March of Standard Model: covering electroweak and top physics at the LHC

Only few selected topics with a bit of bias towards CMS experiment

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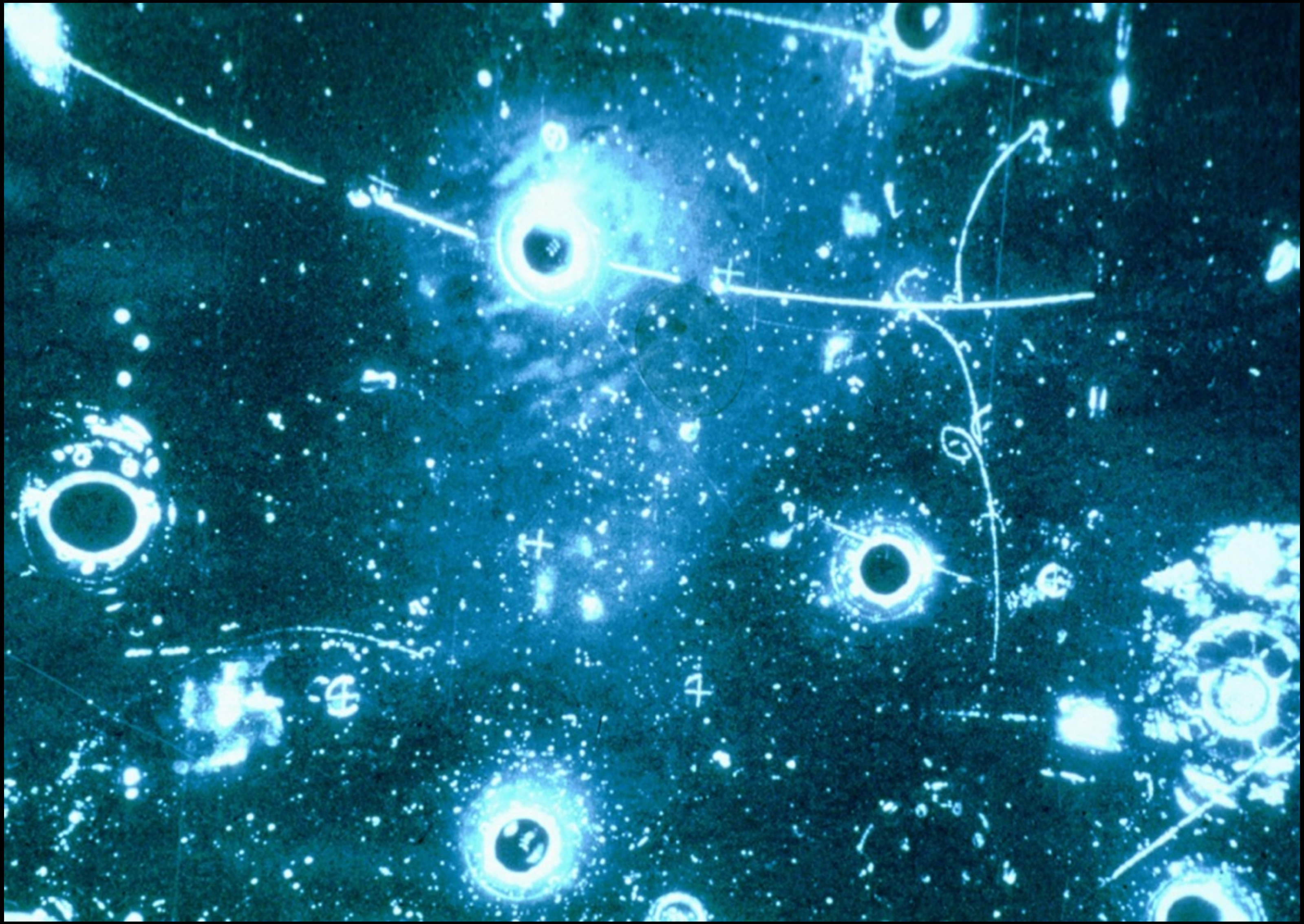
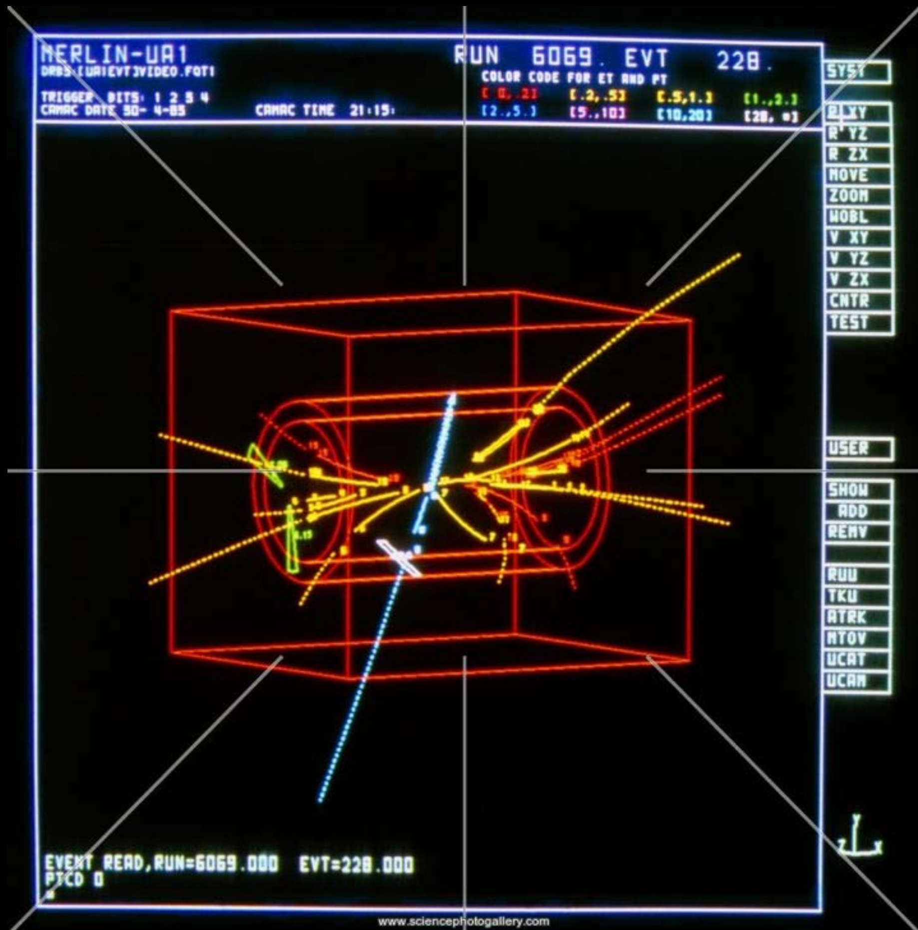
International Meeting on HEP, IOP, Bhubaneswar

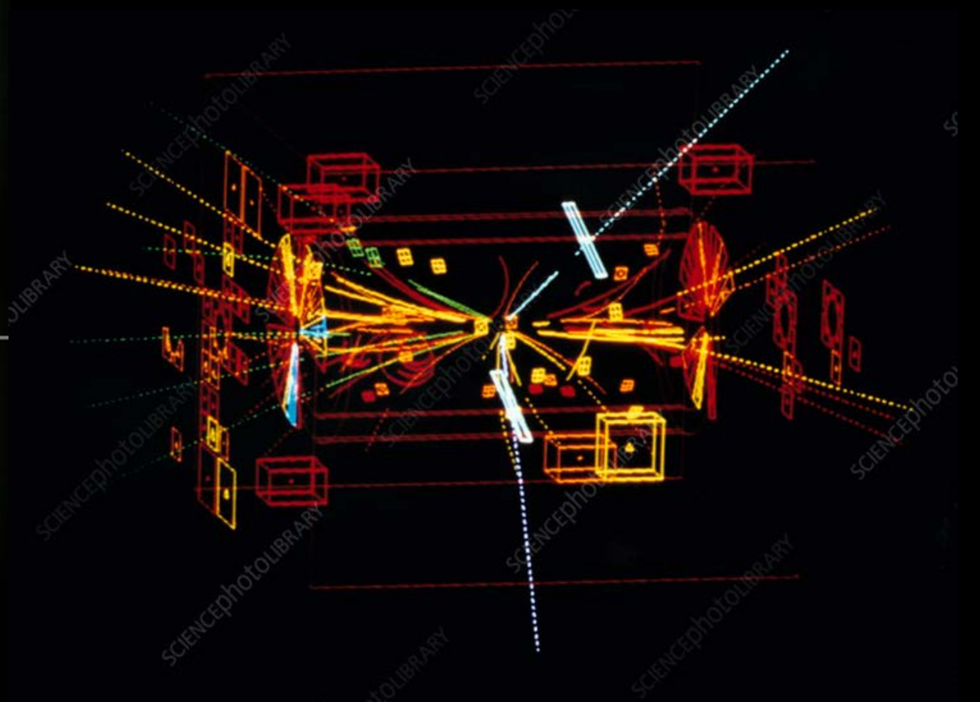
17 - 22 January, 2019

Discovery of neutral current interaction in Gargamelle bubble chamber (1973) → Nobel Prize (1979)

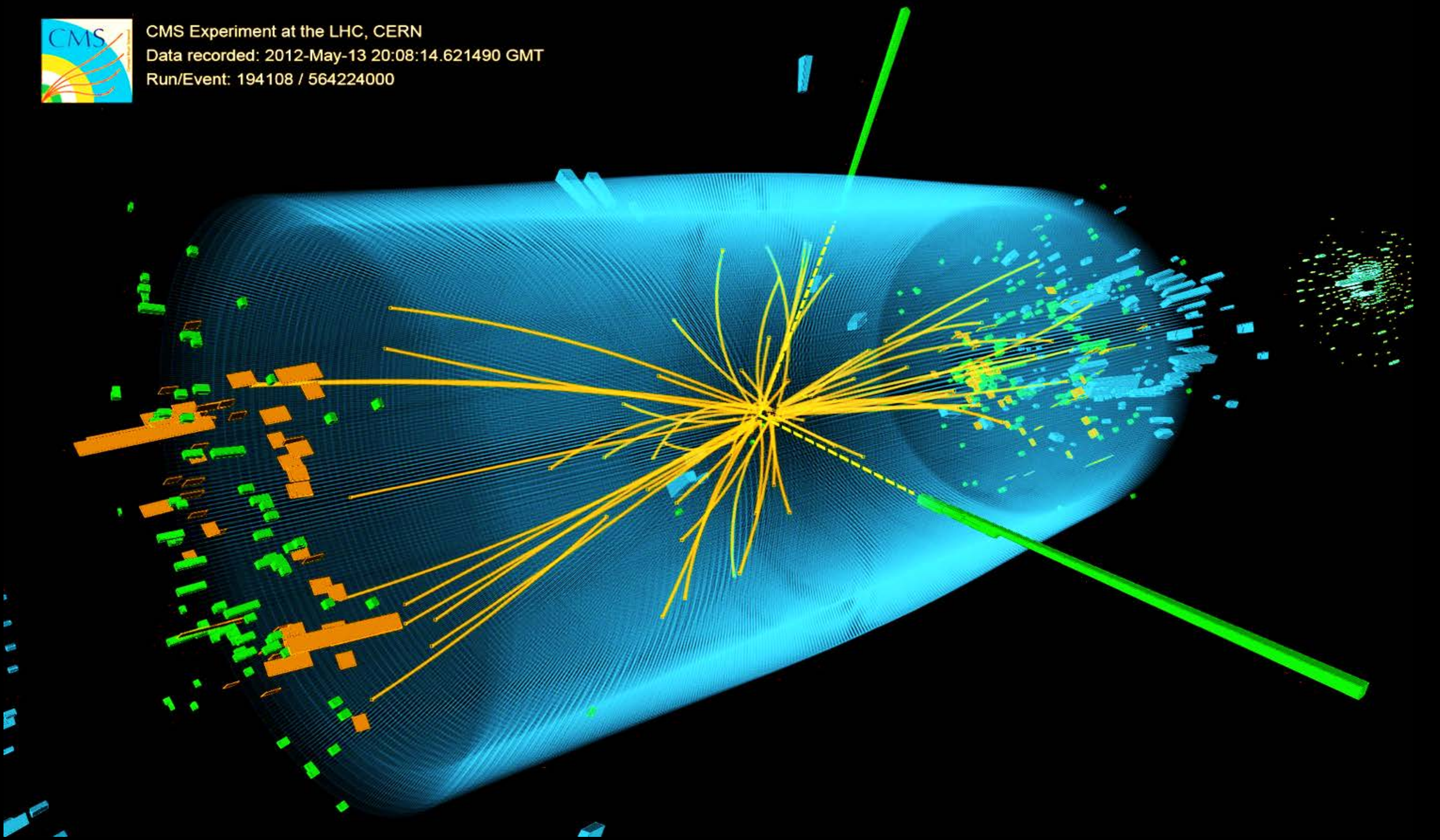


Discovery of W & Z in UA1, UA2 experiments (1983) → Nobel Prize (1984)





Higgs discovery by ATLAS and CMS (2012) → Nobel Prize (2013)



HEP is knocking at the heaven's door

- We have come a long way; but still miles to go before we sleep!

- Direct searches at the LHC has not yet yielded any positive indication for existence of beyond Standard Model (SM) physics at TeV energy scale or higher.

- Surely with only about few % of promised LHC data delivered till now, ***THERE IS HOPE .***
  → This hope is sustained by the exciting deviations from SM in B-physics based on several measurements .
  → These could be hints for *New Physics* (NP) at much higher energy scale than accessible directly at colliders.

- Progress in our field is also ushered in by caring for "*big answerable questions*" and the mode of finding the *knowable unknowns*.

- LHC is testing the limits of Standard Model:
  → it has found the last missing member of the particle zoo: The Higgs boson.
  → it is probing the nature of interactions it envisages at highest energy accessible.

SM is gaining grounds again!

- Being a broad-band machine, as opposed to an e+e- collider, LHC explores the SM dynamics, from flavour physics in B decays at GeV scale to TeV scale scattering of vector boson pairs.

- SM measurements: crucial component of the physics programme at the LHC.
  → quite often there are unsung ballads!
  → huge global efforts by theory and experimental communities.

- Since it is not known in which process and at which energy NP effects will show up, extensive tests for the consistency of SM must be made:
  → via precise measurements of known reactions.

- Other strategies:

➔ New Physics contribution can be modeled via effective field theory (EFT)

➔ Fundamental parameters are extracted from wide ranges of measurements.

➔ Global fit to all electroweak parameters of the SM

Essentials of effective field theory approach

Minimal extension of SM assumes
i) No new states
ii) New operators with dim > 4

- Universal model-independent parametrization of new physics above mass reach

➔ at √s = m_z , modified couplings would lead to rescaling of SM cross section.

- At √s >> m_z , there are many observables and many possibilities.

