Top quark Physics

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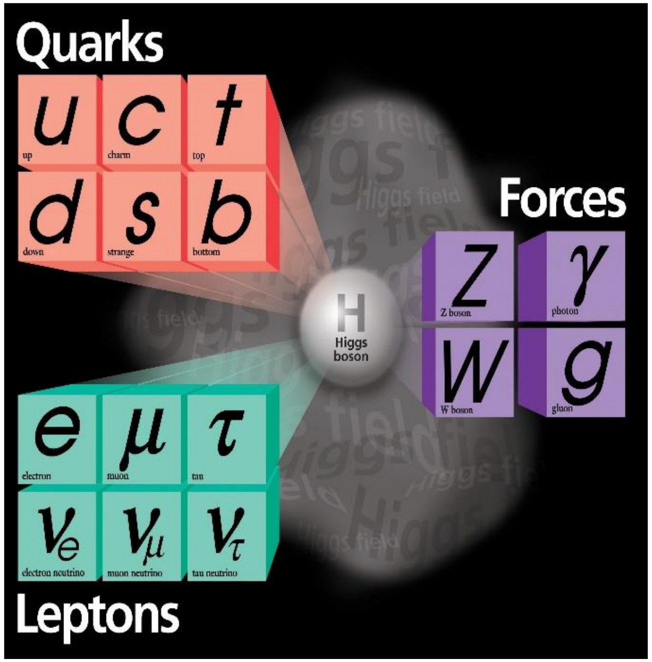
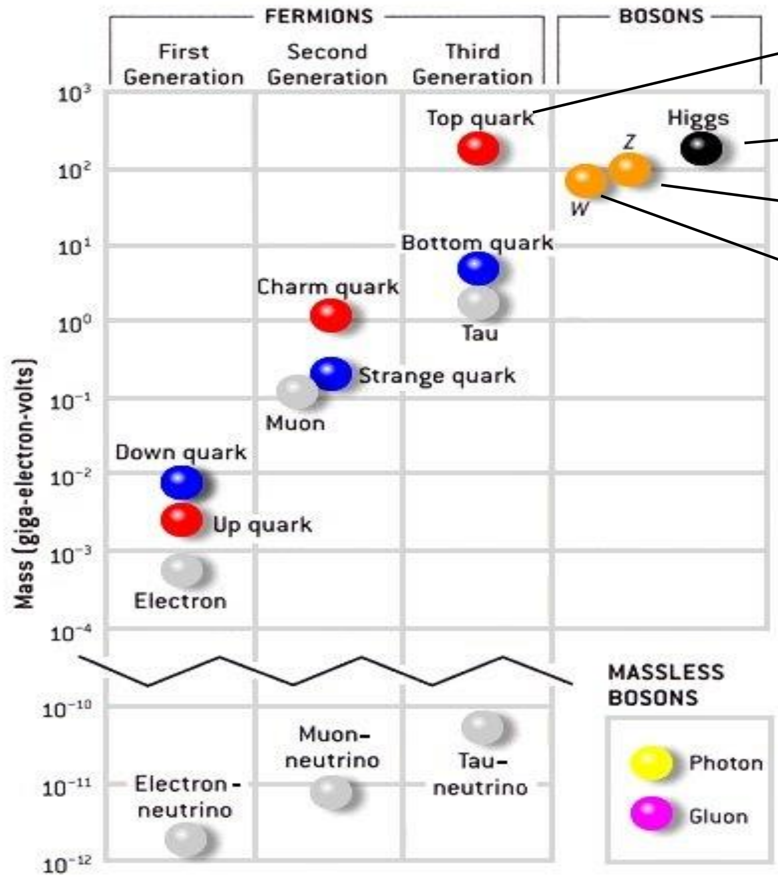
The Standard Model

- ✓ Amazing amount of experimental and theoretical work over 100 yrs
- ✓ Mathematical description of the fundamental building blocks:
  Matter (quarks, leptons)
  Forces (gauge bosons)
- ✓ Very accurate predictions for many experimental setups we can think of
- ✓ Development “guided” by the idea of unifying forces, ultimately one force, e.g. electroweak unification



Top Quark - a Special Fundamental Particle

✓ Top is the heaviest fundamental particle discovered so far



173GeV

125GeV

91GeV

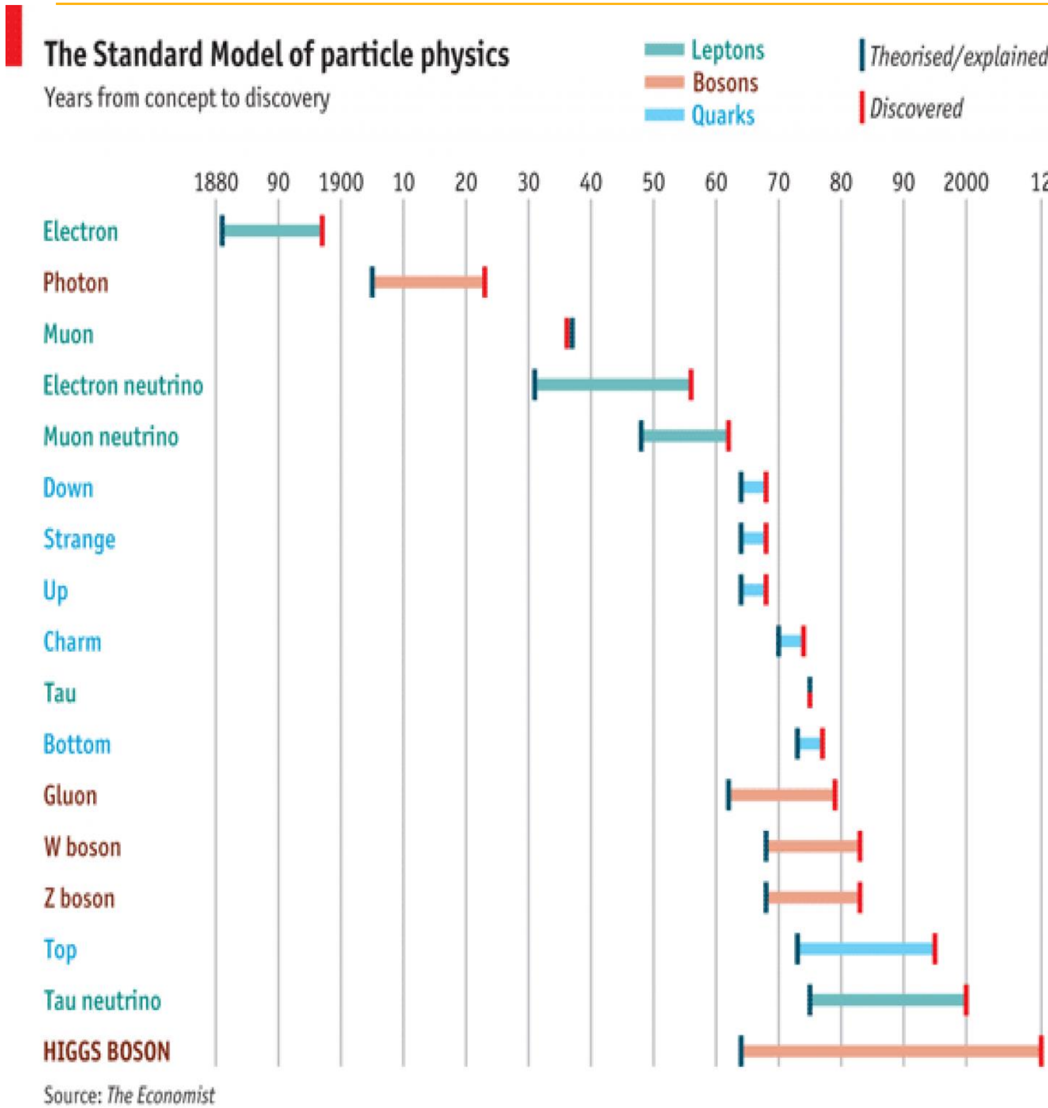
80GeV

✓ Unique short lived quark:
It decays before hadronization

$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production} \\ 10^{-27}\ \mathrm{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime} \\ 10^{-25}\ \mathrm{s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization} \\ 10^{-24}\ \mathrm{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip} \\ 10^{-21}\ \mathrm{s}}}$$

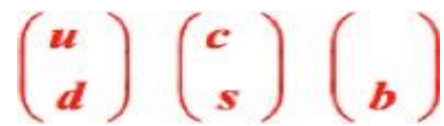
✓ Large Yukawa coupling to Higgs boson
→ λ_t **~ 1 only** m_t **is natural mass**
Special role in EW symmetry breaking ?

From Theorised to Discovered



- 1973, Kobayashi (小林诚) and Maskawa (益川敏英) Predicted the existence of a 3rd generation of quarks
- Explain observed CP violation in kaon decay (2008 NP in phyiscs)

1977, the bottom quark was discovered



If the SM is correct
There should be the top quark

udscb
Discovered within 5 years

top quark was expected to be discovered soon

The Charm and Bottom quark:

	mass	discovery
Charm quark	~1.5GeV	J/ψ-> $c\bar{c}$
Bottom quark	~5.0GeV	ϒ->$b\bar{b}$
	b/c = ~3	**Bound state**

3, 15, 35, 63, ____

- ○ 101
- ○ 121
- ○ 99
- ○ 98

找规律填数。

10,14,22,38,70,134,262,(　　)。

Two suggestions (Naive thoughts) :

1. The top quark might be about three times as heavy as the b quark **~15GeV**
2. Expected a bound ttbar state, with a mass of around **30 GeV**.

The race began!

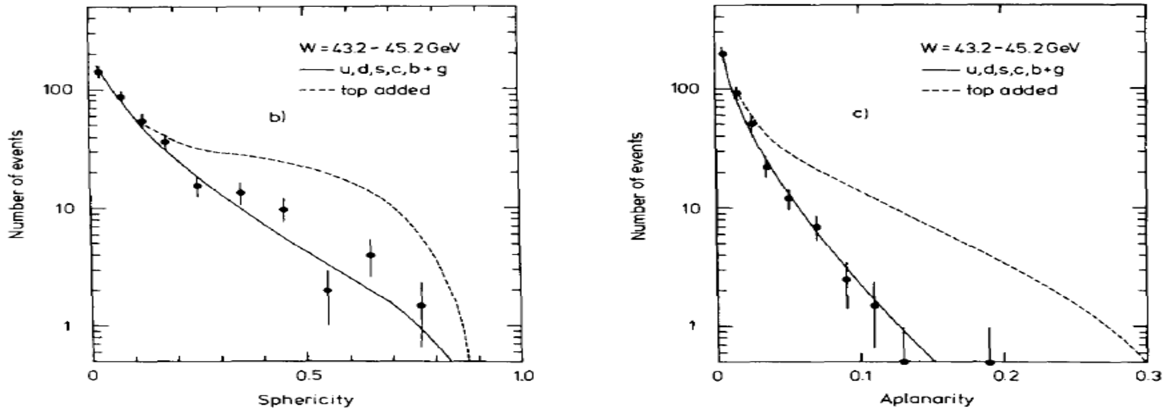
Searches in e^+e^- collider I

✓ PETRA (DESY in Germany), late of 1970's

1. Bound ttbar state were produced → narrow resonance
2. Without forming a bound state → Higher rate of producing hadrons

$$R \equiv \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = 3\sum_f Q_f^2$$

3. If top quarks decay, the angular distribution of decay products is more spherical than that of light quarks



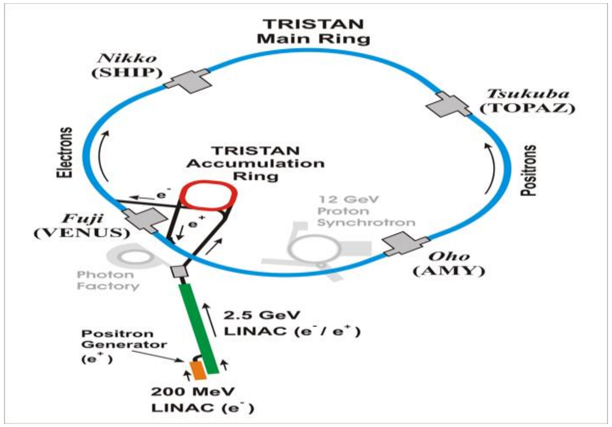
The absence of such signatures => top mass > 23 GeV

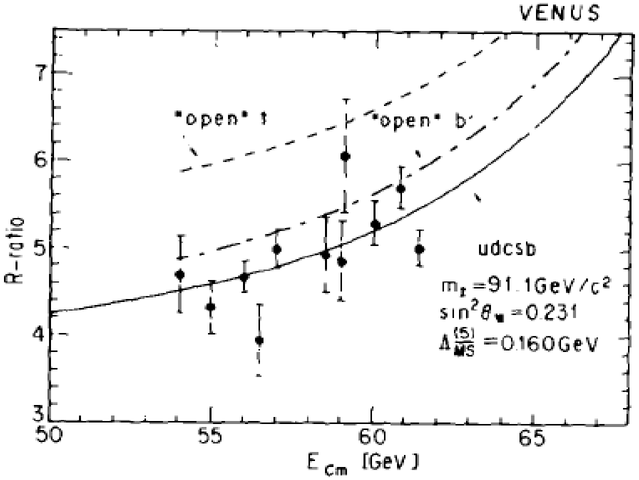
Searches in e^+e^- collider II

✓ TRSTAN (KEK in Japan), early of 1980's

-- Built to study the top quark

-- Similar techniques employed at PETRA





□ Negative results => top mass > 30 GeV

Japan's particle collider bites the dust

10 March 1990

By Michael Cross

THE FLAGSHIP of Japanese science, a particle collider known as TRISTAN,

1981:开始建造,
1986: 建成(30 GeV e+e-)
1990: 改造为同步辐射加速器

Searches in e^+e^- collider III

1989 -- 1990

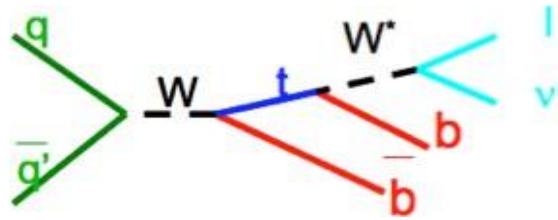
- ✓ SLC : Stanford Linear Collider at SLAC in US
- ✓ LEP : Large electron-position collider at CERN in Europe
  - searched for Z -> t t
  - negative results => top mass > 45 GeV
- ✓ In the SM various Electroweak observables depend on the mass of the top quark

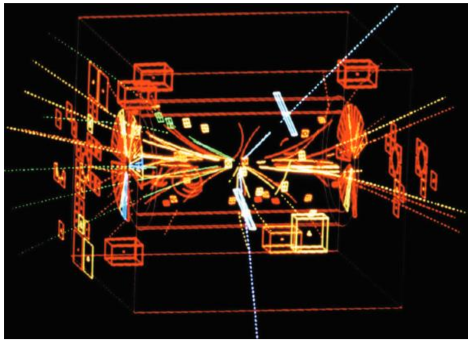
  - Precision measurement of the Z decay
  - top mass < 200-220 GeV
- ✓ Attention turned to hadron colliders --> reach a higher energy

Searches in Hadron Collider I

✓ SppS: super proton-antiproton synchrotron
✓ CERN, √s =540 GeV, built to observe W,Z

☐ Searched for e + ≥ 2 jets or μ + ≥ 2 jets





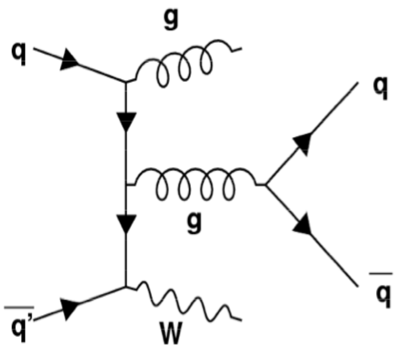
Z candidate event

- By 1985, 12 events were observed at UA1
- Expected background 1.6 events
- Expected signal 10 events (Mtop = 40 GeV)
- Concluded that it's consistent with a 30-50 GeV top quark.

Stopped before claiming discovery
=>W + jets background was underestimated

Searches in Hadron Collider II

- ✓ 1988, UA1 at $Sp\bar{p}S$
- ✓ larger data sample
- ✓ Improved understanding of the background
- ✓ Fake leptons, W+jets, DY, J/Y, bbar/ccbar



channel	observed	expected background
$\mu + \geq 2$ jets	10 events	11.5 ± 1.5 events
$e + \geq 1$ jets	26 events	23.4 ± 2.8 events

(+ 23 expected if M_{top} = 40 GeV)

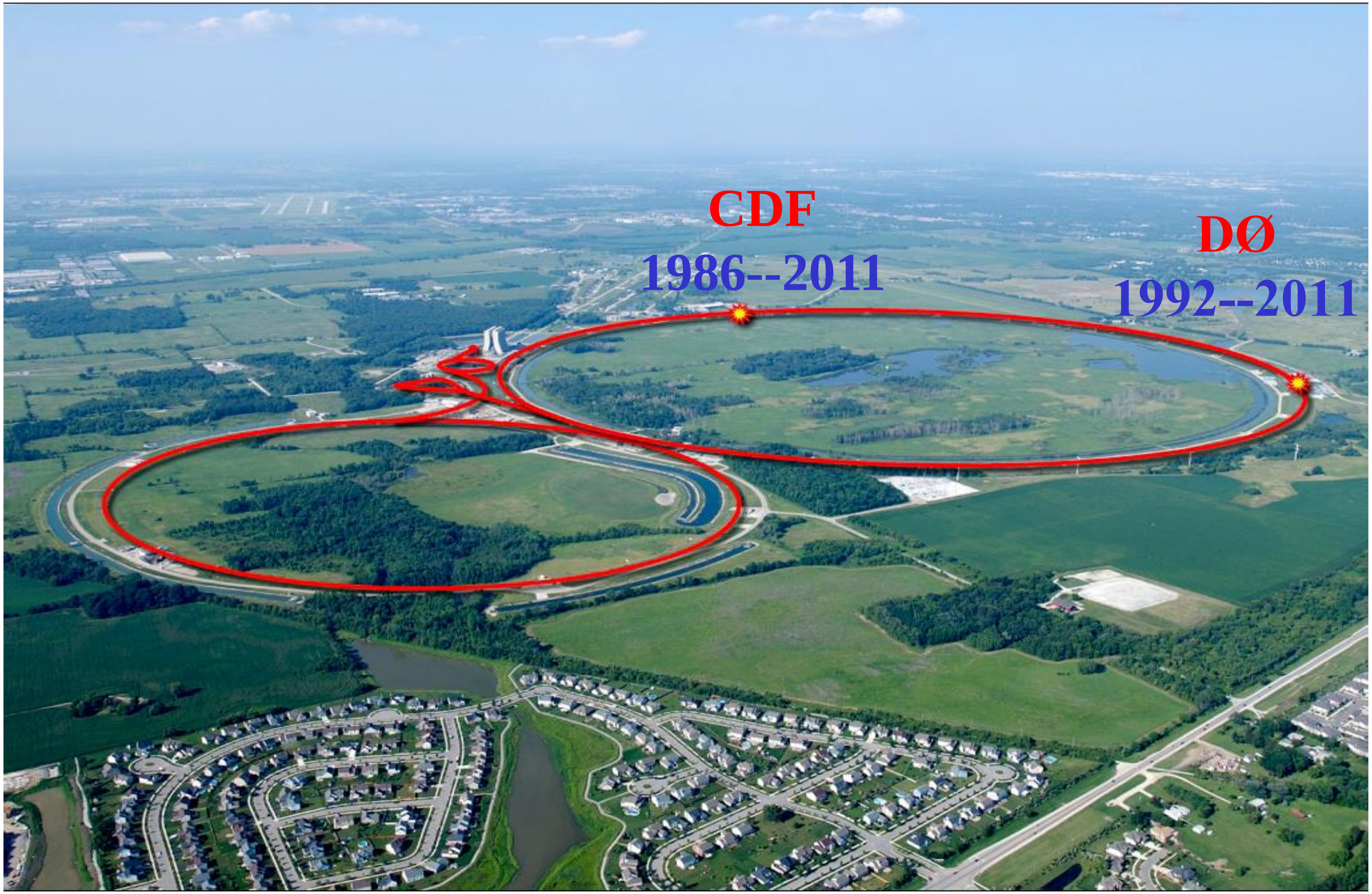
□ **Conclude Mtop > 44 GeV**

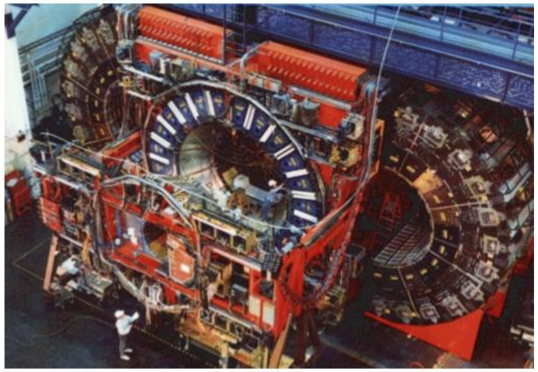
Tevatron (at Fermilab in US) joins the hunt

- ✓ 1988-89: at CERN, UA2 remains after the upgrades
- ✓ √1.8 TeV@Fermilab vs. √0.63 TeV@CERN

Tevatron

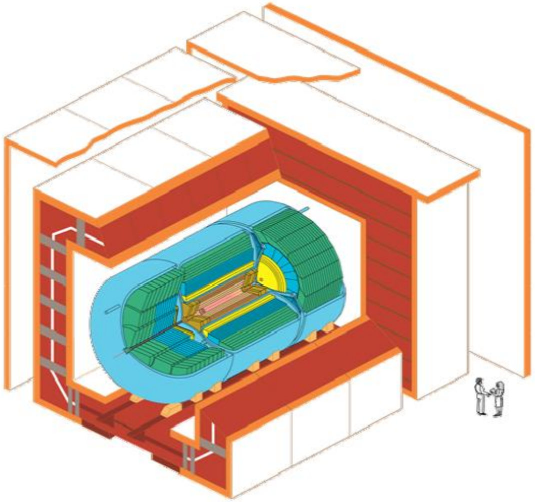
Proton-antiproton collision at 1.8-2.0 TeV





CDF

1976 开始研发
1981 完成设计
1982 开始建造
1986 开始取数

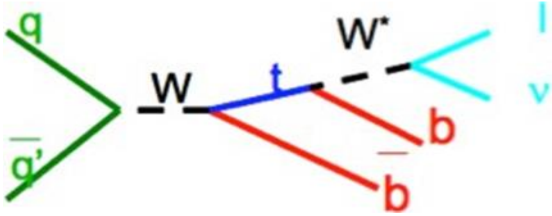


D0

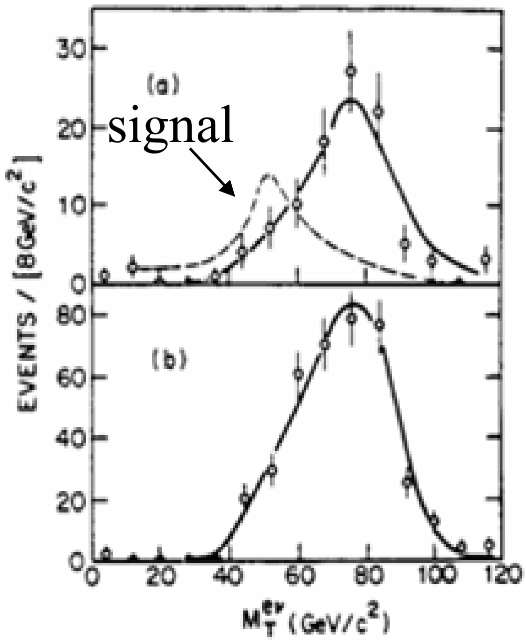
1981 提议实验
1984 完成设计
1991 建造完成
1992 开始取数

Searches in Hadron Collider III

- **CDF**: Start from the hypothesis that Mtop = 40 - 80 GeV



✓ eν + ≥ 2 jets or e μ + ≥ 2 jets
✓ Dominant background: W (on-shell) + jets
✓ While in signal W is off-shell
✓ Discriminant: eν transverse mass
✓ In 1991, Conclude Mtop > 77 GeV



- **UA2@SppS**: uses similar technique as CDF

  ✓ In 1990, Conclude Mtop>69 GeV

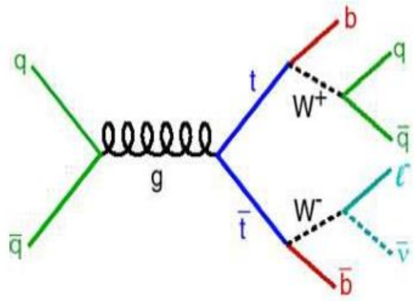
Searches at CDF

- Start to change the searching strategy

- ✓ Mtop > Mb + Mw
- ✓ W bosons in both background and signal are on-shell
- ✓ Not use MT (lv) as discriminant anymore, add b-tagging
- ✓ Search in dilepton channels and single lepton channels

– Dilepton: include ee, μμ, eμ (require missing ET, Z-veto)
– Single lepton: require low pT muon (semi-leptonic b-decays)

In 1992, Conclude Mtop > 91 GeV



Searches at CDF and D0

- ✓ **1992： D0 started data taking**
- ✓ Tevatron with higher luminosity during 1992--1995

D0 ：excellent calorimetry, large solid angle and coverage

CDF：precision vertex detector, good tracker, magnetic spectrometer

D0: optimized search for Mtop =100 GeV at run1A

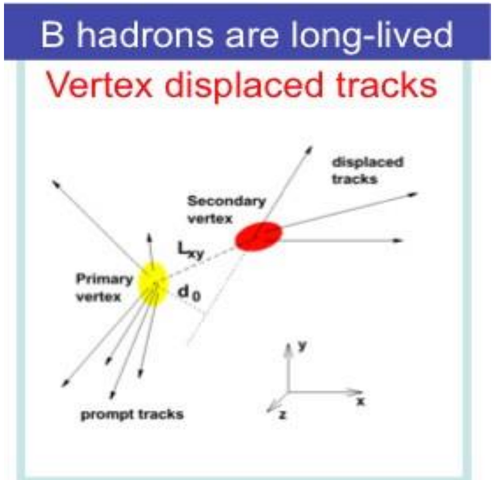
	evt	bkg
– $e\mu+\geq1$jet+MET	1	1.1
– $ee+\geq1$jet+MET	1	0.5
– $e+\geq4$jets+MET	1	2.7
– $\mu+\geq4$jets+MET	0	1.6

⇒ Mtop>131 GeV

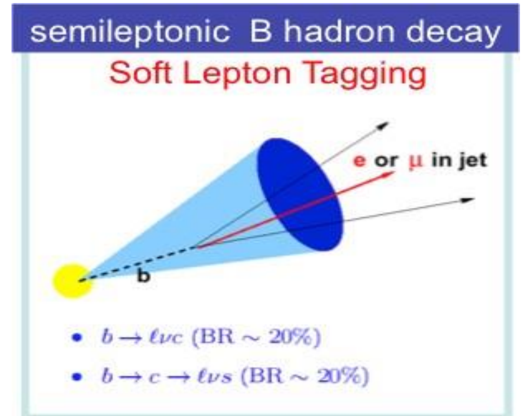
Searches in Hadron Collider IV

✓ Two b-tagging methods

- Top events contain B hadrons
- Few W+jets events contain heavy flavor



more complicated, high efficient (efficiency ~60%)



more simpler, less efficient (efficiency ~15%)

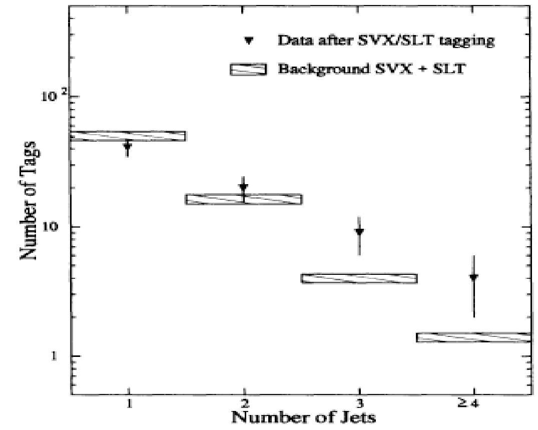
✓ In 1993, report **excess of events**, but not significant (2.8 sigma)

Type	observed	background
DIL	2 events	$0.56^{+0.25}_{-0.13}$
SVX	6 tags	2.3 ± 0.3
SLT	7 tags	3.1 ± 0.3
total	12 events	---

3 common events

First Evidence (1994)

- CDF: an excess of events with 2.8sigma
  - ✓ Skepticism, additional studies, cross-checks
  - ✓ Additional 8 months before publication
- D0: no independent evidence
  - ✓ Added more data and re-optimized
  - ✓ Observed 7 events (expect 4-6 from bkg)



VOLUME 73, NUMBER 2 PHYSICAL REVIEW LETTERS 11 JULY 1994

Evidence for Top Quark Production in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

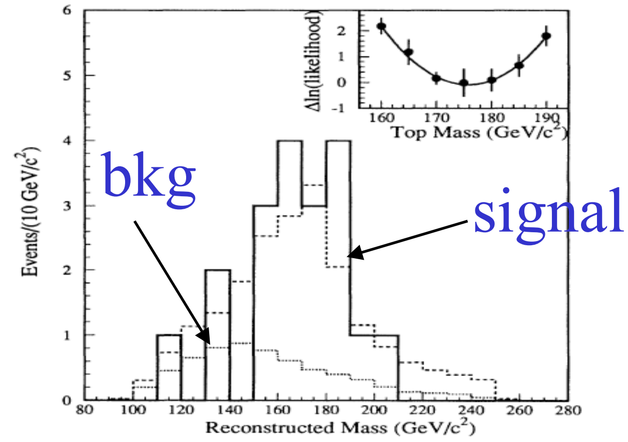
We summarize a search for the top quark with the Collider Detector at Fermilab (CDF) in a sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV with an integrated luminosity of 19.3 pb^{-1}. We find 12 events consistent with either two W bosons, or a W boson and at least one b jet. The probability that the measured yield is consistent with the background is 0.26%. Though the statistics are too limited to establish firmly the existence of the top quark, a natural interpretation of the excess is that it is due to $t\bar{t}$ production. Under this assumption, constrained fits to individual events yield a top quark mass of $174 \pm 10^{+13}_{-12}$ GeV/c^2. The $t\bar{t}$ production cross section is measured to be $13.9^{+6.1}_{-4.8}$ pb.

