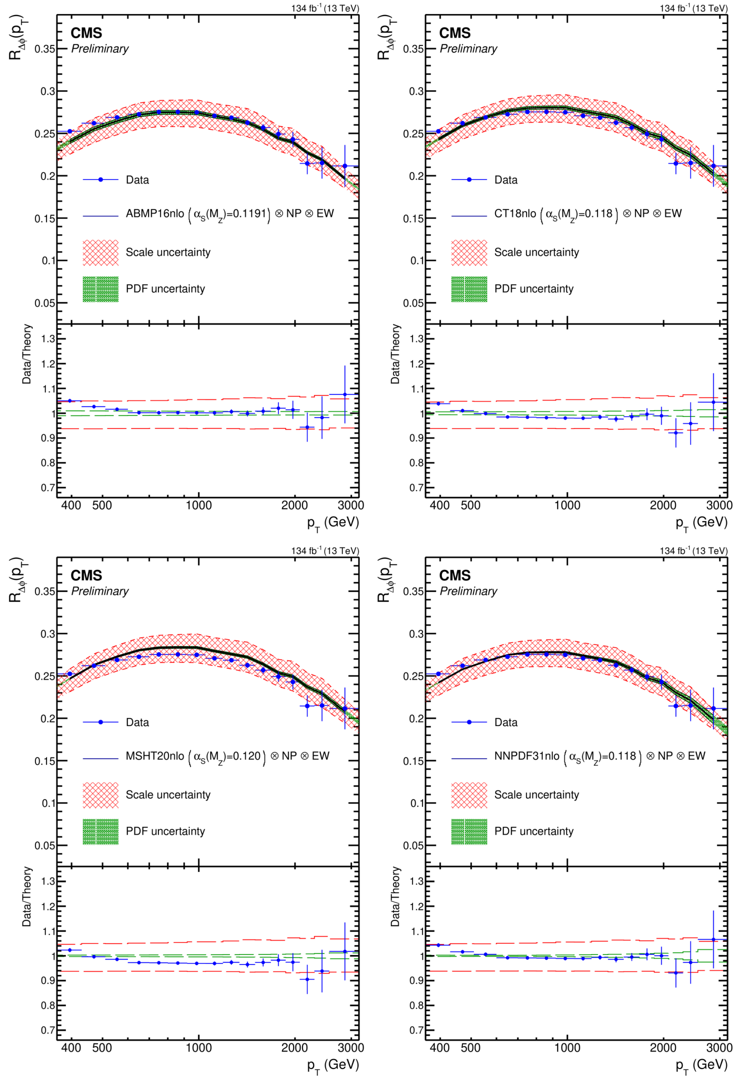
Topologies with at least 3 jets (~ α_s^3) (LO)

$$R_{\Delta\phi}(p_T) = \frac{\sum_{i=1}^{N_{\text{jet}}(p_T)} N_{\text{nbr}}^{(i)}(\Delta\phi, p_{T\text{min}}^{\text{nbr}})}{N_{\text{jet}}(p_T)}$$

Inclusive jets (~ α_s^2) (LO)







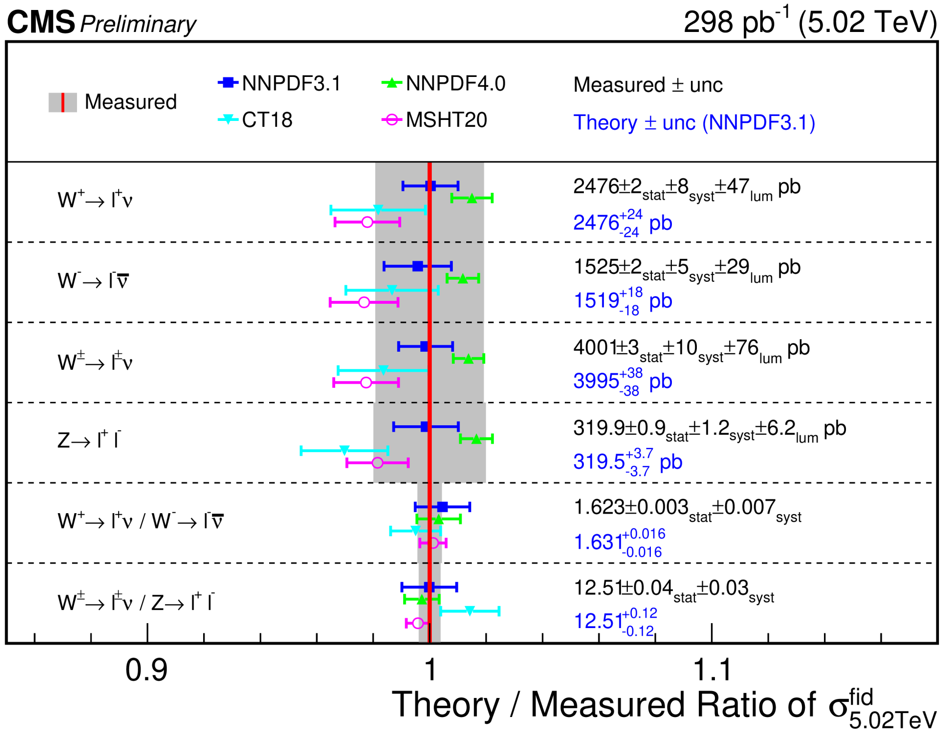
✓ α_S (M_Z) ~ **0.117 with <10% relative uncertainty**

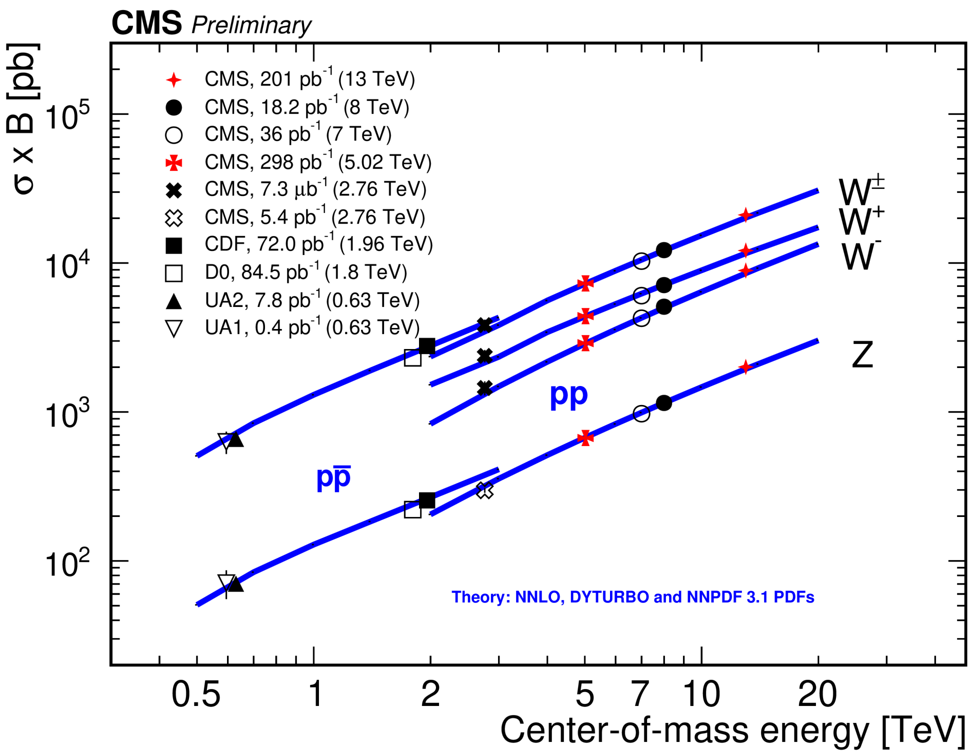
✓ **Running coupling constant demonstrated up to 2 TeV**

Recent measurements with Vector bosons

Summary of W/Z cross-sections (5.02 & 13 TeV)

CMS-PAS-SMP-20-004 (Aug, 2023)



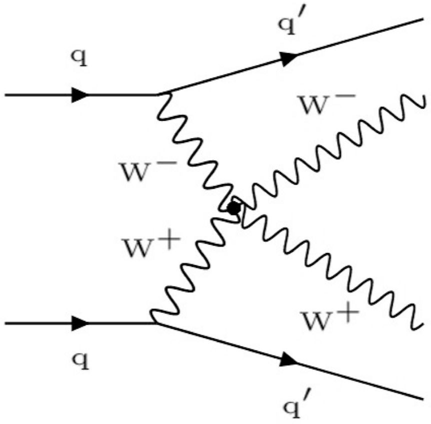


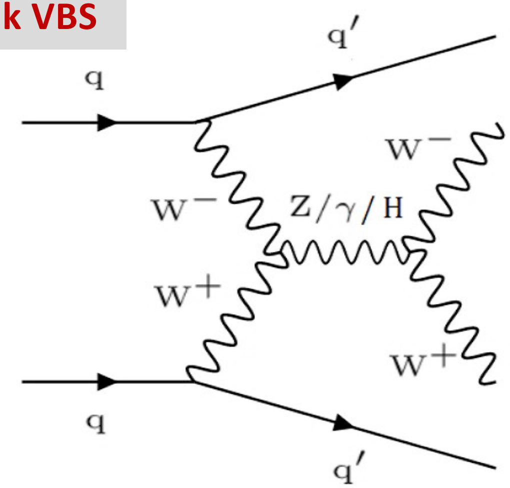
- Precision measurement with the Vector Boson production at $\sqrt{s}$=5.02 TeV ans 13 TeV in agreement with NNLO pQCD calculations
- All other experimental results are summarized as the function of center-of mass energy

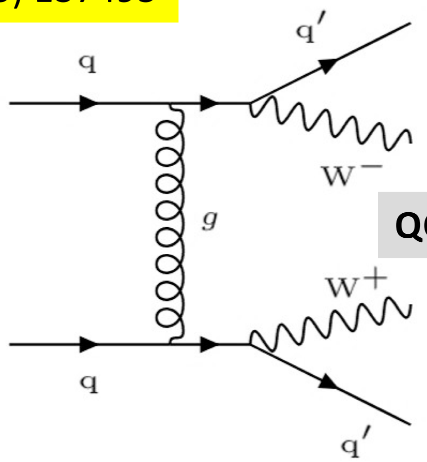
Observation of W^+W^- VBS at the LHC

Electroweak VBS

PLB 841 (2023) 137495







QCD-induced

- Precision measurement with the Vector Boson Scattering (VBS) processes are important for probing the Higgs sectors and hence understanding the electroweak symmetry-breaking
- Oppositely charged leptons with two jets (having high pseudorapidity gap) to target for the WW+2 jets events with the rejection for the QCD-induced processes and ttbar processes.
  - Full Run 2 dataset with event selection for two Isolated leptons (electron/muon) with p_T> 25 (13) GeV, and m_{ll}>50 GeV and 2 jets along with the Missing Transverse Energy p^{mis}_T> 20 GeV
  - At least two jets with pT>30 GeV , $\Delta\eta_{jj}$>2.5 and m_{jj}>300 GeV
  - Further event categorization based on final state lepton flavors