➔ Systematic Taylor expansion of all observables, up to certain order, can be made.

establish SM first

then use (lack of) any deviations to (constrain) characterise new physics

dimension-6 dimension-8

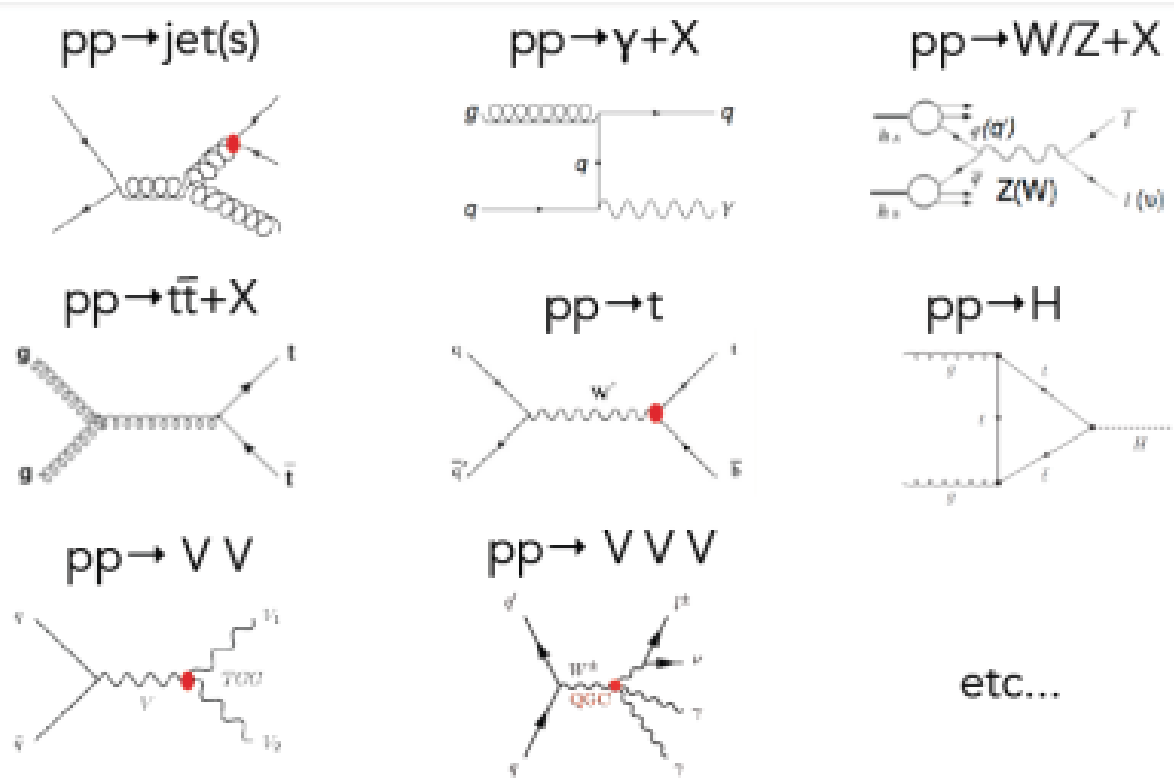
$$\mathcal{L} = \boxed{\mathcal{L}_{SM}} + \boxed{\sum \frac{c_i}{\Lambda^2} \mathcal{O}_i^{d=6} + \sum \frac{c_i}{\Lambda^4} \mathcal{O}_i^{d=8} + \ldots}$$

BSM effects SM particles

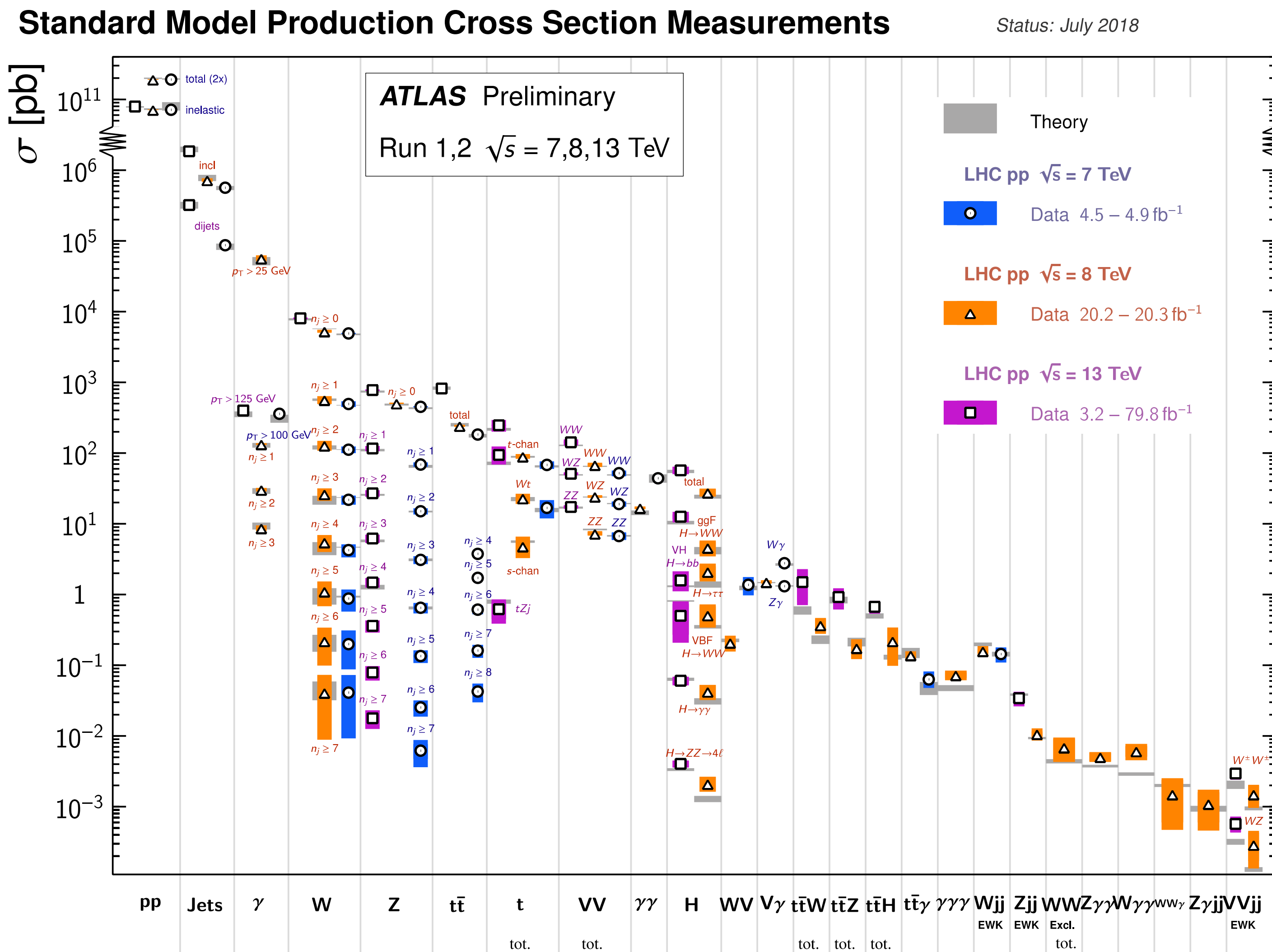
SM back in spotlight

- Quite often SM process are backgrounds to search for new physics

- There are also processes which are being observed for the first time.
  → either due to large luminosity
  → or large available energy making the process accessible kinematically.



ALL are needed for a complete job at LHC.

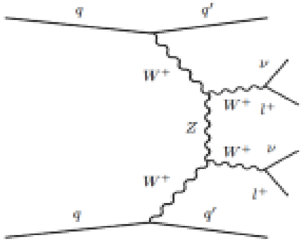


Stairways to heaven: (BSM enthusiasts call it hell)

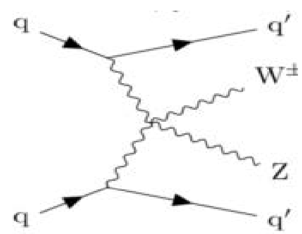
- widely different processes
- confirms the predictive power of the Standard Model
- huge progress on theoretical calculations (NNLO revolution)

Examples: new SM processes measured at the LHC

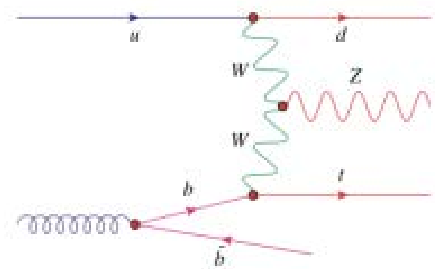
EWK WWjj production

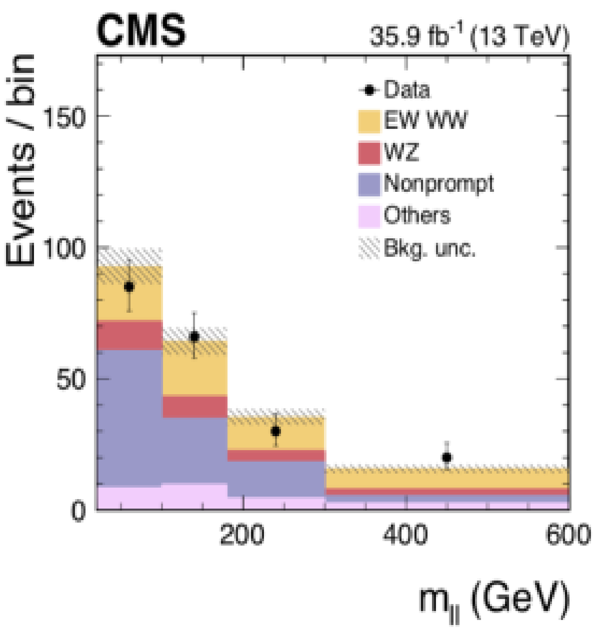


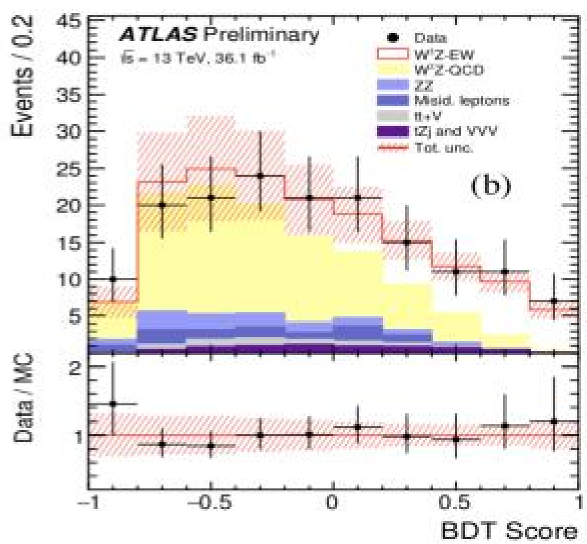
EWK WZjj production

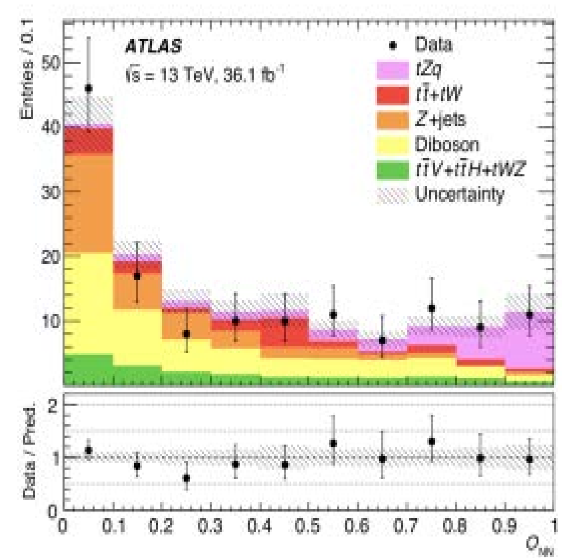


tZ production









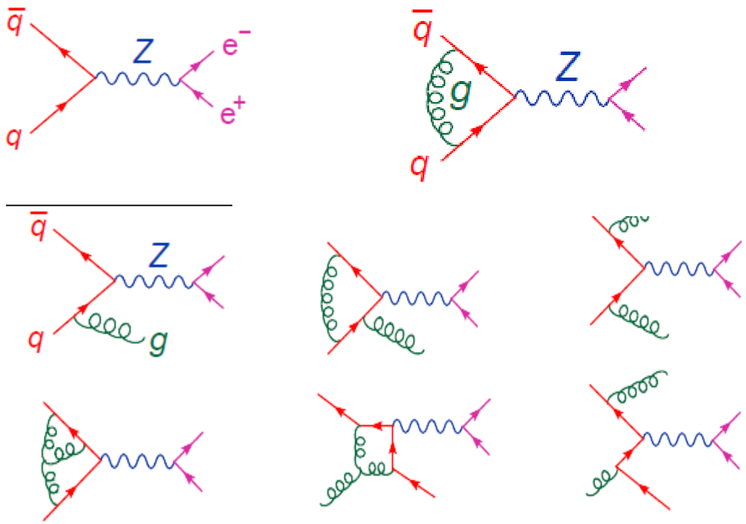
CMS, arXiv:1709.05822

ATLAS-CONF-2018-033

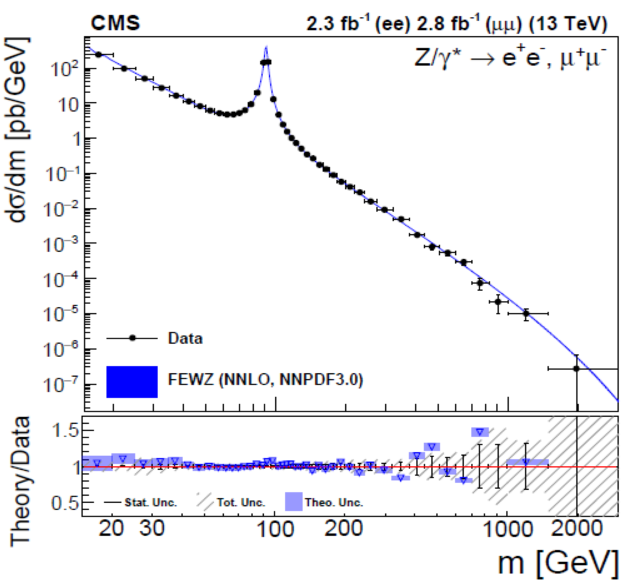
CMS; arXiv:1710.03659

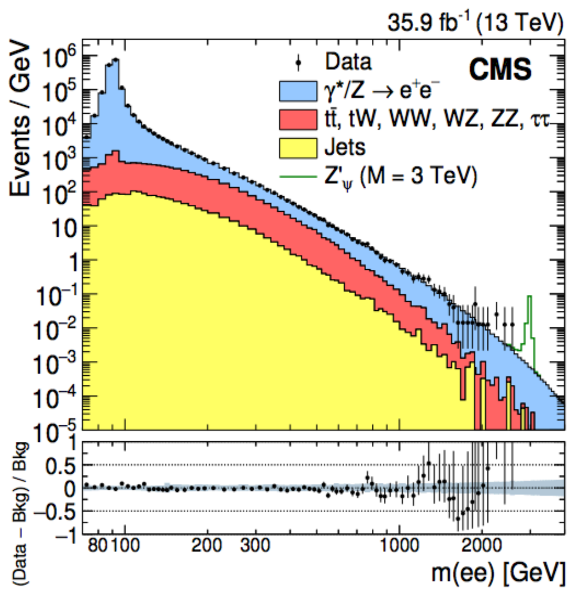
Many other processes eg in top sector: ttW, ttγγ, ttbb,...