First Observation (1995)

CDF: **4.8σ** by using 67/pb data

Channel:	SVX	SLT	Dilepton
observed	27 tags	23 tags	6 events
expected background	6.7 ± 2.1	15.4 ± 2.0	1.3 ± 0.3
background probability	2×10^{-5}	6×10^{-2}	3×10^{-3}

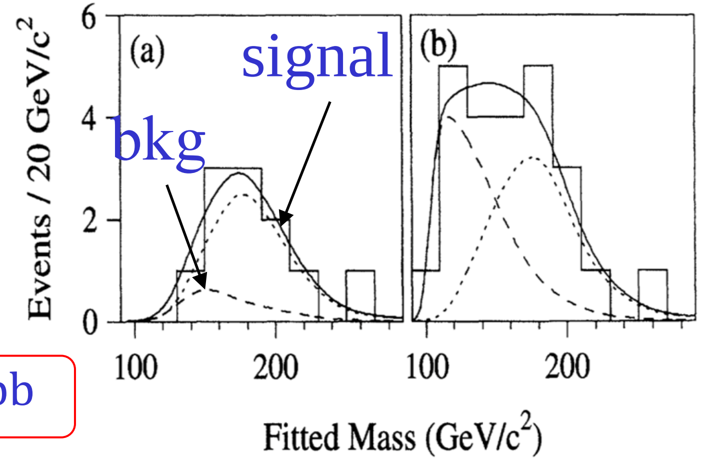
$M_t = 176 \pm 8 \pm 10$ GeV $\quad \sigma_{t\bar{t}} = 6.8^{+3.6}_{-2.4}$ pb



D0: **4.6σ** by using 50/pb data

- ✓ Dilepton/single lepton (mu b-tagging)
- ✓ Observed： 17
- ✓ Expected background: 3.8±0.6

$M_t = 199^{+19}_{-21} \pm 22$ GeV $\quad \sigma_{t\bar{t}} = 6.4 \pm 2.2$ pb

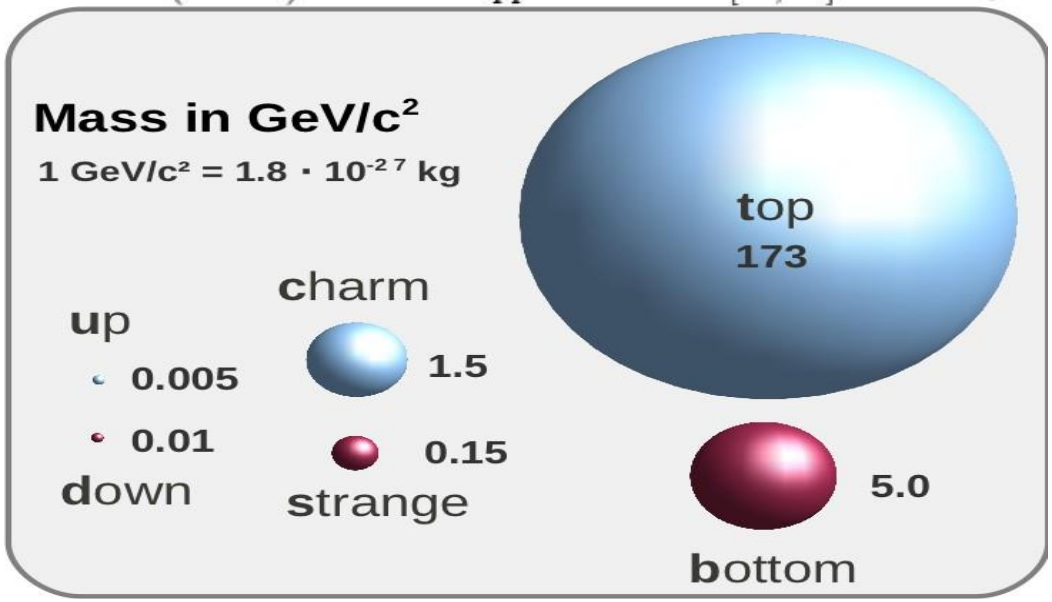


CDF and D0 papers submitted simultaneously

PRL 74(1995) 2626-2631 PRL 74(1995) 2632-2637

Milestones of Top Quark Discovery

Year	Collider	Particles	References	Limit on m_t
1979–84	PETRA (DESY)	e^+e^-	[50]–[63]	$> 23.3\ \mathrm{GeV}/c^2$
1987–90	TRISTAN (KEK)	e^+e^-	[64]–[68]	$> 30.2\ \mathrm{GeV}/c^2$
1989–90	SLC (SLAC), LEP (CERN)	e^+e^-	[69]–[72]	$> 45.8\ \mathrm{GeV}/c^2$
1984	$Sp\bar{p}S$ (CERN)	$p\bar{p}$	[75]	$> 45.0\ \mathrm{GeV}/c^2$
1990	$Sp\bar{p}S$ (CERN)	$p\bar{p}$	[76, 77]	$> 69\ \mathrm{GeV}/c^2$
1991	TEVATRON (FNAL)	$p\bar{p}$	[78]–[80]	$> 77\ \mathrm{GeV}/c^2$
1992	TEVATRON (FNAL)	$p\bar{p}$	[81, 82]	$> 91\ \mathrm{GeV}/c^2$
1994	TEVATRON (FNAL)	$p\bar{p}$	[84, 85]	$> 131\ \mathrm{GeV}/c^2$

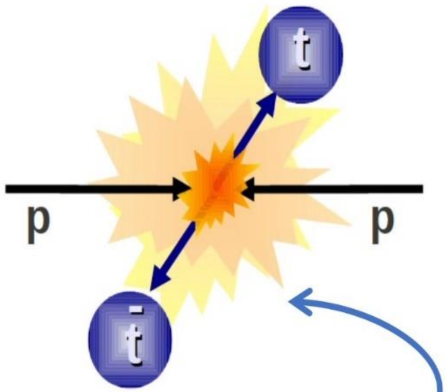


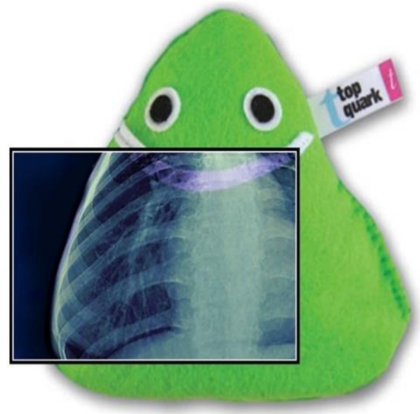
- ✓ It was not discovered until 1995
- ✓ Mainly due to its large mass ~173 proton mass.
- ✓ The heaviest fundamental particle discovered so far!

Things We Learn from Top Quark Discovery

- ✓ We need faith and patience.
  - Long journey from late of 1970's to 1995.
  - Nothing found --- narrow down searching range (set limit) --- wrong conclusions --- optimize --- evidence --- discovery --- cross check
- ✓ We need right machines.
  - High enough energy to produce such heavy particles.
  - High enough luminosity to produce enough events.
- ✓ We need right searching strategies.
  - Sensitive channels --- large signal and small background
  - Powerful discriminants between signal and background
  - Accurate estimates of background

What do we study for top quarks?



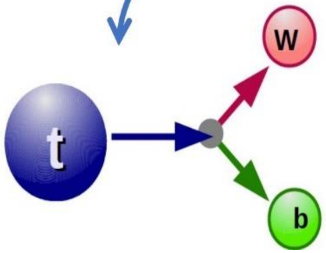


Intrinsic properties:

- Mass
- Charge
- Lifetime
- Width
- …

Production:

- Production rate
- Differential distributions
- New production mechanisms
- Single top-quark production
- Top-quark pair production
- Associated production of top quarks with *W, Z, γ, H, j, bb, tt, jj, γγ ...*
- ...

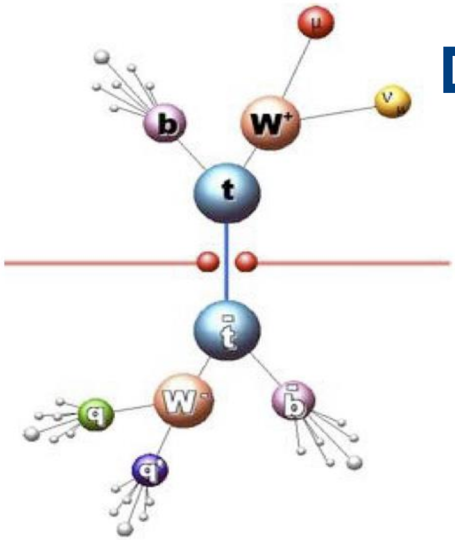


Decays:

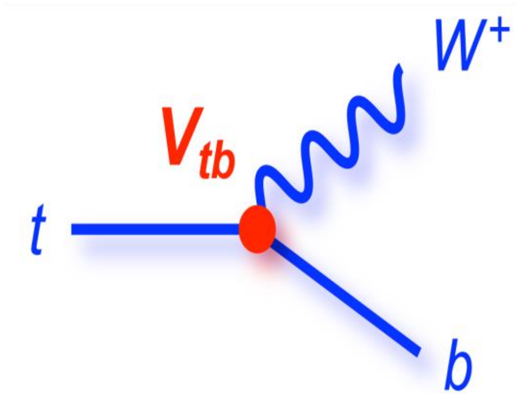
- Various decay channels
- SM & BSM
- Couplings *W, Z, γ & H*
- Spin correlations
- …

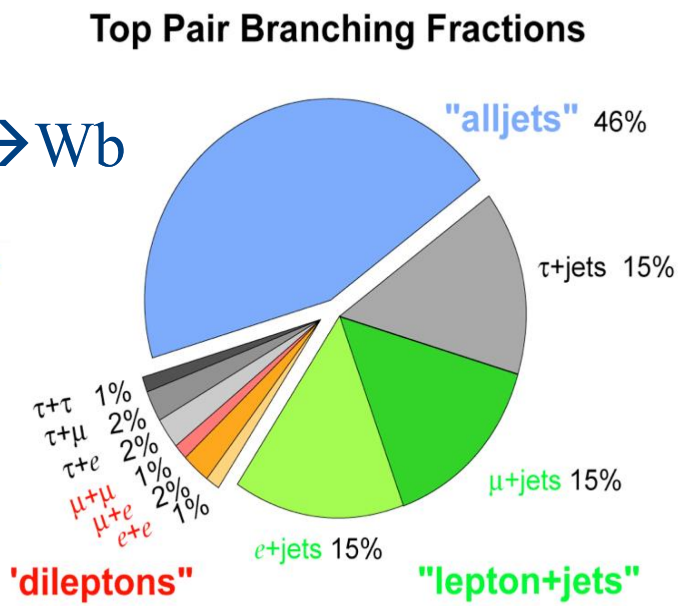
Production and Decays

- Top quarks (mostly) produced in pair

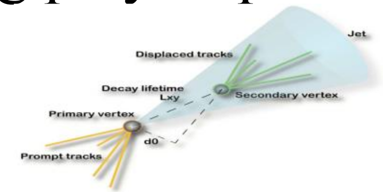


- Almost always t →Wb





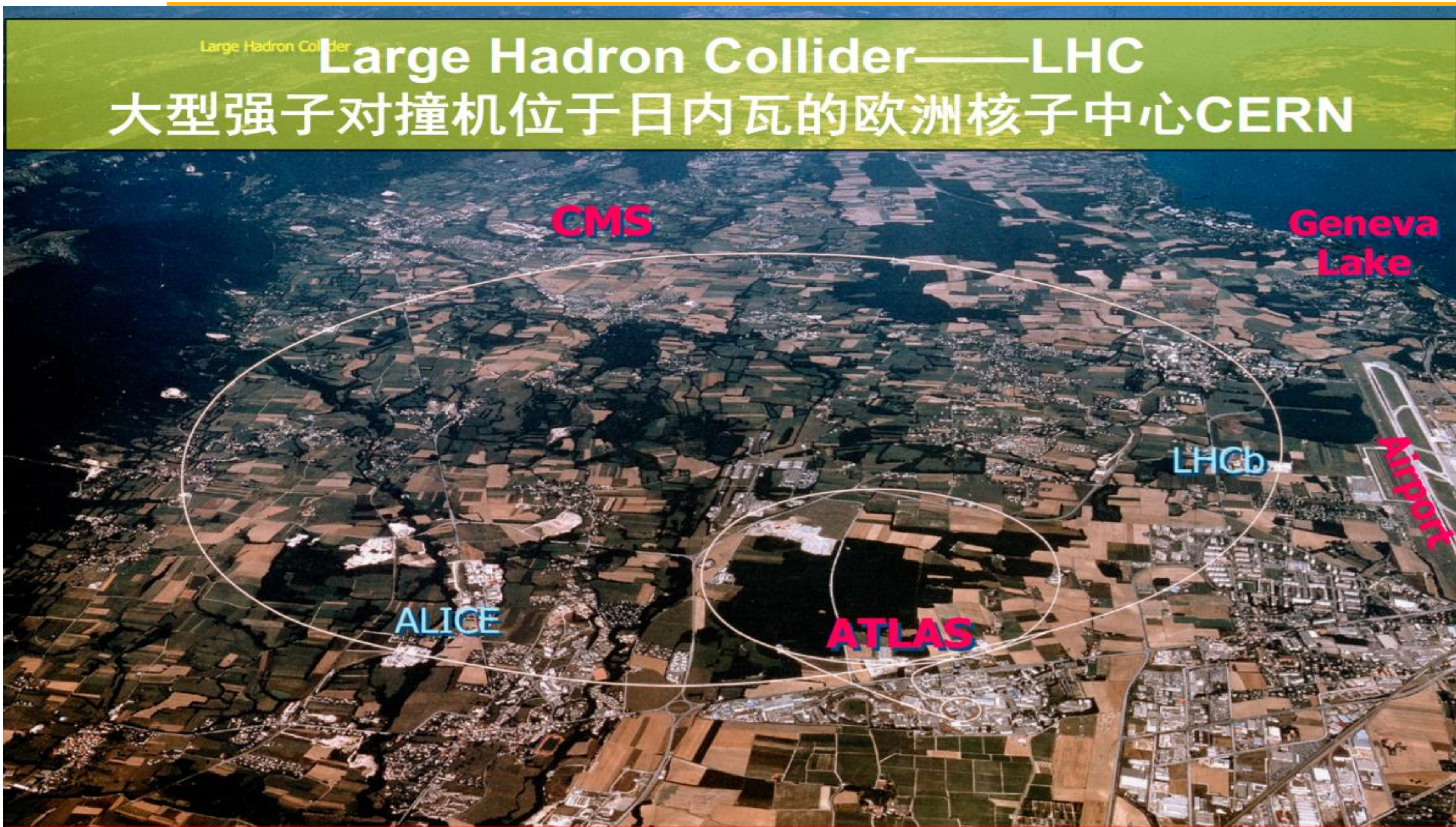
- ✓ Top pair final states depend on W decay
- ✓ b-jets always present
- ✓ b-tag play important role



- ✓ Dilepton (ee, μμ, eμ):
  - BR~5%, 2 leptons+2 b-jets+2 neutrinos
- ✓ Lepton (e or μ) + jets
  - BR~30%, one lepton+4jets (2 from b)+1 neutrino
- ✓ All hadronic
  - BR~44%, 6 jets (2 from b), no neutrinos

BR
Bkg

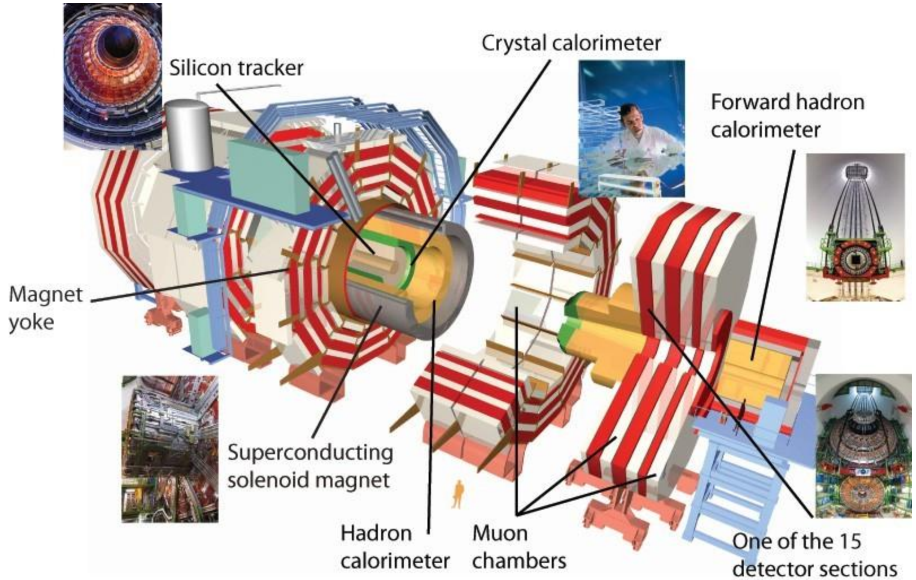
Where?



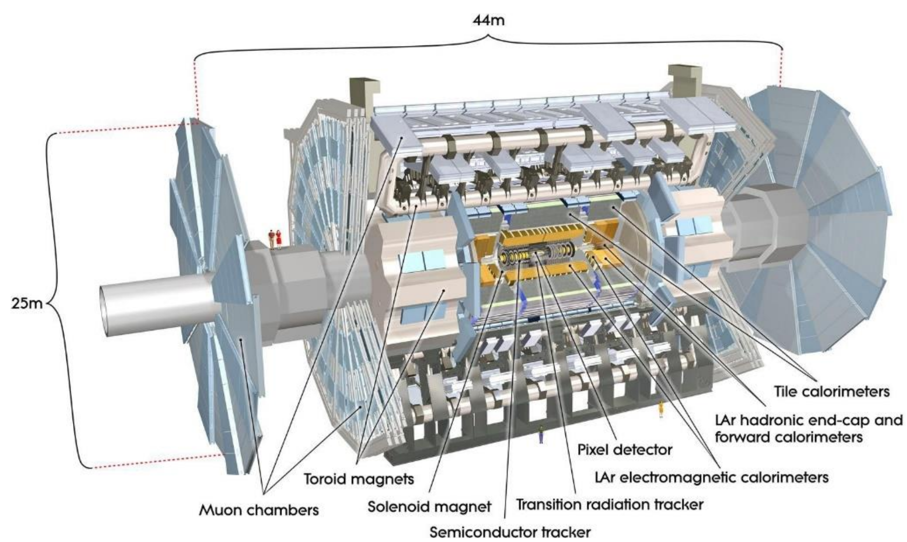
- 周长27公里，横跨瑞士-法国边境
- 世界上最大、能量最高的对撞机 —— 粒子物理研究的最前沿

How?

Weight: 14000t

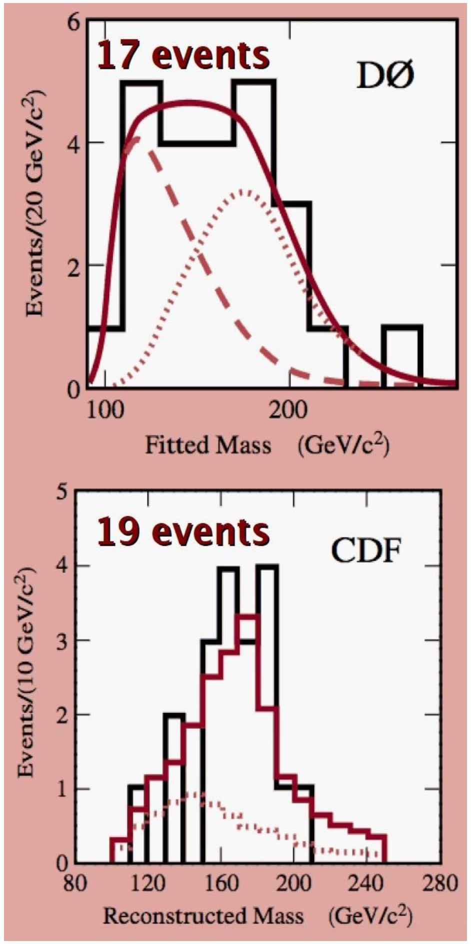


Weight: 7000t

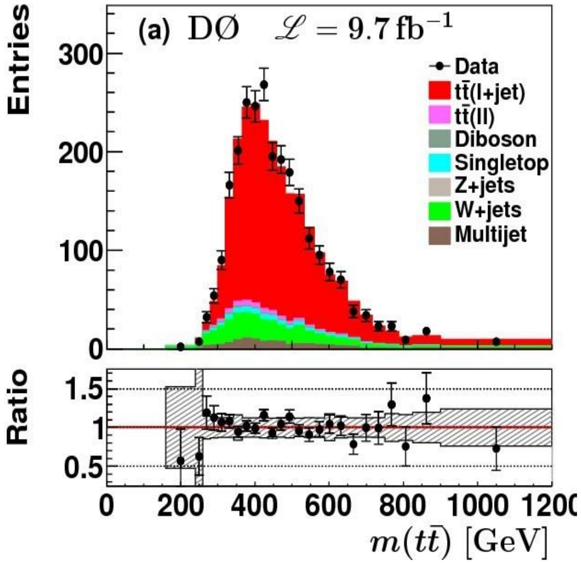


The past...

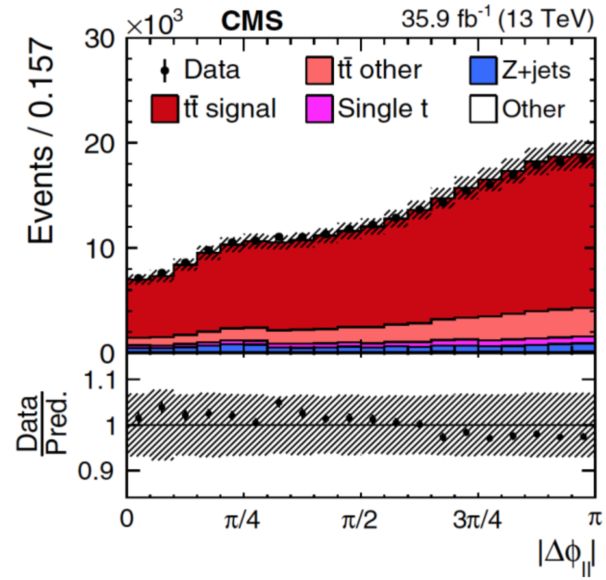
Tevatron: 1995



1000's events (Tevatron Run II)



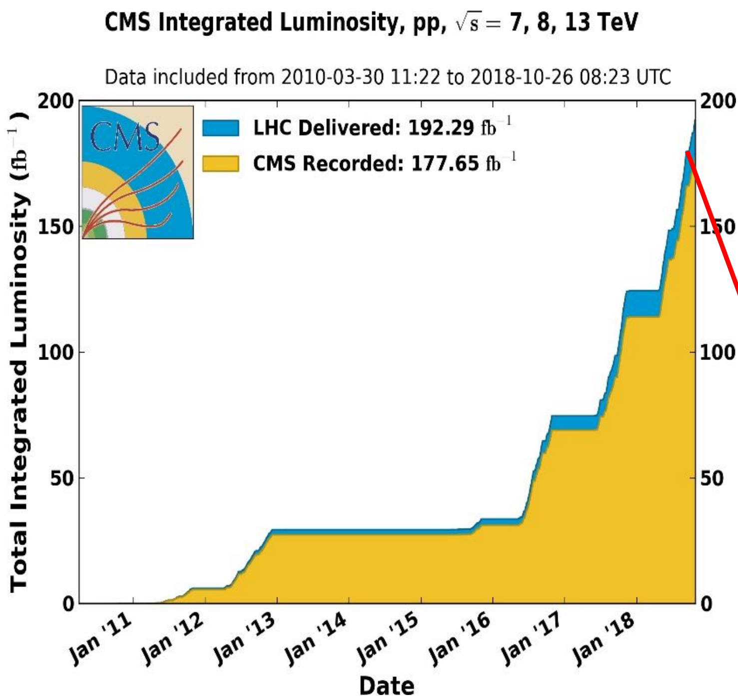
100,000's events (LHC Run 1 & 2)

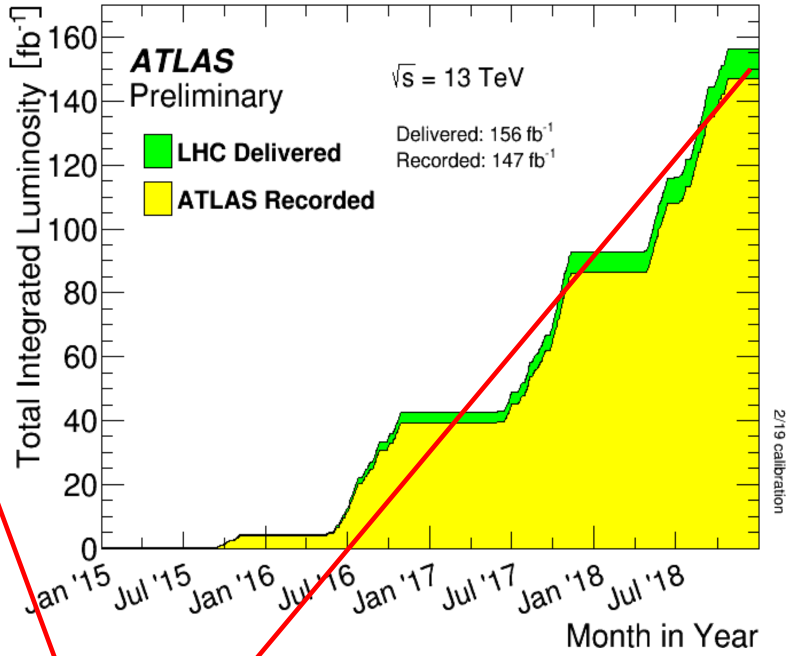


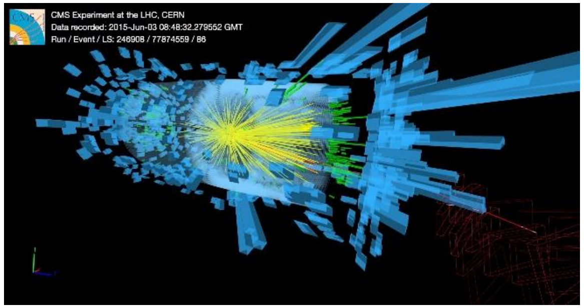
- ✓ Establish top quark SM
- ✓ First differential measurements
- ✓ Searches...