Observation of W^+W^- VBS at the LHC

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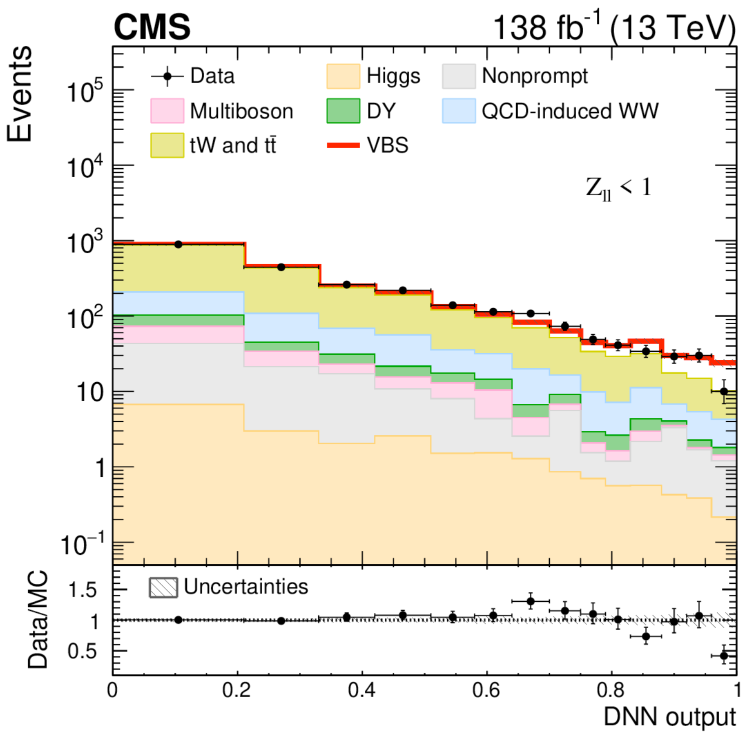
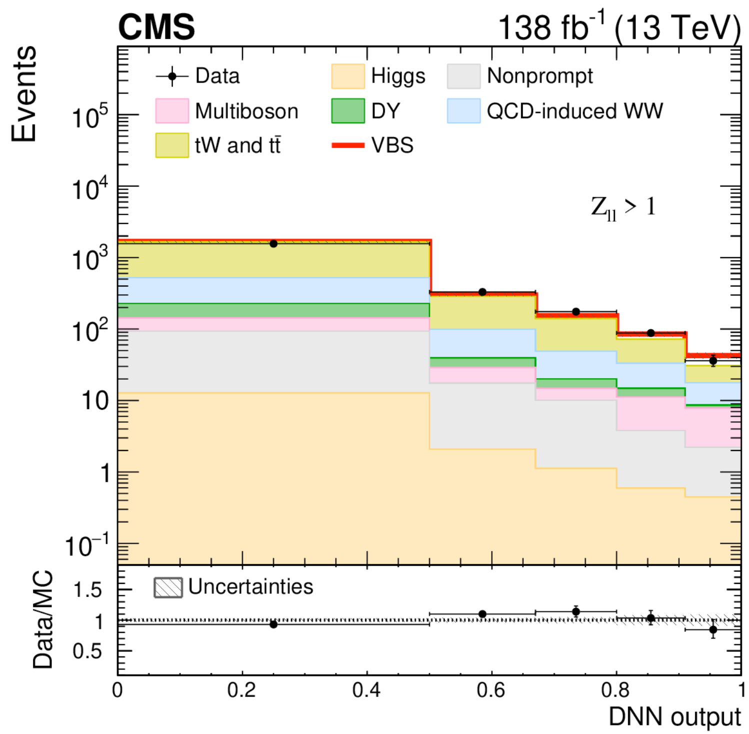
Signal enriched eμ region





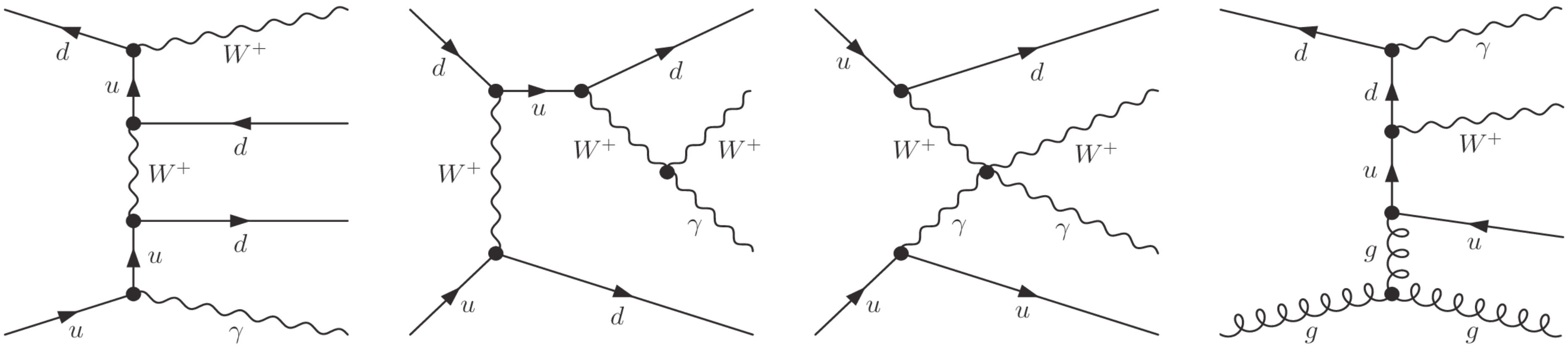
Observed (expected) signal significance of 5.6σ (5.2σ)

- Data-driven background normalization using dedicated control regions for major backgrounds-- Top, DY
- Deep Neural Network training to identify signal events
- W+W- VBS fiducial cross-section measured through simultaneous fits of DNN and other discriminating observables:

$\sigma_{fiducial}$ = 10.2 ± 2.0 fb
σ_{SM} = 9.1 ± 0.6 fb

Wγ+ 2 jets production at the LHC

PRD 105 (2022) 052003



Non-VBS Electroweak | **Electroweak VBS** | **QCD-induced**

- Precision measurement with the Vector Boson Scattering (VBS) processes are important for probing the Higgs sectors and hence understanding the electroweak symmetry-breaking
- Event selection optimized for the Vector Boson Scattering (VBS) signal (Wγ+2 jets) with the rejection for the non-VBS electroweak (EWK) and QCD-induced processes
  - Isolated electron/muon p_T> 35 GeV, a photon (p_T> 25 GeV) and 2 jets along with the Missing Transverse Energy p^{mis}_T> 30 GeV
  - Large pseudorapidity difference between the jets and azimuthal balancing between (jets, Wγ) systems

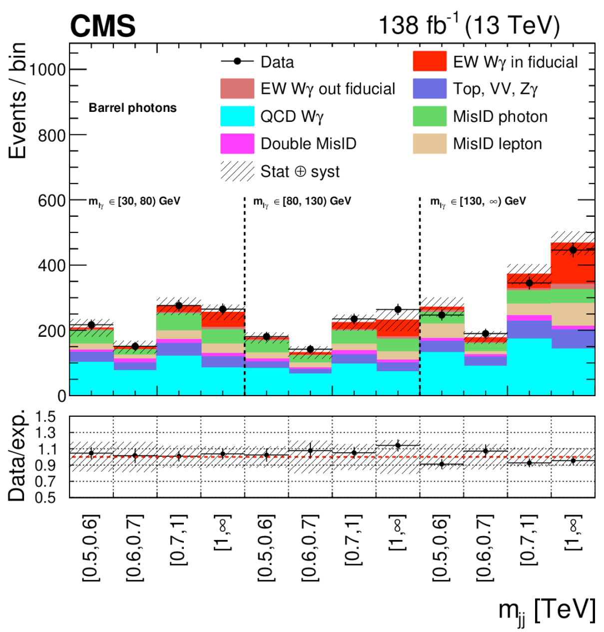
Wγ+ 2 jets Cross-section Measurements

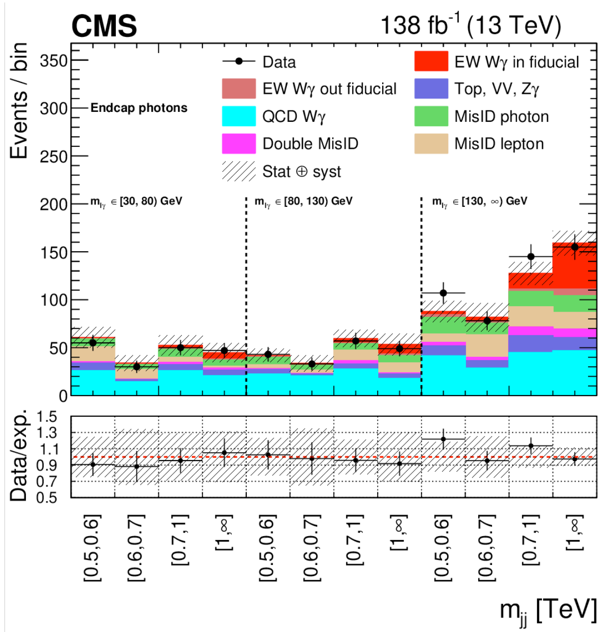
- Event categorization based on the barrel/enadcap photons and in bins of $m_{l\gamma}$ & m_{jj}
- Measurement of EWK-only and EWK+QCD fiducial and differential cross-sections in several observables -- p_T^{γ} , p_T^{l} , p_T^{j1}, m_{jj}, $m_{l\gamma}$, $\Delta\eta_{jj}$

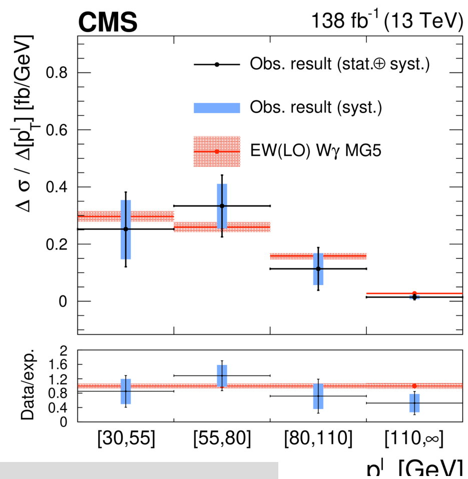
PRD 105 (2022) 052003

- Measurements are consistent with the SM predictions :

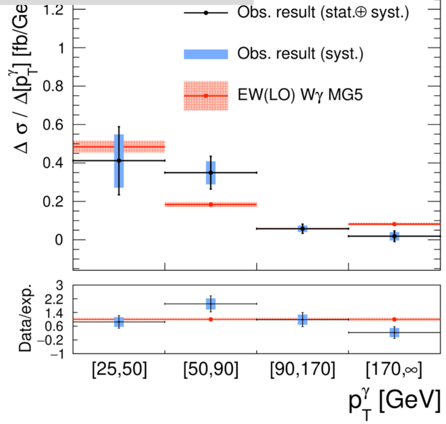
$\sigma_{EW}^{fid} = 19.2\,^{+4.0}_{-3.9}$ fb & $\sigma_{EW+QCD}^{fid} = 90\,^{+11.}_{-10}$ fb