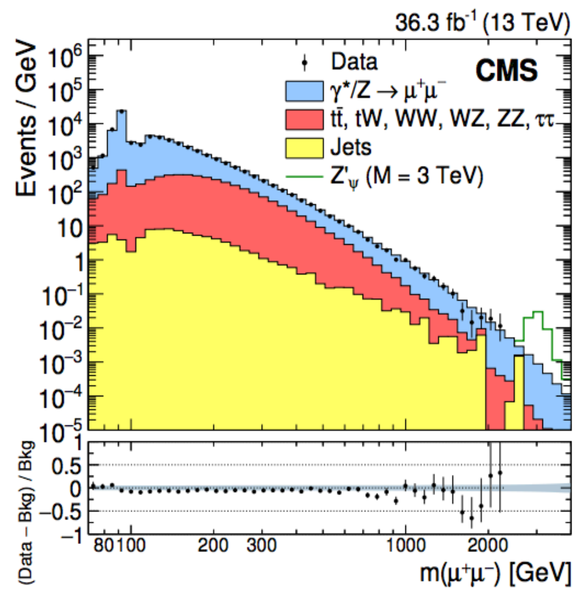
Drell-Yan process



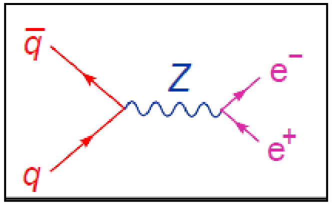
- *Candle* measurement at hadron colliders
- Provides test of perturbative calculations in SM including higher order effects.
- Background to many processes, including search for beyond standard model (BSM)



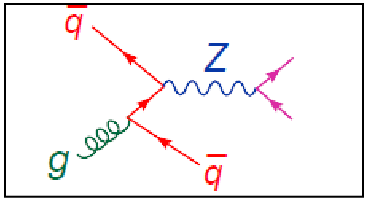




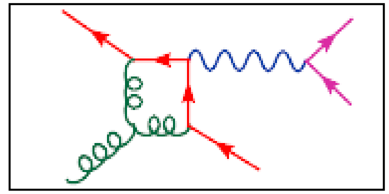
ϕ* differential cross section in Drell-Yan process



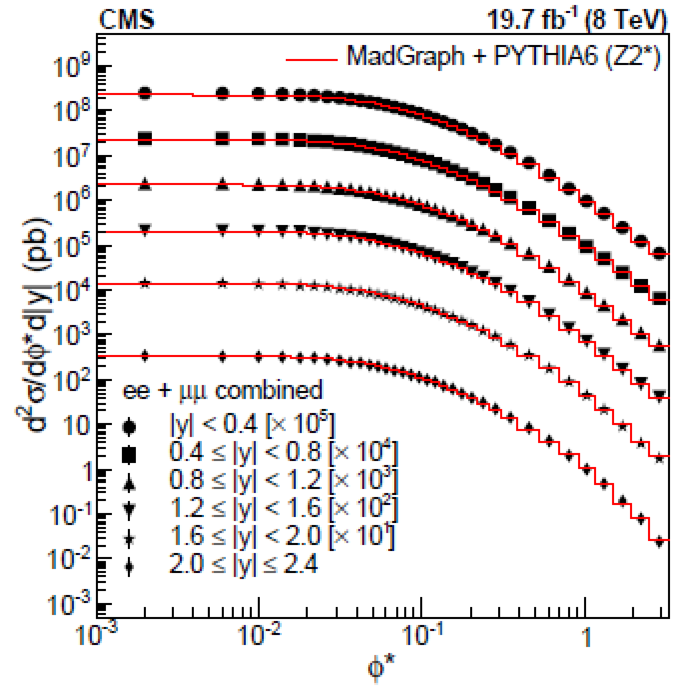
LO



NLO



NNLO



- At leading order Z has only longitudinal boost
- With higher order corrections Z has also transverse boost
  ➔ non-zero transverse momentum

CMS SMP-17-002
1710.07955
JHEP 03 (2018) 172

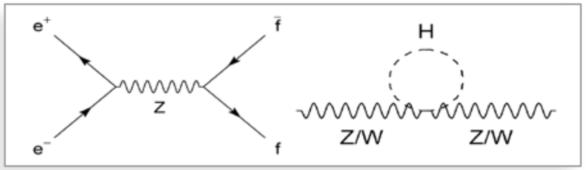
- Measurements show need to include leading-log resummation.
- Related kinematic variable with better accuracy for measurement of angles than muon momenta

$$\phi^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right)\sin(\theta^*_\eta)$$

- **Precision measurement (better than 0.1%) confirms SM predictions,**

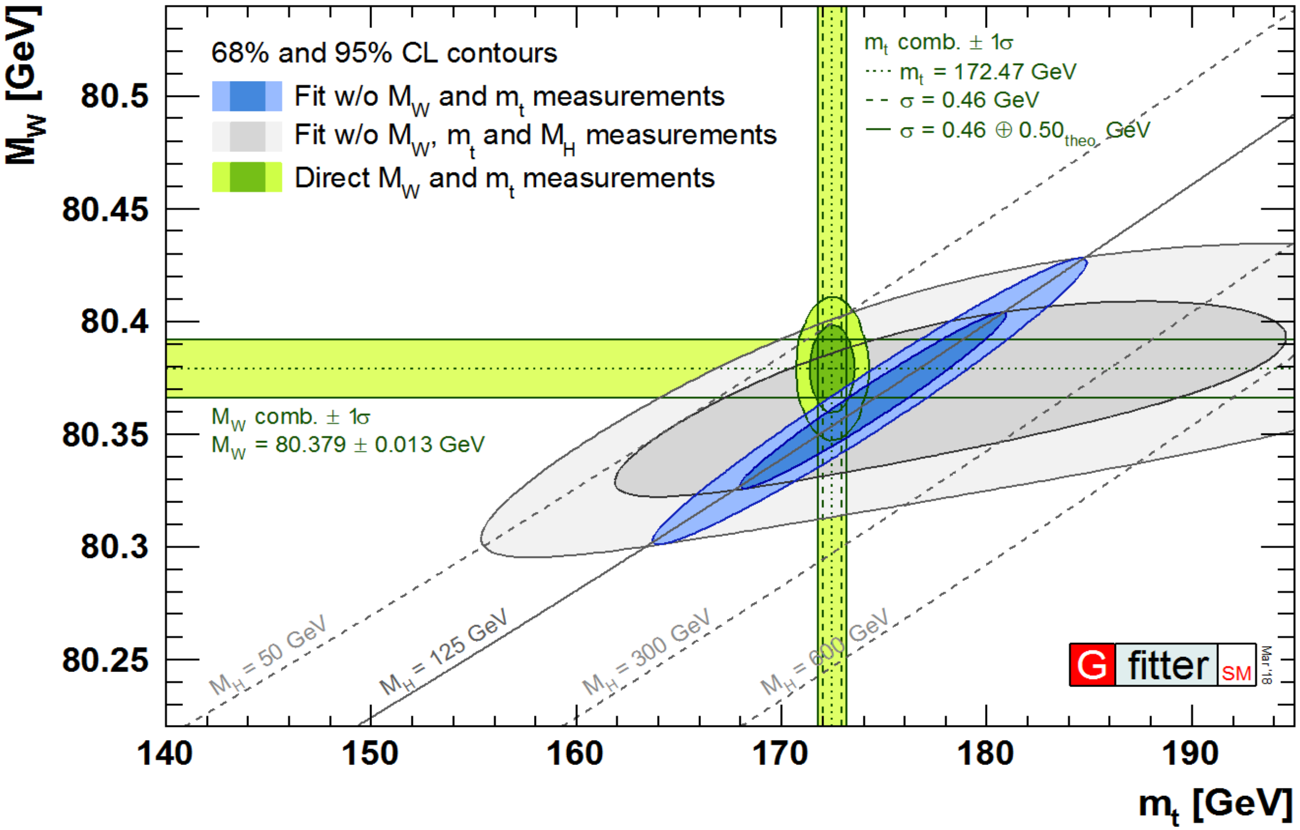
Global electroweak fit → needs the Higgs boson

Discovery of Higgs over-constrains the fit
and dramatically improves predictability.



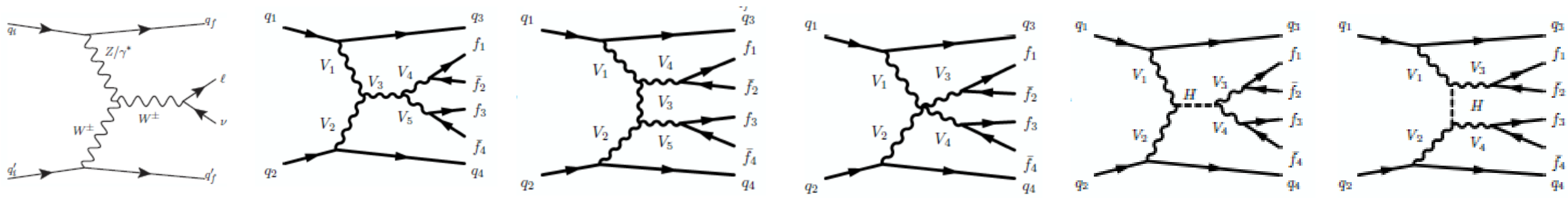
Additional inputs from LHC underlines need for precision measurements:

→ m(top)
→ M(W)
→ m(Higgs)
→ $\sin^2\theta_{eff}$

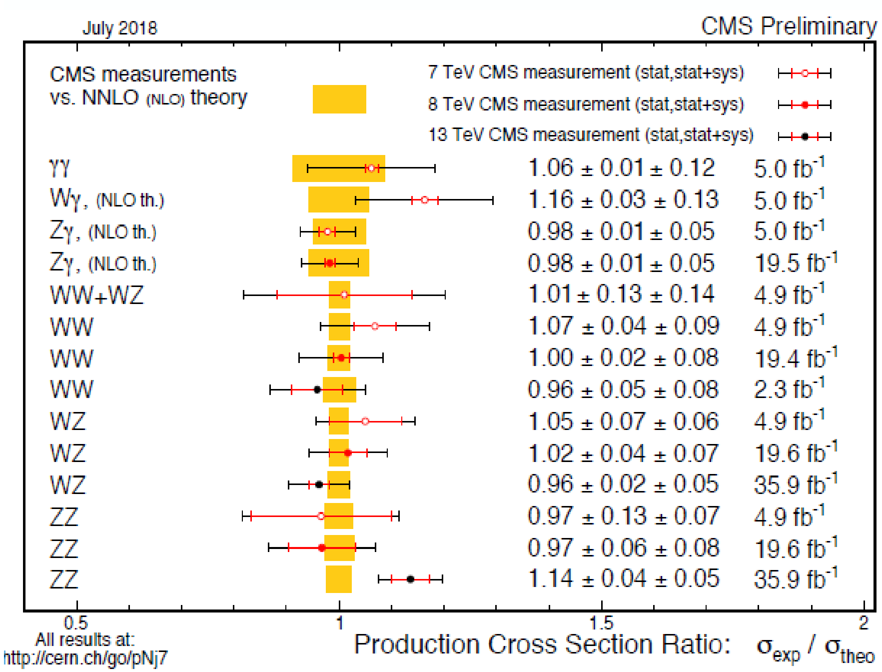


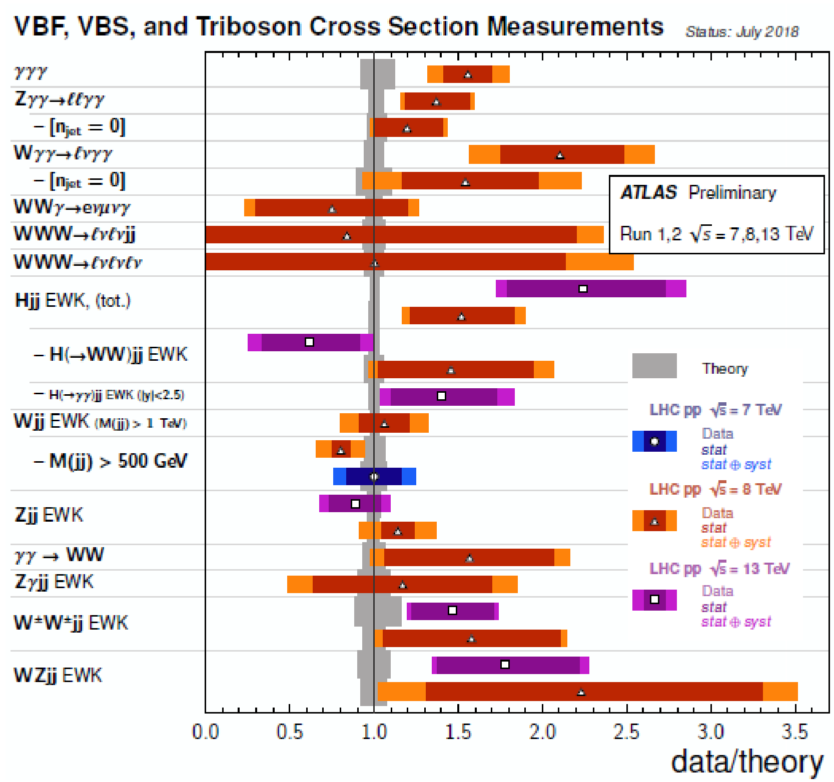
Multiboson productions

- Electroweak production of gauge bosons at LHC ➔ vector boson fusion/scattering
- Anomalous gauge couplings: triple and quartic → accessible for the first time!

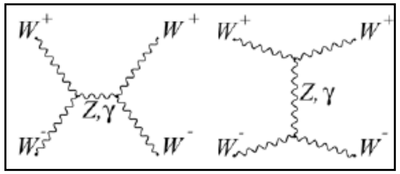


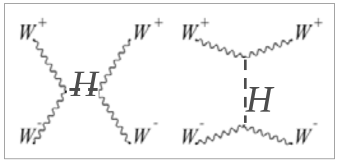
- Includes WH, ZH couplings!





EW processes where Higgs plays critical role





- Unitarity: ➔ for only Z and γ exchanged processes , the amplitude of (longitudinal) $W_L W_L$ scattering violates unitarity

- Higgs boson acts as "moderator" to unitarise

  high-energy longitudinal vector boson scattering.

$$A_{Z,\gamma}\left(W^+W^- \to W^+W^-\right) \propto \frac{1}{\upsilon^2}(s+t)$$

$$A_H\left(W^+W^- \to W^+W^-\right) \propto -\frac{m_H^2}{\upsilon^2}\left(\frac{s}{s-m_H^2}+\frac{t}{t-m_H^2}\right)$$

Look in VBS scattering for bump in high dijet invariant mass distributions.

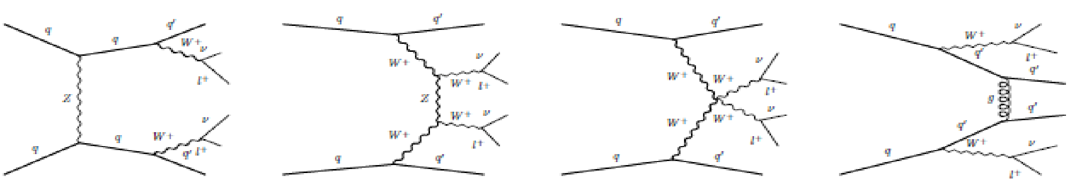
- Same-sign WW selection greatly reduces strong production.
- Removes s-channel Higgs process:

CMS SMP-17-004
1709.05833
PRL

EW VBS

Non-VBS production

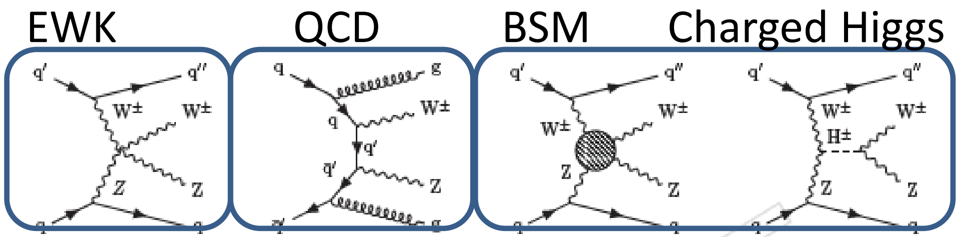
Strong production



CMS observation with 5.5σ
Signal strength: 0.9 ± 2.2

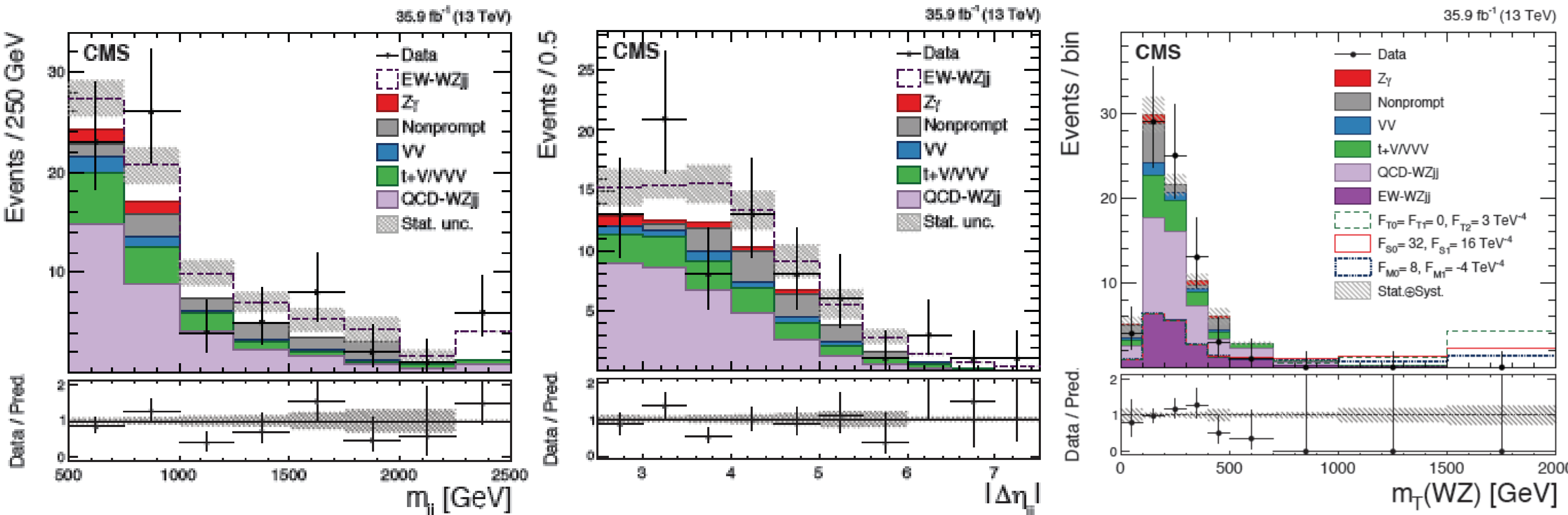
Fiducial x-sec: 3.83 ±0.66(stat) ±0.35(syst) fb

WZ vector boson scattering



VBS process: unique topology

→ Forward- backward energetic jets at high rapidity



$$m_{\mathrm{T}}(\mathrm{WZ}) = \sqrt{(E_{\mathrm{T}}(\mathrm{W}) + E_{\mathrm{T}}(\mathrm{Z}))^2 - (\vec{p}_{\mathrm{T}}(\mathrm{W}) + \vec{p}_{\mathrm{T}}(\mathrm{Z}))^2}$$

- At higher values of m_T (WZ) anomalous coupling effects may show up.
- Fiducial cross section $\sigma(pp \rightarrow WZ)$ = 3.18 +0.71 =0.63 fb

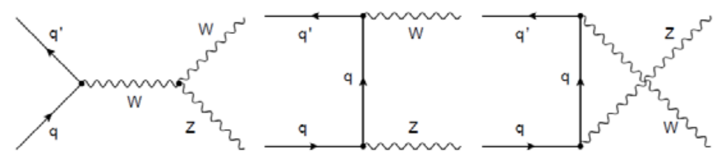
No deviation from SM observed.