- ✓ non-SM ?
- ✓ Multi-differential precision measurements
- ✓ Searches...

The present...LHC Run II

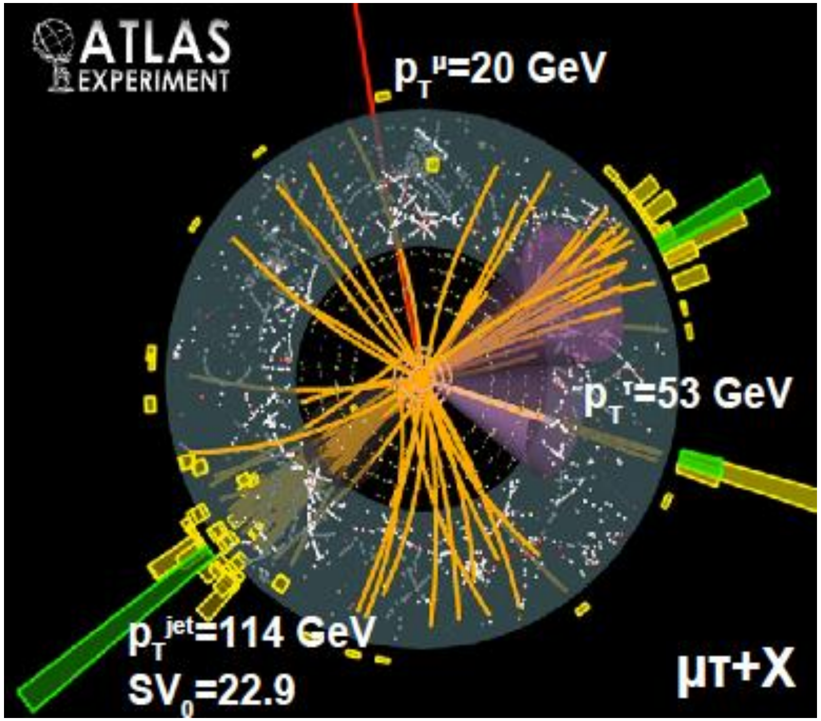


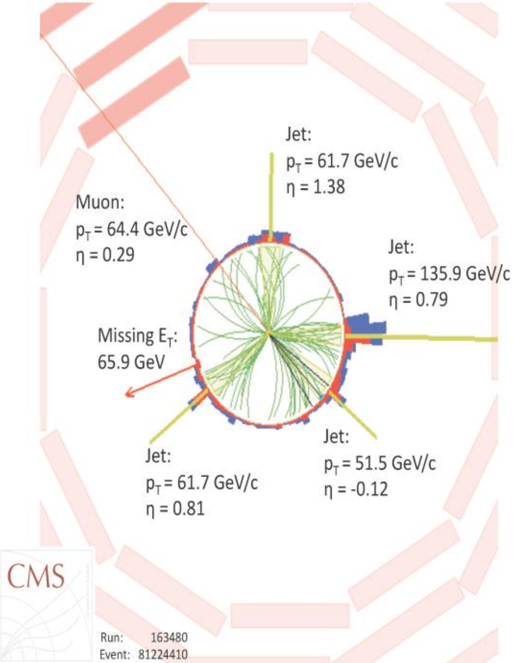




Full Run II provides about
~ 120M tt pairs
~ 30M single top
~ 120k ttZ, tZ
~ 30k ttH

Selection of top quark events





✓ Trigger:

– single or double (isolated) lepton

✓ Leptons:

– e/μ, p_T>20/30 GeV, |eta|<2.5

– Identification/reconstruction

– Tracker/calorimeter isolation

✓ Jets:

– at least 2 jets, p_T>30 GeV, |eta|<2.5

– anti-kT algorithm, with cone 0.4-0.5

– b-tagging is optional

✓ Missing transverse energy:

– Typically require 30-40 GeV

Cross section measurement

Number of observed events

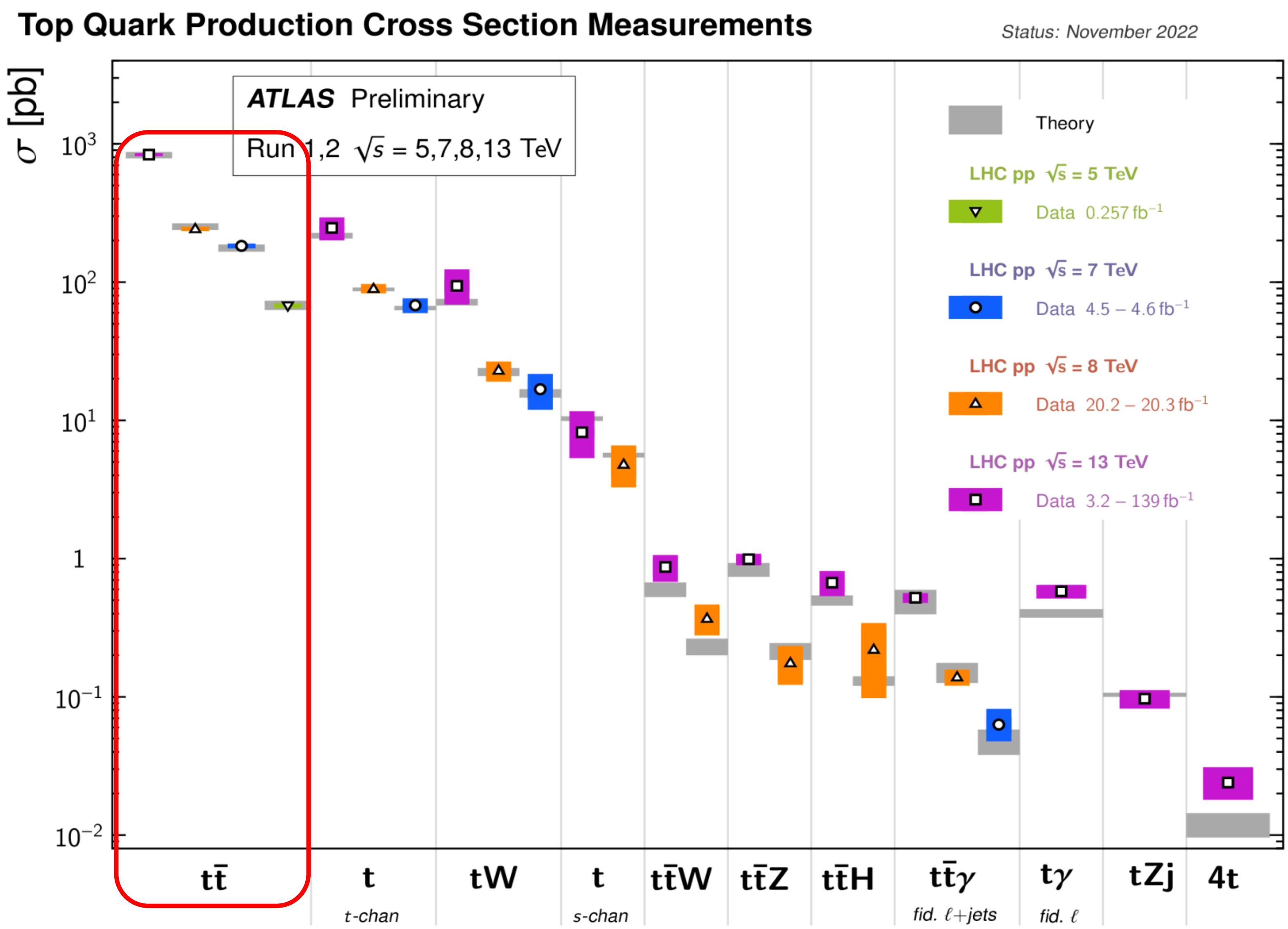
Number of background events (from data or from theory)

$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bgd}}{\varepsilon_{t\bar{t}} \cdot \int L dt}$$

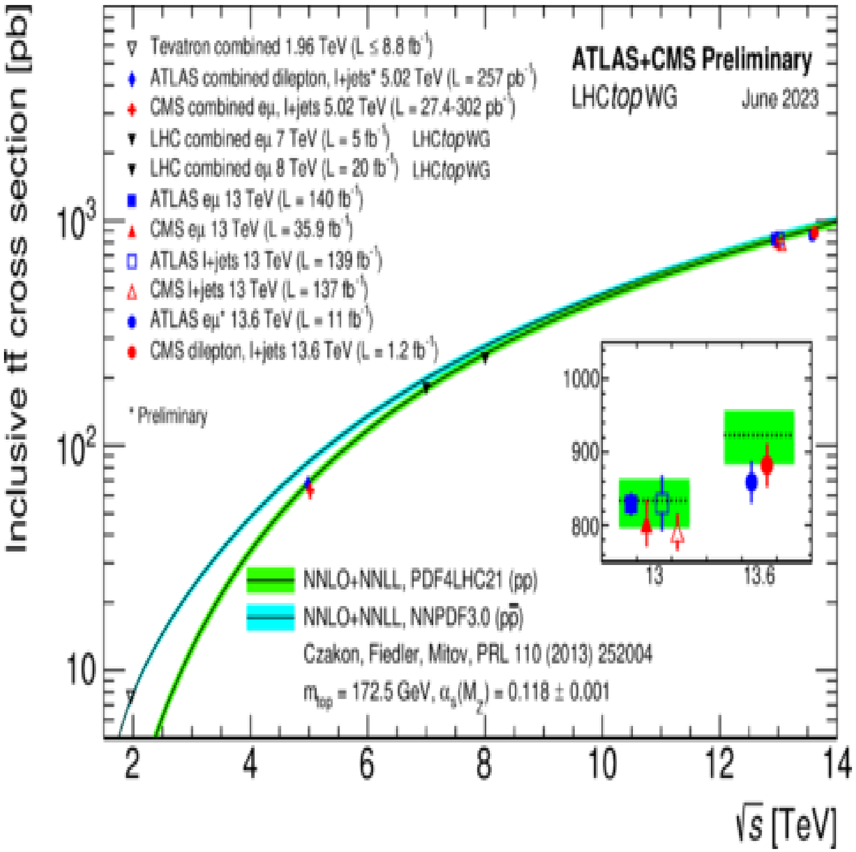
Efficiency (experimental: detector, efficiencies)

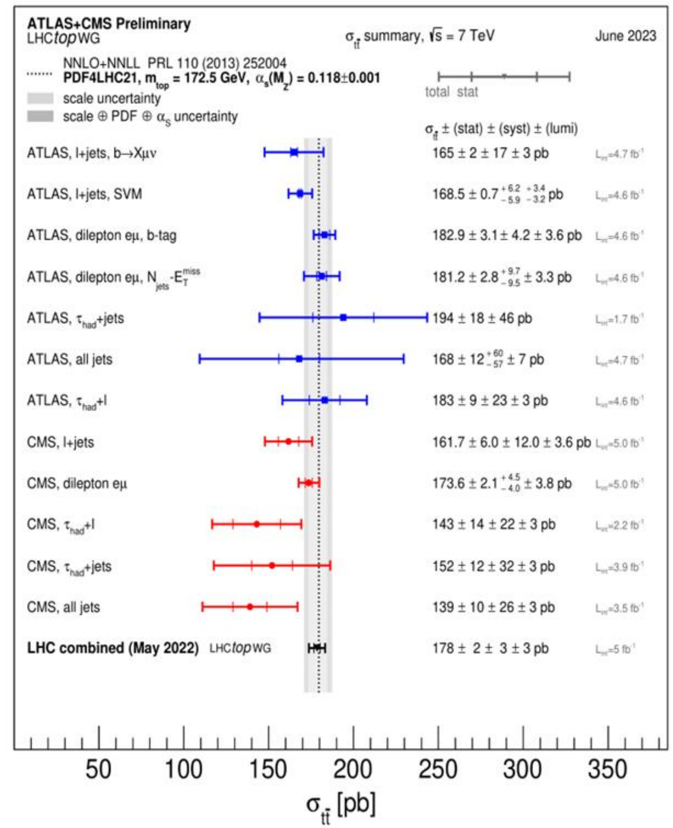
Luminosity (determined by amount of data, accelerator, triggers, etc)

Top pair production



Inclusive top pair cross sections



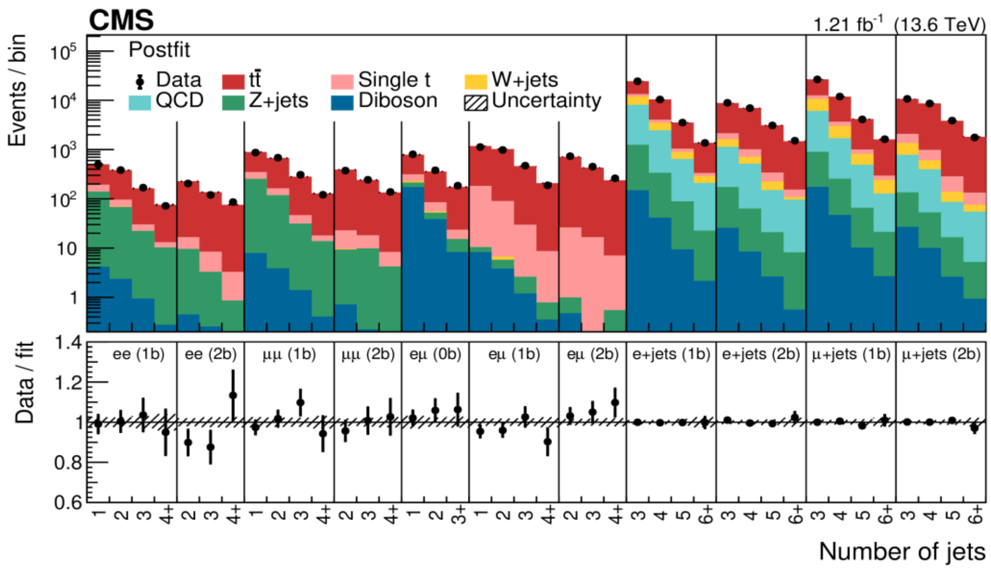


- ✓ Measured in all channels (0/1/2L)
- ✓ Measured at all energies (2, 5, 7, 8, 13, 13.6TeV)
- ✓ Agreement with SM at unprecedented precision

First look at LHC run-3 data!

✓Very first measurements of **inclusive ttbar cross section at 13.6 TeV** by CMS:.

- ML fit to bins in # of leptons / lepton flavors / # of (b-)jets
- In-situ calibrations of lepton, JES, b-tag efficiencies.



Source	Uncertainty (%)
Lepton ID efficiencies	1.6
Trigger efficiency	0.3
JES	0.7
b tagging efficiency	1.1
Pileup reweighting	0.5
ME scale, $t\bar{t}$	0.6
ME scale, backgrounds	0.1
ME/PS matching	0.1
PS scales	0.3
PDF and α_S	0.3
Single t background	1.0
Z+jets background	0.3
W+jets background	0.0
Diboson background	0.5
QCD multijet background	0.3
Statistical uncertainty	0.5
Combined uncertainty	2.6
Integrated luminosity	2.3

$$\sigma(t\bar{t}) = 887^{+43}_{-41}\,(\text{stat+syst}) \pm 53\,(\text{lumi})\ \text{pb}$$

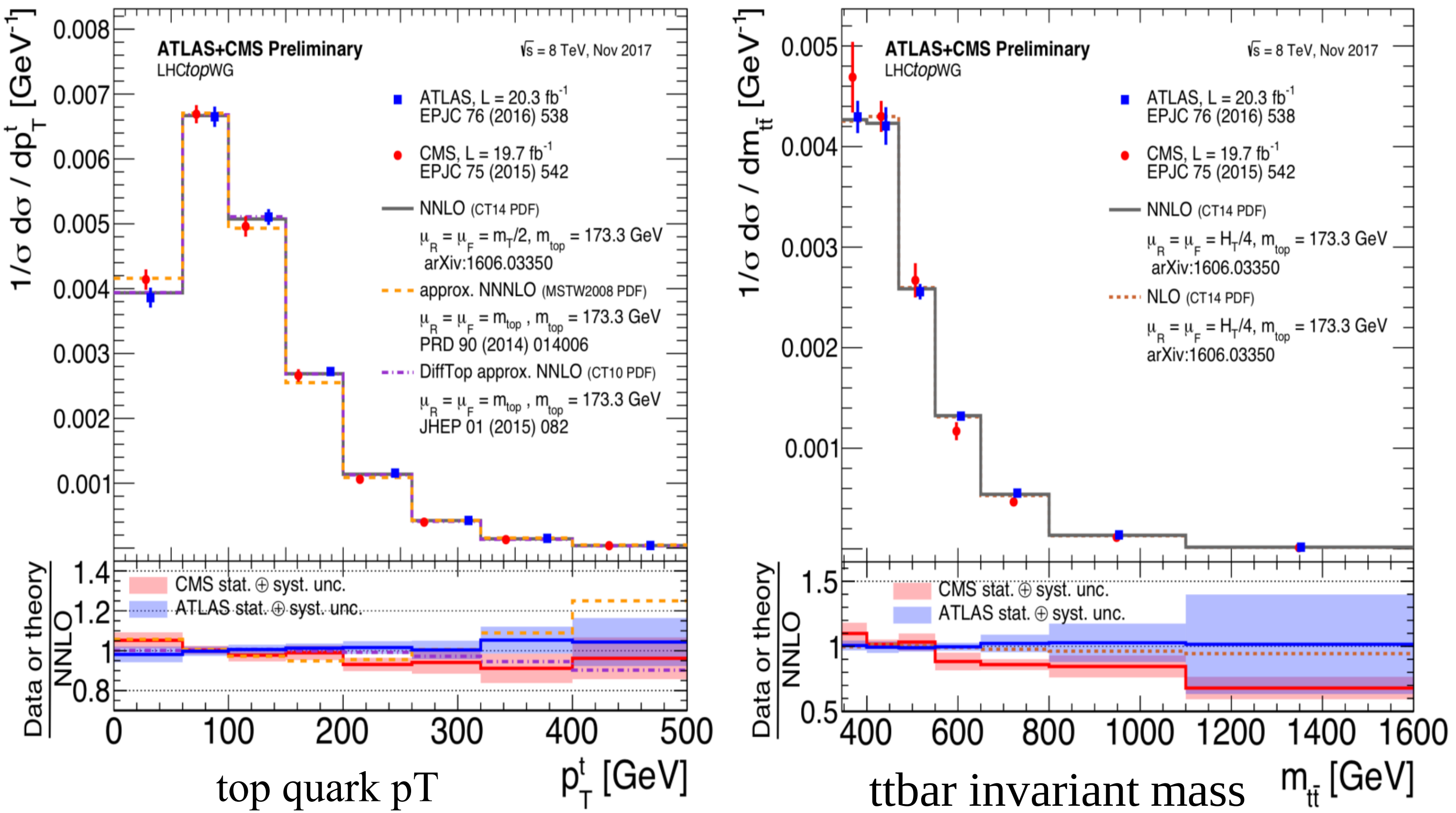
$$\textit{Theory:}\ \sigma(t\bar{t}) = 921^{+18}_{-16}\ \text{pb}$$

arXiv:2303.10680
Submitted to JHEP

Differential cross section

- ✓ Cross sections measured as a function of pT, eta, invariant mass of the final state leptons, top quarks, ttbar system, etc.
- ✓ Good agreement with expectations

$$\frac{1}{\sigma_{t\bar{t}}}\frac{d\sigma_{t\bar{t}}}{dX}$$



top quark pT

ttbar invariant mass

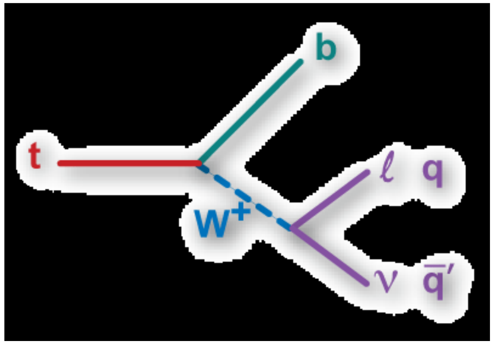
EPJC 73(2013) 2339, arXiv:1610.04191, TOP-20-001, TOP-20-006

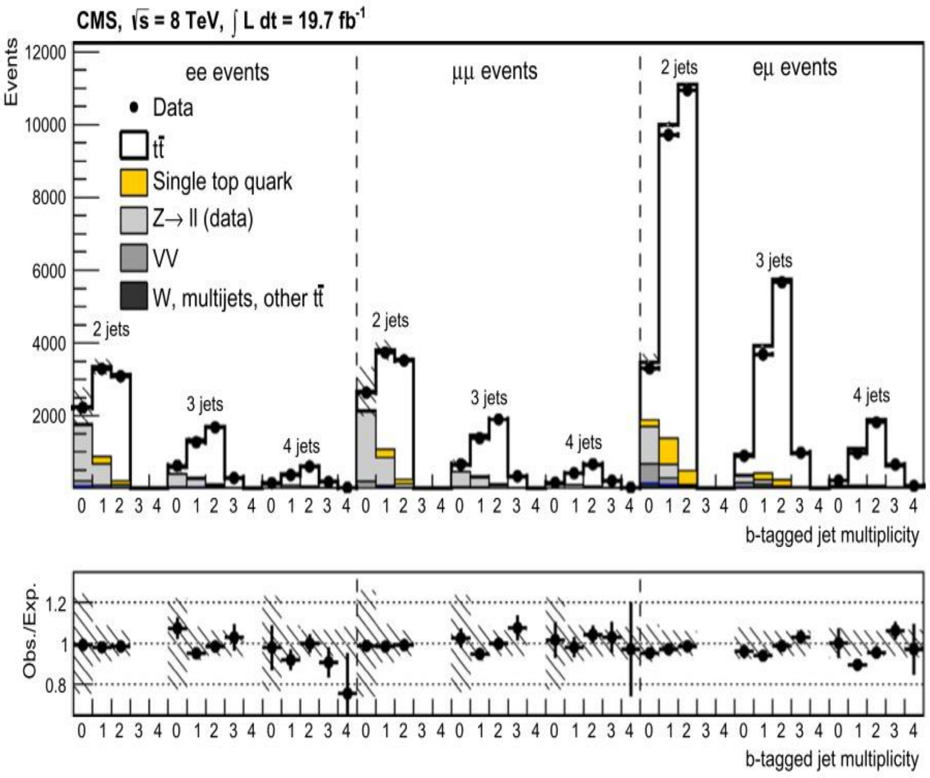
Cross section in the R measurement

PLB 736(2014)33

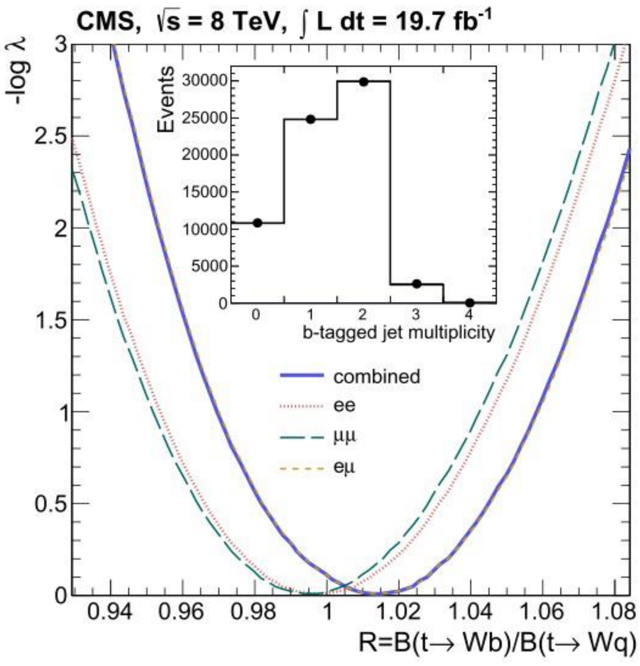
$$R \equiv \frac{BR(t \to Wb)}{BR(t \to Wq)} \approx |V_{tb}|^2$$