Differential cross-section



γγ→WW/ZZ production at the LHC

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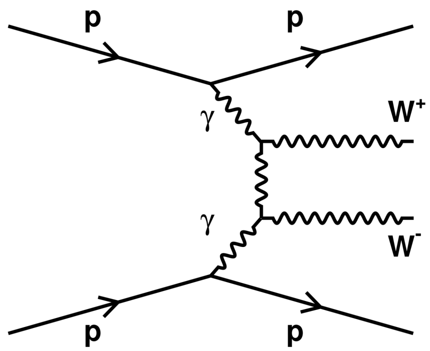
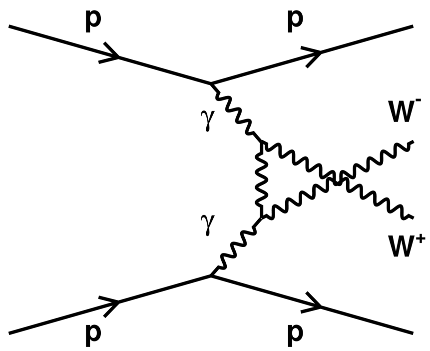
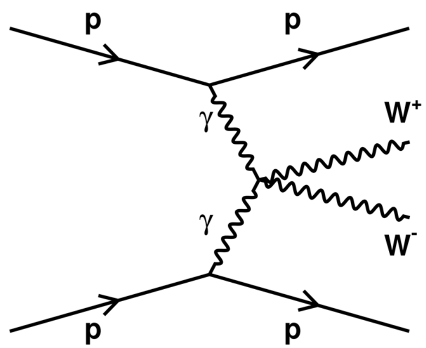
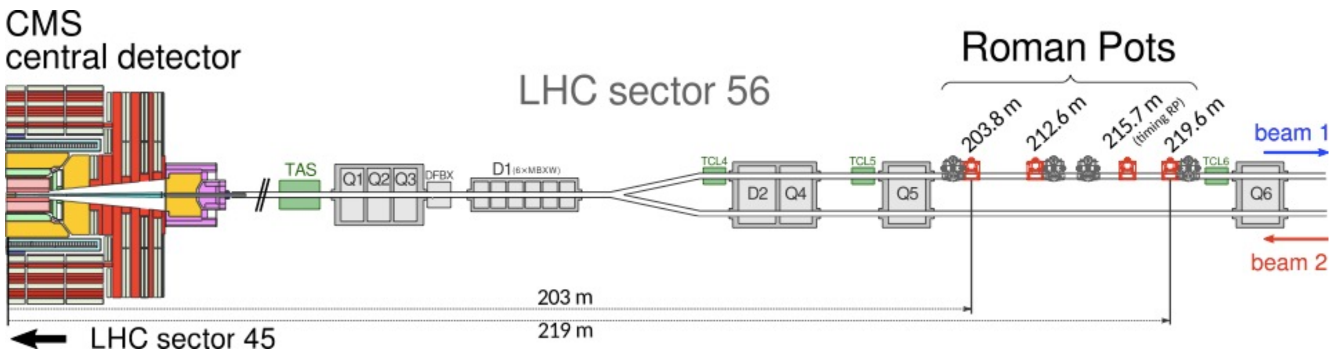






- ✧ Aim to probe SM quartic coupling at tree level
- ✧ BSM contributions (resonant and non-resonant) accessed through effective-field-theory (EFT) approach
- ✧ Events with in-tact protons in the forward region
    - ✧ PPS can detects proton momenta ~200m from the CMS IP using the LHC magnets
    - ✧ SM cross-sections: 50 fb (γγ→WW) & 0.5 fb (γγ→ZZ)



γγ→WW/ZZ production at the LHC

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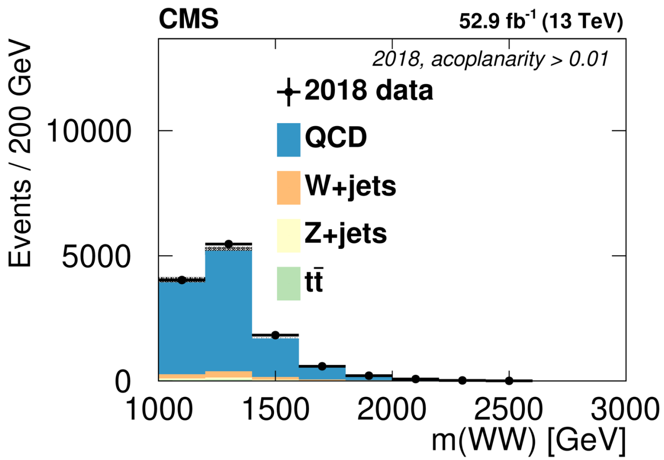
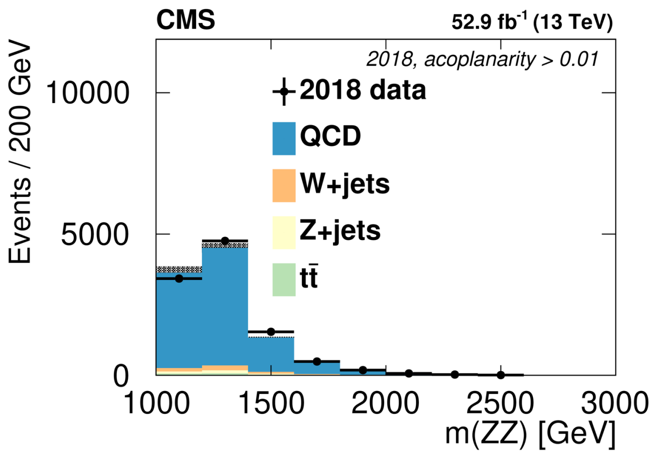
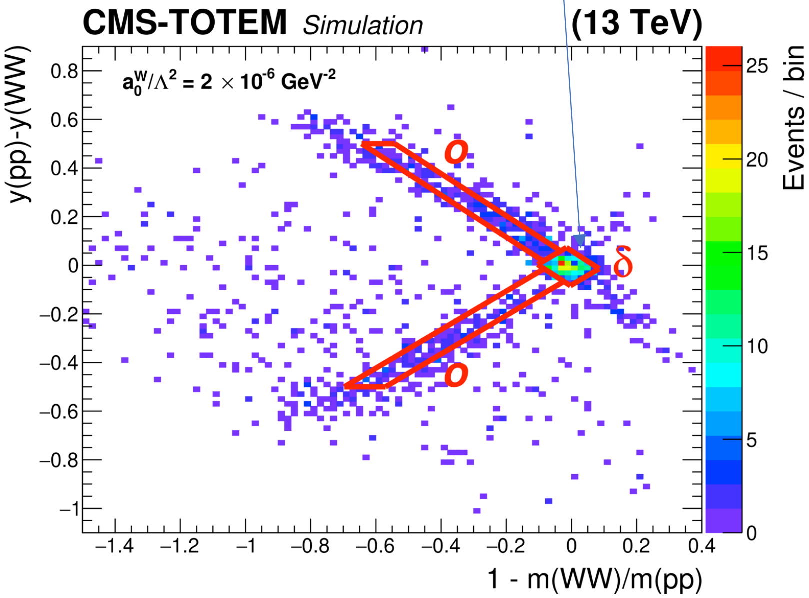
- ✧ Search for weak vector bosons in boosted and merged jets m_{jj} >1126 GeV
- ✧ Background estimated from the control regions
    - ✧ Inverting the observables for jet topology and p-p matching
- ✧ Further discrimination between WW and ZZ events using sum of jet masses
- ✧ **Limits on fiducial cross-section considering m_{VV}>1 TeV and proton fractional charge <20%**
- ✧ **cross-section upper limit at 95%**
    - ✧ **σ (pp →pWWp) <67 fb**
    - ✧ **σ (pp→pZZp) <43 fb**