Inclusive WZ production

CMS PAS SMP-18-002

- Sensitive to WWZ coupling

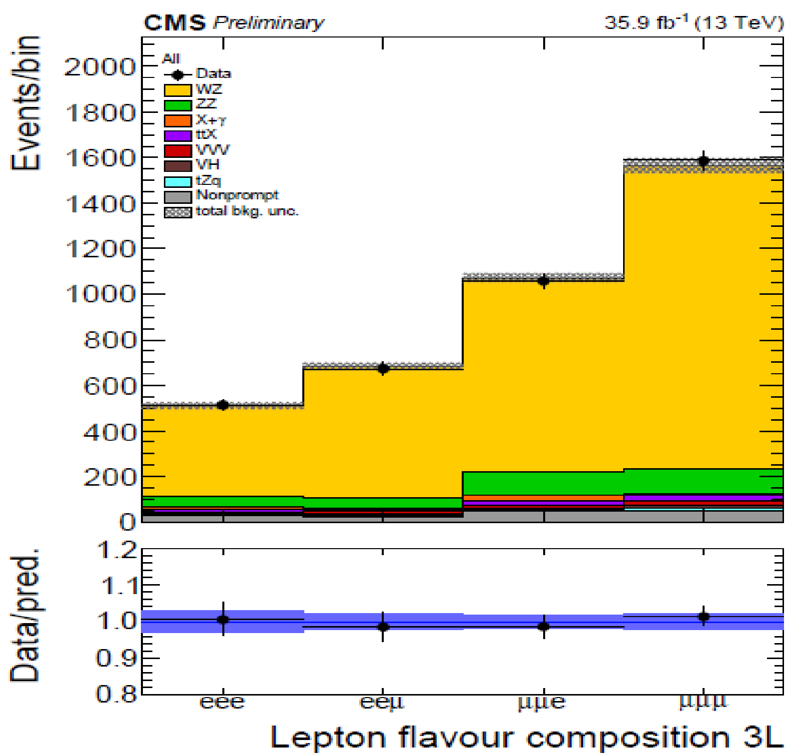
→ Only TGC with W & Z are allowed in SM

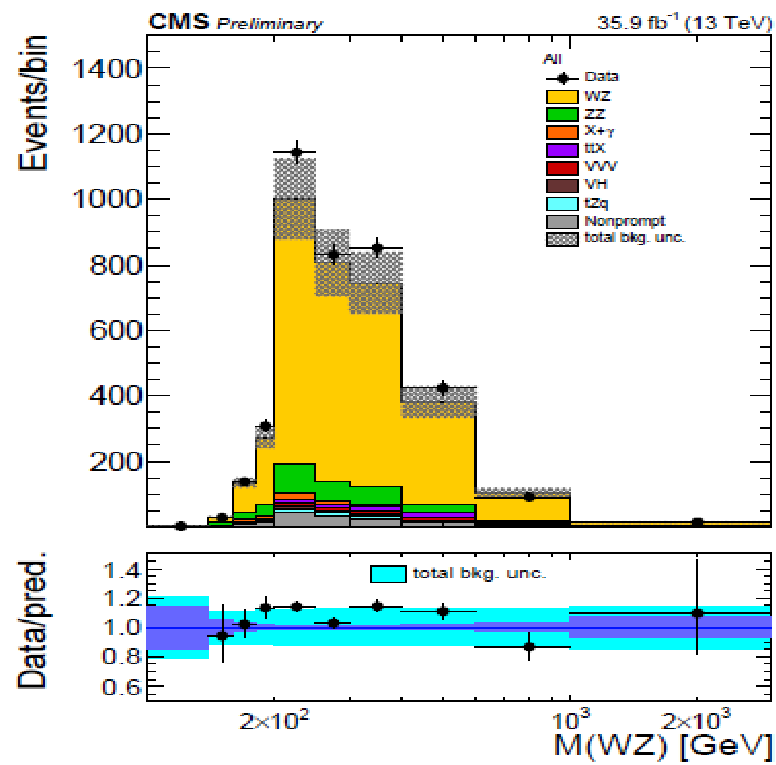


- $\sigma(pp \rightarrow WZ) = 48.09 +2.98 -2.78$ pb

  → Compare with SM prediction at NNLO: 49.98 ±~ 2%

  → higher order contributions at LHC must be taken into account





Top physics

- Really special → heaviest fundamental particle seen till now from Naturs's basket.
  → discovered 25 yrs. back , but several properties were not measured until now.
  eg., couplings to weak gauge boson and Higgs boson

- Plays an important role in m_H stabilization

- Testing ground for perturbative calculations (NNLO + $\alpha^3{}_{EW}$

- Rates and kinematics are sensitive to m_t, $\alpha_{s,}$ PDF

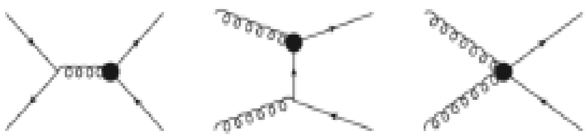
- Top decays before hadronization → spin info passed on to daughter
  (spin-flip time-scale larger than lifetime and QCD time-scale)

- Background for many searches of Higgs boson and new particle beyond SM physics.

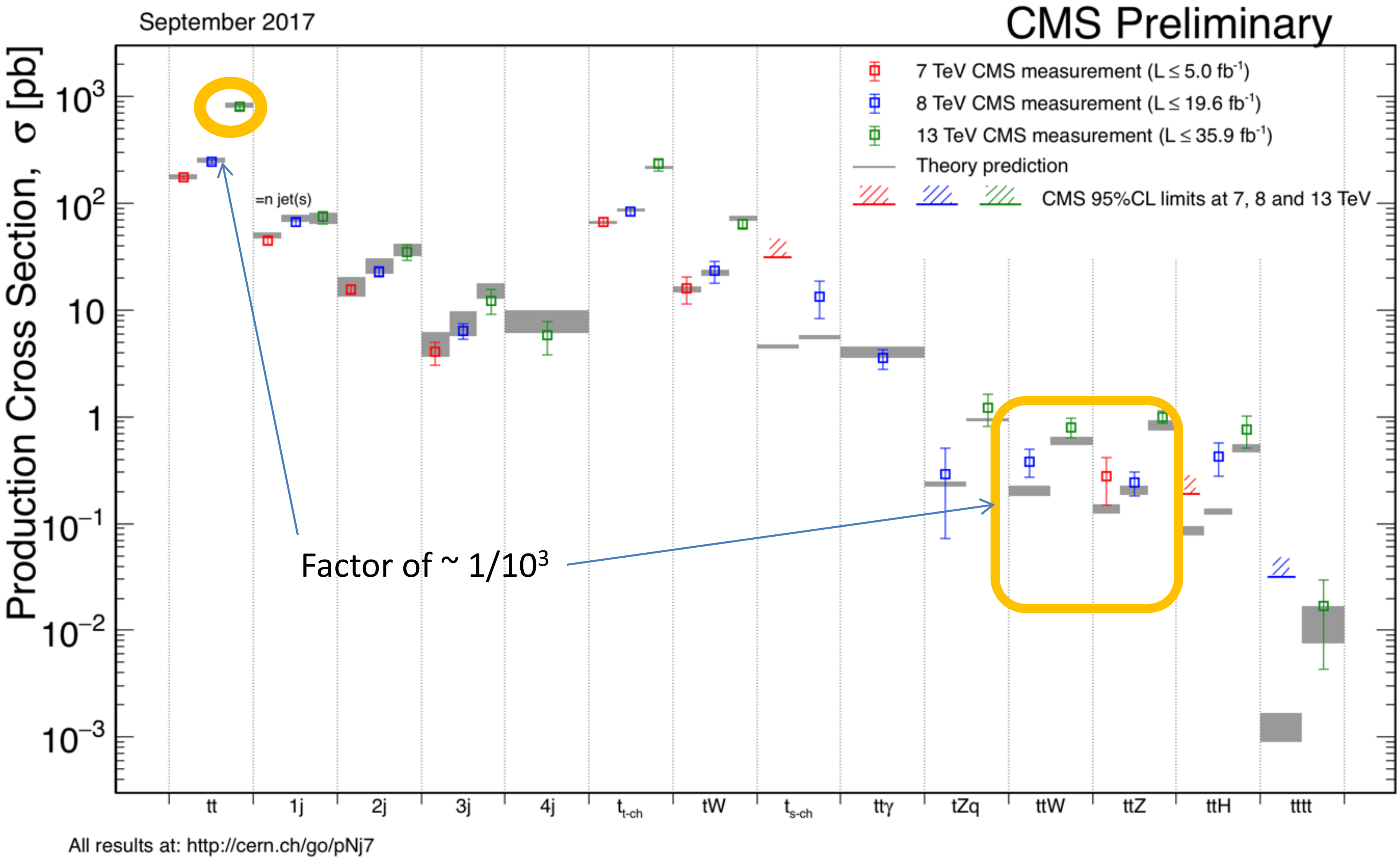
- Top as portal to BSM?
  →eg., in production (Z' → tt), in decay (t → H^+ b)

- New interaction can be described in EFT

A la F. Maltoni
- It is rich, strong, naked, popular
- It goes beyond

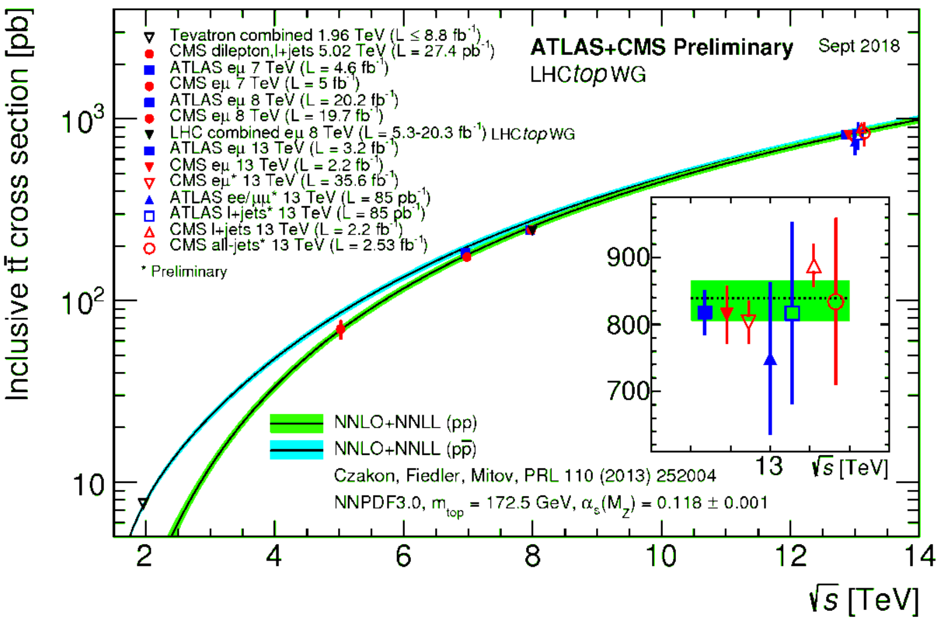


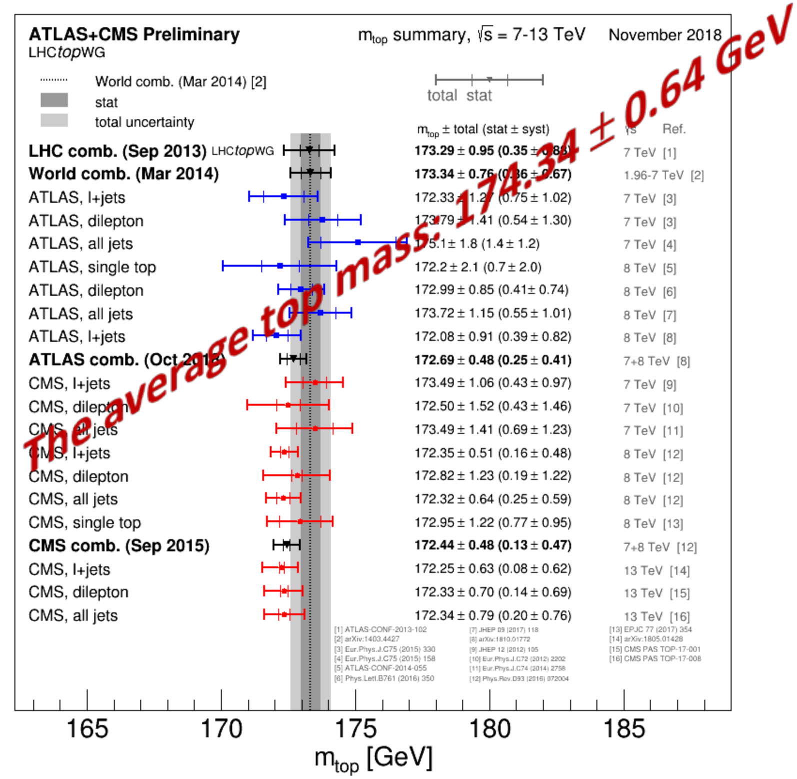
Inclusive top production rates



Large energy available at the LHC opens up the possibility for production of multiple heavy particles In a given interaction.