- ✓ Measure R:
- ✓ Dilepton final state



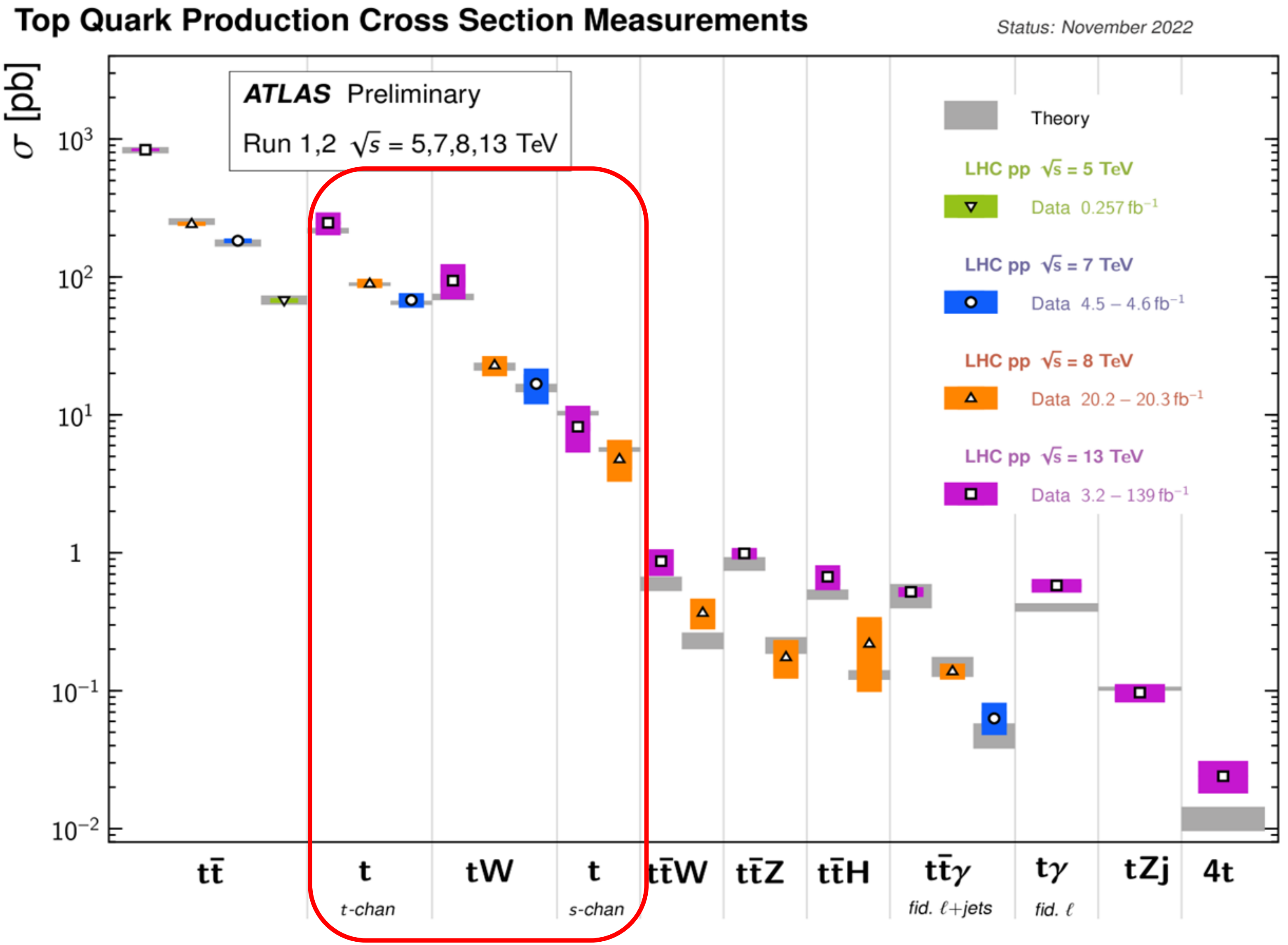


$$\sigma(t\bar{t}) = 238 \pm 1\,(\text{stat.}) \pm 15\,(\text{syst.})\ \text{pb}$$

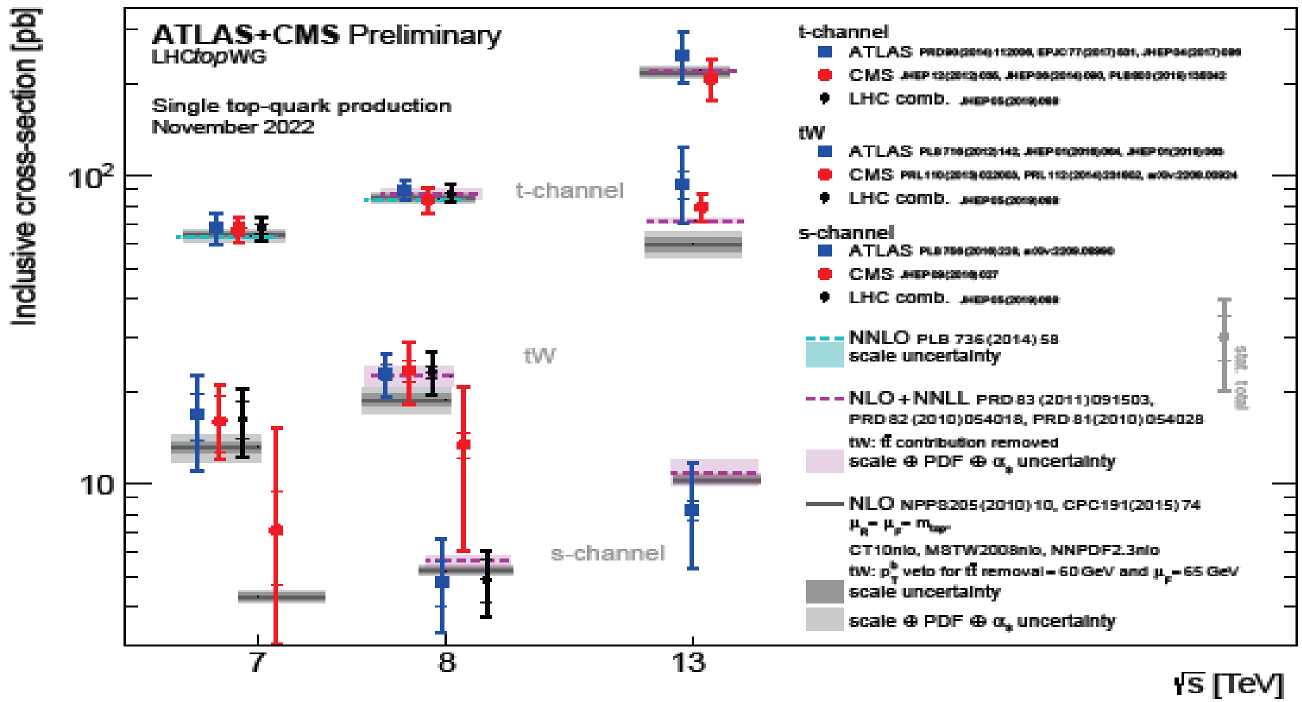


$$R = 1.01 \pm 0.03\ (stat. + syst.)$$

Single top production

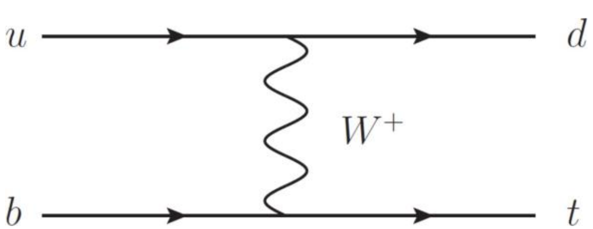


Single top production

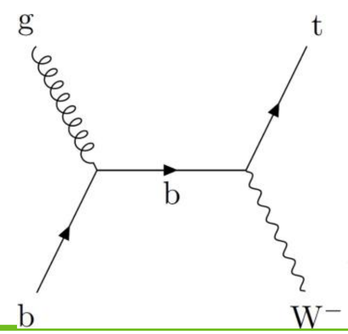


Inclusive xsec measurements are in good agreement w/ NLO+NNLL & NNLO prediction.

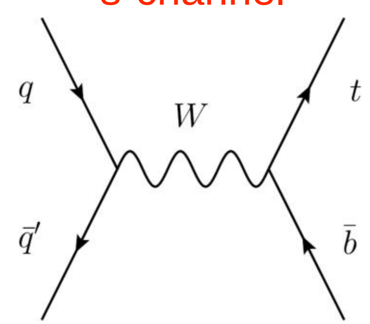
t-channel



tW-channel



s-channel



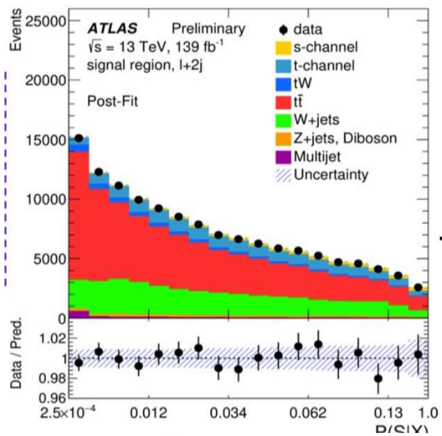
JHEP 06 (2023) 191

Single top cross section

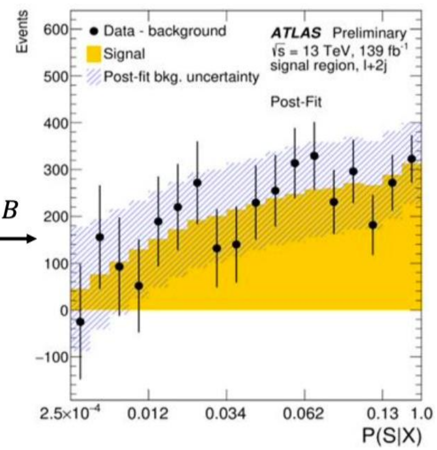
JHEP 07 (2023) 046

s-channel

- ✓ Observed at Tevaton
- ✓ Very complicated at LHC:
  --small cross section, large backgrounds
- ✓ Matrix Element technique to separate S/B



D − B



- Result:

$$\sigma_{\text{meas.}} = 8.2 \pm 0.6\,(\text{stat.})^{+3.4}_{-2.8}\,(\text{syst.})\ \text{pb}$$

- Compatible with SM prediction:

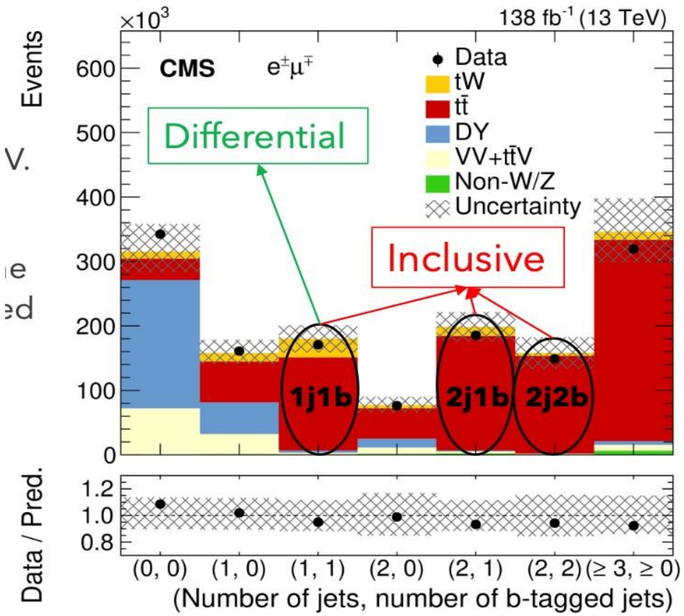
Significance 3.3 (3.9) obs.(exp)

dominated by modelling and JES

Source	$\Delta\sigma/\sigma$ [%]
$t\bar{t}$ normalisation	$+24/-17$
Jet energy resolution	$+18/-12$
Jet energy scale	$+18/-13$
Other s-channel modelling sources	$+18/-8$

tW channel

- ✓ Inclusive and differential XS in eμ channel



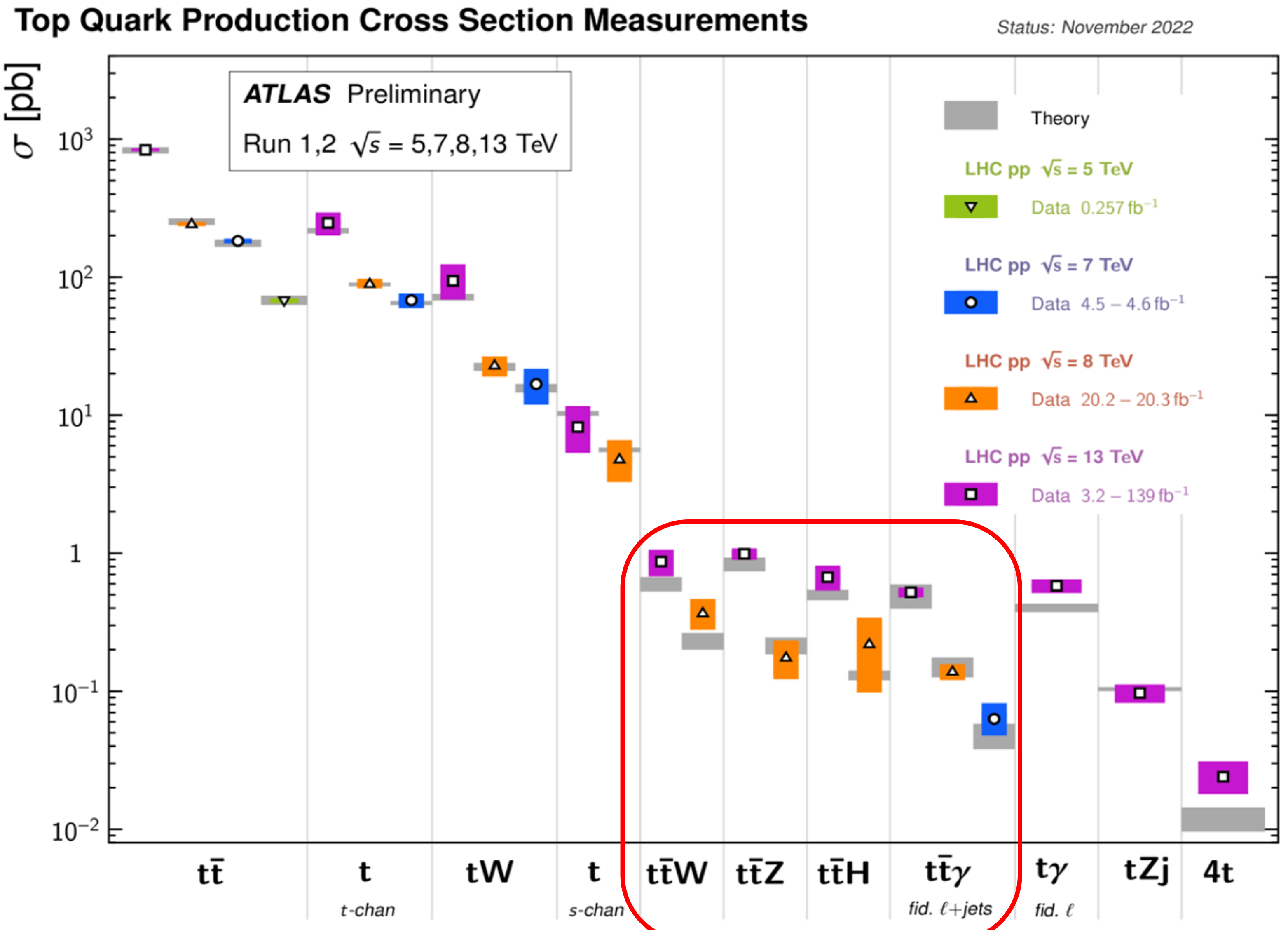
$$\sigma_{tW} = 79.2 \pm 0.8\,(\text{stat}) \pm^{7.0}_{7.2}\,(\text{syst}) \pm 1.1\,(\text{lumi})\ \text{pb}$$

10% uncertainty

In agreement with predictions

- ➢ tW is also measured in single lepton channel by ATLAS (8 TeV) and CMS (13 TeV)
- ➢ Less precise than dilepton

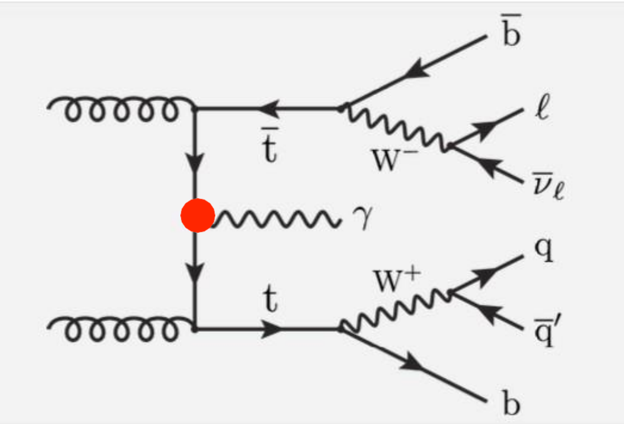
tt + X production

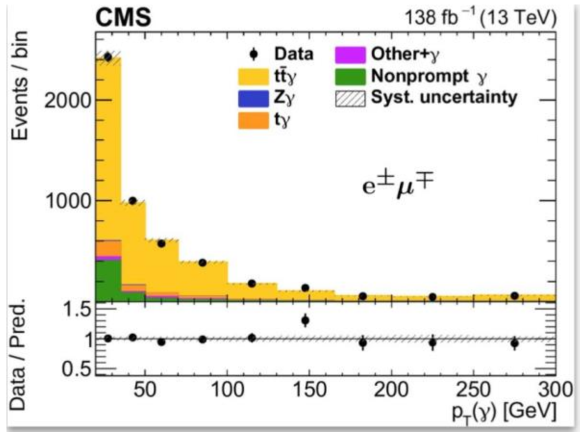


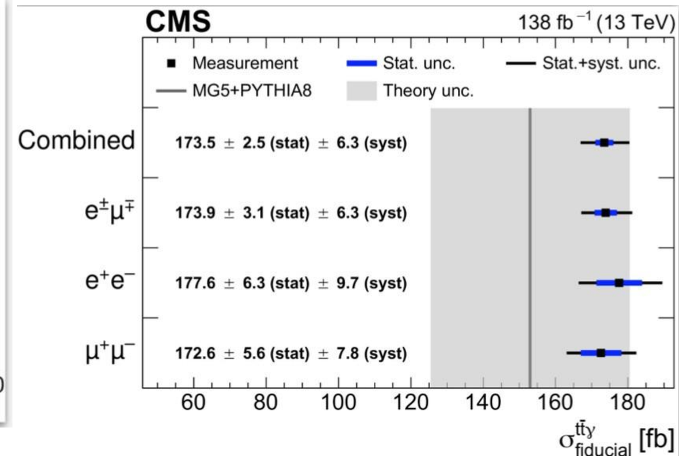
ttγ production

JHEP 05 (2022) 091

- New CMS measurement in dilepton channel

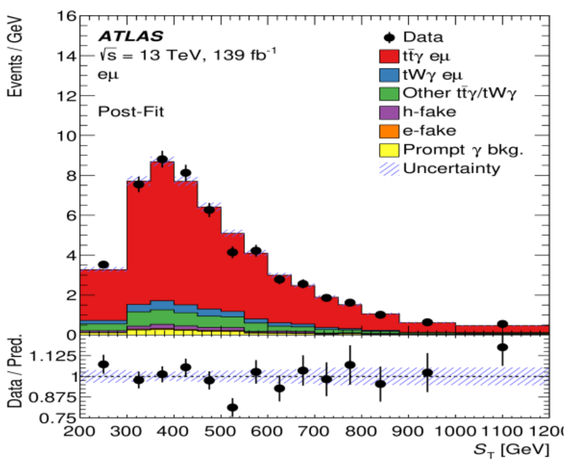


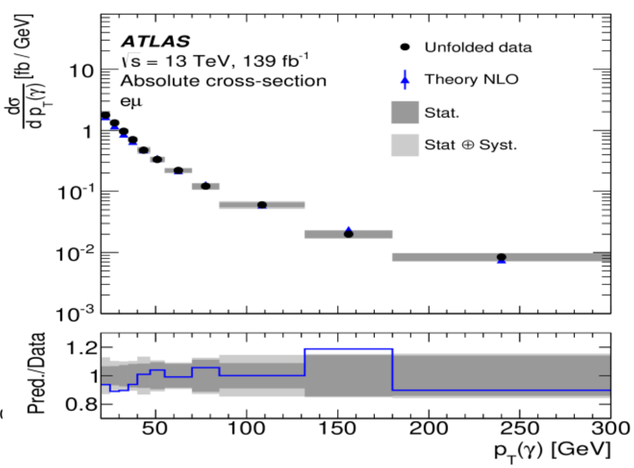




- Precision 4%
- Prediction from MG5aMC (LO+NLO k-factor) is lower

JHEP 09 (2020) 049



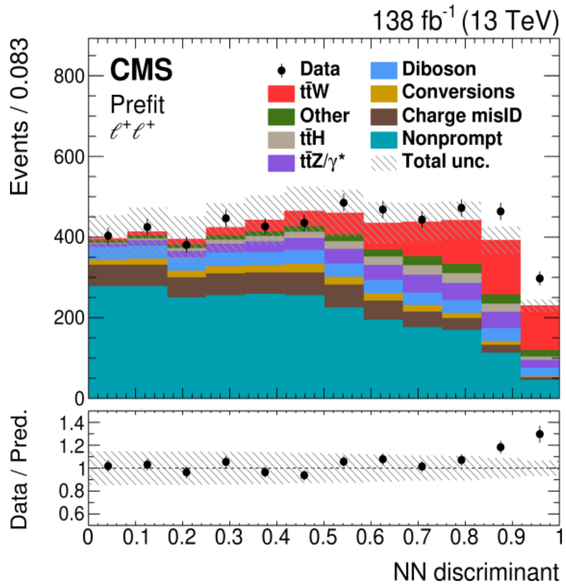


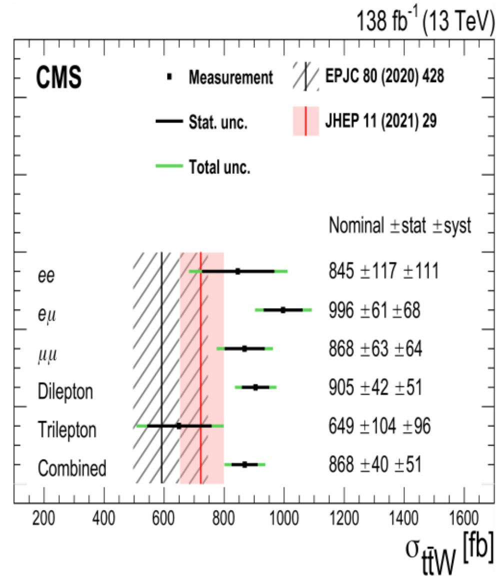
In agreement with the predictions from the SM

ttW measurement: CMS

2-lepton Same Sign and tri-lepton final states

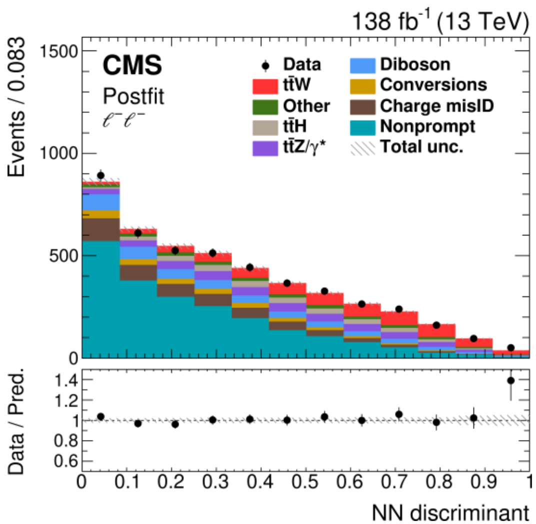
arXiv:2208.06485

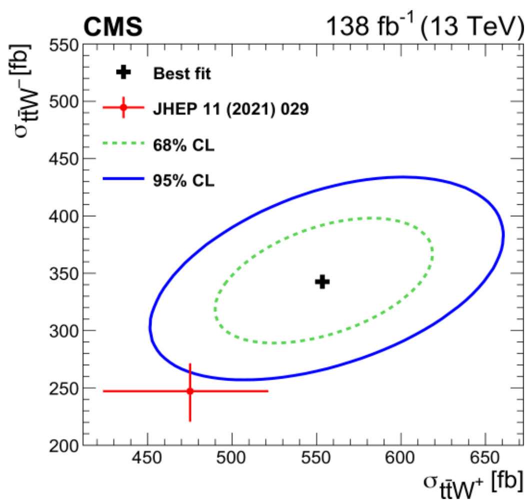




Combined cross section corresponds to $\mu_{ttW} = 1.47$

$R(ttW+/ttW-) = 1.61 \pm 0.15$ (stat) $^{+0.07}/_{-0.05}$ (syst)



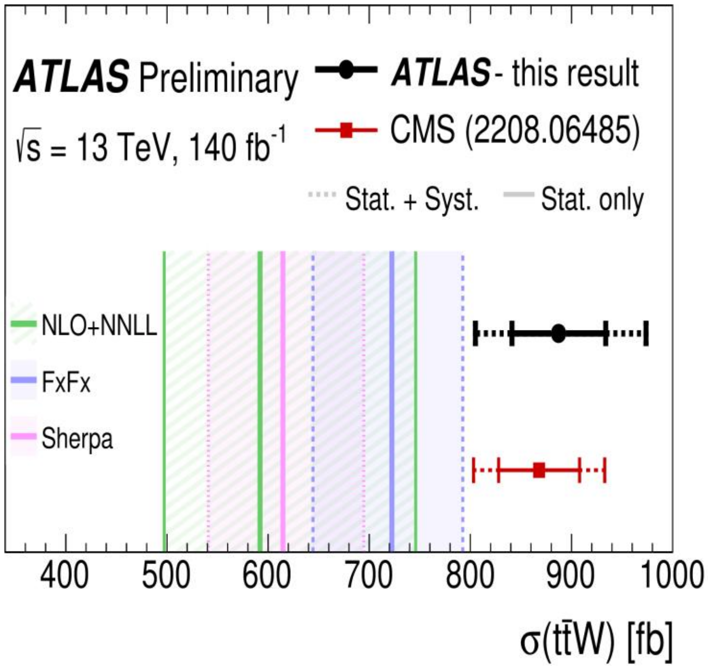


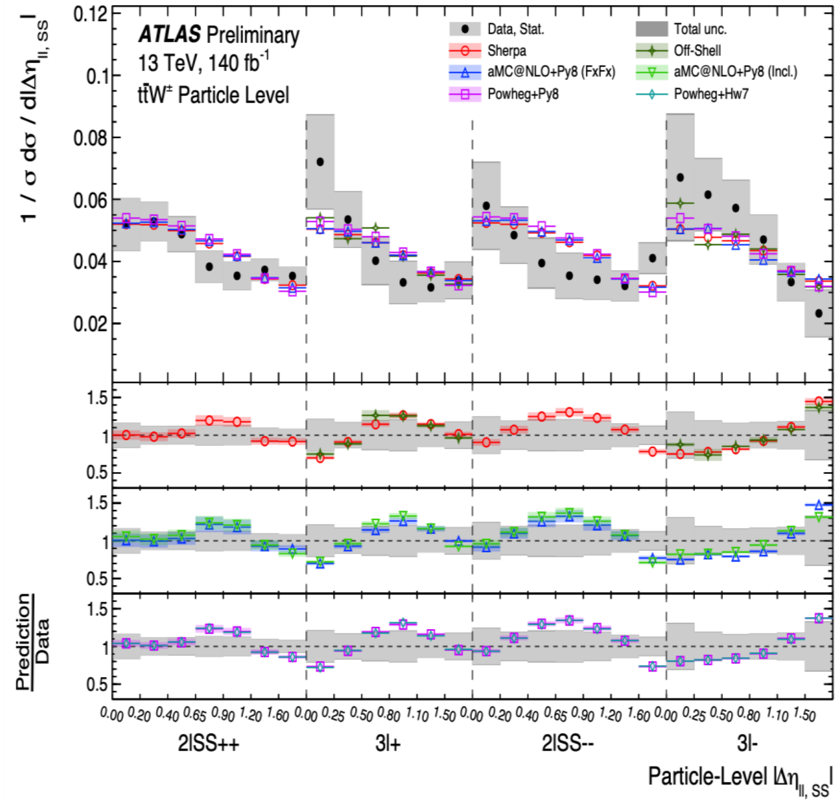
Significant deviation from prediction for ttW+/ttW- ratio = 1.94+0.37-0.24

ttW measurement: ATLAS

ATLAS-CONF-2023-019

- ✓ Inclusive cross section measurements for $t\bar{t}W$, $t\bar{t}W$+/–, and the ratio;
- ✓ Differential measurements for 9 kinematic observables; compatibility with data is tested by $\chi 2$.