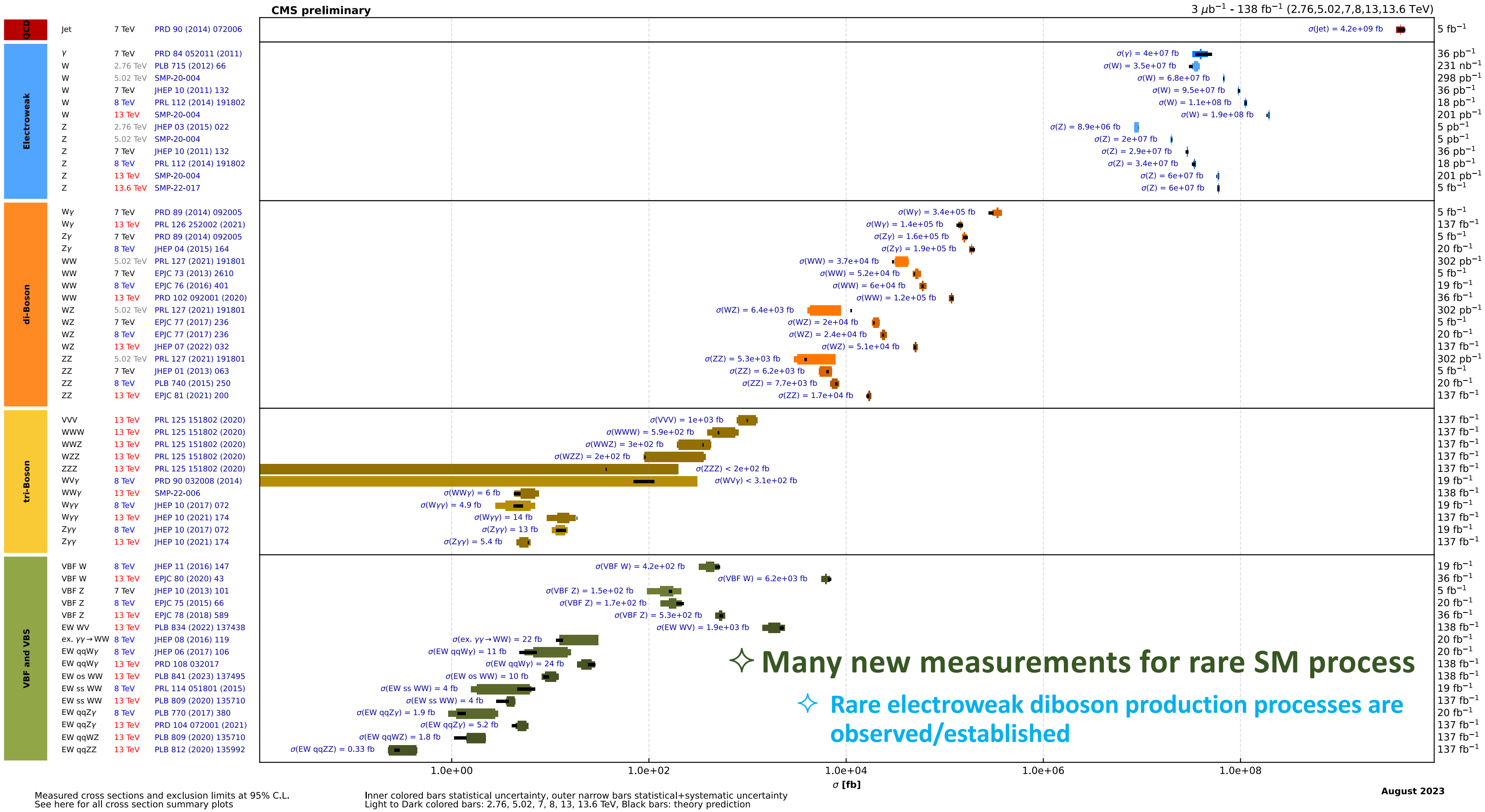




Both protons matched



Summary of SM cross-section measurements

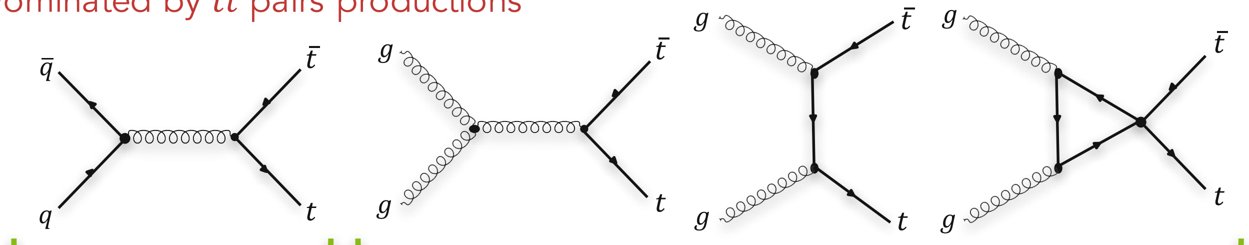


- ✧ **Many new measurements for rare SM process**
  - ✧ **Rare electroweak diboson production processes are observed/established**

Recent Top results (Run II & Run III)

Top quark production modes at LHC

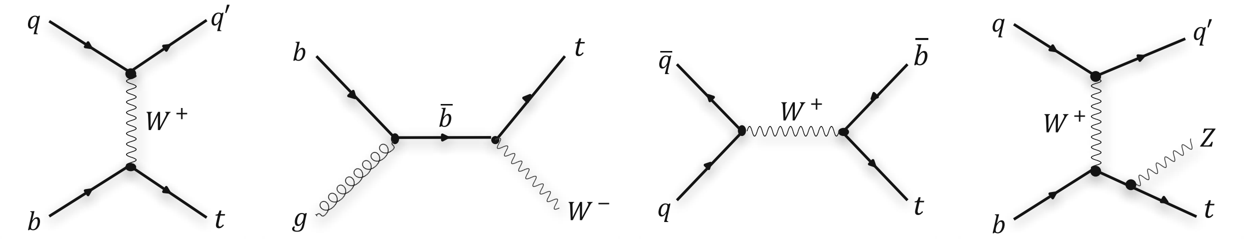
Dominated by $t\bar{t}$ pairs productions



quark-antiquark annihilation
(~10%)

gluon-gluon fusions
(~ 90%)

Single top-quark productions



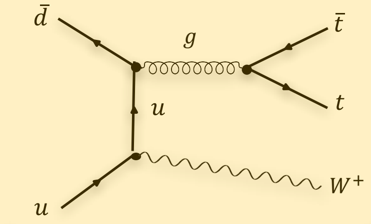
t-channel
(~73%)

tW associated production
(~24%)

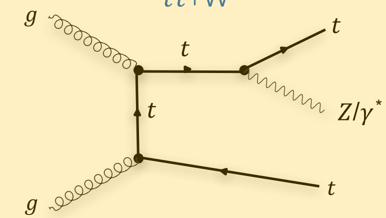
s-channel
(~3%)

tZ production
(<1%)

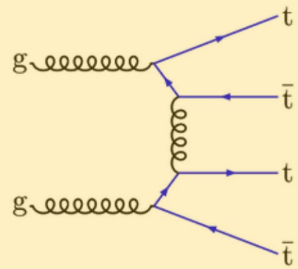
Other productions



$t\bar{t}$+W



$t\bar{t}$+Z/γ^*



4-tops

Top pair-production cross-section at √s=13.6 TeV

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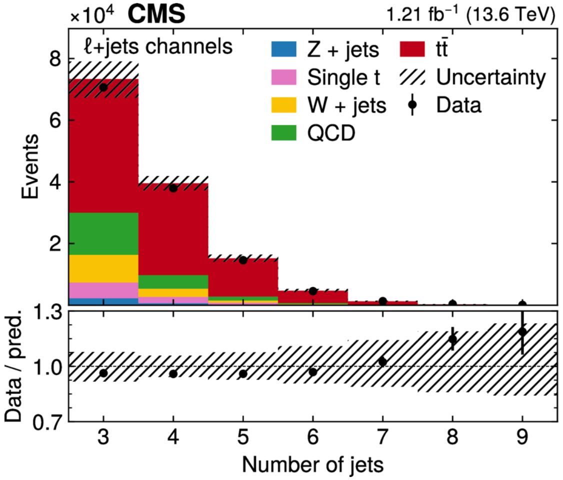
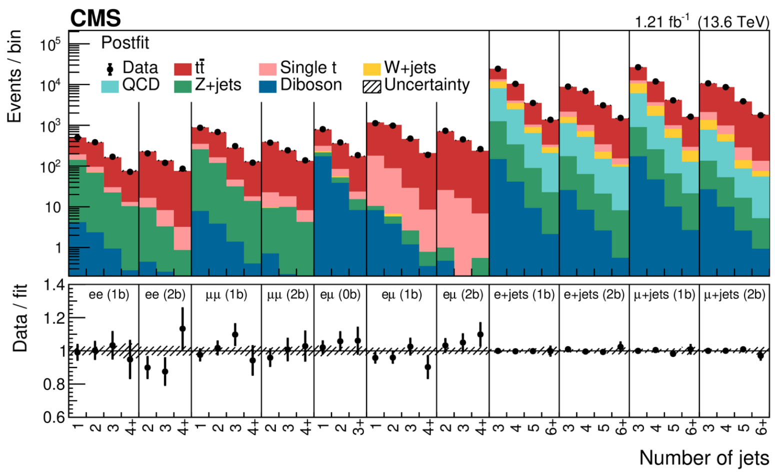
- First measurement of pair production cross-section using 1.21 fb^{-1} dataset in semi-leptonic and di-leptonic modes
- Event categorization based on the lepton flavor and number of b-jets
- Extraction of cross-sections fitting the yields in each category of events





Source	Uncertainty (%)
Lepton ID efficiencies	1.6
Trigger efficiency	0.3
JES	0.6
b tagging efficiency	1.1
Pileup reweighting	0.5
ME scale, $t\bar{t}$	0.5
ME scale, backgrounds	0.2
ME/PS matching	0.1
PS scales	0.3
PDF and α_S	0.3
Top quark p_T	0.5
tW background	0.7
t-channel single-t background	0.4
Z+jets background	0.3
W+jets background	<0.1
Diboson background	0.6
QCD multijet background	0.3
Statistical uncertainty	0.5
Combined uncertainty	2.5
Integrated luminosity	2.3

- $\sigma_{measured}$ = 881 ± 23 ± 20 (lumi) pb
- $\sigma_{SM} = 924^{+32}_{-40}$ pb

Top pair-production cross-section at √s=13.6 TeV

arXiv:2308.09529 (accepted by PLB)

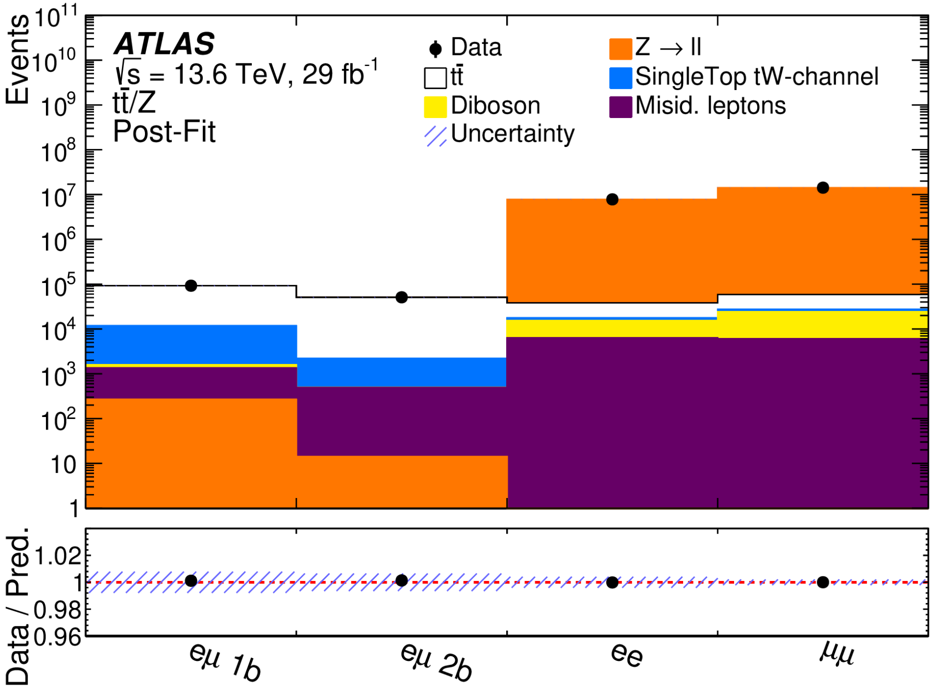
Measure $t\bar{t}$ and Z cross-section simultaneously, 29 fb^{-1}

- eμ channel for $t\bar{t}$
- ee and μμ for Z cross-section
- ratio cancels lumi dependence

Strategy

- count b-tag multiplicity
- also extract b-tag efficiency

$$N_1 = L\sigma_{t\bar{t}}\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\text{bkg}},$$
$$N_2 = L\sigma_{t\bar{t}}\epsilon_{e\mu}C_b\epsilon_b^2 + N_2^{\text{bkg}},$$



Results

- $\sigma_{t\bar{t}} = 850 \pm 3\,(\text{stat.}) \pm 18\,(\text{syst.}) \pm 20\,(\text{lumi.})$
- $R_{t\bar{t}/Z} = 1.145 \pm 0.003\,(\text{stat.}) \pm 0.021\,(\text{syst.}) \pm 0.002\,(\text{lumi.})$