Top quark pair production and top mass





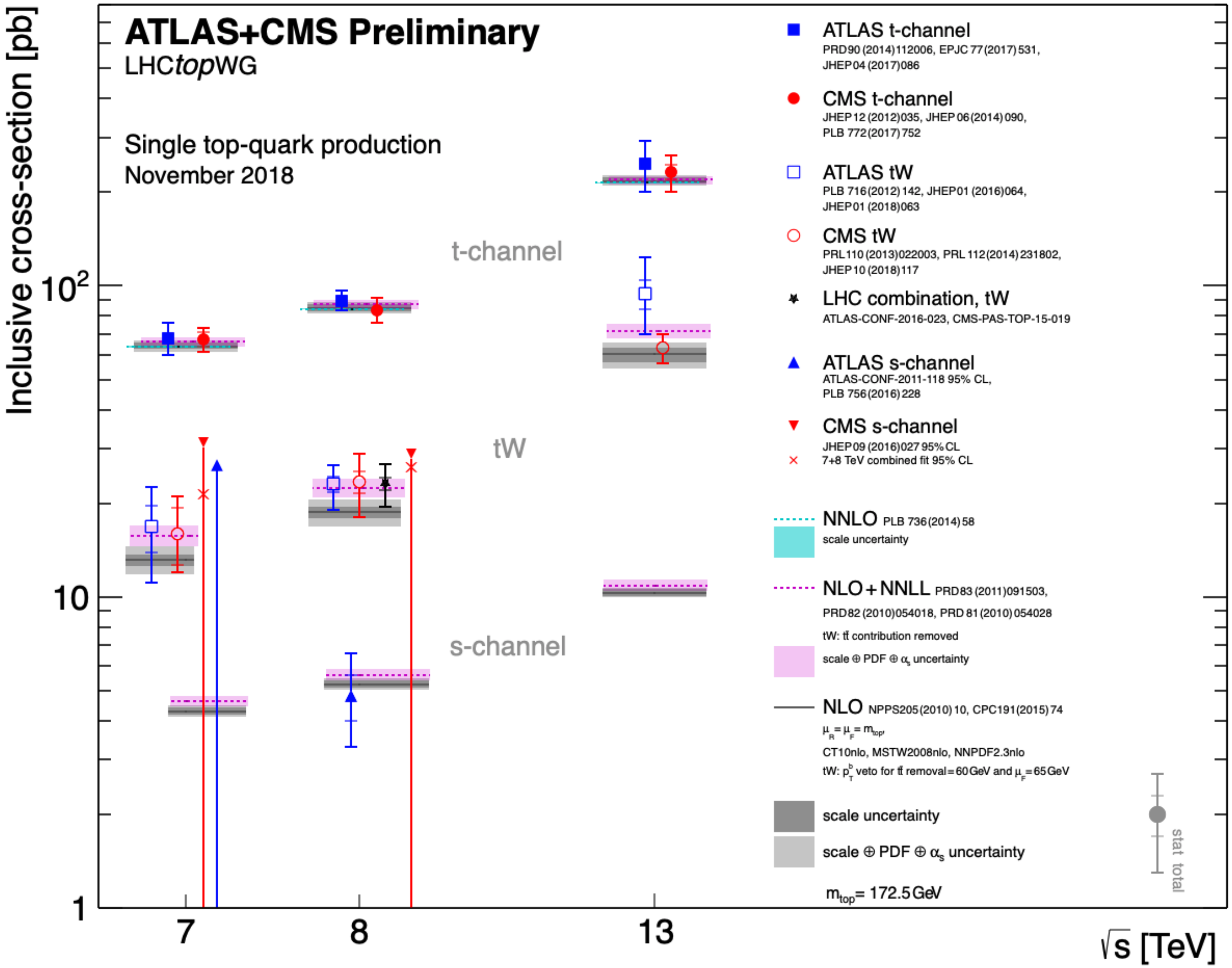
- Huge amount of work at LHC by experimentalists and theoreticians

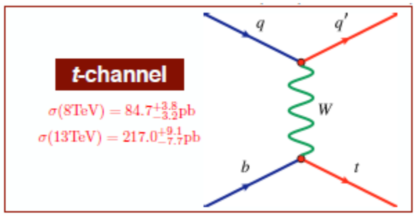
- Great improvements during last several years ➔ precision ~ 0.3%

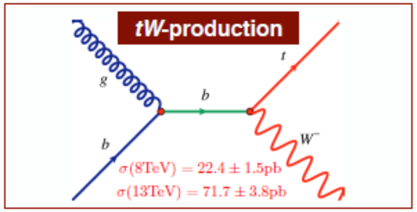
→ hadronization model uncertainties one of the main limitations

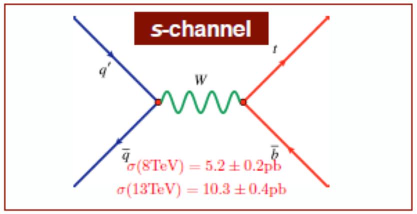
- a la P.Nason: direct measurements measure the pole mass up to corrections of the order of a hadronic scale.
- Differences in measurement using various event generators could be due to non-perturbative effects, parton shower modeling as well as interface with NLO

Single top quark production





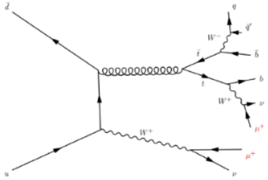


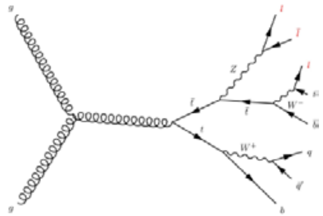


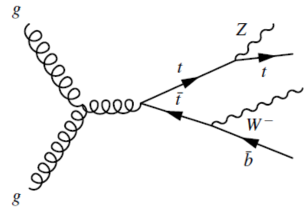
Why interesting?

- Measure V_{tb}, m(top),..
- Probe for BSM
- Constrain PDF
- Tune event generators
- Background for Higgs

Tops playing in doubles vs. single vector boson







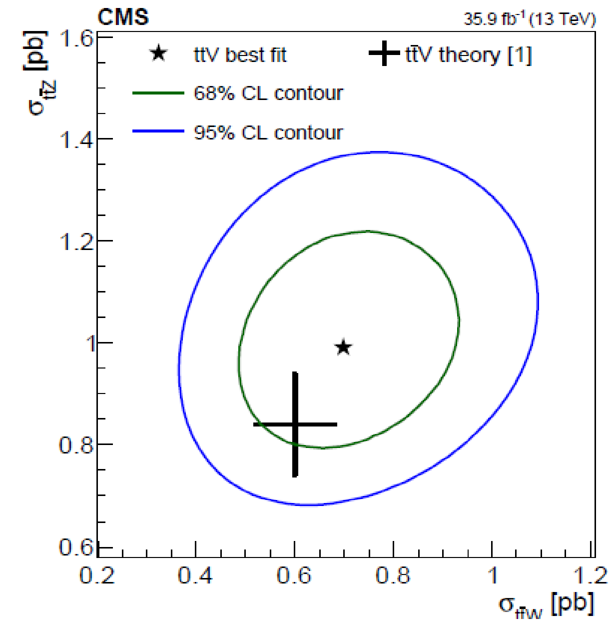
3 exclusive analyses:
i) Same sign dilepton pair for ttW
ii) 3 lepton for ttZ
iii) 4 lepton for ttZ

$$\sigma(\mathrm{pp} \to \mathrm{t\bar{t}W^+}) = 0.58 \pm 0.09\,(\mathrm{stat})^{+0.09}_{-0.08}\,(\mathrm{syst})\,\mathrm{pb},$$

$$\sigma(\mathrm{pp} \to \mathrm{t\bar{t}W^-}) = 0.19 \pm 0.07\,(\mathrm{stat}) \pm 0.06\,(\mathrm{syst})\,\mathrm{pb}.$$

$$\sigma(\mathrm{pp} \to \mathrm{t\bar{t}W}) = 0.77^{+0.12}_{-0.11}\,(\mathrm{stat})^{+0.13}_{-0.12}\,(\mathrm{syst})\,\mathrm{pb},$$

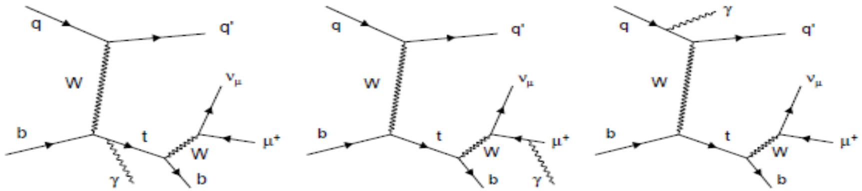
$$\sigma(\mathrm{pp} \to \mathrm{t\bar{t}Z}) = 0.99^{+0.09}_{-0.08}\,(\mathrm{stat})^{+0.12}_{-0.10}\,(\mathrm{syst})\,\mathrm{pb}.$$



- General good agreement between prediction and data

- Interpretation of the measurement in the context of EFT
- **No identifiable operator found which affects ttW cross section independently.**

Single top quark in association with a photon



CMS Top-17-016
arXiv: 1808.02913
PRL

$$\boxed{\Gamma_\mu(q^2) = -ie\left\{\gamma_\mu\left[F_{1V}(q^2) + F_{1A}(q^2)\gamma_5\right] + \frac{\sigma_{\mu\nu}}{2m_t}q^\nu\left[iF_{2V}(q^2) + F_{2A}(q^2)\gamma_5\right]\right\}}$$

$$\boxed{\begin{aligned} F_{1V}(0) &= Q_t, \\ F_{2V}(0) &= a_t Q_t, \\ F_{2A}(0) &= d_t\frac{2m_t}{e} \end{aligned}}$$

F: form factors, known to 1-loop in EW and 2-loops in QCD

a_t: anomalous magnetic moment, =0.02 in SM

d_t: electric dipole moment, violates CP conservation ~ 10^{-30} e in SM

- Cross section sensitive to BSM

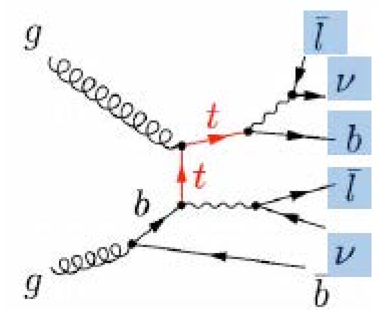
- Extremely difficult to measure a_t and d_t due to vanishing lifetime of top in terms of dim-5 operators, in EFT

$$\boxed{\mathcal{L}_{\text{eff}} = -\frac{1}{2}\left[c\,\bar{t}_L\sigma_{\mu\nu}t_R + c^*\,\bar{t}_R\sigma_{\mu\nu}t_L\right]F^{\mu\nu}}$$

$\sigma(pp \rightarrow t\,\gamma)$ * $Br(t \rightarrow \mu\nu b)$ = 115± 17 (stat) ± 30(syst) fb

4.4 σ observation , consistent with SM

Single top in association with W



σ(tW) = 63.1± 1.8(stat) ± 6.4(syst) ± 2.1(lumi) pb
σ(tW) SM, NLO + NNLL = 71.7 ± 1.8 (scale) ± 3.4(PDF) pb

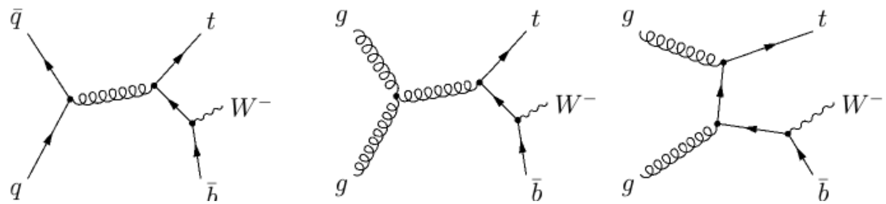
- WWbb production

CMS Top-17-018
arXiv: 1805.07399
JHEP10(2018)117

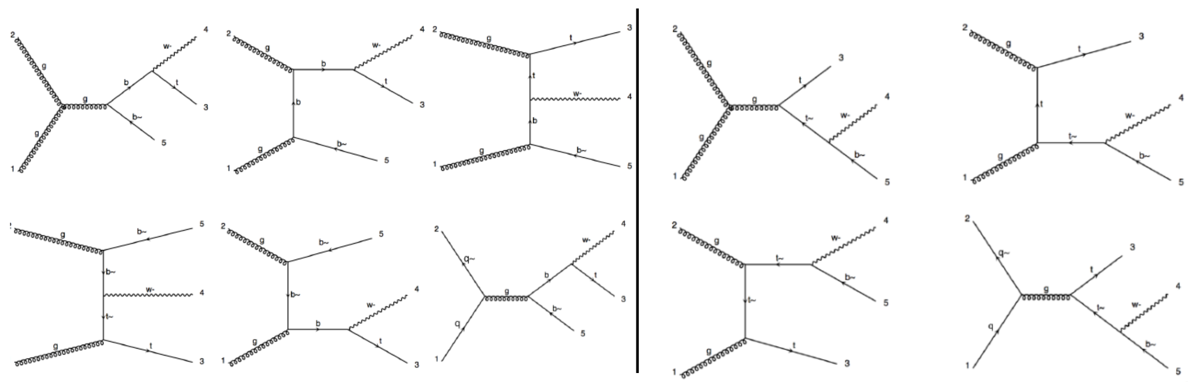
ATLAS JHEP
arXiv:1612.07231

- Crucial: Interference of tt production at NLO with tW production

tt NLO-



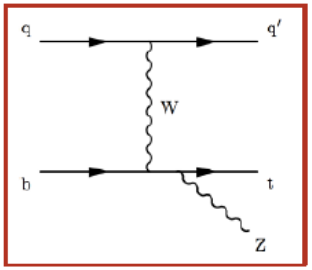
tW NLO-interference



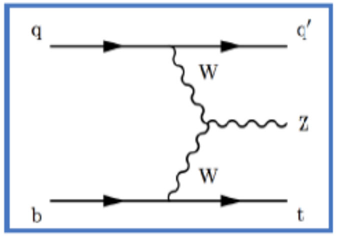
Use techniques of
- diagram removal,
- diagram subtraction
- handlie leptonic decays

w/o narrow width approx.

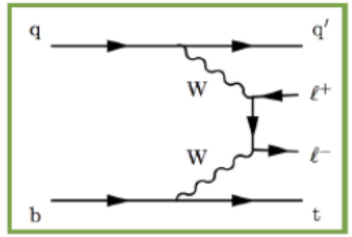
Single top in association with Z



Top-Z coupling, complementary to ttZ

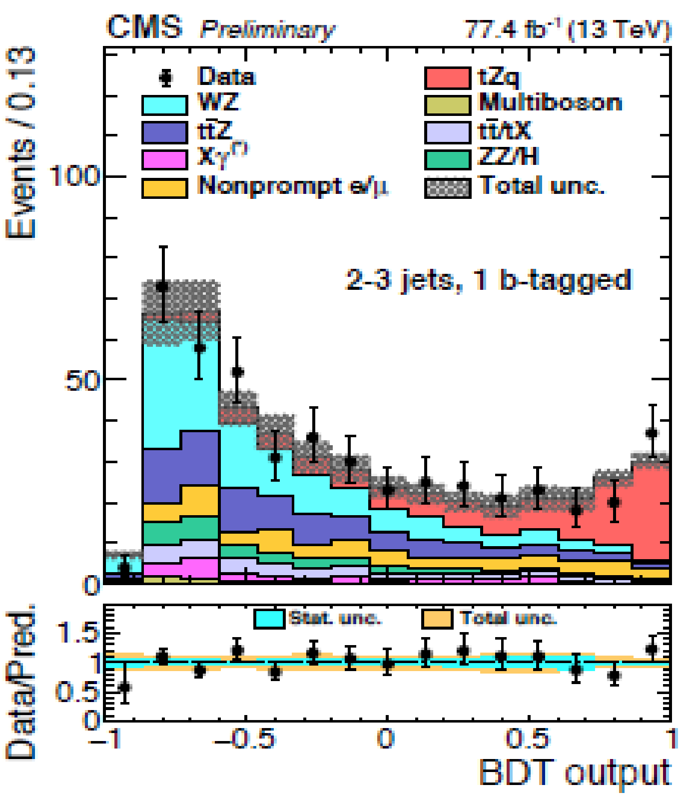


Sensitive to WWZ vertex



No on-shell Z

CMS TOP-18-018
1812.05900
PRL



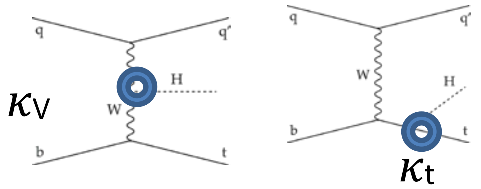
- First observation by CMS using
  → final state : 3 ℓ + b-jet + forward jet
  → L = 77.4/ fb (2016+2017 data of CMS)
- Observed (expected) significance 8.2(7.7) σ

$$\sigma(tZq \to t\ell^+\ell^- q) = 111 \pm 13(stat)^{+11}_{-9}(syst)\ \mathrm{fb}$$

$\sigma(tZq,\ Z \to \ell\ell) \sim 94.2 \pm 3.1$ fb (NLO SM scale uncert)

Single top in association with Higgs

- tHq process exposes the relative sign of Htt & HWW couplings via interference. (ttH cannot)

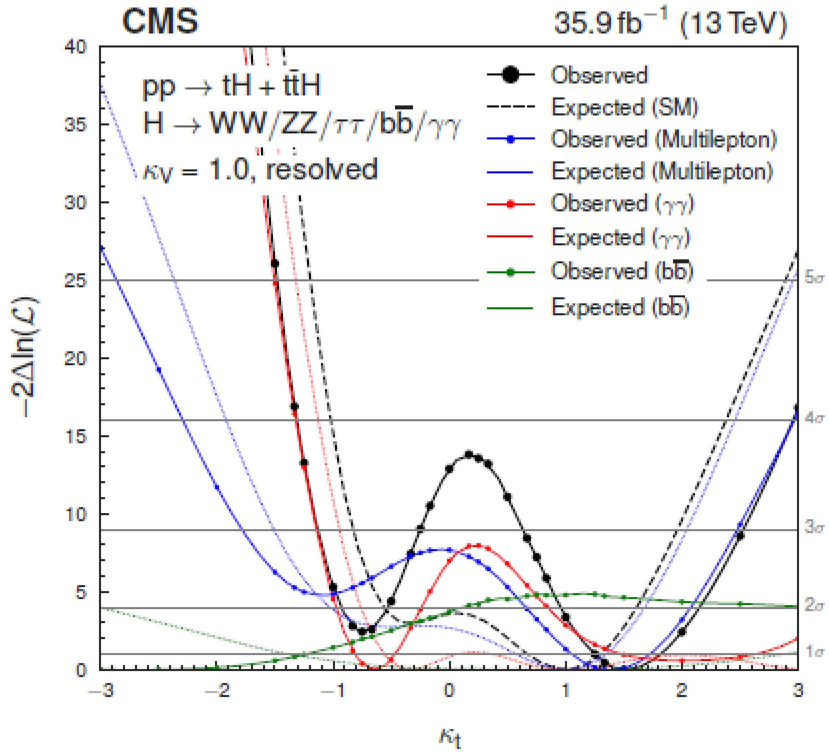


- Destructive interference in SM: $\sigma_{tHq}(\kappa_V = \kappa_t = 1)$ = 70.96 fb (at $\sqrt{s}$ = 13 TeV)

- Large enhancement for negative relative sign between κ_t and κ_V in tHq production e.g., $\sigma_{tHq}(\kappa_V = -\kappa_t = 1)$ = 792.7 fb.