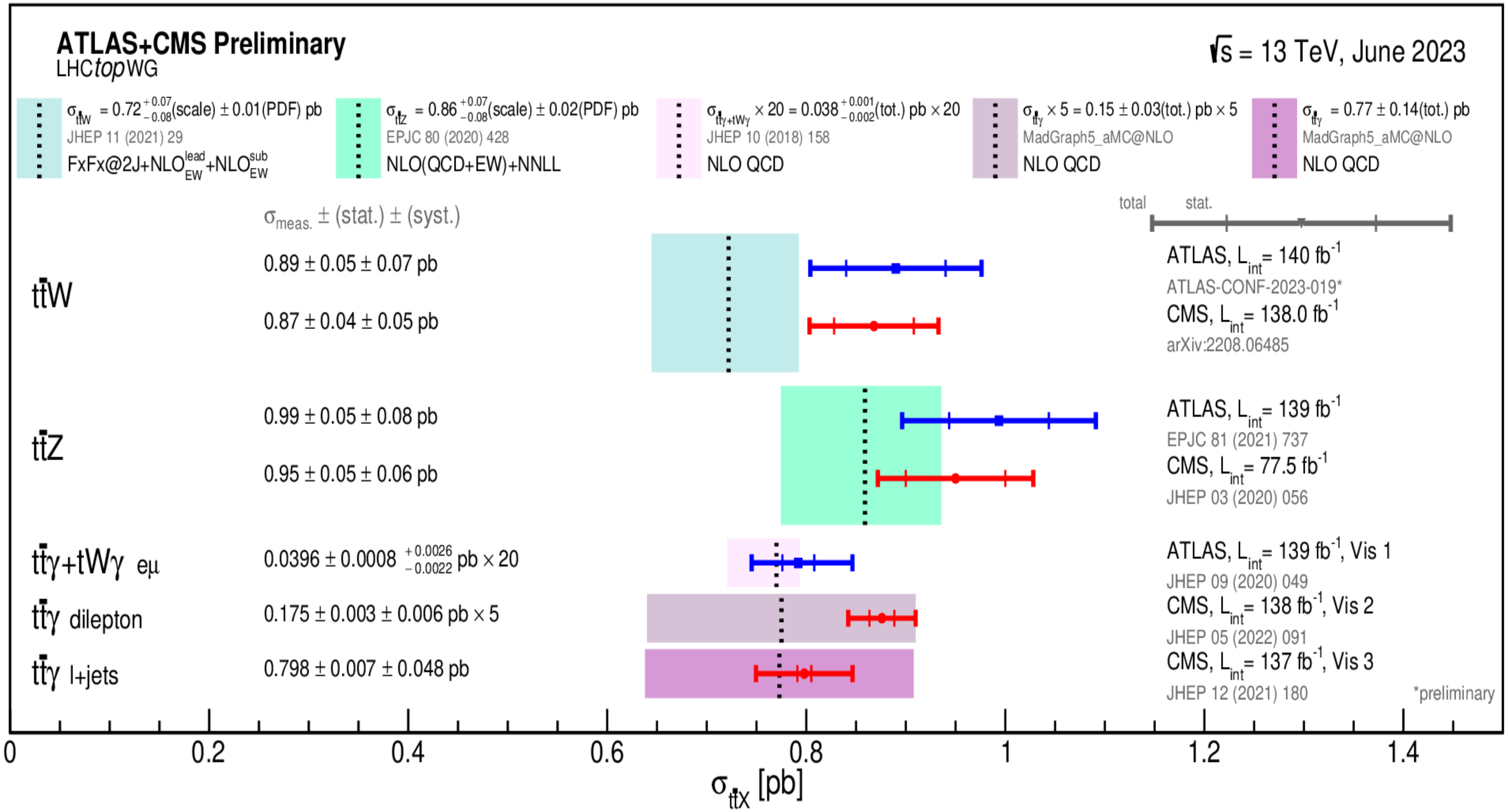




- ✓ Inclusive x-sec is compatible with CMS
- ✓ Larger than prediction.

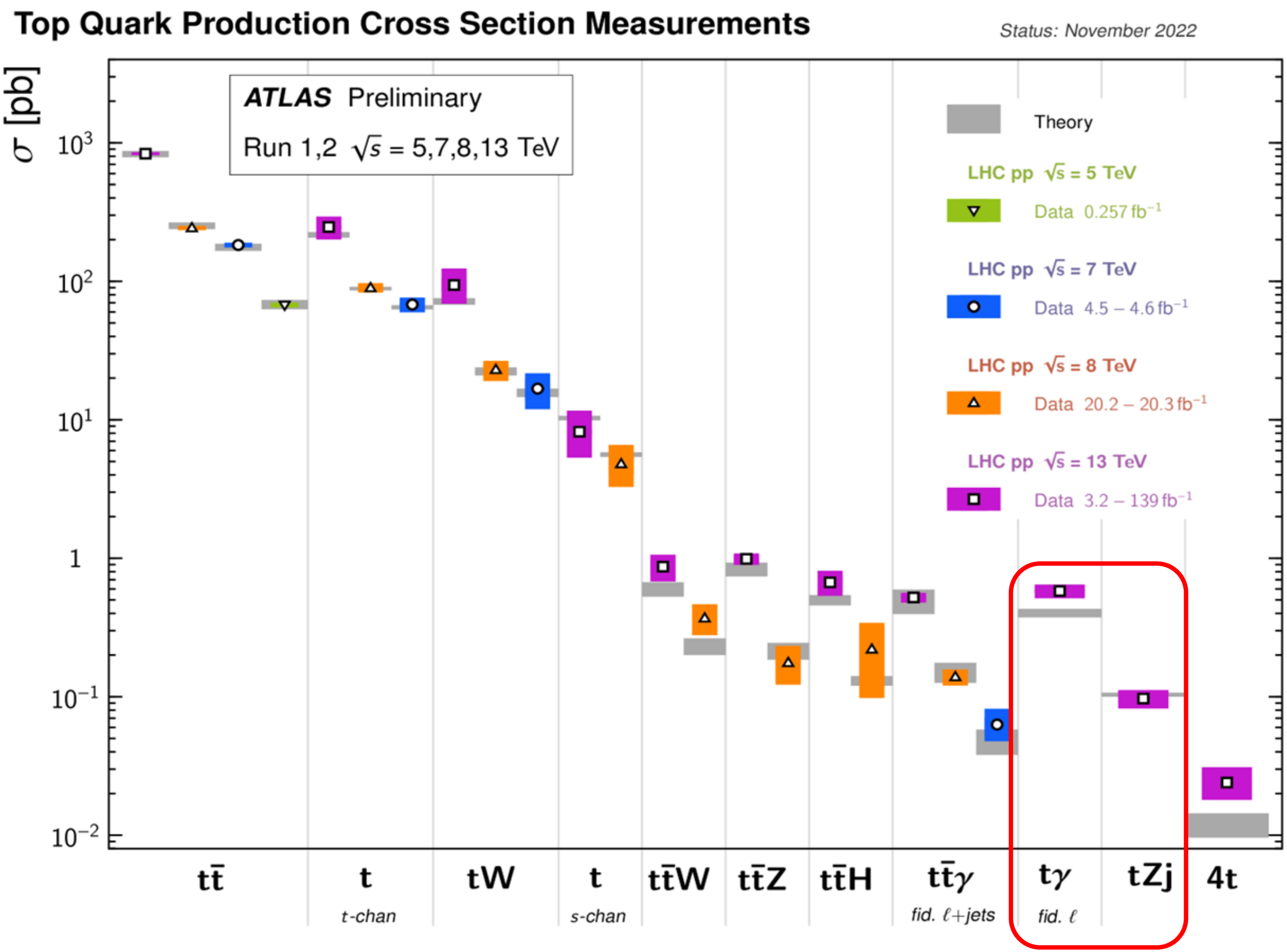
Good agreement of data with MC setups

tt+X summary

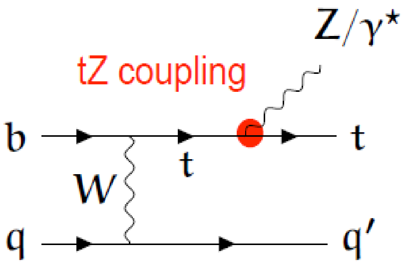


More works on ttW……..

t + X production



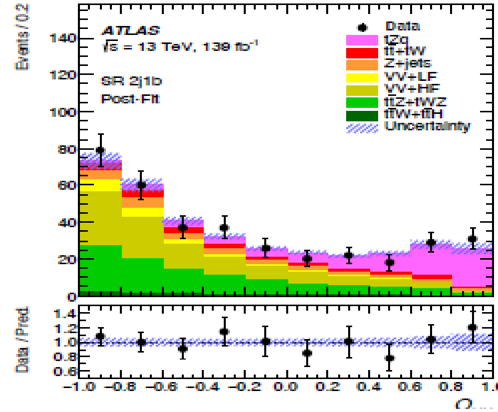
tZq production



Z(ll)

blν

forward jet

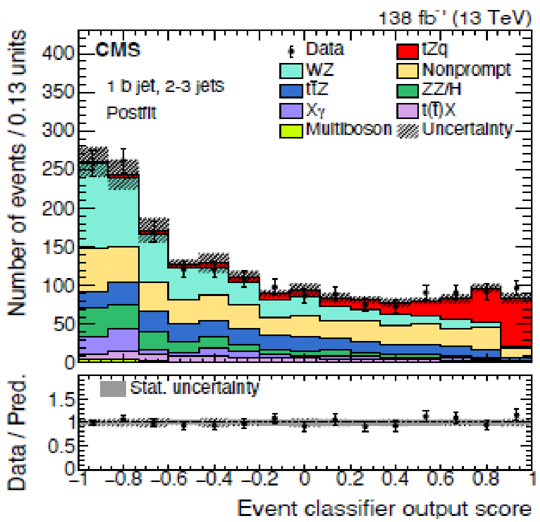


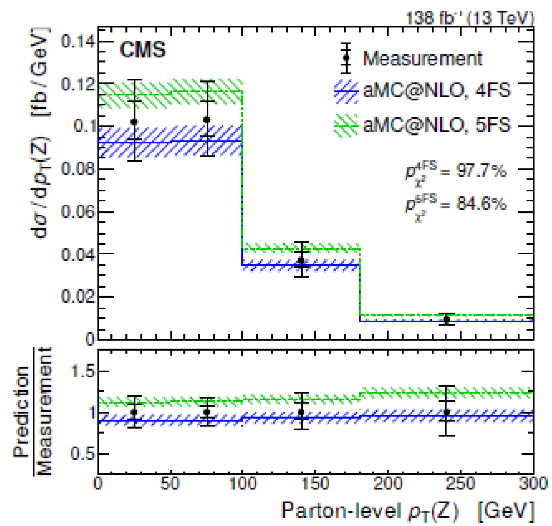
JHEP 07 (2020) 124

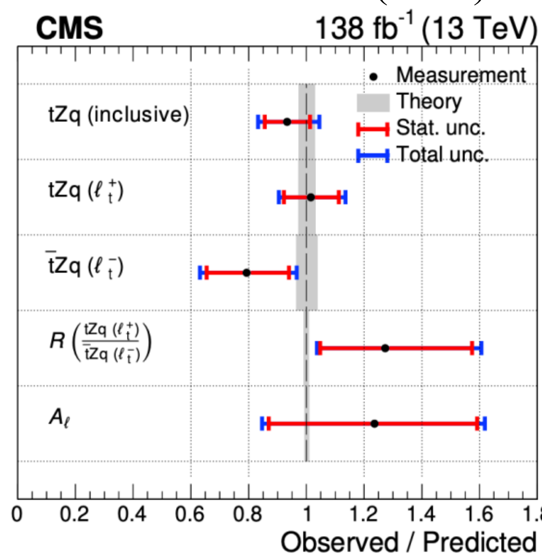
cross section measured with 14% uncertainty

- ✓ Observed by ATLAS and CMS
- ✓ New CMS analysis with full run2 data set

JHEP 02 (2022) 107







11% cross section uncertainty

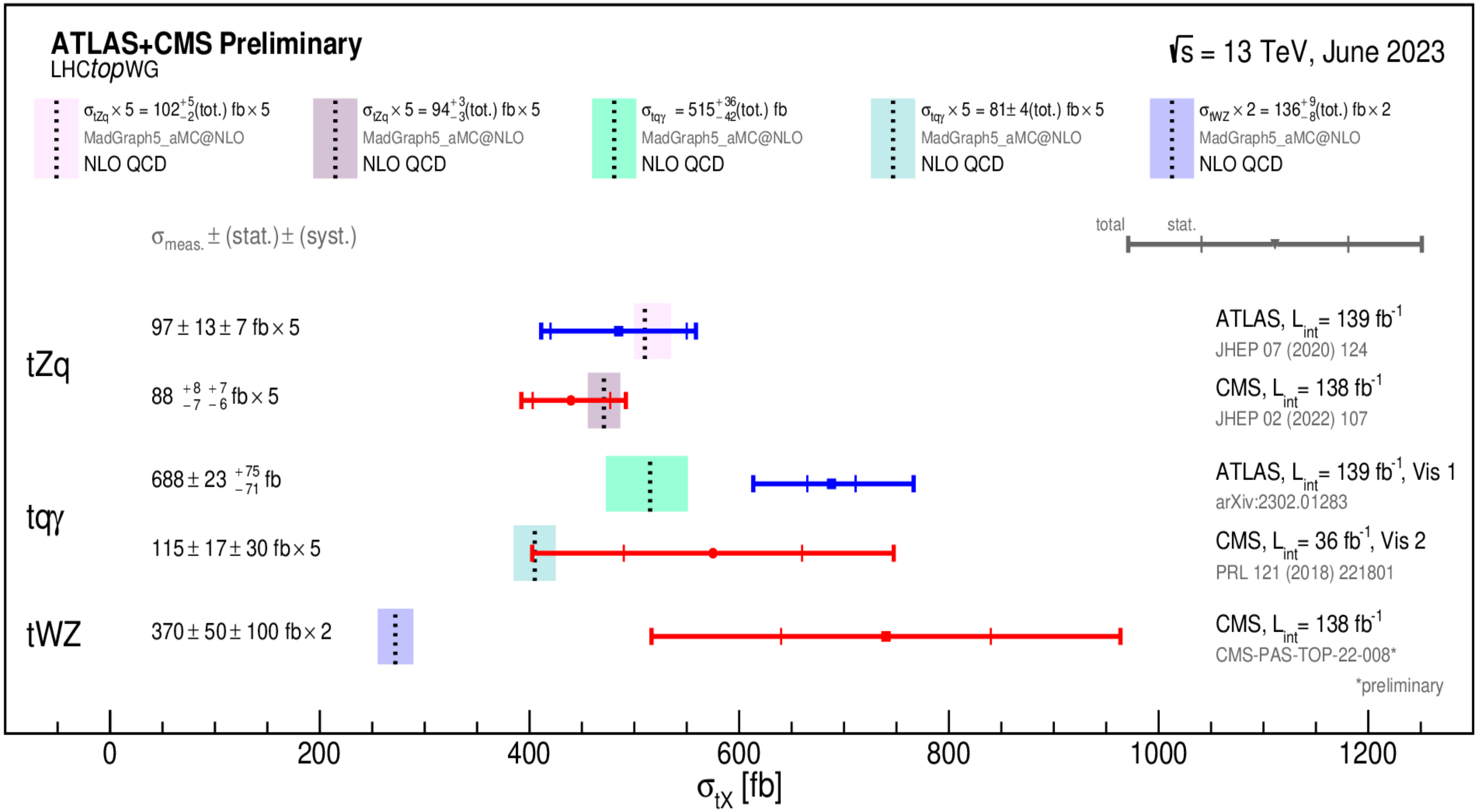
first parton and particle level differential measurements

first measurement of ratio

Precision is expected to improve with more statistics in Run 3

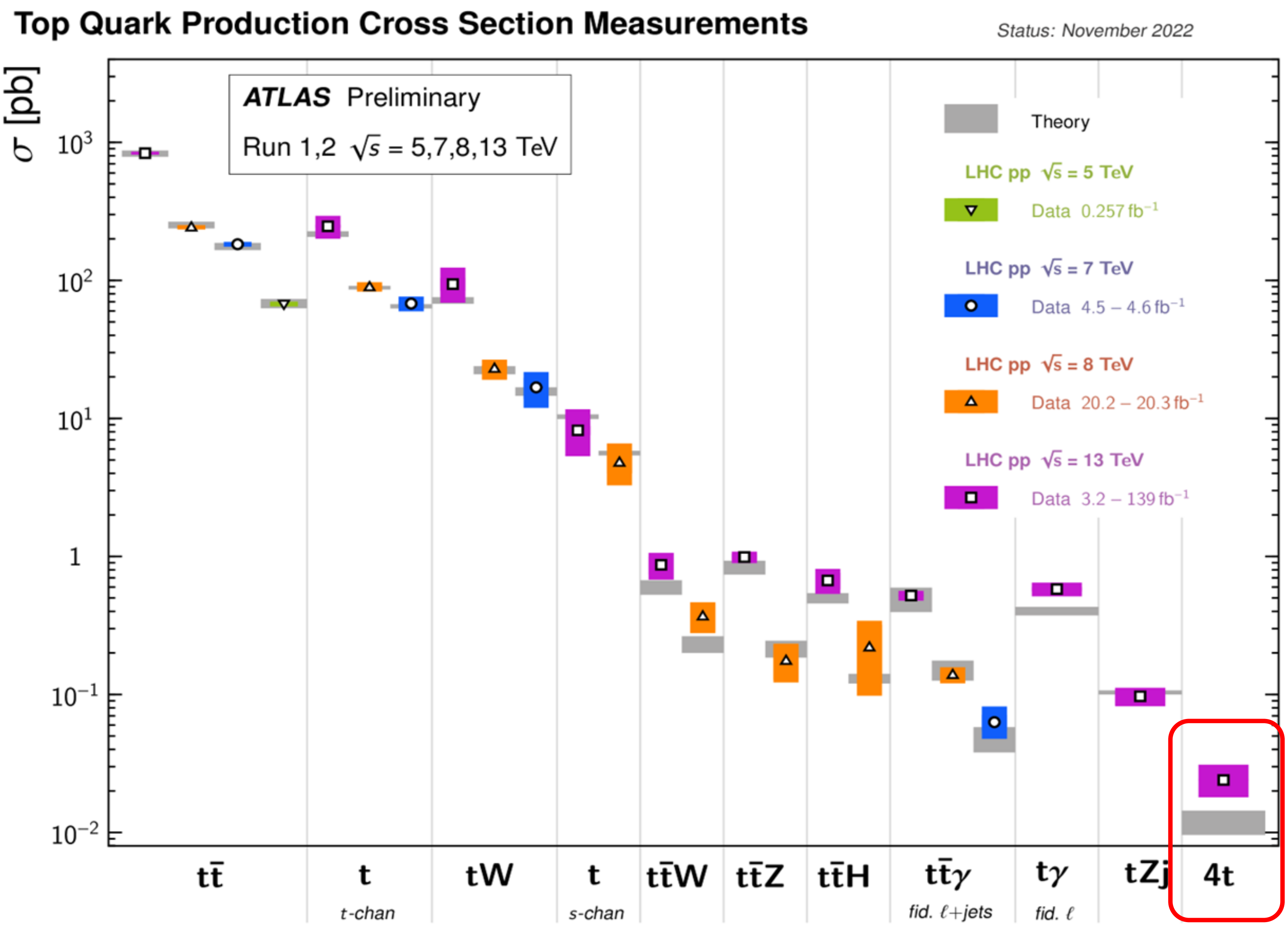
$$R\left(\frac{tZq\ (\ell_t^+)}{\bar{t}Zq\ (\ell_t^-)}\right)$$

t+X summary

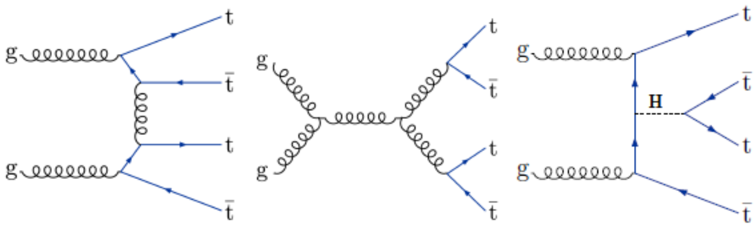


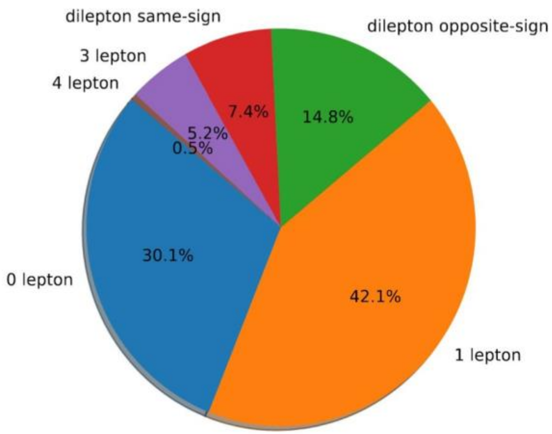
ATLAS+CMS Preliminary
LHCtopWG
√s = 13 TeV, June 2023
σtZq × 5 = 102 +5 −2 (tot.) fb × 5
MadGraph5_aMC@NLO
NLO QCD
σtZq × 5 = 94 +3 −3 (tot.) fb × 5
MadGraph5_aMC@NLO
NLO QCD
σtqγ = 515 +36 −42 (tot.) fb
MadGraph5_aMC@NLO
NLO QCD
σtqγ × 5 = 81 ± 4(tot.) fb × 5
MadGraph5_aMC@NLO
NLO QCD
σtWZ × 2 = 136 +9 −8 (tot.) fb × 2
MadGraph5_aMC@NLO
NLO QCD
σmeas. ± (stat.) ± (syst.)
total
stat.
tZq
97 ± 13 ± 7 fb × 5
ATLAS, Lint = 139 fb-1
JHEP 07 (2020) 124
88 +8 −7 +7 −6 fb × 5
CMS, Lint = 138 fb-1
JHEP 02 (2022) 107
tqγ
688 ± 23 +75 −71 fb
ATLAS, Lint = 139 fb-1, Vis 1
arXiv:2302.01283
115 ± 17 ± 30 fb × 5
CMS, Lint = 36 fb-1, Vis 2
PRL 121 (2018) 221801
tWZ
370 ± 50 ± 100 fb × 2
CMS, Lint = 138 fb-1
CMS-PAS-TOP-22-008*
*preliminary
0
200
400
600
800
1000
1200
σtX [fb]

4-top production



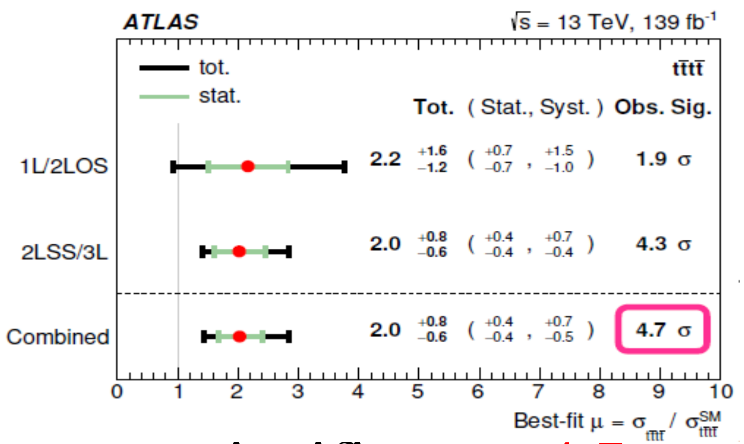
4-top searches



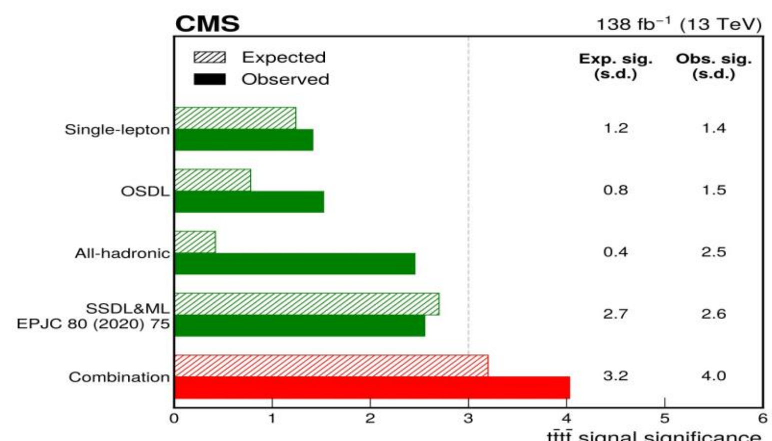


- ✓ Very rare production in SM
- ✓ Heaviest particle final state
- ✓ Many different final states
- ✓ Sensitivity to the top quark Yukawa coupling
- ✓ Important input to effective field theory interpretations

Evidences from both experiments!