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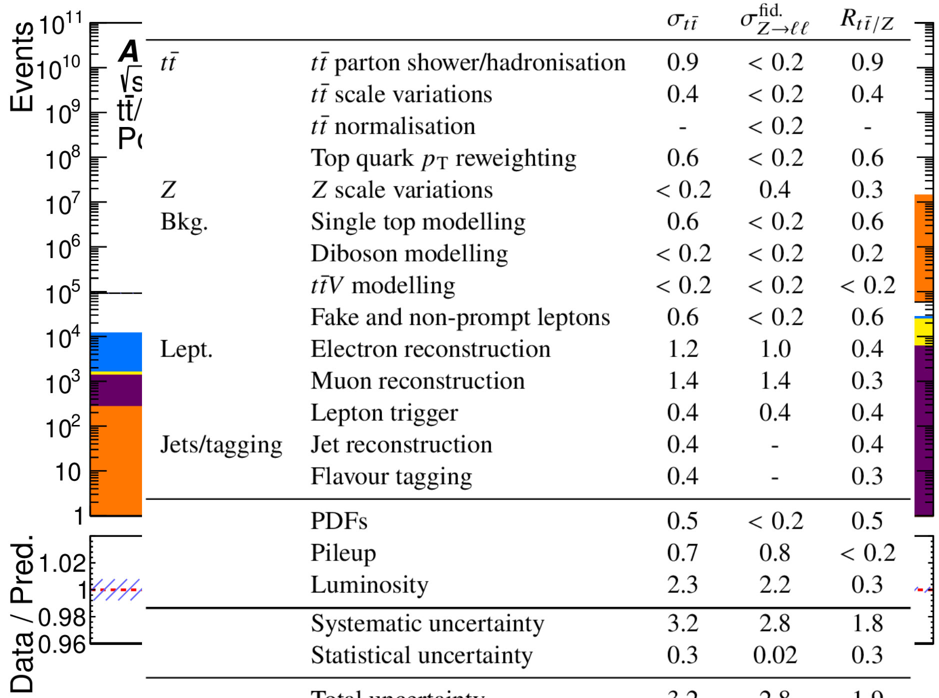

Category		Uncertainty [%]		
		$\sigma_{t\bar{t}}$	$\sigma^{\text{fid.}}_{Z\to\ell\ell}$	$R_{t\bar{t}/Z}$
$t\bar{t}$	$t\bar{t}$ parton shower/hadronisation	0.9	< 0.2	0.9
	$t\bar{t}$ scale variations	0.4	< 0.2	0.4
	$t\bar{t}$ normalisation	-	< 0.2	-
	Top quark p_{T} reweighting	0.6	< 0.2	0.6
Z	Z scale variations	< 0.2	0.4	0.3
Bkg.	Single top modelling	0.6	< 0.2	0.6
	Diboson modelling	< 0.2	< 0.2	0.2
	$t\bar{t}V$ modelling	< 0.2	< 0.2	< 0.2
	Fake and non-prompt leptons	0.6	< 0.2	0.6
Lept.	Electron reconstruction	1.2	1.0	0.4
	Muon reconstruction	1.4	1.4	0.3
	Lepton trigger	0.4	0.4	0.4
Jets/tagging	Jet reconstruction	0.4	-	0.4
	Flavour tagging	0.4	-	0.3
	PDFs	0.5	< 0.2	0.5
	Pileup	0.7	0.8	< 0.2
	Luminosity	2.3	2.2	0.3
	Systematic uncertainty	3.2	2.8	1.8
	Statistical uncertainty	0.3	0.02	0.3
	Total uncertainty	3.2	2.8	1.9

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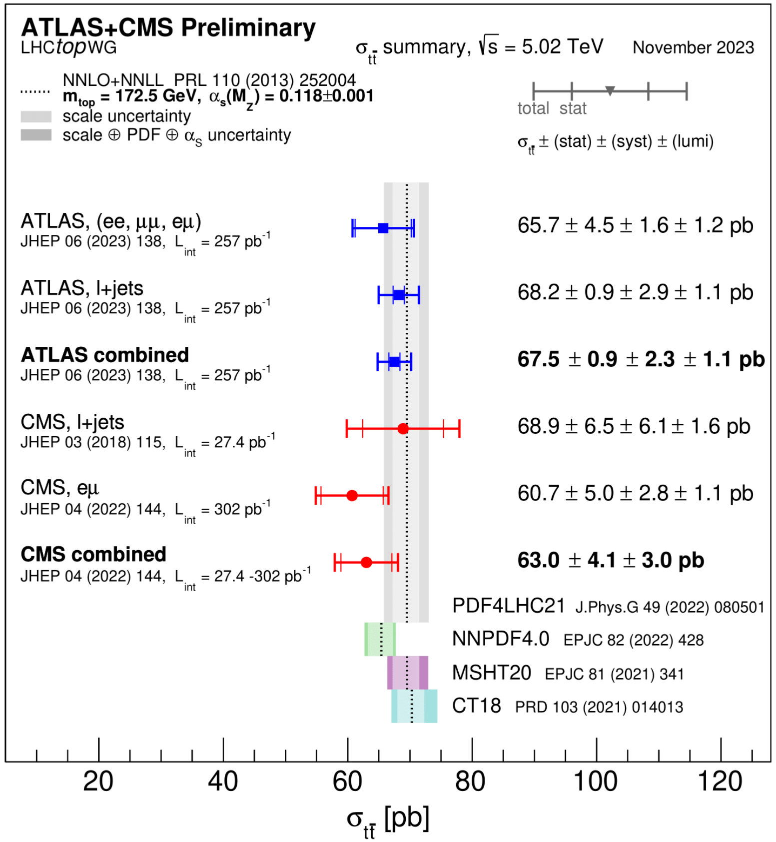
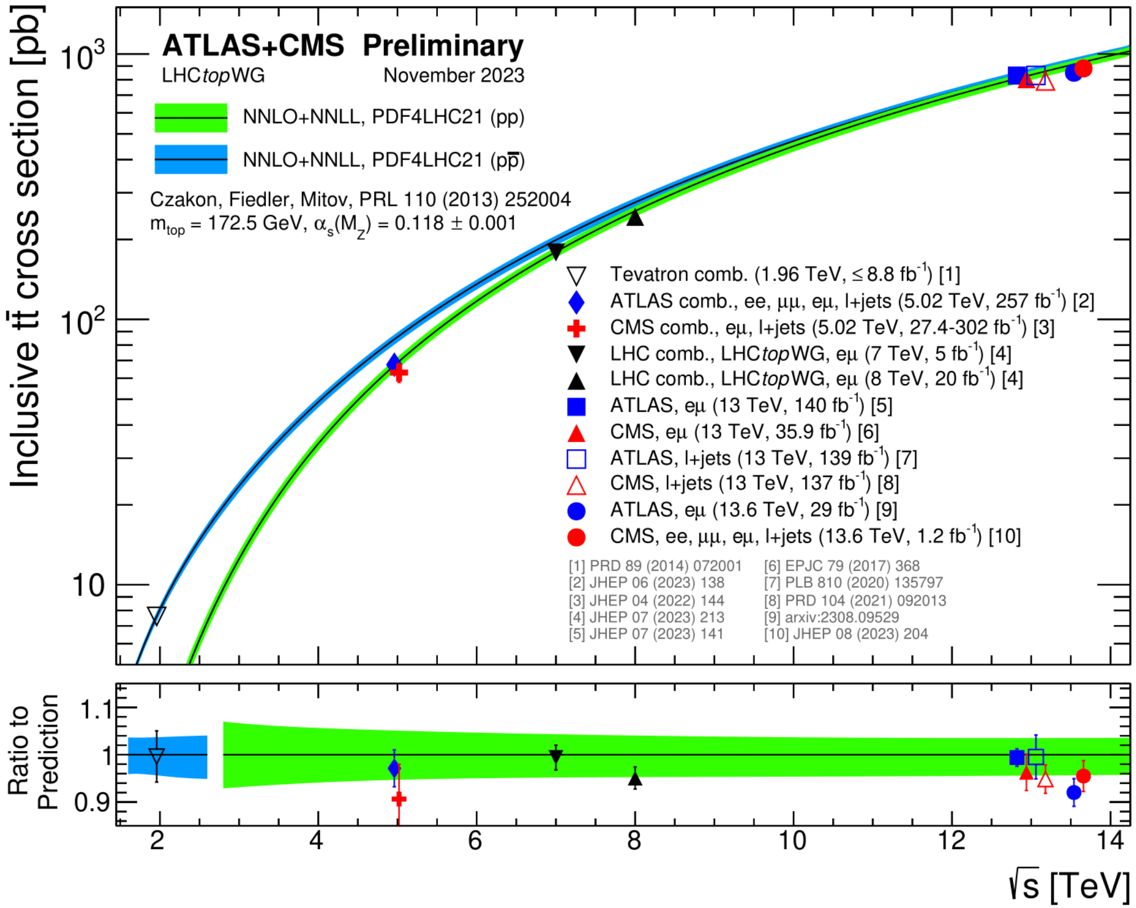
Summary of σ_{tt} measurements

LHC Top Working Group Combination (Nov, 2023)

Top pair-production cross-section at √s=5.02 TeV

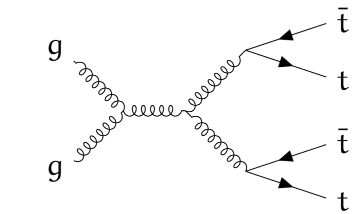


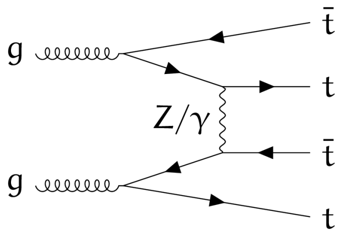


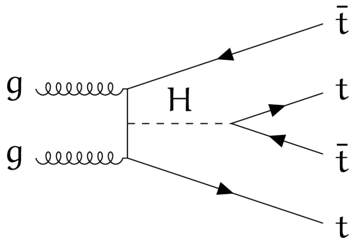
Observation of 4 top quarks

EPJC 83 (2023) 496

- Very rare (~14 fb) process sensitive to new physics models (2HDM, compositeness, SUSY)