- Combined limit on σ(tHq+tHW+ttH)xBR(H→WW*,$\tau\tau$,ZZ,bb,gg)

- **Exclude : y_t below -0.9**



CMS HIG-18-009
1811.09696
PRD

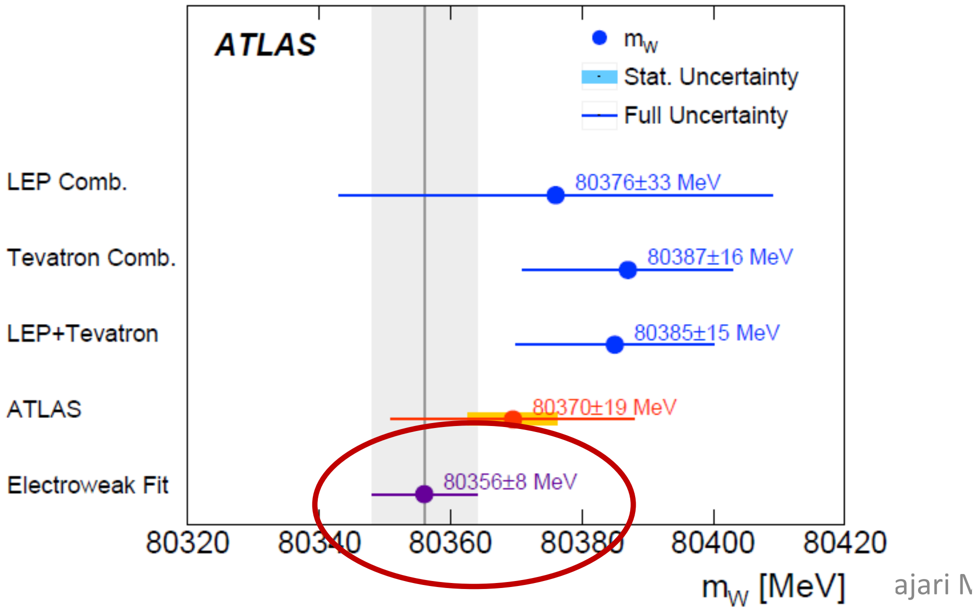
Precision for W mass

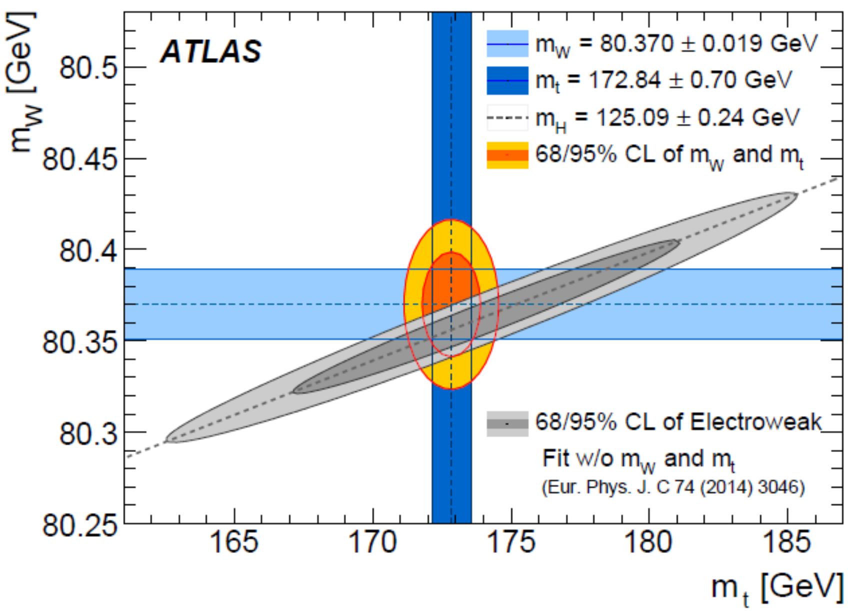
ATLAS
1701.07240

- Currently, $m_W = 80370 \pm 7_{\text{stat}} \pm 11_{\text{exp syst}} \pm 14_{\text{mod syst}}$ MeV
  $= 80370 \pm 19$ MeV (global fit: → 8 MeV!)
- **Ultimate goal Δm_W 5 MeV → achievable in future with low luminosity runs**

- Though only moderate increase in CM energy, extremely high luminosity helps in fantastic precision in crucial inputs of SM: W and top masses.
- Ultimate precision at LHC in m(W) : 0.02%, m(top): 0.3%

- Need to understand the systematics: experimental AND theoretical .





Physics potential of high luminosity & high energy LHC

Today discuss only briefly about HL-LHC

Reference Parameters:

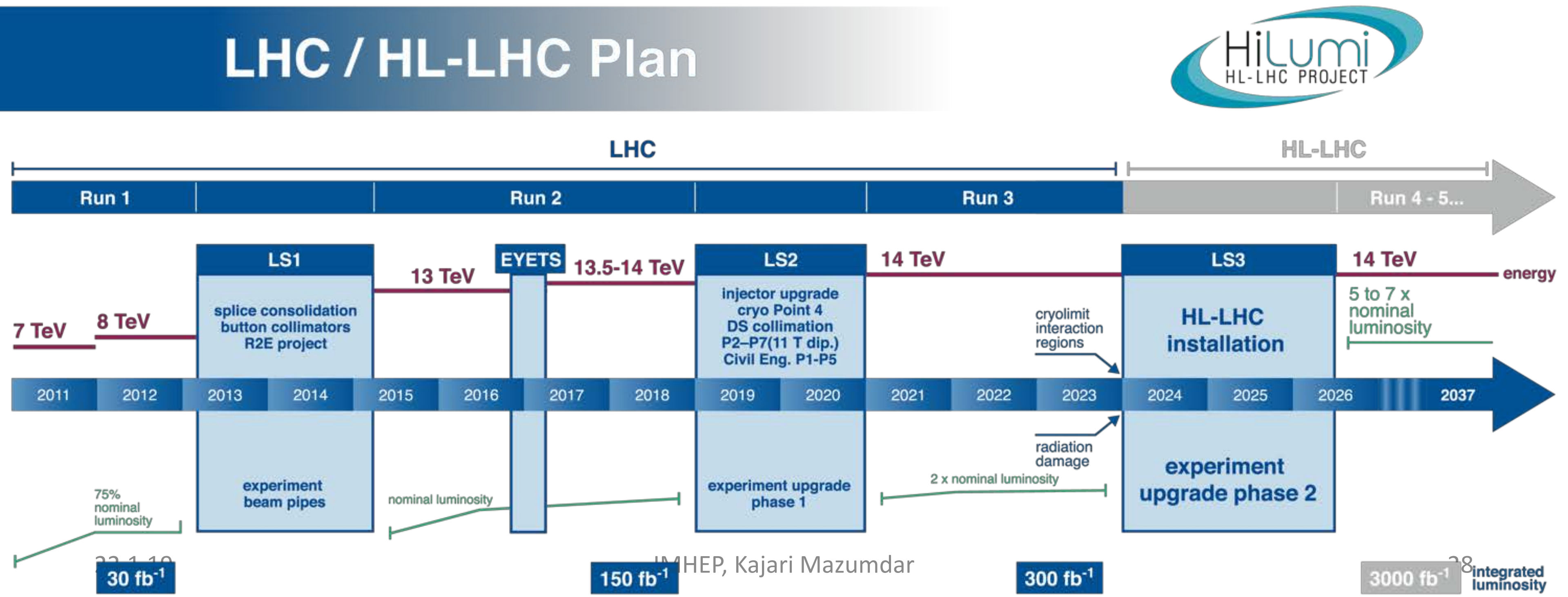
HL-LHC: √ s = 14 TeV; L = 3 ab^{-1} for ATLAS and CMS, for LHCb: 50 → 300 fb^{-1}

HE-LHC: √ s = 27 TeV; L = 15 ab^{-1} for ATLAS and CMS, for LHCb: 3 ab^{-1}

Year-long workshop to document E_{beam} dependence of achievable physics.

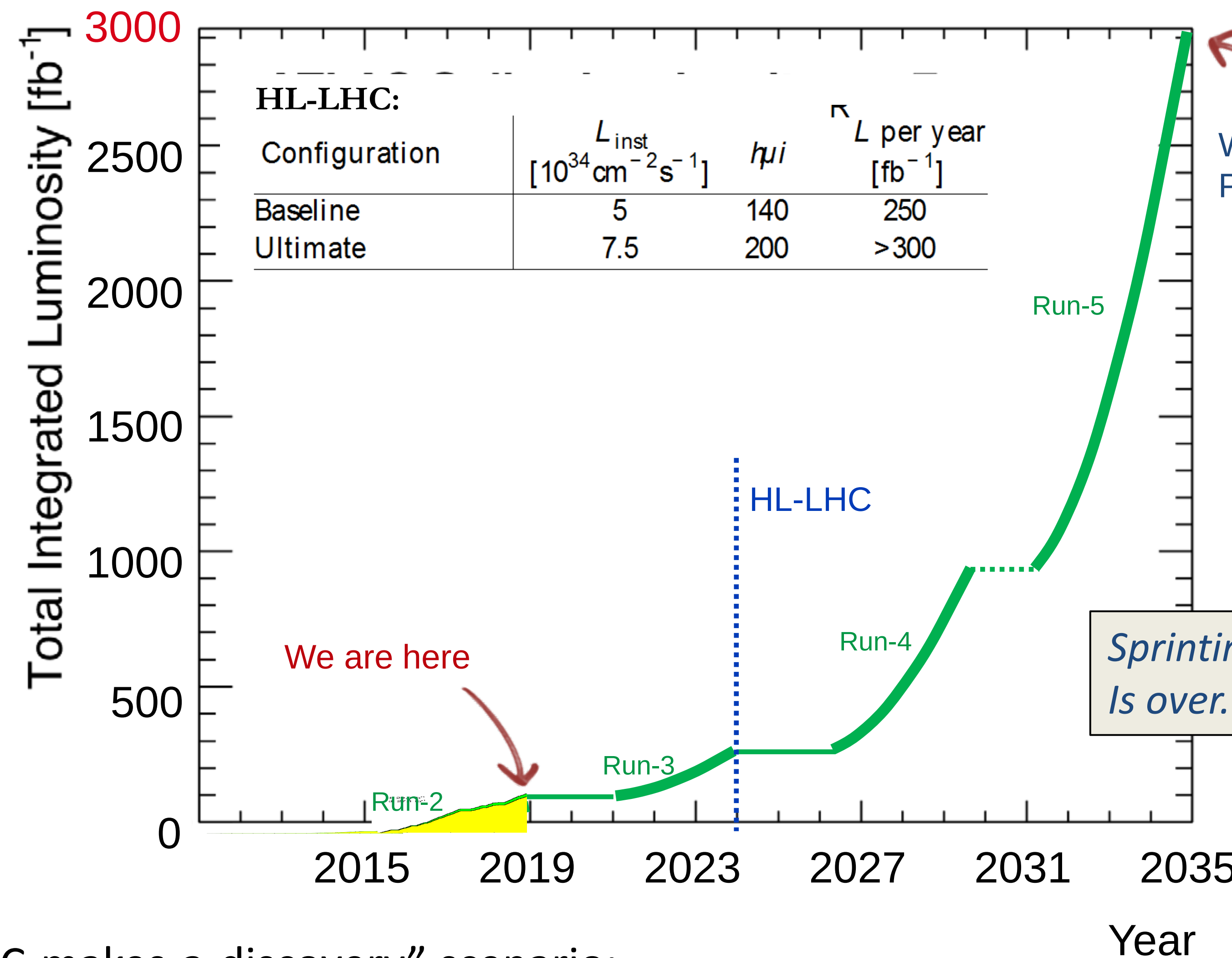
Reports are being finalized for final Jamboree at CERN in March, 2019.

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCWorkshop



Future of LHC: HL-LHC

We live in **data-driven times**, experimental results guide us to the next stage.



Configuration	L_{inst} [10^{34} cm^{-2}s^{-1}]	$\langle\mu\rangle$	$\int L$ per year [fb^{-1}]
Baseline	5	140	250
Ultimate	7.5	200	>300

We will be going here.
Possibly ,up to 4 ab^{-1}

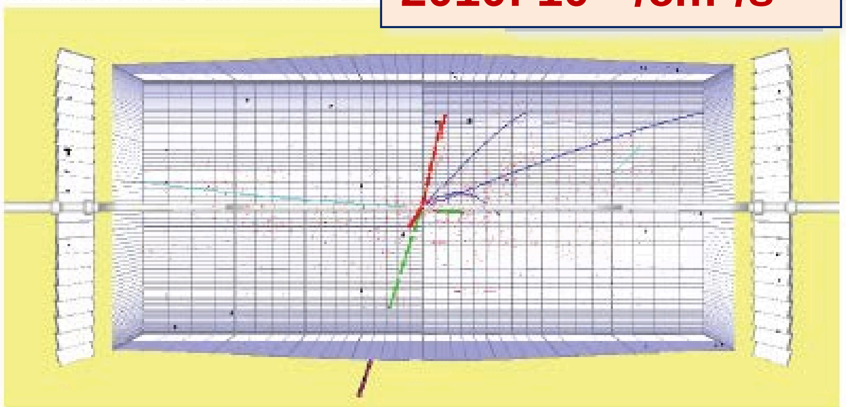
Sprinting at LHC
Is over. marathon now

The"LHC-makes-a-discovery" scenario:

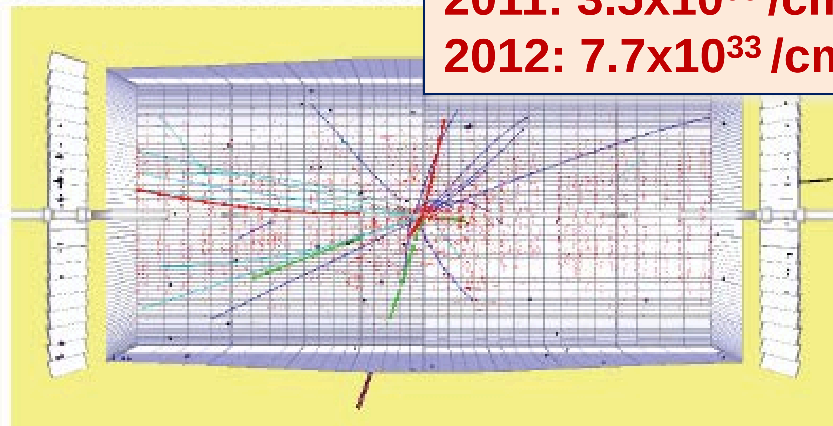
✓Find the detailed characteristics ➔ 300 /fb is not enough!