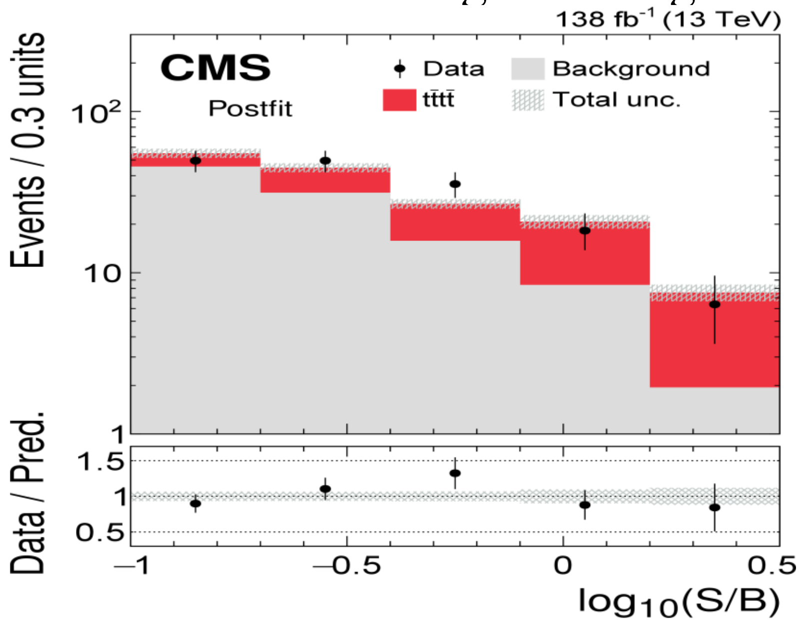
significance: 4.7σ

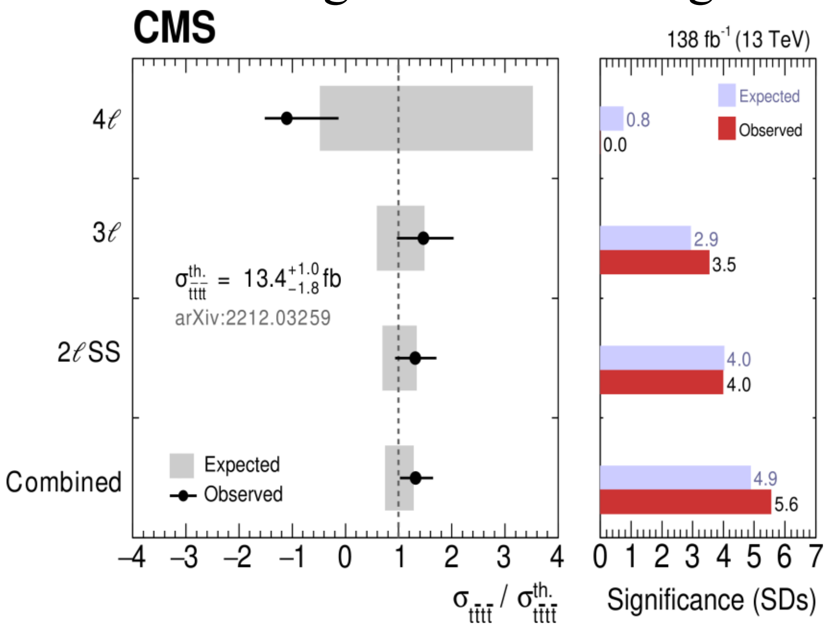


significance: 4.0σ

Observation of 4-top productions: CMS

- ✓ Re-analyze/re-optimize the analysis of full Run-2 data in same-sign 2ℓ, 3ℓ, 4ℓ channels.
- ✓ Simultaneous binned profile likelihood fit to signal & control regions to extract the signal strength.





$\sigma_{t\bar{t}t\bar{t}} = 17.9^{+3.7}_{-3.5}\,(\text{stat})^{+2.4}_{-2.1}\,(\text{syst})$ fb

Prediction: $\sigma_{t\bar{t}t\bar{t}} = 13.4^{+1.0}_{-1.8}$ fb

Notable improvements with ML:
lepton ID, b-tagging,
signal vs. background discrimination.

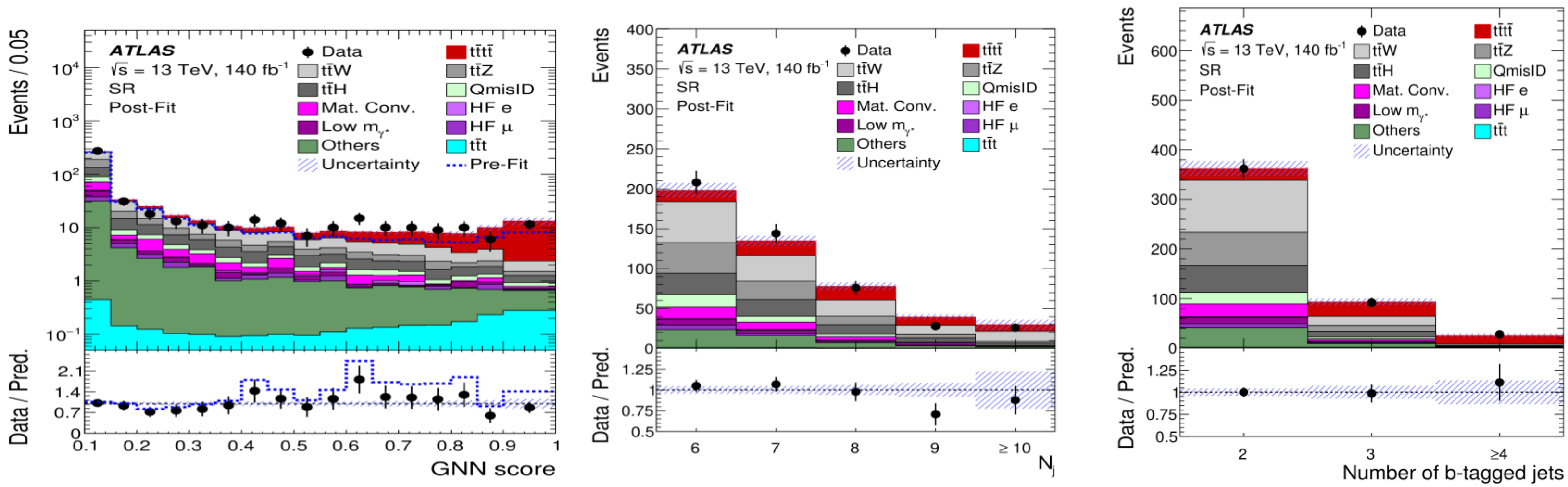
arXiv:2305.13439
Submitted to PLB

- ✓ **Significance: 5.5σ (obs) / 4.9σ (exp)**
- ✓ Slightly larger than prediction, but still compatible.

Observation of 4-top productions: ATLAS

- ✓ Same-sign 2ℓ & 3ℓ, ≥6 jets, ≥2 b-jets.
- ✓ Graph Neural Network (GNN) trained to separate signal from background.
- ✓ Signal extraction by simultaneous fits to GNN scores in signal and control regions

Also gives the first limits on 3-tops:
$\sigma(t\bar{t}t) < 41$ fb
$\sigma(t\bar{t}tW) < 30$ fb
$\sigma(t\bar{t}tq) < 100$ fb
@ 95% CL, $\mu(4t) = 1.9$



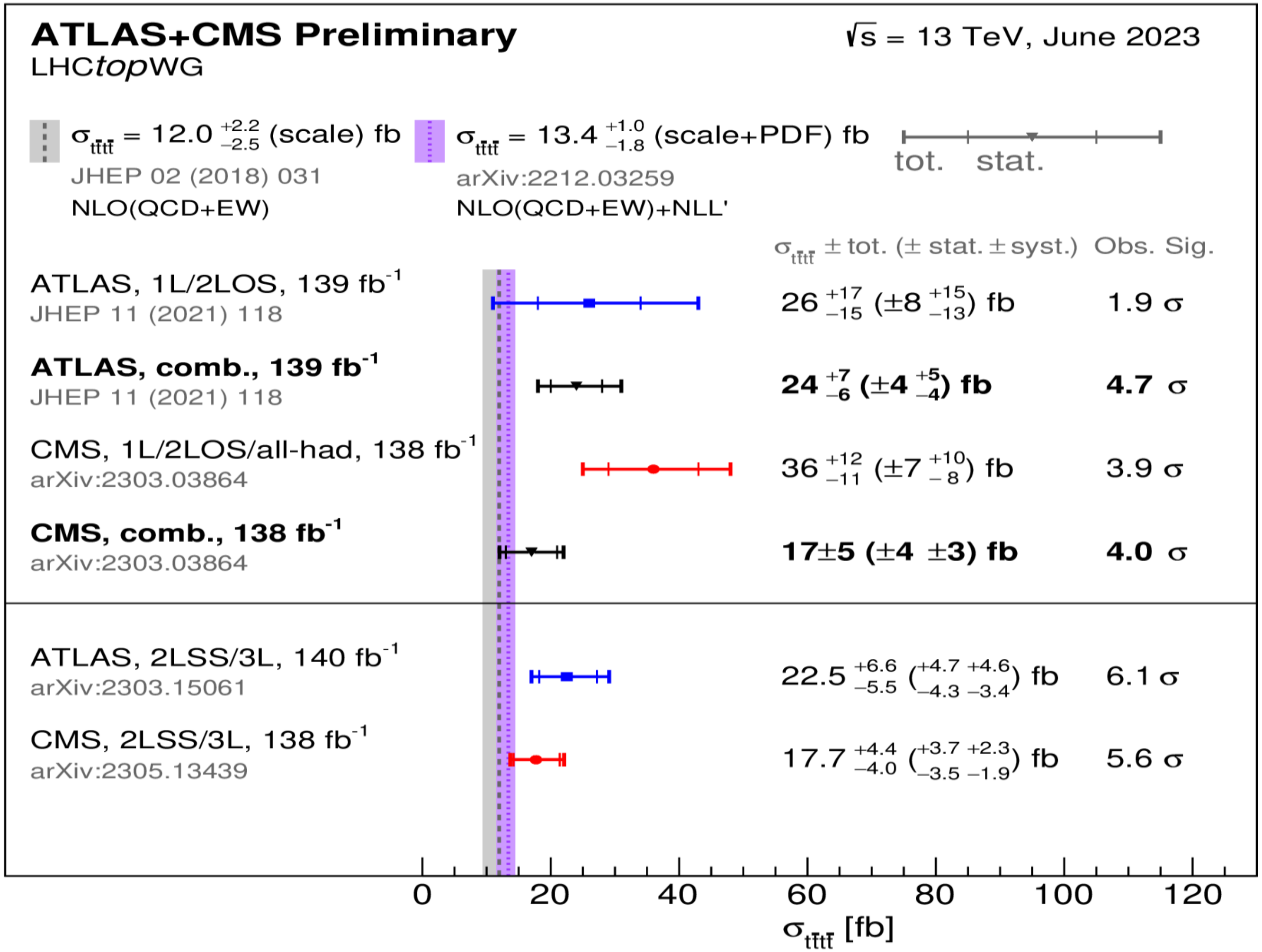
- ✓ **Significance: 6.1σ (obs) / 4.3σ (exp)**
- ✓ Compatible with SM prediction within 1.9σ

EPJC 83 (2023) 496

Signal strength: $\mu = 1.9 \pm 0.4\,(\text{stat})^{+0.7}_{-0.4}\,(\text{syst})$

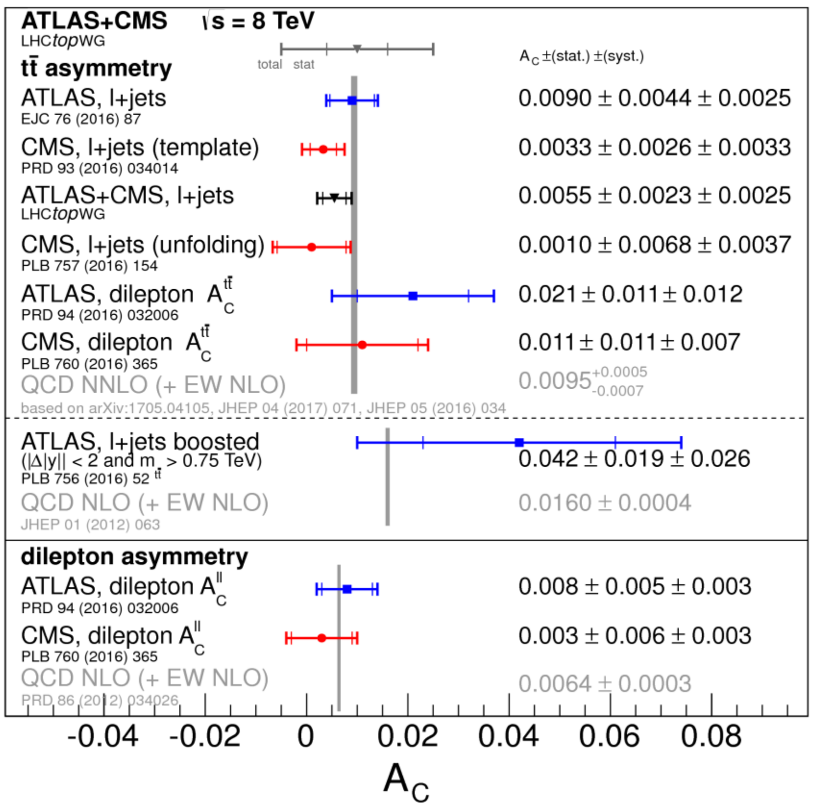
$\Rightarrow \sigma_{t\bar{t}t\bar{t}} = 22.5^{+6.6}_{-5.6}$ fb

4-tops summary



Top quark properties

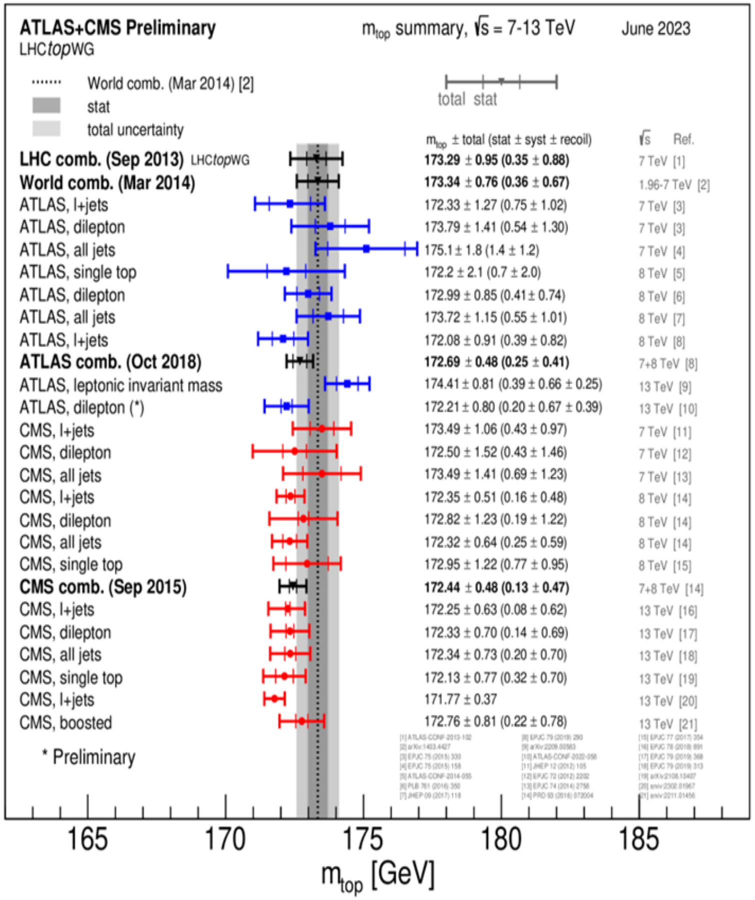
- ✓ Now at LHC is possible to reach un-precedent precisions for the property measurements
- ✓ Now measured not only in ttbar but also in single top and tt+X events



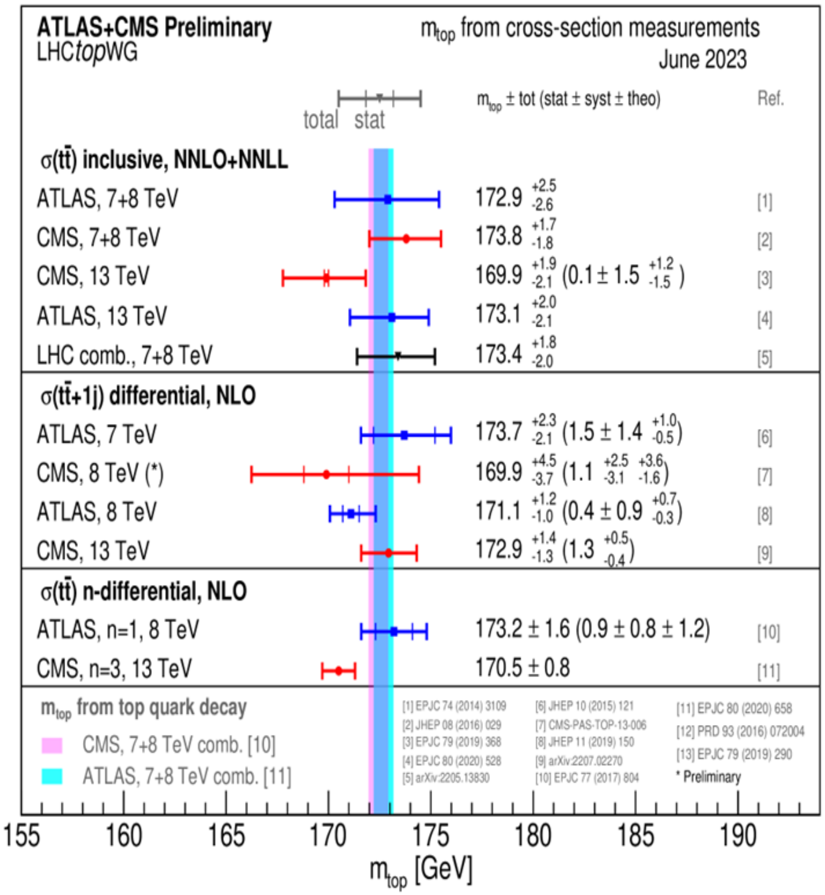
Top mass
Top spin
Top polarisation
Asymmetries
B-fragmentation
Color reconnection
CP properties
………

Top mass

Direct measurements
from reconstruct invariant mass of top quark decay products



Indirect measurements
from observable directly sensitive to top mass (e.g. cross section)

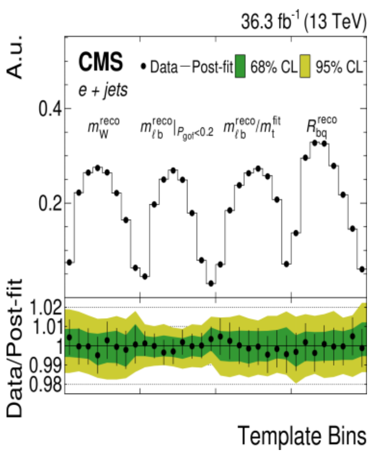


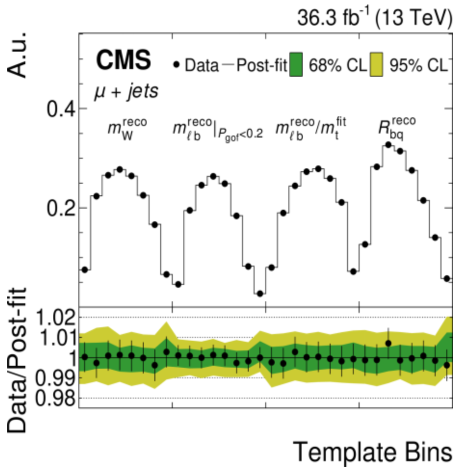
Theoretical advances needed

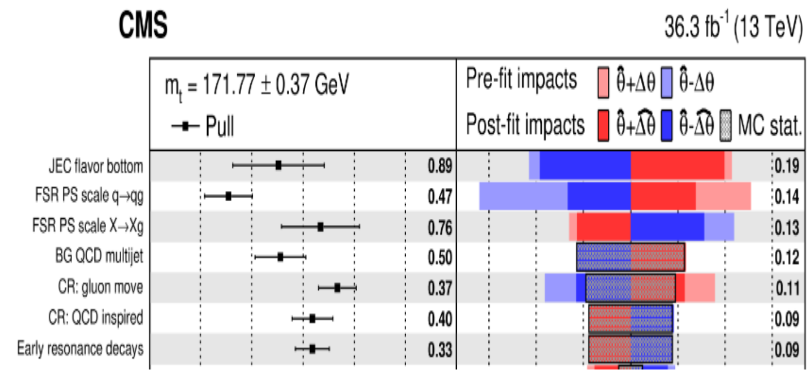
CMS measurements

arXiv:2302.01967
Submitted to EPJC

✓tt l+jets: profile LH fit to 5 observables in different event categories



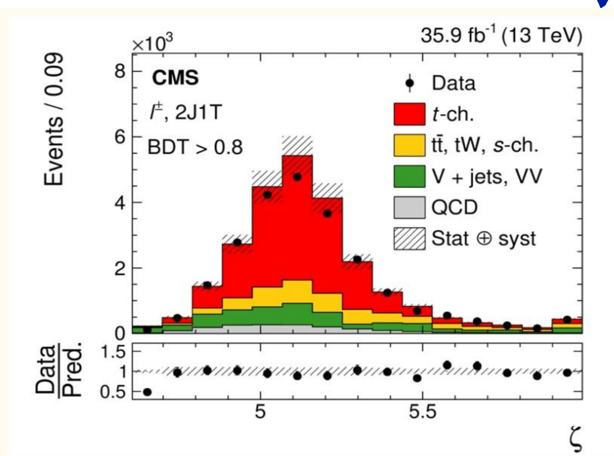




- Significant pull and constraint of FSR PS scale q->qg due to m_W^{reco}

✓ Most precise measurement with 0.37 GeV uncertainty

✓ t-channel single top: ML fit to $\zeta = \ln(m_t/1\ \text{GeV})$



$$m_t = 172.13^{+0.76}_{-0.77}\ \text{GeV}$$

$$R_{m_t} = \frac{m_{\bar{t}}}{m_t} = 0.9952^{+0.0079}_{-0.0104}$$

$$\Delta m_t = m_t - m_{\bar{t}} = 0.83^{+1.79}_{-1.35}\ \text{GeV}$$

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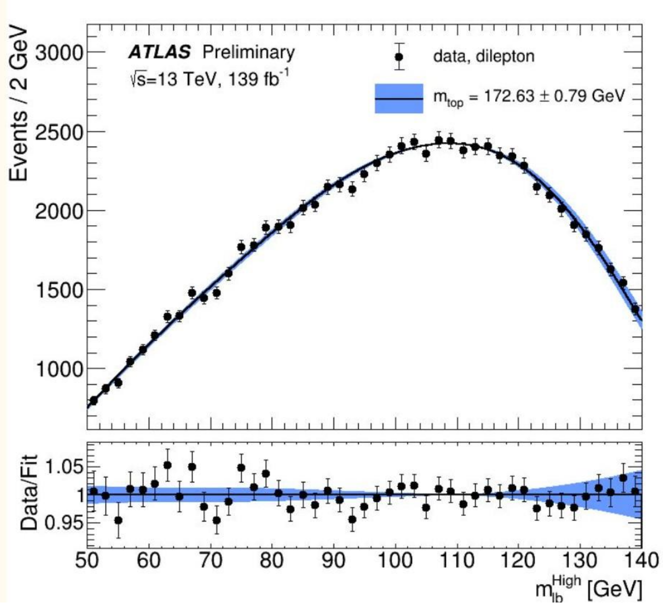
ATLAS measurements

Template method

- **DNN to select b/lepton pairings**
- **Select permutation with highest DNN score**

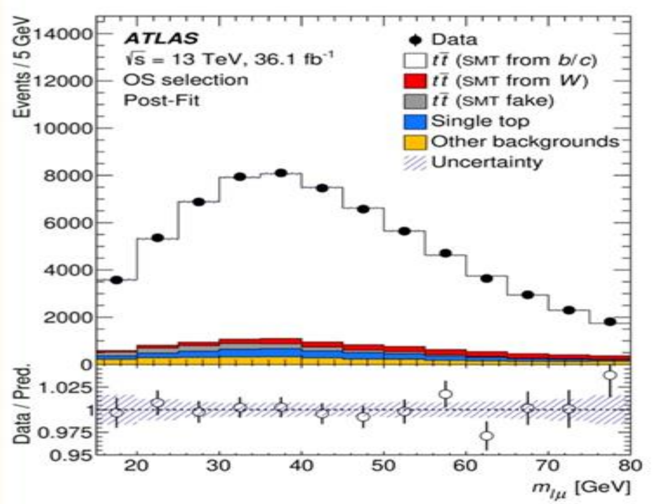


$$m_{top}^{dilepton} = 172.63 \pm 0.20\,(stat) \pm 0.67\,(syst) \pm 0.37\,(recoil)\ GeV$$

✓ Dominant by modelling and JES

Top mass using soft muon tag

- Invariant mass $m_{l\mu}$ sensitive to m_t
- reduced sensitivity to JES
- sensitive to fragmentation modelling



$$174.41 \pm 0.39\,(\text{stat.}) \pm 0.66\,(\text{syst.}) \pm 0.25\,(\text{recoil})\ \text{GeV}$$

✓ consistent at 2σ level with previous results

- ➢ Ttbar modelling is the largest challenge for future measurements
- ➢ Require input from theory and experiments

ATLAS-CONF-2022-058

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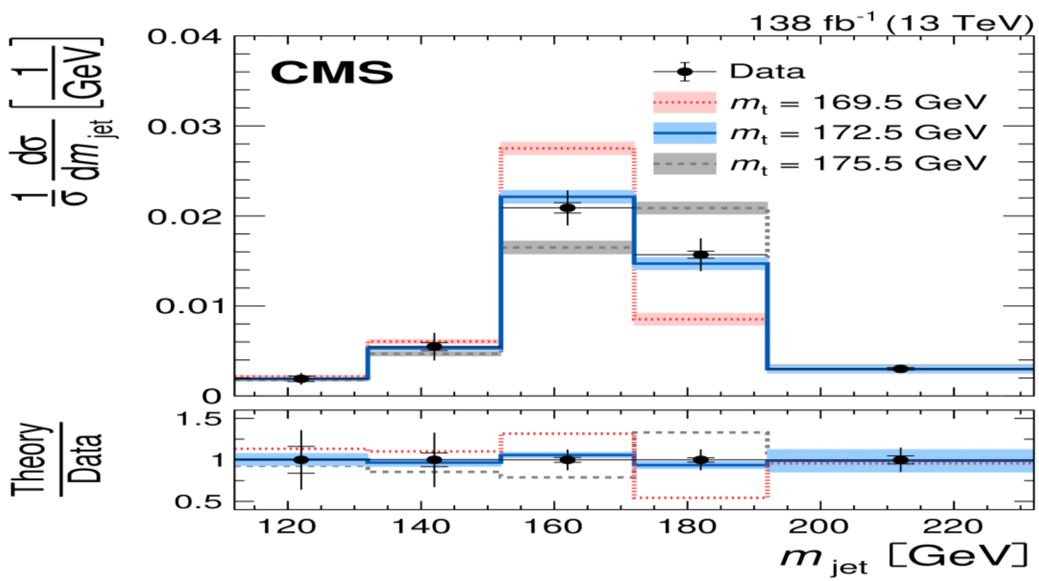
Top mass from boosted jet mass

- ✓ XCone exclusive algorithm to reconstruct jets and sub-jets
  → improved resolution
- ✓ Dedicated calibration of FSR using substructure variables, and dedicated jet mass calibration
- ✓ Comparable precision to direct measurements



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$$m_t = 172.76 \pm 0.22\,(\text{stat}) \pm 0.57\,(\text{exp}) \pm 0.48\,(\text{model}) \pm 0.24\,(\text{theo})\,\text{GeV}$$
$$= 172.76 \pm 0.81\,\text{GeV}.$$

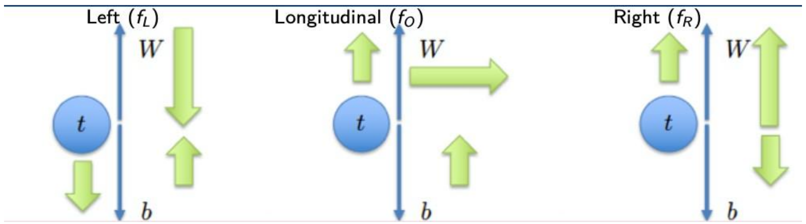
First top mass measurement in boosted regime.