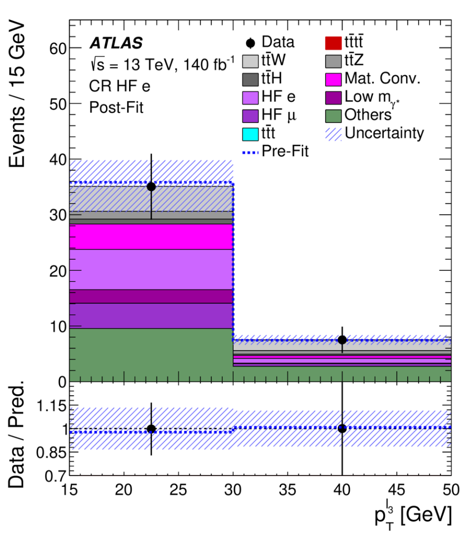


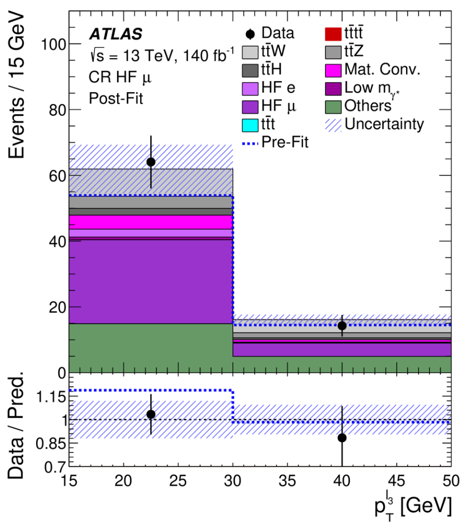


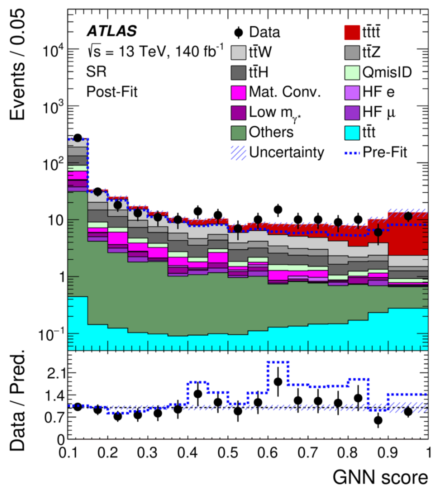


Observation combining several channels

- 2ℓSS and 3ℓ channels
- 8 control regions – $t\bar{t}W^+$ and $t\bar{t}W^-$ are determined independently
- non-prompt leptons determined from p_T (3rd lepton)
- employ Graph Neural Network, check distributions for GNN score > 0.6
- measure: $\sigma_{t\bar{t}t\bar{t}} = 22.5^{+6.6}_{-5.5}$ pb, 6.1σ significance







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EPJC 83 (2023) 496

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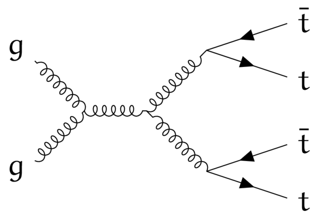

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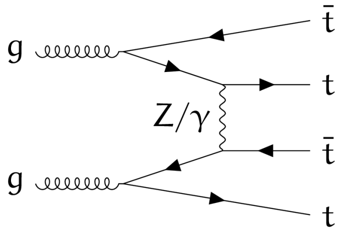

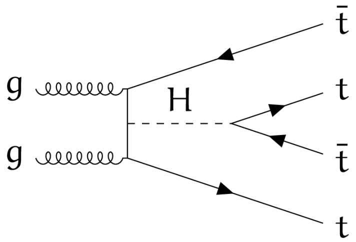

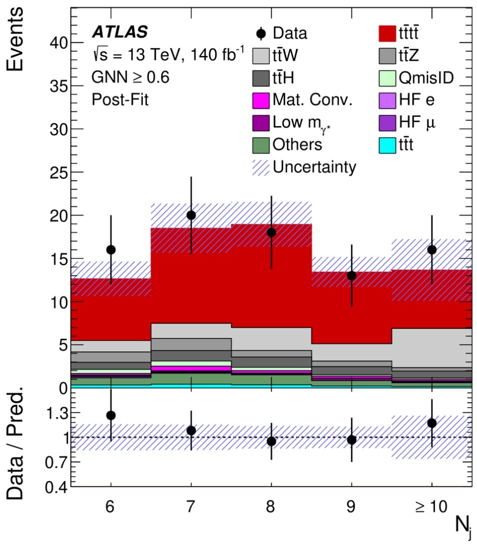

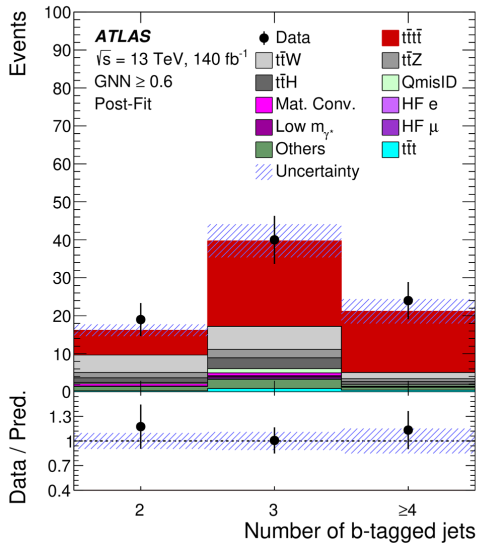

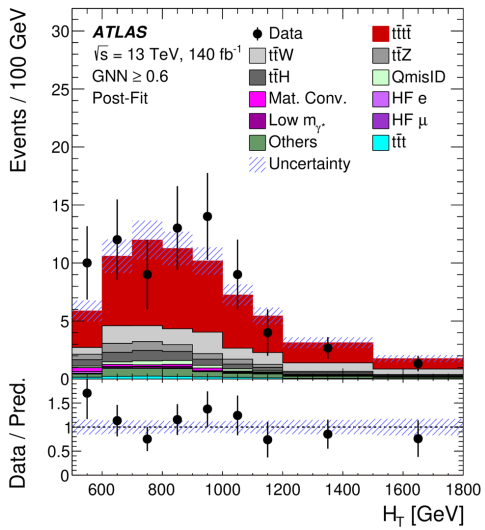

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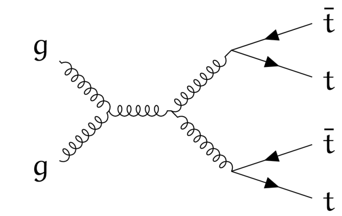

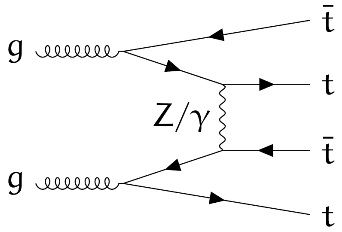

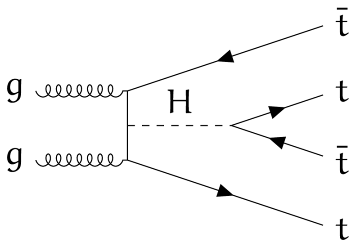

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- expected significance 4.9σ (ATLAS 4.3σ)
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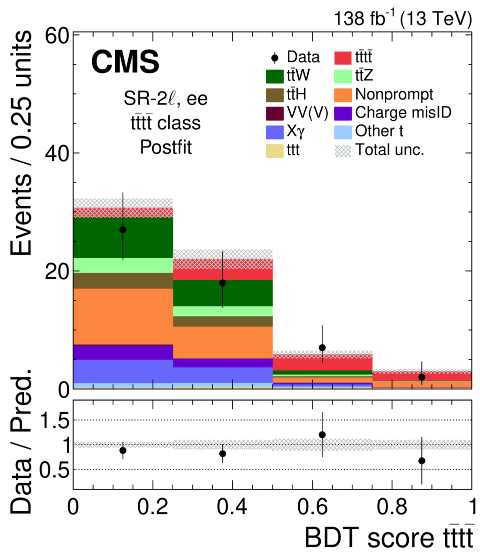

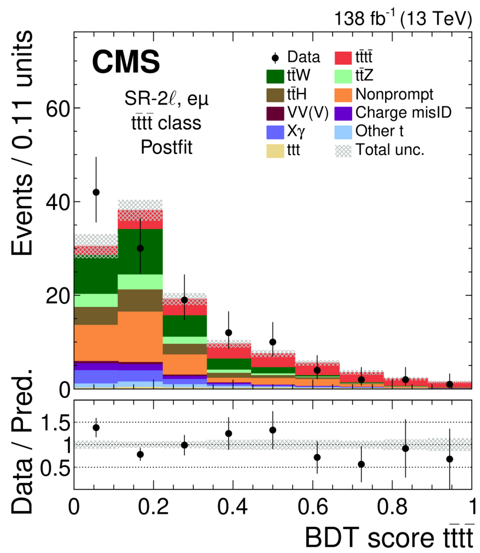

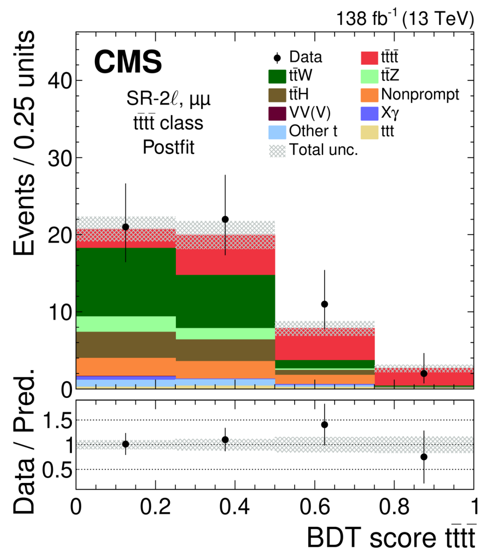

PLB 847 (2023) 138290

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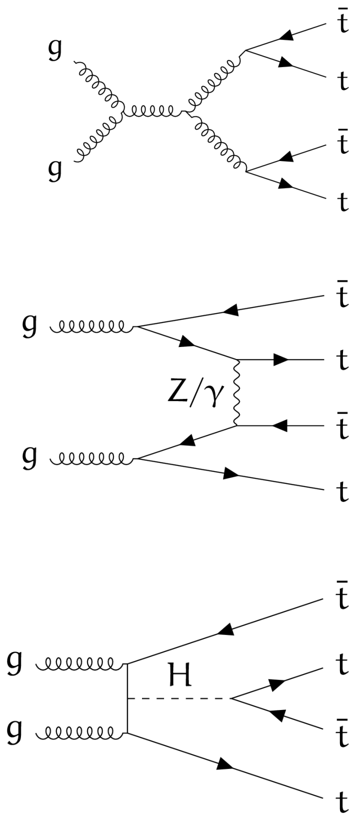

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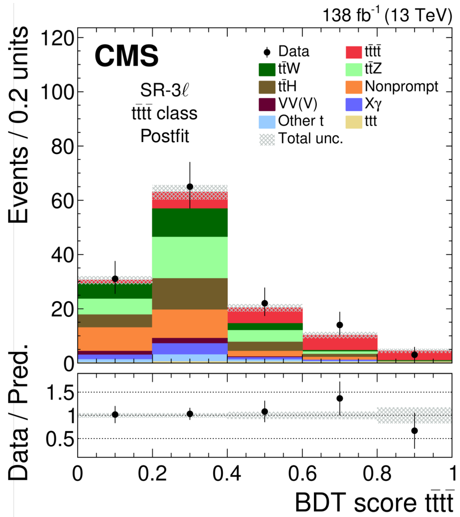