Experimental Challenge at High Luminosity LHC

2010: 10^{32} /cm^2/s

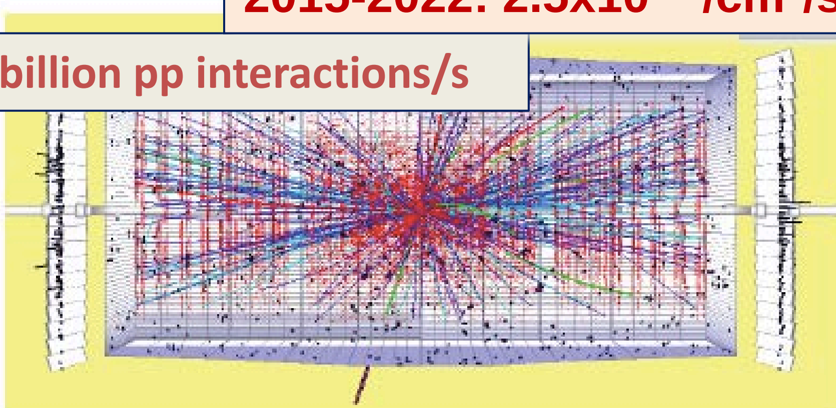


2011: 3.5×10^{33} /cm^2/s
2012: 7.7×10^{33} /cm^2/s



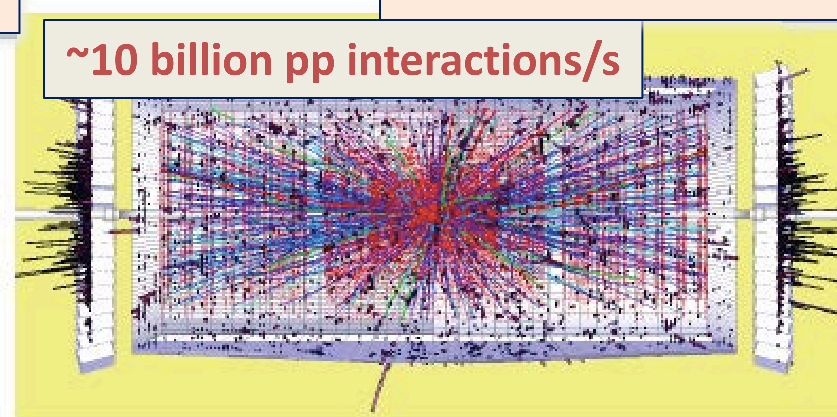
2015-2022: 2.5×10^{34} /cm^2/s

~1 billion pp interactions/s



> 2026: $0.5\text{-}1\times10^{35}$ /cm^2/s

~10 billion pp interactions/s



Scale of electroweak physics does not change with luminosity

Tracking, Calorimetry and Triggering, in particular for low to medium p_T objects, need fine granular and radiation hard detectors, new strategies in DAQ and Software.

Electroweak physics at HL-LHC

1. Test the SM theory of EWSB via a comprehensive portfolio of (multi) boson production measurements : rich sector, always!

Most significant motivations:

(i) Check the role of Higgs in restoring the unitarity of gauge boson interactions

→ measure **W_L W_L scattering in $W^{\pm}W^{\pm}$ production** via vector boson fusion

(ii) Test electroweak gauge invariant effective field theory

→ measure **triple and quartic gauge interactions in V_1V_2 scattering**, $V_{1,2}$ = W, Z

Caveat: all the processes have very small rate, interesting physics lies at the high tail of transverse momentum, invariant mass, etc. .

2. Improve the precision of EW observables, eg., M_W , $\sin^2 \vartheta_W$

3. Produce precision constraints on PDFs (eg. lepton charge asymmetry in W events)

4. Test predictions of perturbative QCD vs. anomalous effect due to BSM

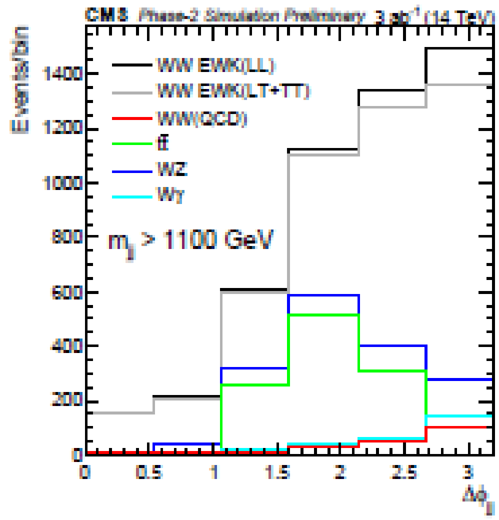
→ differential distributions reveal the effect of higher order quantum corrections.

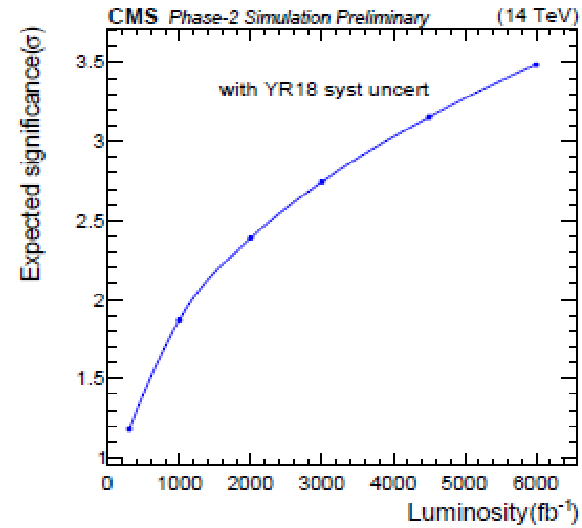
Vector boson scattering

- Signal $V_L V_L$: ~ 5 to 10% of the total VV scattering rate; background: $V_L V_T$, $V_T V_T$

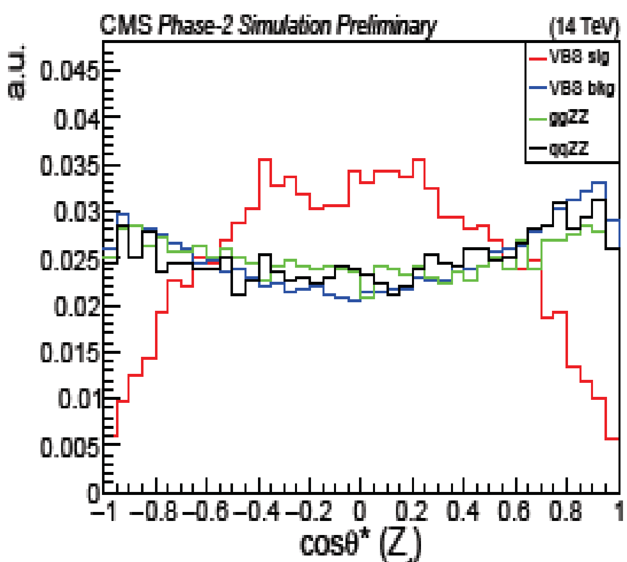
Significance in 3/ab :
$W_L W_L$: 2.7σ , $Z_L Z_L$: 1.4σ

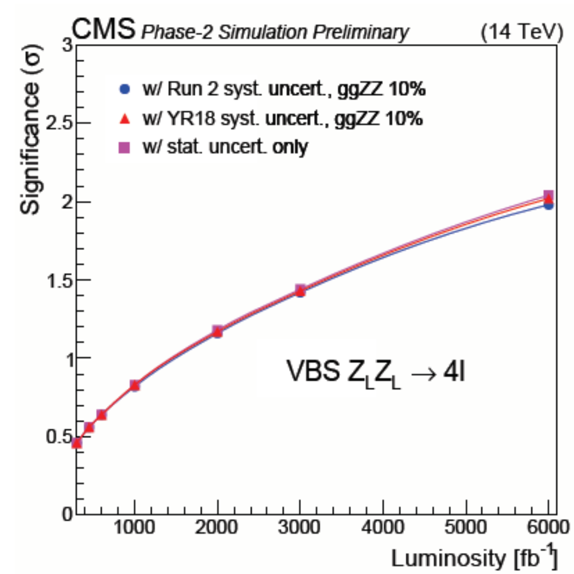
Combination of CMS and ATLAS
➔ 3σ significance for $W_L W_L$





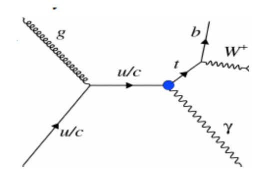
ZZ scattering: 4l + 2j





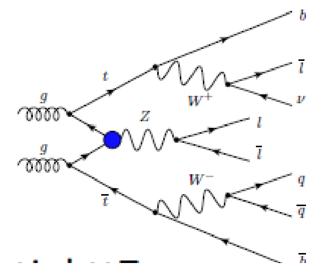
Top physics at HL-LHC

- Large rate allows to investigate new phase-space corners using boosted tops



- FCNC processes accessible , eg., Br.($t \rightarrow c\gamma$) =1.5* 10^{-4}

- Anomalous ttZ coupling from differential distributions



- Study 4top (tttt) production → sensitive to BSM
  → measure σ_{tttt} with 9% statistical uncertianty

- Top mass crucial input for electroweak fit
  → must be measured precisely

σ_{tt}	~ 1 nb	→ 3B top pairs
$\sigma_{t\text{-channel}}$	~ 200 pb	→ 600M tops
$\sigma_{s\text{-channel}}$	~ 10 pb	→ 30M tops
$\sigma_{tt\gamma/V/H}$	~ 1 pb	→ 3M top pairs
σ_{tH}	~ 10 fb	→ 30k tops
σ_{tttt}	~ 9 fb	

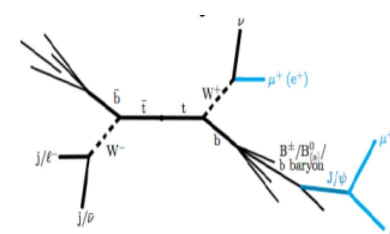
i) Traditional method systematics dominated →
reconstruct invariant mass of top decay products

For 3/ab , Δm_t = 0.2 GeV (~ 0.1 %)

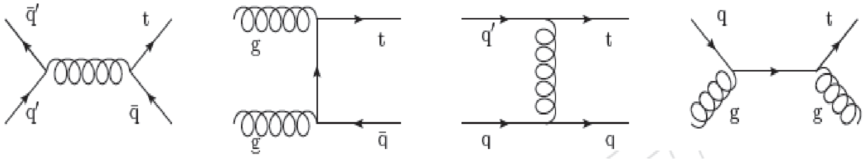
→ mainly due to theory uncertainty related to "pole" mass of top

ii) Measure decay length of b-hadrons in tt decays to achieve Δm_t = 0.6 & 0.4 GeV

iii) Use $t \rightarrow Wb \rightarrow \ell\, \nu + (J/\psi + X)$ to achieve Δm_t = 0.8 & 0.6 GeV

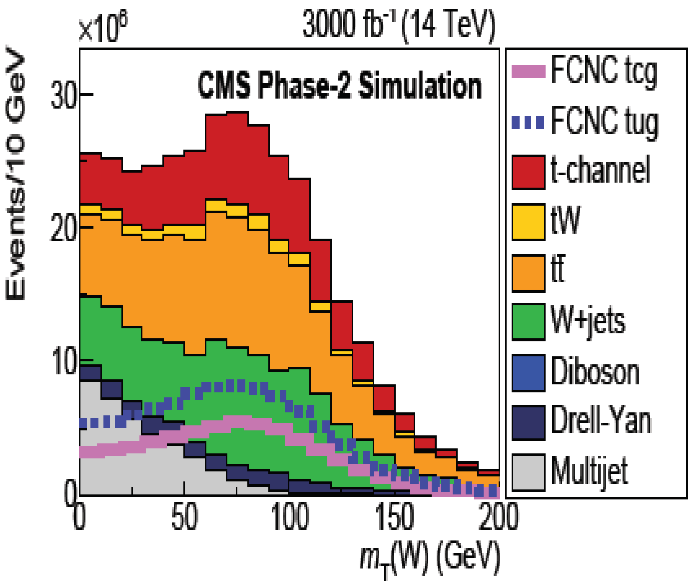


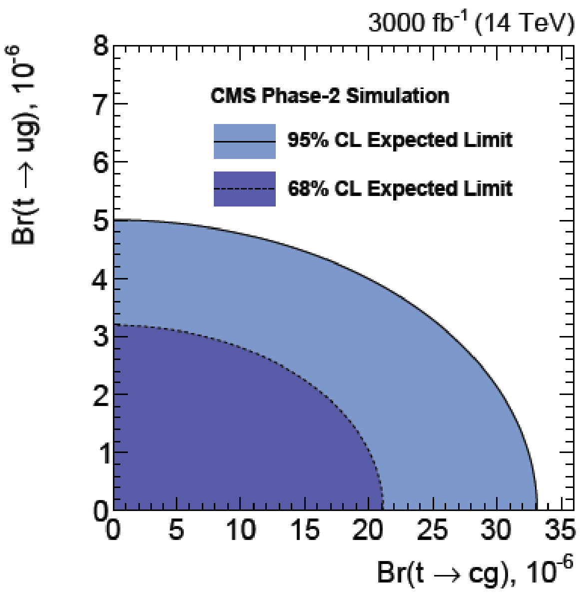
FCNC in top production

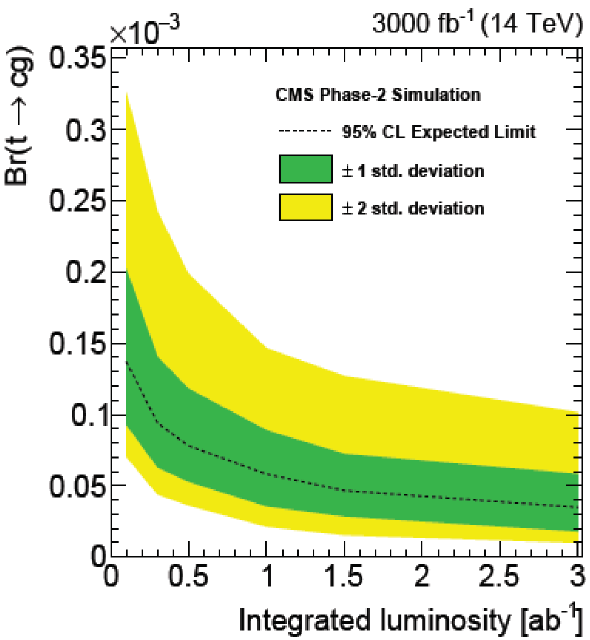


- FCNC involving top is less constrained
- Can be studied better in inclusive single top production processes

- Use model-independent effective Lagrangian: $\mathfrak{L} = \frac{\kappa_{tqg}}{\Lambda} g_s \bar{q} \sigma^{\mu\nu} \frac{\lambda^a}{2} t G^a_{\mu\nu}$







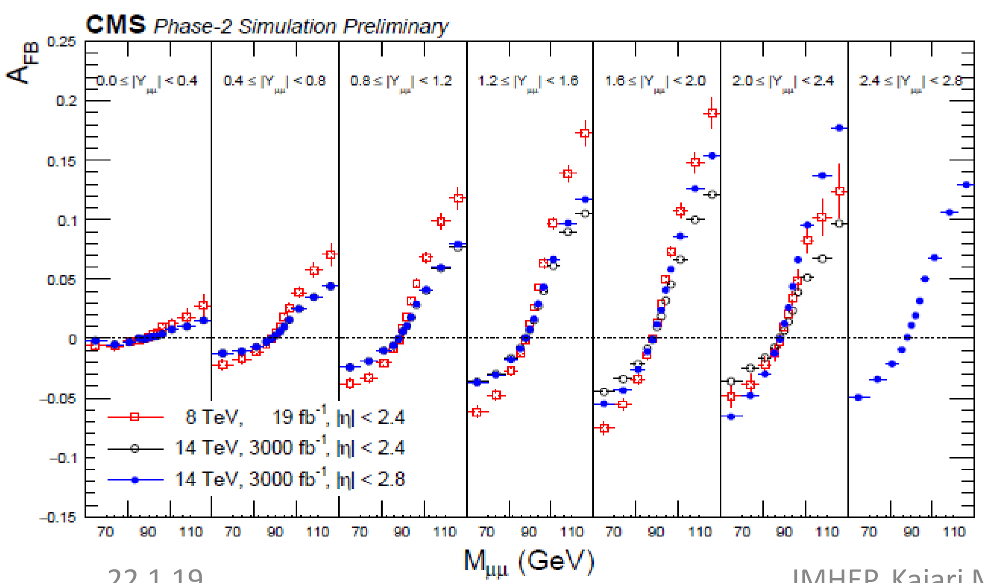
95% CL upper limit on effective coupling: better by order of magnitude compared to current limits