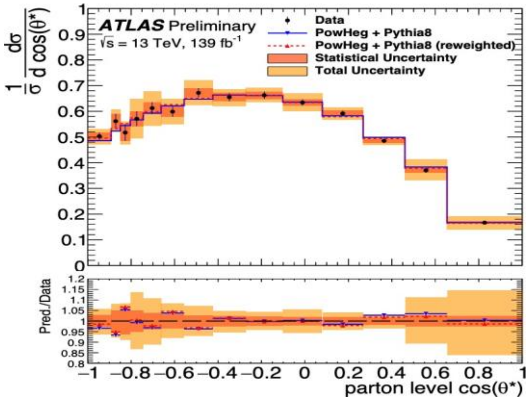
W polarization in top events

arXiv:2209.14903

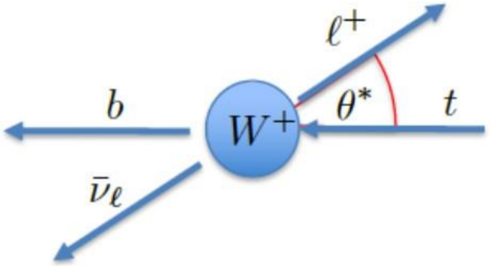
✓ Probe of Wtb vertex

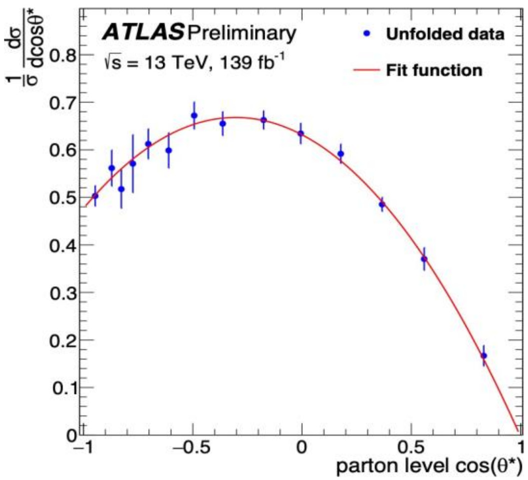
New method in dilepton channel: mesure absolute and normalised differential distributions in cos θ^*

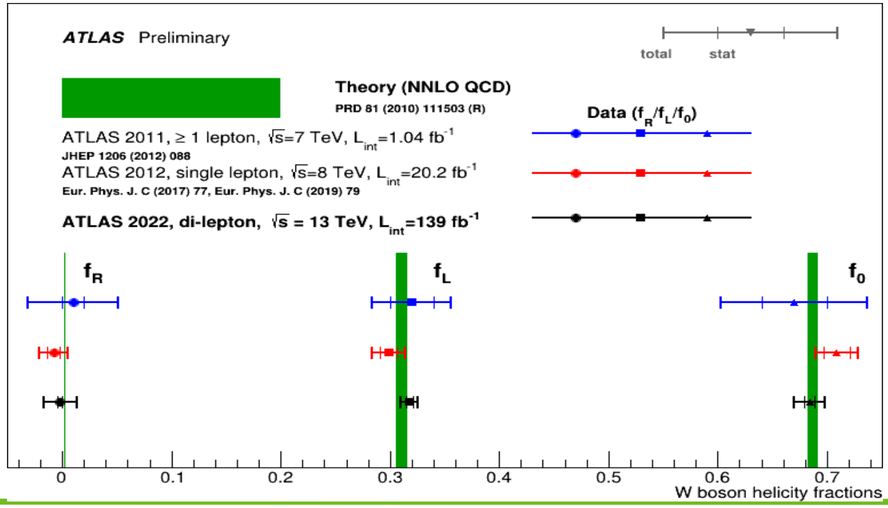




W rest frame







$f_0 = 0.684 \pm 0.015$ (stat. + syst.)

$f_L = 0.318 \pm 0.008$ (stat. + syst.)

$f_R = -0.002 \pm 0.015$ (stat. + syst.)

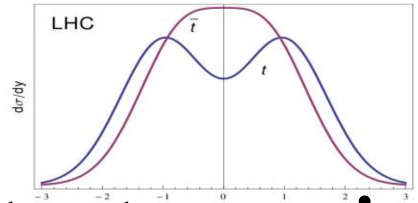
Systematically dominated

Charge asymmetry in tt

arXiv:2208.02751

arXiv:2208.12095

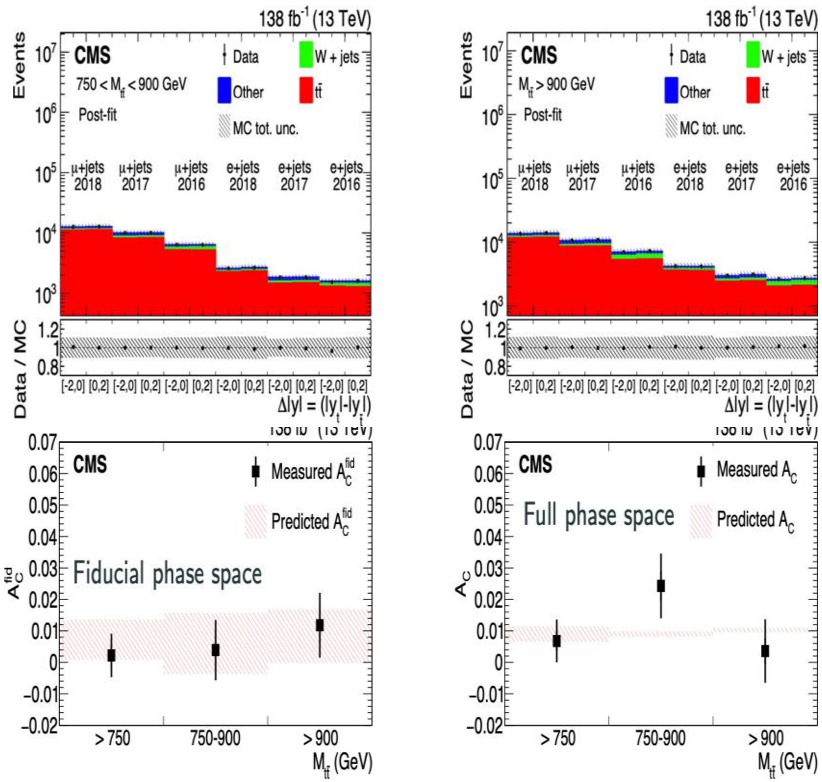
- ✓ Central-forward in ttbar events
- ✓ No asymmetry at LO
- ✓ Higher order effects in $q\bar{q} \to t\, t$



$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

$$(\Delta|y| = |y_t| - |y_{\bar{t}}|)$$

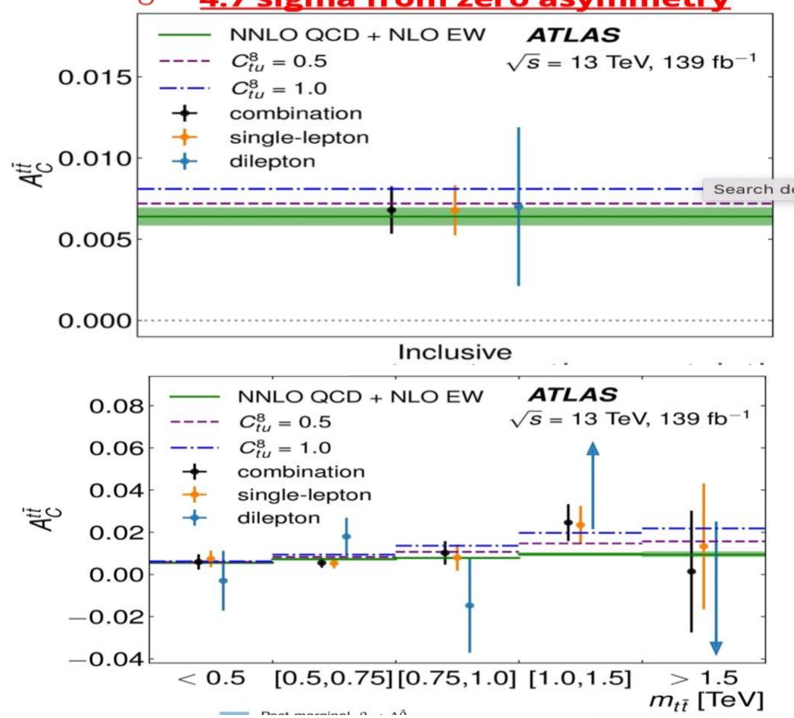
- Boosted regime, single lepton channel
- two $M_{t\bar{t}}$ bins: [750, 900], [900, ∞]



Good agreement with prediction

- Single and dilepton channels
- Resolved and boosted regime

- A_{tt} = 0.0068 ± 0.0015(stat+syst.).
   - 4.7 sigma from zero asymmetry



Expect improvement with additional data

Energy asymmetry in $t\bar{t}$

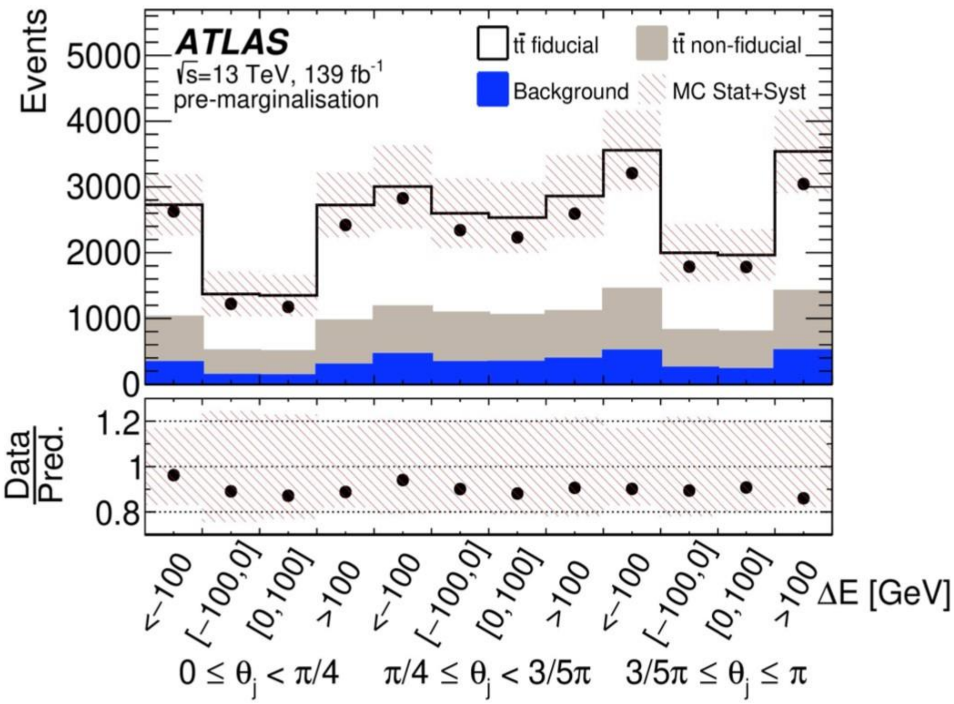
EPJC 82 (2022) 374

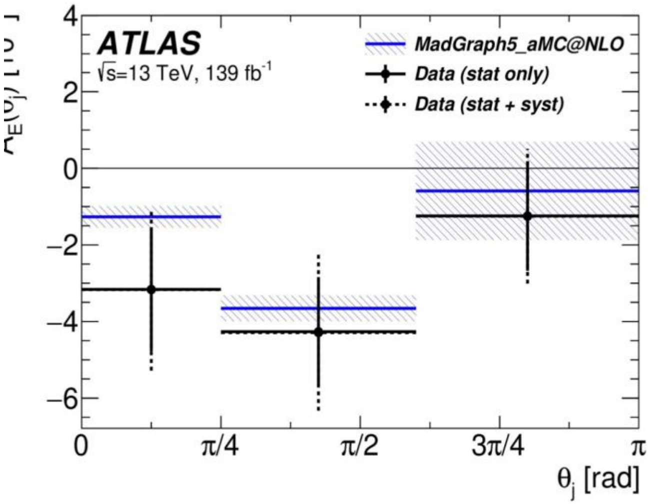
- ✓ Asymmetry between the energies of top and anti-top
- ✓ Measured in $t\bar{t}$+j events in boosted regime

$$A_E(\theta_j) \equiv \frac{\sigma^{\text{opt}}(\theta_j|\Delta E > 0) - \sigma^{\text{opt}}(\theta_j|\Delta E < 0)}{\sigma^{\text{opt}}(\theta_j|\Delta E > 0) + \sigma^{\text{opt}}(\theta_j|\Delta E < 0)}$$

$$\sigma^{\text{opt}}(\theta_j) = \sigma(\theta_j|y_{t\bar{t}j} > 0) + \sigma(\pi - \theta_j|y_{t\bar{t}j} < 0)$$

Angle between the jet and z-axis
Effect increases with jet pT



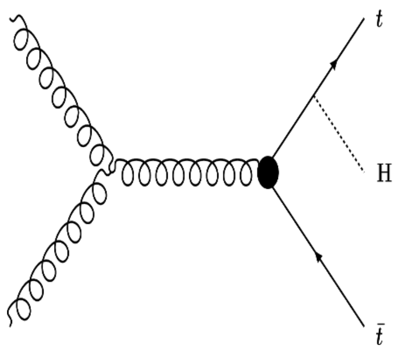


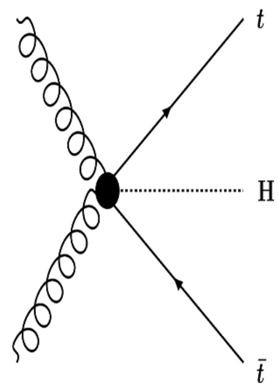
Agrees with prediction

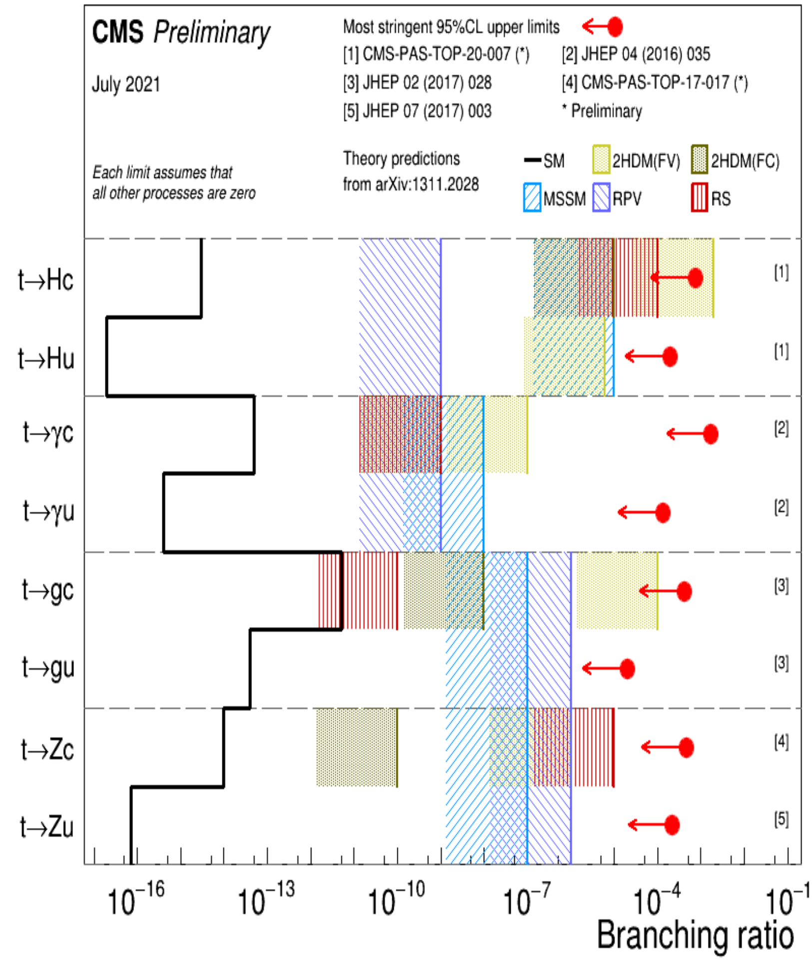
Statistically limited

Tool to search for new physics:

- ✓ Many BSM models are expected to involve top quarks. Possible to perform direct searches for new resonances and FCNC
- ✓ Use the precise measurements to set a limit on new operators in an EFT framework





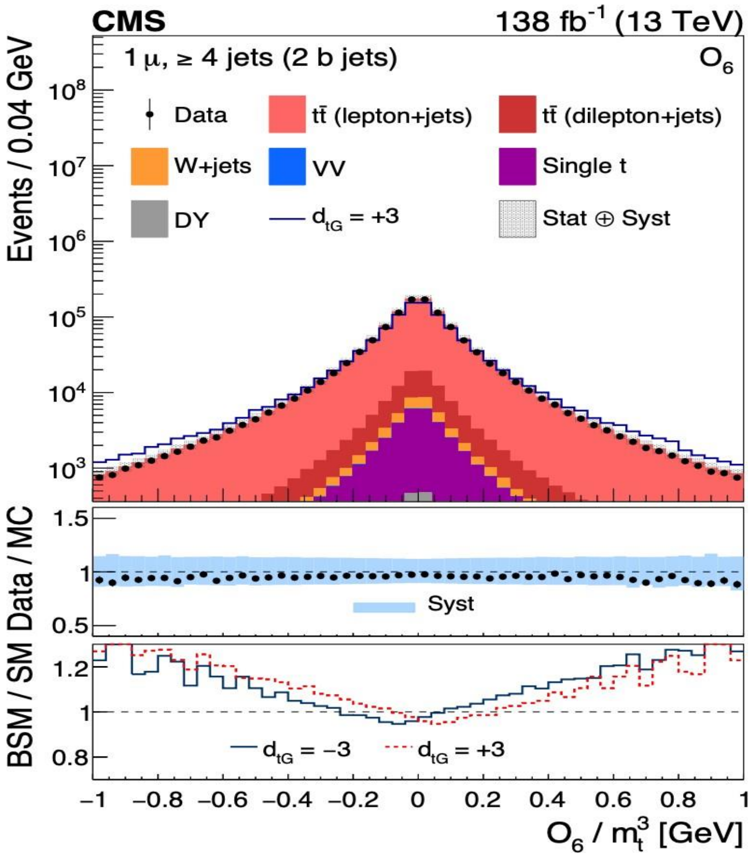


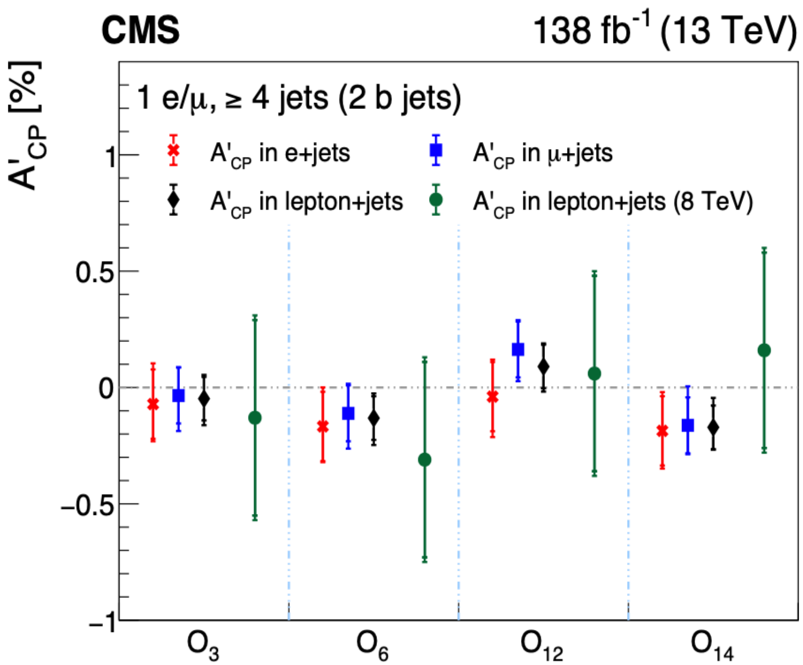
CP violation in ttbar

arXiv:2205.02314

- ✓ Construct 4 CP-sensitive observables
- ✓ Define and measure asymmetry

$$A_{CP} = \frac{N(O_i>0) - N(O_i<0)}{N(O_i>0) + N(O_i<0)},$$
$$i = 3, 6, 12, 14$$





0.04 ± 0.10 (stat) ± 0.07 (syst)

In agreement with SM value of zero

Flavor Changing Neutral Currents

FCNC: top couples to light quarks (u/c) and neutral bosons (γ,Z,H,g)

- ✓ Forbidden at tree level in SM
- ✓ Very small rates predicted
- ✓ Deviations would give hint for NP

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

Searches for FCNC

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arXiv:2208.11415

arXiv:2205.02537

✓ Improved limit by factors 3.3 to 5.4 from previous analysis

Coupling	BR limits $[10^{-5}]$ Expected	Observed
$t \to u\gamma$ LH	$0.88^{+0.37}_{-0.25}$	0.85
$t \to u\gamma$ RH	$1.20^{+0.50}_{-0.33}$	1.22
$t \to c\gamma$ LH	$3.40^{+1.35}_{-0.95}$	4.16
$t \to c\gamma$ RH	$3.70^{+1.47}_{-1.03}$	4.46

Improved limit by x2 from 8 TeV analysis

$\mathcal{B}(t \to u + g) < 0.61 \times 10^{-4}$

$\mathcal{B}(t \to c + g) < 3.7 \times 10^{-4}$

Large impact from systematics

$\mathcal{B}(t \to Zq)$ $[10^{-5}]$		
tZu	LH	6.2
tZu	RH	6.6
tZc	LH	13
tZc	RH	12

✓ Improved limit by factors 3 to 5 from previous analysis

$\mathcal{B}(t \to uH) < 0.94 \times 10^{-3}$, $\mathcal{B}(t \to cH) < 0.69 \times 10^{-3}$ — $H \to \tau\tau$

$\mathcal{B}(t \to uH) < 0.79 \times 10^{-3}$, $\mathcal{B}(t \to cH) < 0.94 \times 10^{-3}$ — $H \to bb$

$\mathcal{B}(t \to uH) < 0.19 \times 10^{-3}$, $\mathcal{B}(t \to cH) < 0.73 \times 10^{-3}$ — $H \to \gamma\gamma$

$t \to uZ$

$t \to u\gamma$

$t \to ug$

$t \to uH$

$t \to cZ$

$t \to c\gamma$

$t \to cg$

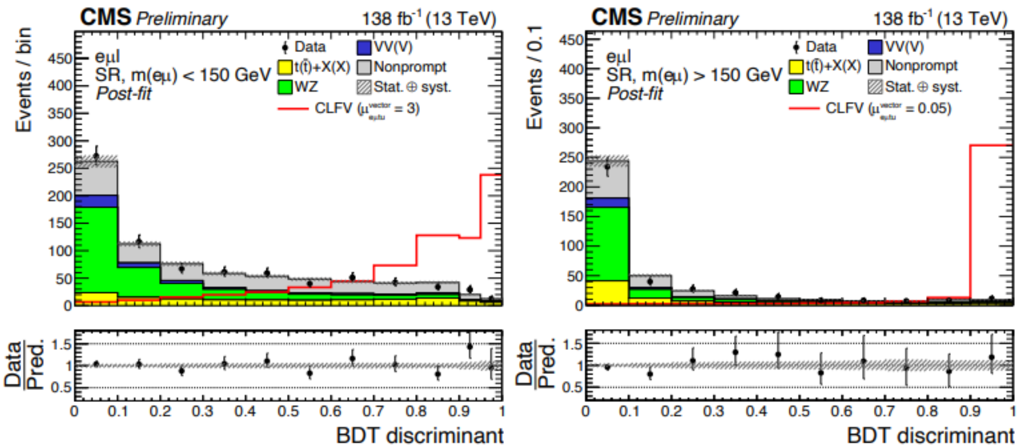
$t \to cH$

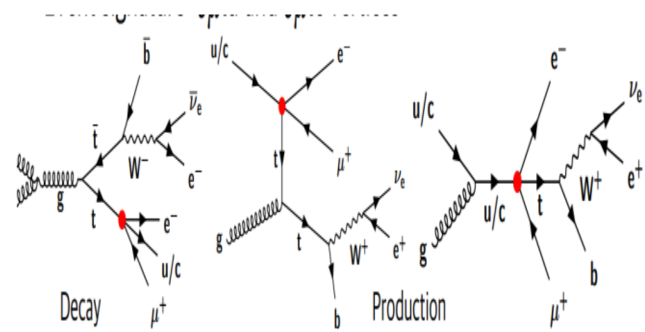
- All searches except tgq are statistically limited

gained sensitivity by including regions sensitive to couplings in top production and decay

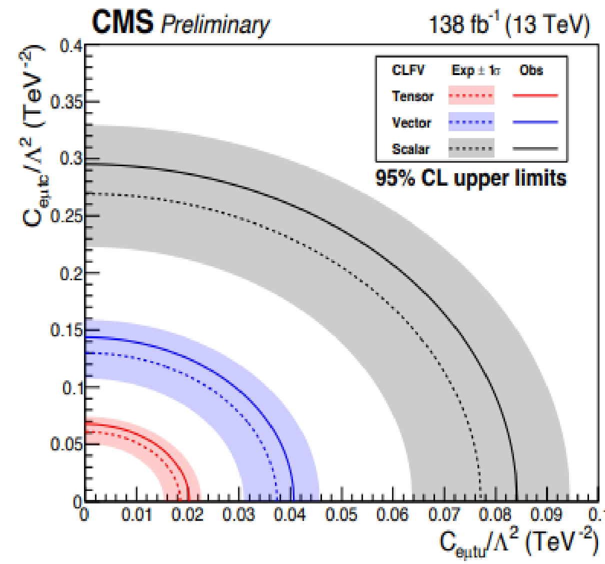
Charged Lepton Flavor Violation (CLFV)

- ✓ Search for CLFV in trilepton channel
- ✓ BDT for signal extraction





CLFV coupling	Lorentz structure	$C_{e\mu tq}/\Lambda^2$ (TeV^{-2}) exp $(-\sigma, +\sigma)$	obs	$\mathcal{B}(t \to e\mu q) \times 10^{-6}$ exp $(-\sigma, +\sigma)$	obs
$e\mu tu$	tensor	0.019 (0.015, 0.023)	**0.020**	0.019 (0.013, 0.029)	**0.023**
	vector	0.037 (0.031, 0.046)	**0.041**	0.013 (0.009, 0.020)	**0.016**
	scalar	0.077 (0.064, 0.095)	**0.084**	0.007 (0.005, 0.011)	**0.009**
$e\mu tc$	tensor	0.061 (0.050, 0.074)	**0.068**	0.209 (0.143, 0.311)	**0.258**
	vector	0.130 (0.108, 0.159)	**0.144**	0.163 (0.111, 0.243)	**0.199**
	scalar	0.269 (0.223, 0.330)	**0.295**	0.087 (0.060, 0.130)	**0.105**



In agreement with expected

CMS TOP-22-005

Dark Matter + top

Search for DM + ttbar(→l+jets,all hadr.)