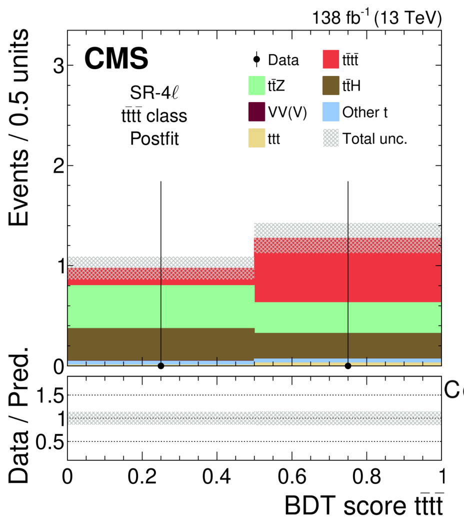

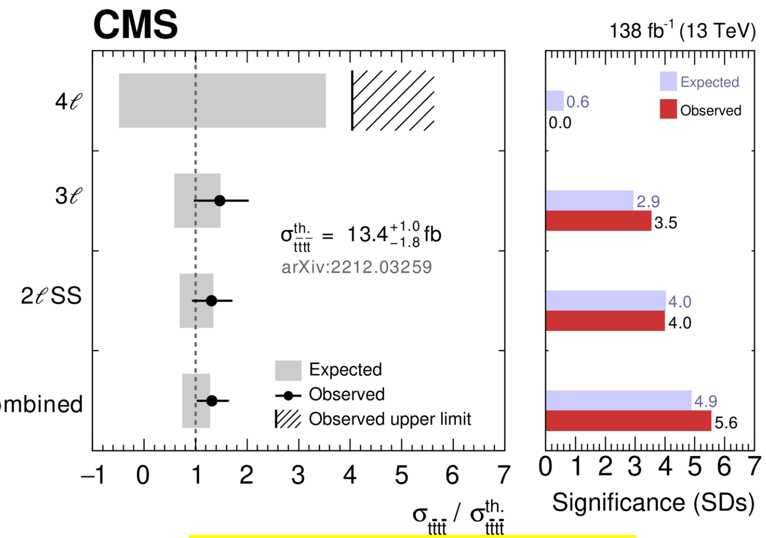

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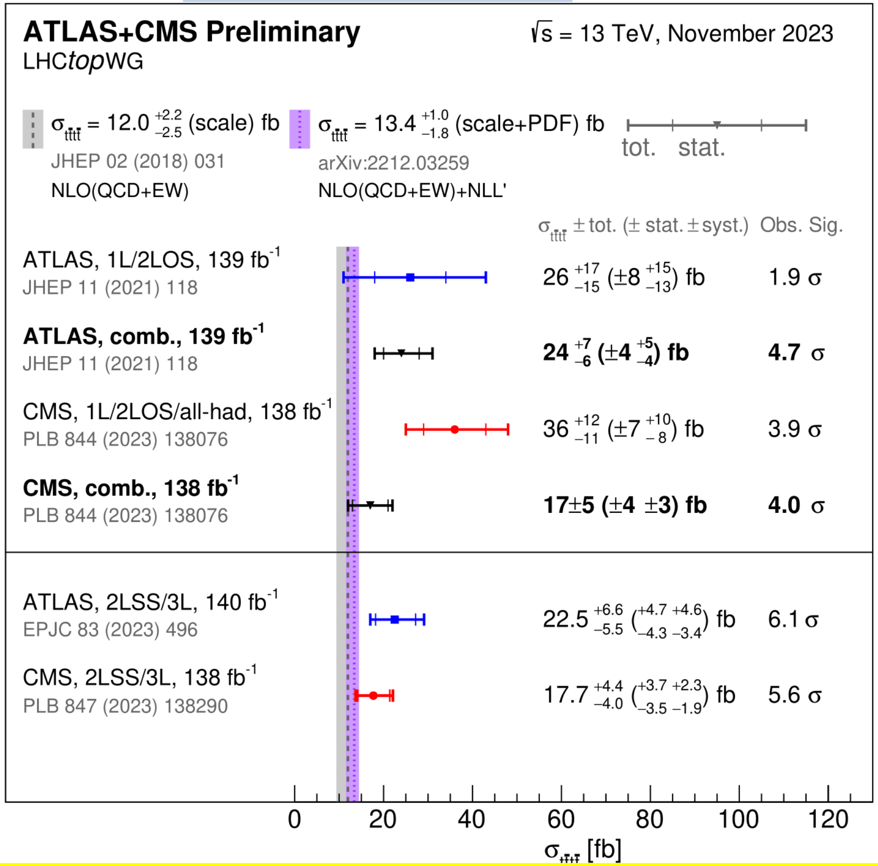
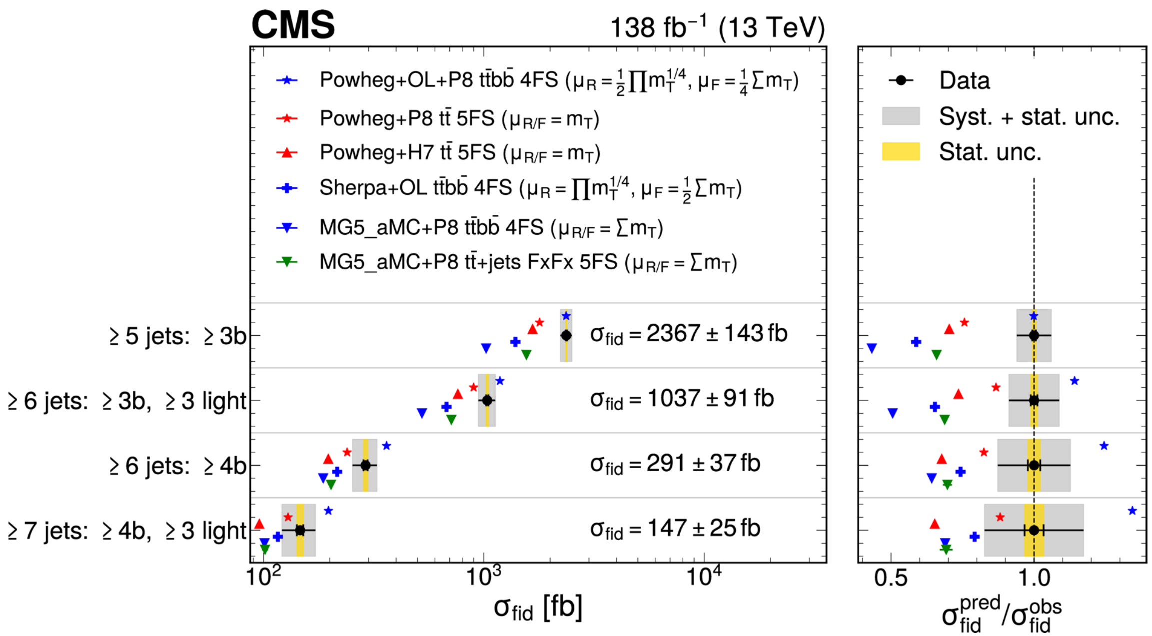
Summary of rare top processes

4 top cross-section



LHC Top Working Group Combination (Nov, 2023)

arXiv:2309.14442; submitted to JHEP

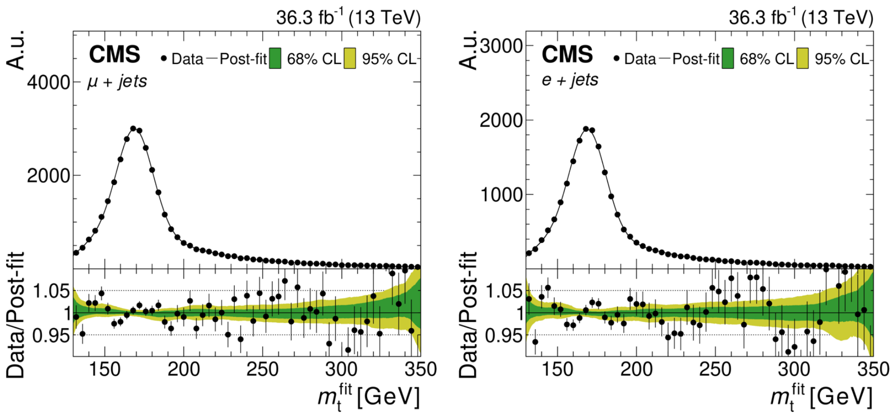


$t\bar{t}b\bar{b}$ difficult to model. Updated results, including differential cross-sections as input to improve predictions

→important also for precise $t\bar{t}t\bar{t}$ and $t\bar{t}H$ measurements

Top mass measurement

LHC Top Working Group Combination (June, 2023)

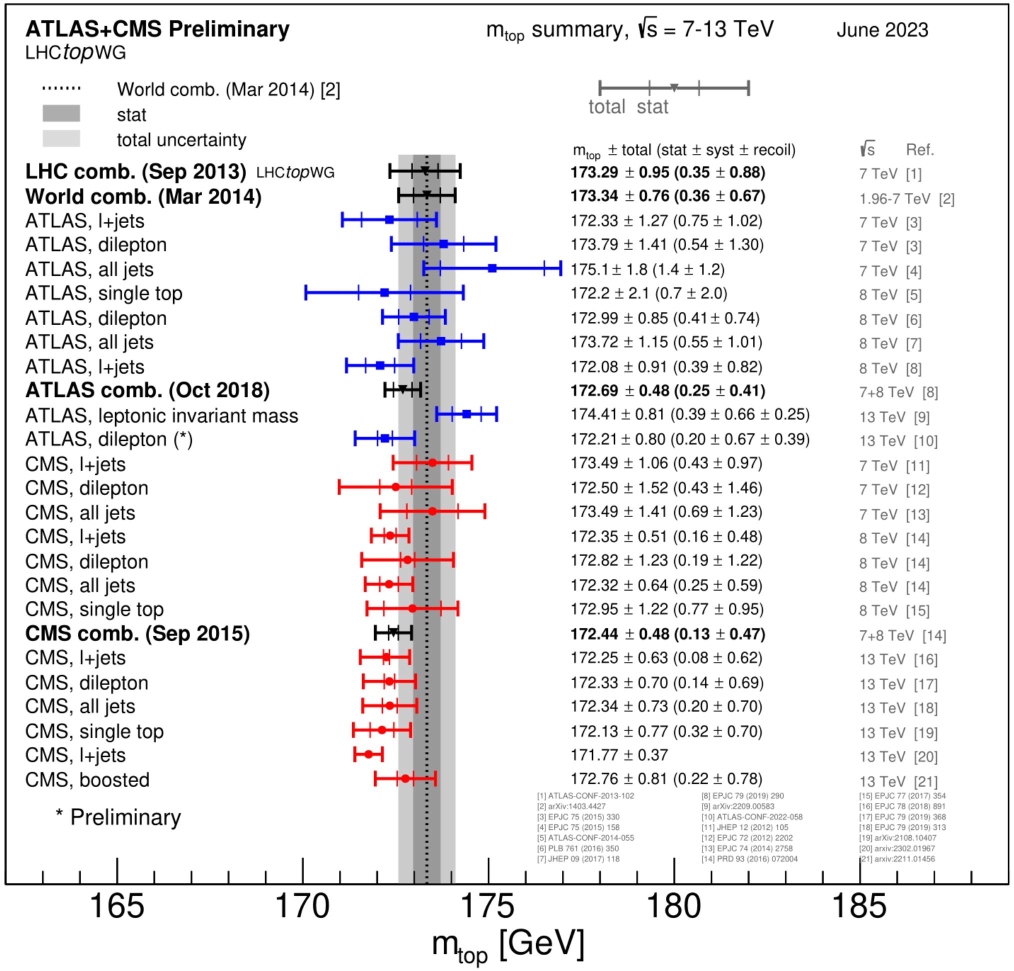


EPJC 83 (2023) 963

Lepton+jets channel with kinematic fit and profile likelihood method using up to five observables