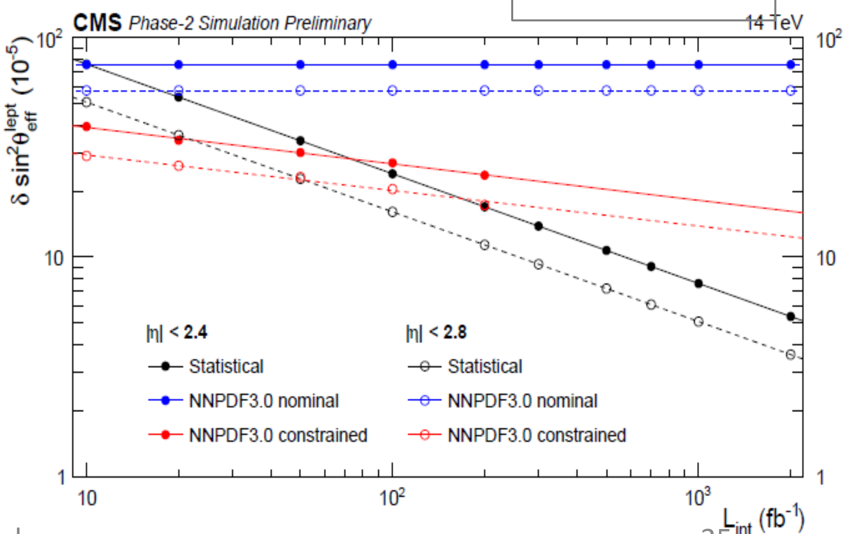
$$\boxed{|\kappa_{tcg}|/\Lambda < 5.2 \times 10^{-3}\ (9.1 \times 10^{-3})\ \mathrm{TeV}^{-1}}$$

Forward backward asymmetry in dilepton events

- Asymmetry arises due to vector and axial vector couplings of leptons to weak, neutral gauge boson $A_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}$ $\cos\theta^* = \frac{2(p_1^+ p_2^- - p_1^- p_2^+)}{\sqrt{M^2(M^2 + P_{\mathrm{T}}^2)}} \times \frac{P_z}{|P_z|}$
- angle ϑ^* measured in Collins-Soper frame, defined in terms of lab kinematics.
- Effective weak mixing angle sensitive to additional gauge boson Z'
  → mass & rapidity dependence of A_{FB} used to extract $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$
- Accurate measurement of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ can be used to constrain PDFs

CMS FTR-17-001





Conclusion

- Standard Model is marching confidently, withstanding all weathers.!

→ presented a small sample of interesting results from LHC experiments in the electroweak and top quark sectors.

- Particle physics has entered an era of uncertainty: with LHC machine operational since almost a decade.

→ it is not clear if Nature cares for *naturalness.*

- Luminosity drives our ability to measure low cross-section processes.

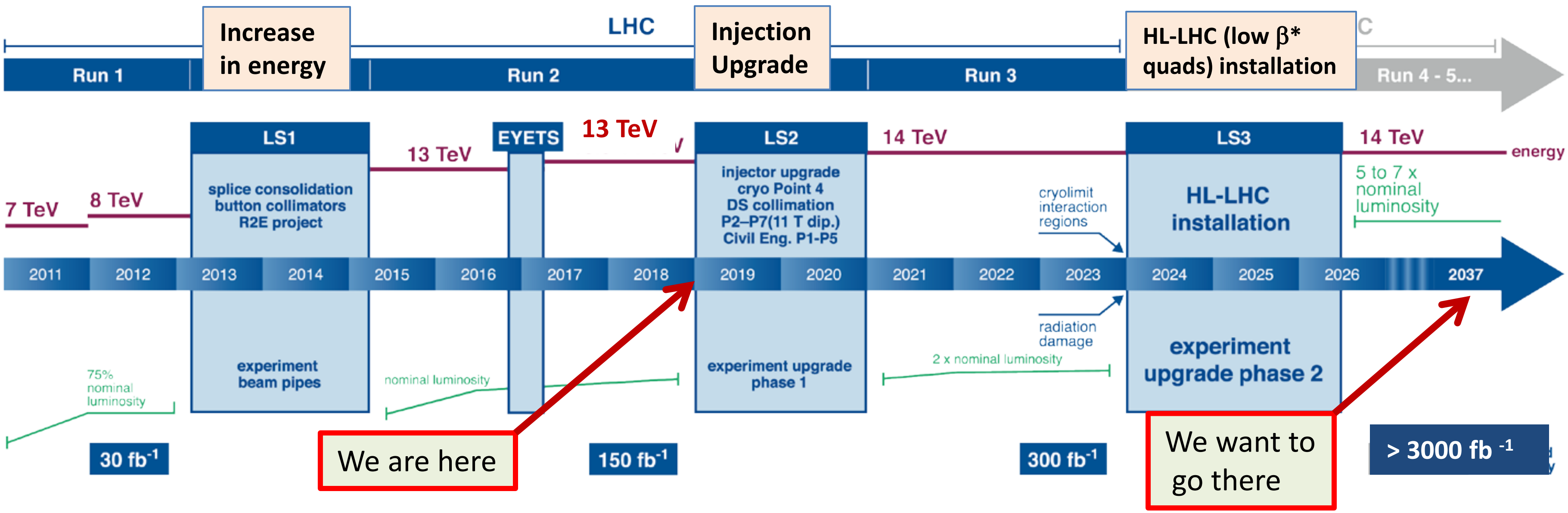
→ as LHC accumulates more data we must extensively search for deviations from predictions of Standard Model since production of new, heavy particles at the LHC in next few years is almost impossible.

- May be the Indian community gears up for what is realistically possible at the LHC?

Thank you!

Backup

Roadmap of the LHC



Run2 (2015 - 2018) : √s = 13 TeV
- Instantaneous luminosity: L ~ 2.2*10^{34}/cm^2/s
- Pile Up (PU) ~ 50 on average
- Integrated lumi: $\mathcal{L}$ ~ 160 /fb

Phase-1 upgrade of CMS: 2013-2020

Run3 (2021 - 2023) : √s = 14 TeV
- L = 2.5*10^{34}/cm^2/s , PU > 50
- $\mathcal{L}$ ~ 300 /fb by end 2023

Run4 (2026 – 203X): √s = 14 TeV

→ **More data!**

HL-LHC (2026 --): approved project
- L = (5 – 7.5)*10^{34}/cm^2 /s
- PU = 140 - 200
- $\mathcal{L}$ = 3000 - 5000 /fb in about 10 years
- Present detectors built 20 years back will not be able to handle the challenge of the machine

→ **Phase-2 upgrade of CMS during 2024-2026**

H/Z → J/ψ + γ

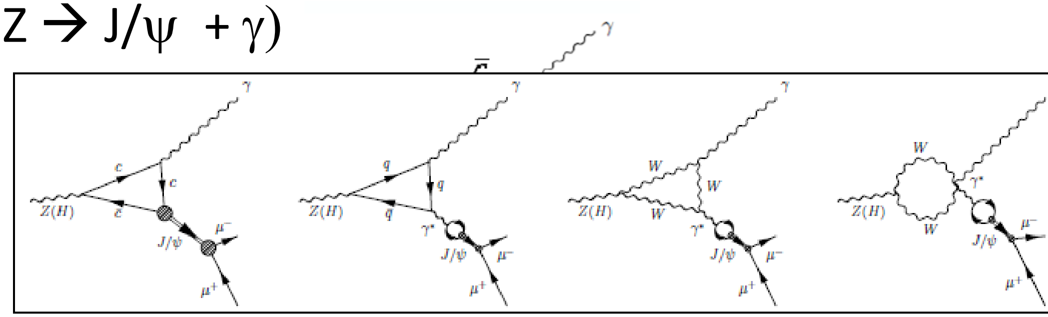
CMS SPM-17-012
arXiv: 1810.0046
EPJC

- Higgs coupling to 2nd generation fermion: test of nature of Yukawa coupling
- Can be probed via H→ J/ψ + γ → sensitive to BSM

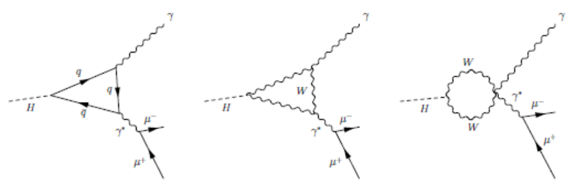
indirect process
Br = $3.25*10^{-6}$

Direct process
Br = $5.48*10^{-8}$

- Branching ratio for H larger than (Z → J/ψ + γ)
- But Z production: much higher



Dalitz decays of Higgs

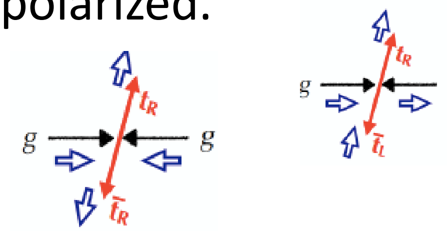


Channel	Polarization	σ (fb) at 95% CL	$\mathcal{B}$(Z (H) → J/$\psi\gamma$) at 95% CL	$\frac{\mathcal{B}(\mathrm{Z\ (H)} \to \mathrm{J}/\psi\gamma)}{\mathcal{B}_{\mathrm{SM}}(\mathrm{Z\ (H)} \to \mathrm{J}/\psi\gamma)}$
	Unpolarized	$4.6\ (5.3^{+2.3}_{-1.6})$	$1.4\ (1.6^{+0.7}_{-0.5}) \times 10^{-6}$	15 (18)
$\mathrm{Z} \to \mathrm{J}/\psi\gamma$	Transverse	$5.0\ (5.9^{+2.5}_{-1.7})$	$1.5\ (1.7^{+0.7}_{-0.5}) \times 10^{-6}$	16 (19)
	Longitudinal	$3.9\ (4.6^{+2.0}_{-1.4})$	$1.2\ (1.4^{+0.6}_{-0.4}) \times 10^{-6}$	13 (15)
$\mathrm{H} \to \mathrm{J}/\psi\gamma$	Transverse	$2.5\ (1.7^{+0.8}_{-0.5})$	$7.6\ (5.2^{+2.4}_{-1.6}) \times 10^{-4}$	260 (170)

Spin density matrix in ttbar events

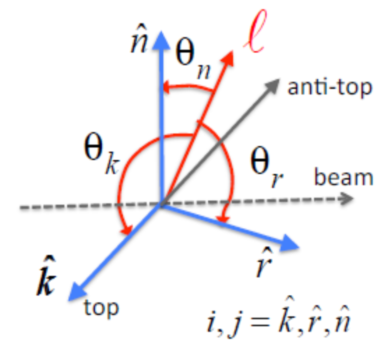
CMS TOP-18-006

ttbar production rate depends on Spin correlations and top polariztion
Due to parity invariance of QCD tops are produced mainly unpolarized.
➔ Spins of top-pairs are strongly correlated, depends on m_{tt}
➔ Low m m_{tt} : RR/LL helicity pairs dominate
➔ High m_{tt} : RL/LR helicity pairs dominate



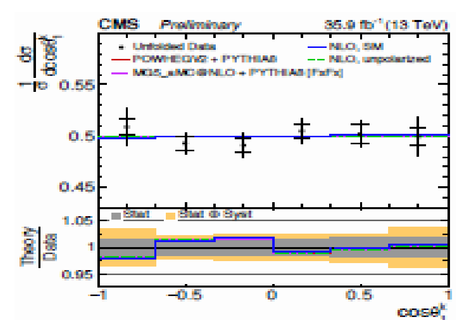
Measure multiple differential distributions to constrain BSM

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^i_+ d\cos\theta^j_-} = \frac{1}{2}(1 + B^i_+\cos\theta^i_+ + B^j_-\cos\theta^j_- - C_{ij}\cos\theta^i_+ d\cos\theta^j_-)$$



Can be reduced to single differential eqns. In terms of polarization coeff., s (B) diagonal and off-diagonal elements of spin-density matr
Differential cross section analysis with dilepton angular distribution

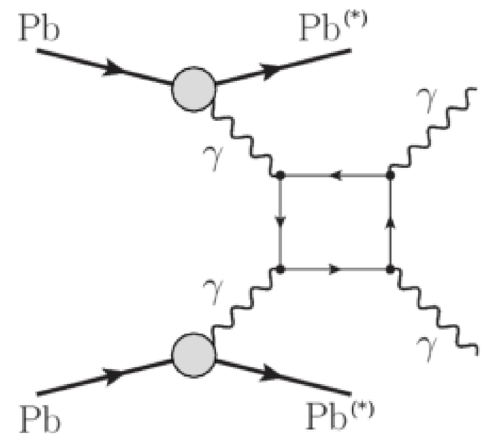
Flat angular distribution ➔ unpolarized tops
Consistent with NLO SM predictions

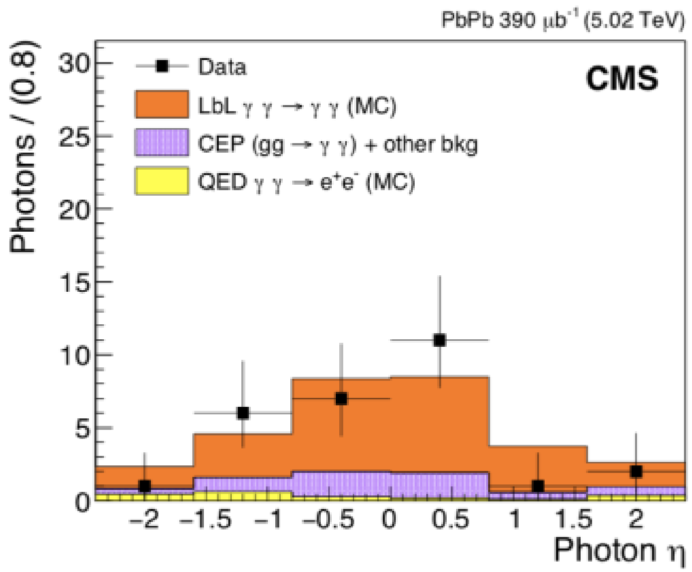


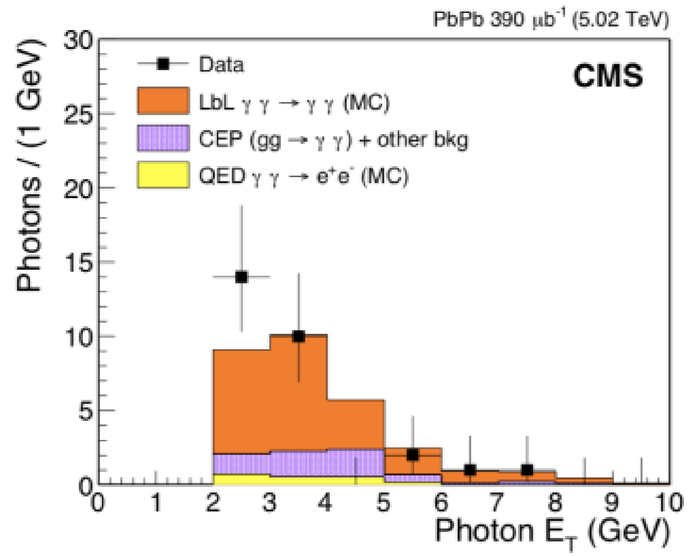
Light-by-light Scattering

- Select ultra-peripheral collisions in PbPb
- Exclusive 2-photon final state selection
- Small acoplanarity (< 0.01)
- Small diphoton p_T (< 1 GeV)
- 14 events found, 3.8 background events est.
- Similar to ATLAS result: arXiv:1702.01625

arXiv:1810.04602







$\sigma_{\text{fid}}(\gamma\gamma \to \gamma\gamma) = 120 \pm 46\,(\text{stat}) \pm 28\,(\text{syst}) \pm 4\,(\text{theo})\,\text{nb}$ TH $\sigma_{\text{fid}}(\gamma\gamma \to \gamma\gamma) = 138 \pm 14\,\text{nb}.$