m_{top}=171.77 +/- 0.37 GeV

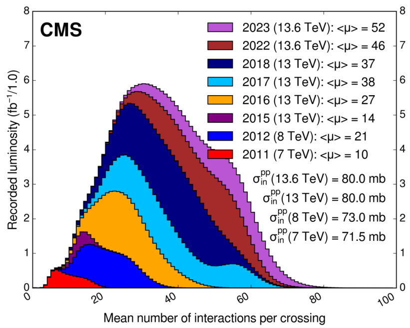
- 0.2% relative uncertainty

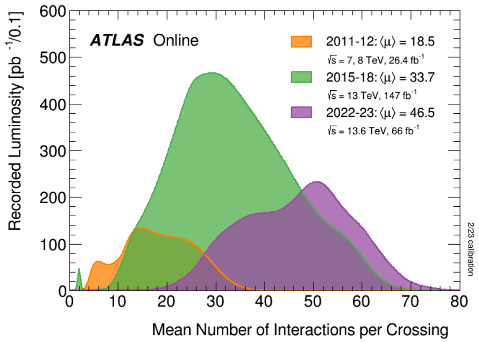


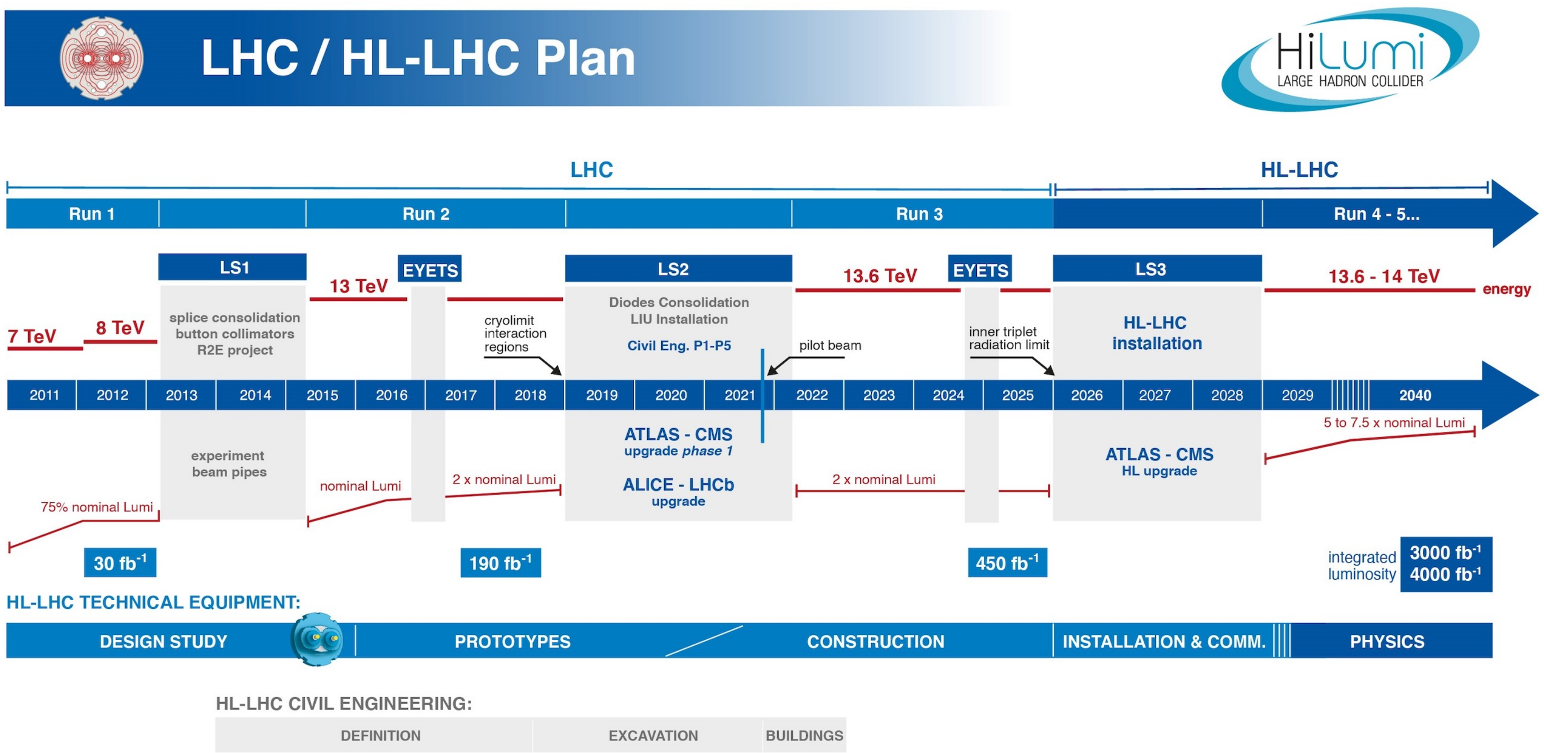
Summary & Conclusions

- ✧ **Due to exceedingly well LHC performance, the SM measurements reached to an unprecedented regime**
  - ✧ **No deviation from the SM have been observed so far**
  - ✧ **Extraordinary new measurements have been performed/completed with the full/partial Run 2 dataset**
  - ✧ **Challenging to reduce systematics (theory and experiment)**
- ✧ **Increased statistics allows the scope for differential cross-section measurements in SM and Top quark processes**
  - ✧ **EWK VBS and rare top quarks processes have been observed/established**
- ✧ **Run 3 statistics would improve the measurement precision further, although with additional pile-up events deteriorating the detector performance**
  - ✧ **Scope for probing the BSM physics further**

Challenges ahead – pile-up







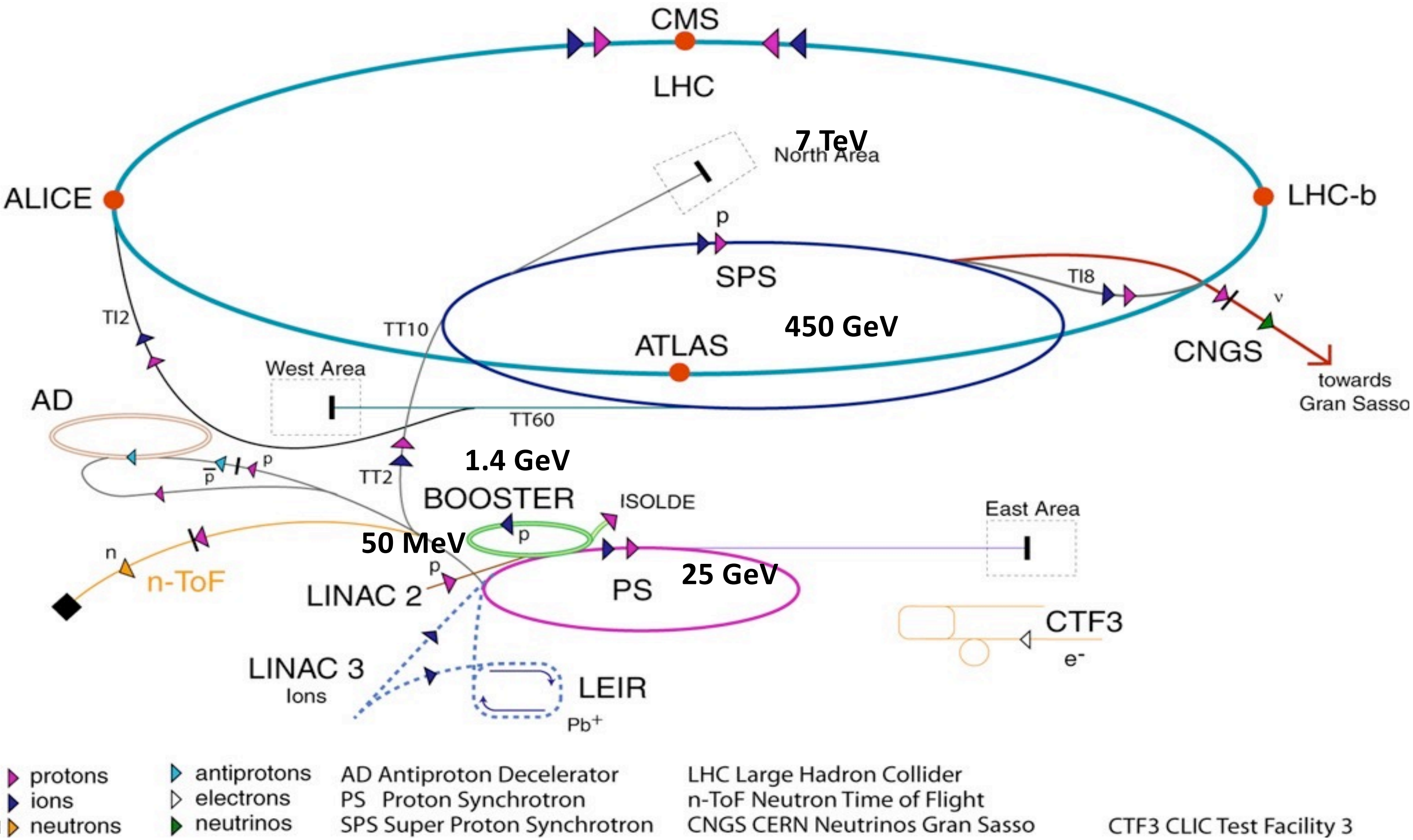
- ✧ **Major data-taking (with the HL-LHC) 3 ab^{-1} is yet to be commence**
  - ✧ **However, typical pile-up is projected to be 140-200**

References

- ✧ ATLAS SMP: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
- ✧ CMS SMP: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP
- ✧ ATLAS Top: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
- ✧ CMS Top: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
- ✧ LHCTopWG: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWG

Extras

LHC Accelerator Complex



LHC Performance

- LHC Run III started in 2022 at √s=13.6 TeV and LHC has been setting new record-breaking luminosity
- Exceedingly well performance by the LHC with delivered luminosities increasing rapidly
- Many precision measurements and rare processes studies have been plausible mostly due to the LHC performance "beyond the design goal".

- **Run I -- 2010-12**
- **Run II – 2015-18**
- **Run III – 2022-**