- ✓ Shape of MET distribution
- ✓ Signature: ttbar+MET
- ✓ Top-tagging categorization
- ✓ Signal events at large MET

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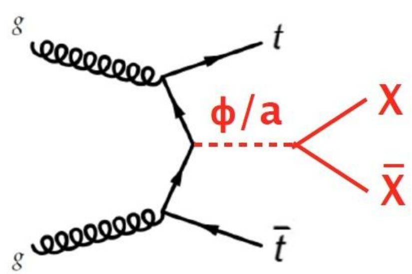
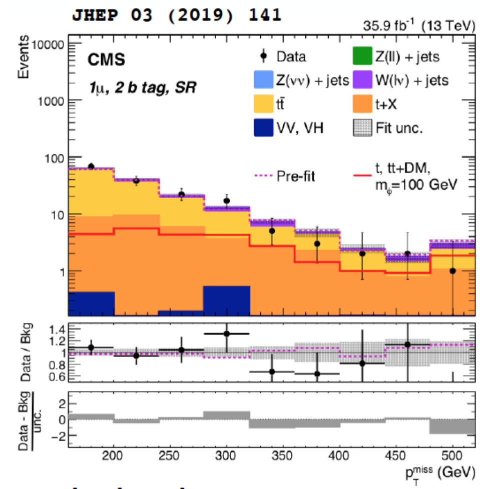
DM mediater

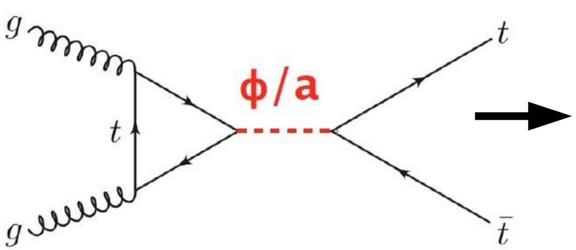


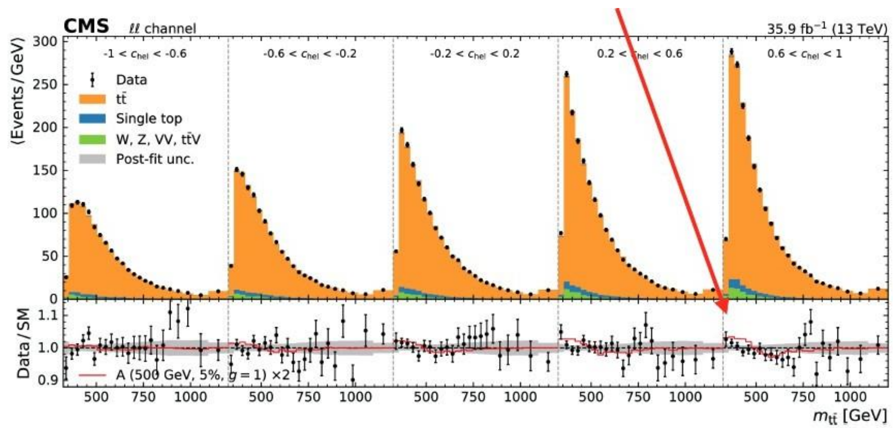
Dark Matter



Pseudo-scalar particles alter the m(tt) with a wiggle

Direct DM production



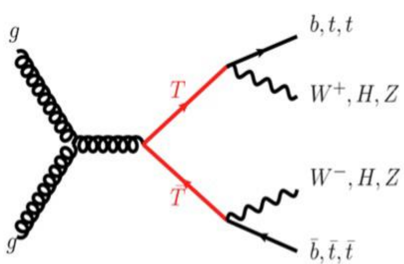


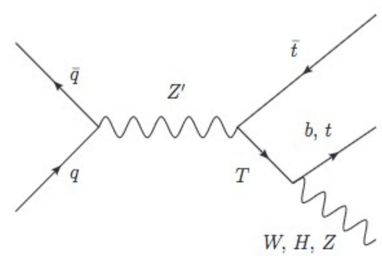
Vector-like quarks + top

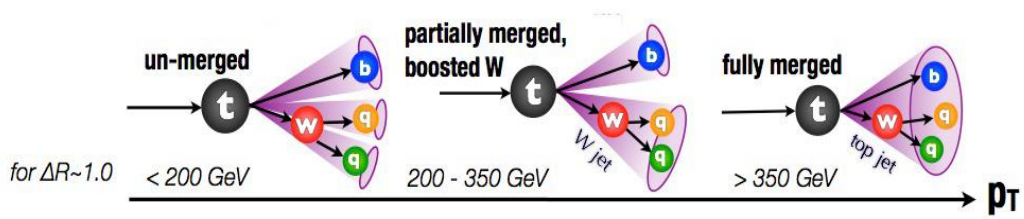
- ✓ Predicted in many BSM models, aim to solve the hierarchy problem
  - – in multiplets: singlet, doublet, triplet
  - – left- and right-handed component with same quantum numbers
- ✓ VLQs can mix with SM quarks and modify the couplings to the Z/W/Higgs
- ✓ Search for VLQ single and pair production
  - – Most searches assume VLQs couple/decay to SM particles (bosons and B2G quarks)
- ✓ Busy events, a lot of top quarks, bottom quarks, leptons and jets in final state

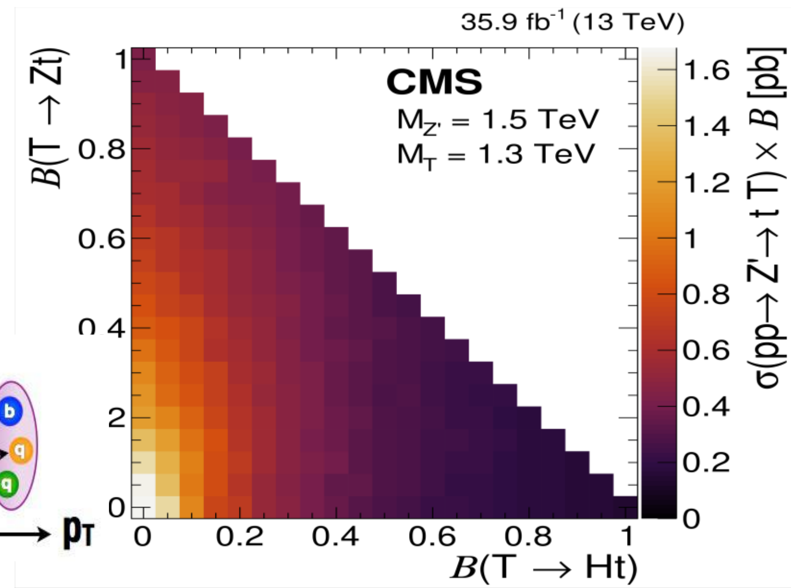
– Example: 2 tops in final state, look for resolved/merged top quark decays

– use top/H/W/Z taggers to find hadronic decays



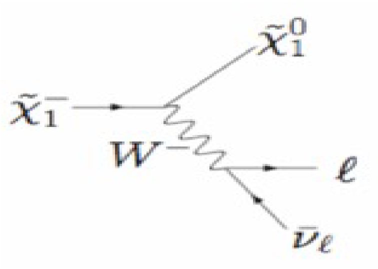






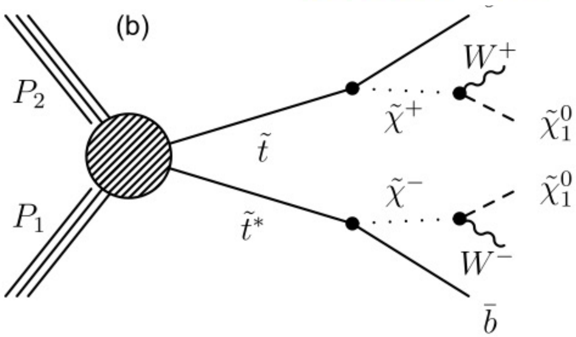
SUSY + Top

- ✓ SUSY is one plausible extension of the SM
- ✓ Due to the heavy top quark, mass splitting between 2 stops can be large, such that the lighter stop can be even lighter than the top quark
- ✓ Decays dictated by mass spectrum of other SUSY particles



Similar signature as in ttbar

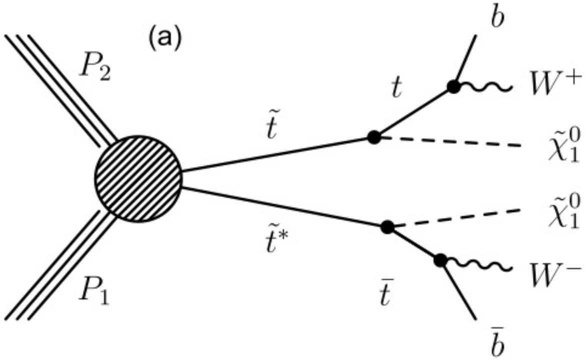
Light stop $m_{\tilde{t}_1} \lesssim m_t$



$$\tilde{t} \rightarrow b\tilde{\chi}^+ \rightarrow bW\tilde{\chi}_1^0$$

Heavy stop

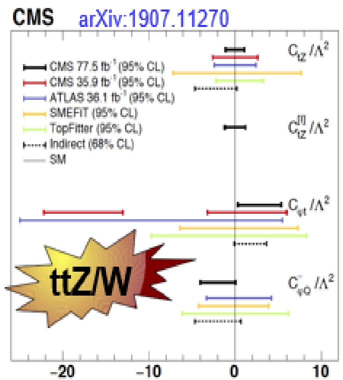
$$\tilde{t} \rightarrow t\tilde{\chi}^0$$



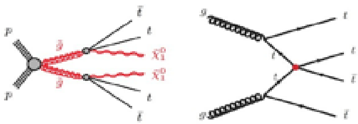
$$\tilde{t} \rightarrow t\tilde{\chi}_1^0 \rightarrow bW\tilde{\chi}_1^0$$

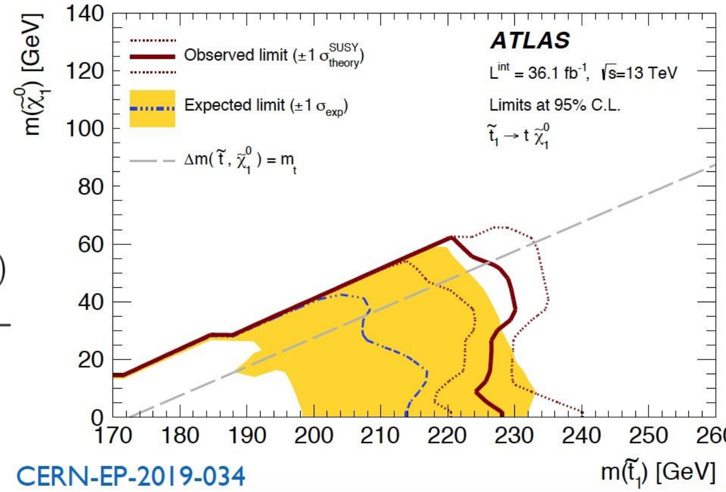
New friends for the top ?

Effective Field Theory (EFT) approach is now widely used to search for off-resonance effects due to BSM contributions

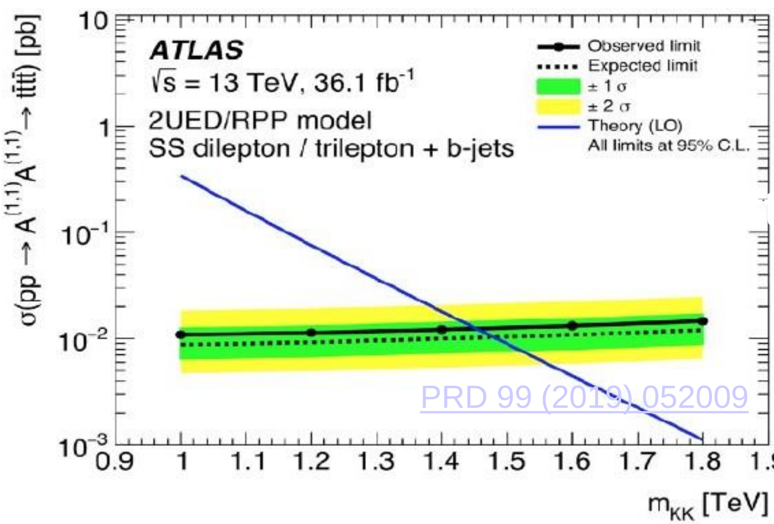


$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)} \mathcal{O}_i^{(6)}}{\Lambda^2}$$

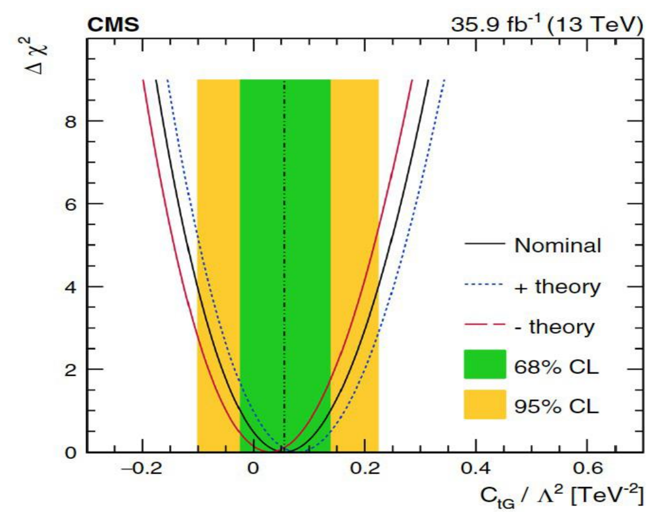


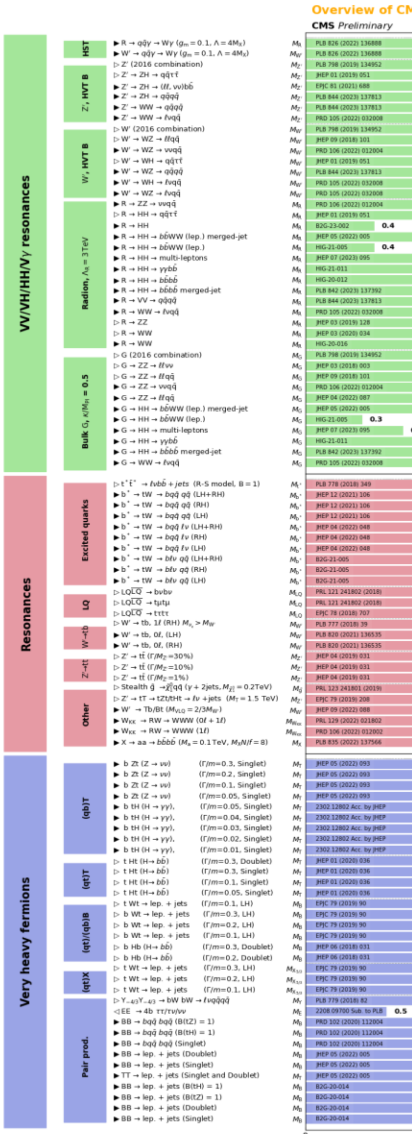


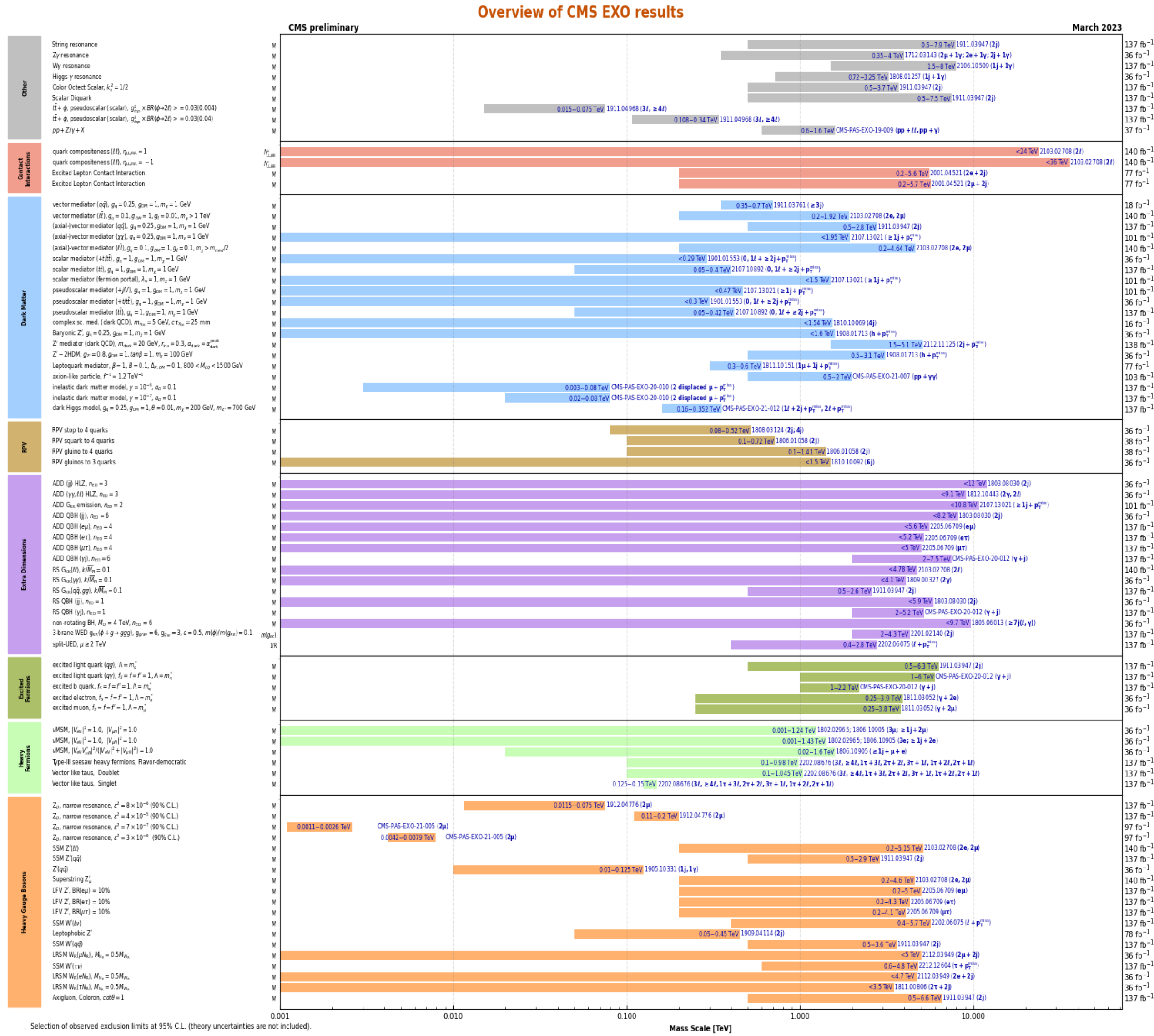
PRD 100 (2019) 072002



PRD 99 (2019) 052009



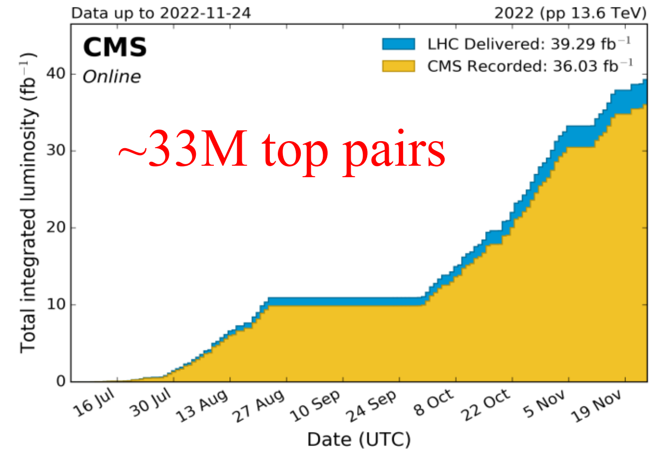

Overview of CM
CMS Preliminary
VV/VH/HH/Vγ resonances
Resonances
Very heavy fermions
HST
Z', HVT B
W', HVT B
Radion, Λ_R = 3TeV
Bulk G, k/M_Pl = 0.5
Excited quarks
LQ
W'→tb
Z'→tt
Other
(qb)T
(qt)T
(qt)/(qb)B
(qt)X
Pair prod.


Overview of CMS EXO results
CMS preliminary
March 2023
Other
Contact Interactions
Dark Matter
RPV
Extra Dimensions
Excited Fermions
Heavy Fermions
Heavy Gauge Bosons
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).
Mass Scale [TeV]

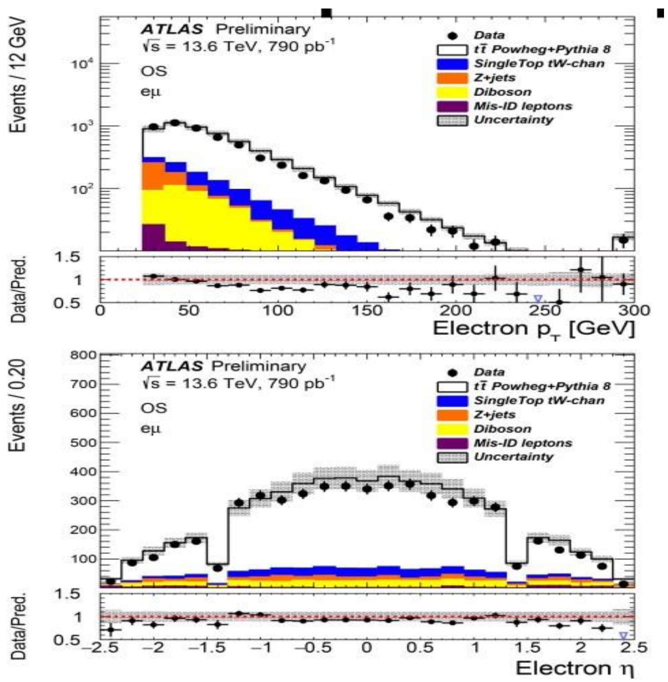
Run3 started!

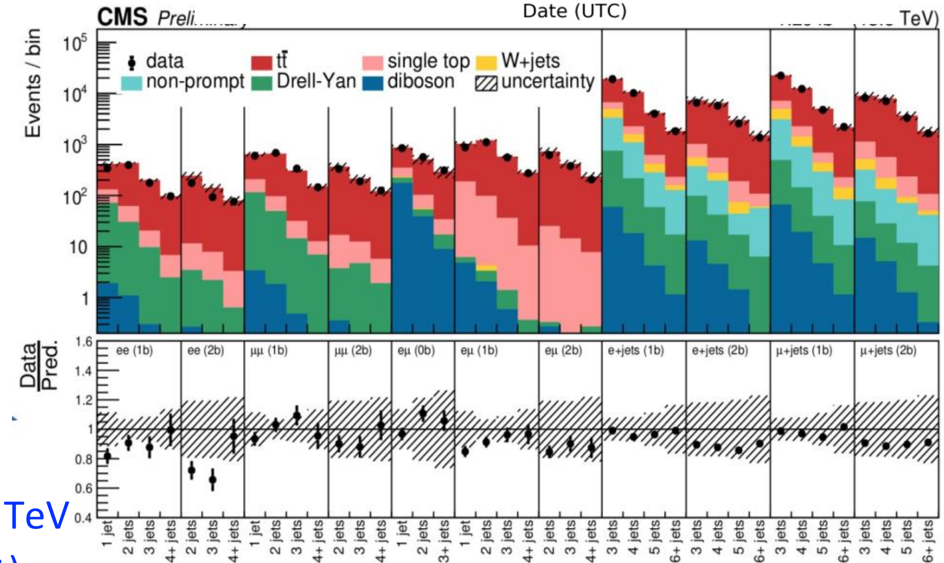
CMS-PAS-TOP-22-012

- ✓ Top quark is still there!
- ✓ Allows to exercise the analysis chain and validate the performance of all components



~33M top pairs





$$\sigma_{t\bar{t}} = 887^{+43}_{-41}(\mathrm{stat+sys}) \pm 53(\mathrm{lumi})\ \mathrm{pb}$$

- ✓ Assuming ~250/fb per experiment at 13.6 TeV
- ✓ And cross section ~920 pb (tt) + ~330 pb (t)
- ✓ Run 3 will provide twice more ttbar and single top data sets

Top at HL-LHC

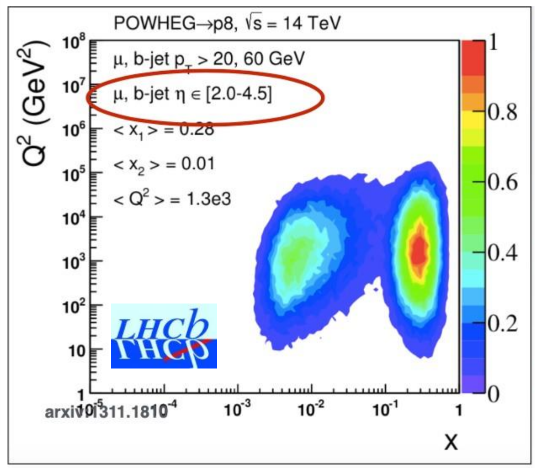
Very forward top (LHCb): access to high-x PDF, essential to understand potential signs for new heavy states

HL-LHC
- 14 TeV → not a bump-hunt machine
- 3-4 ab-1
- 140-200 Pileup

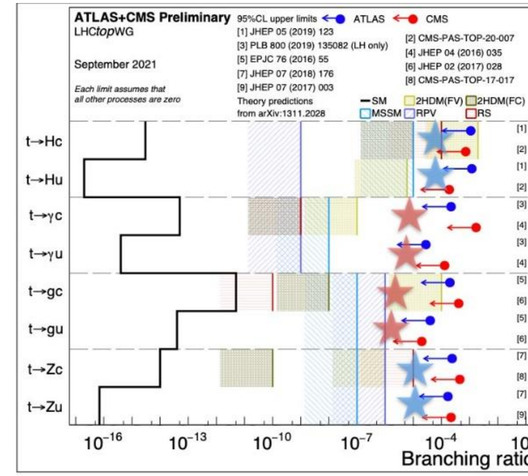
Huge yield (in terms of approx. top units)
- 3B ttbar events
- 300M tW
- 30M s-channel
- 3M ttV
- 30k 4 top

Unprecedented challenges for detectors and reconstruction
- Radiation
- Occupancy
- Particle density

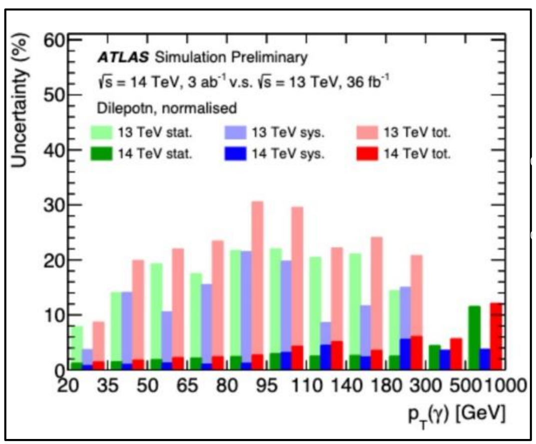
Only seen 5% of the LHC data



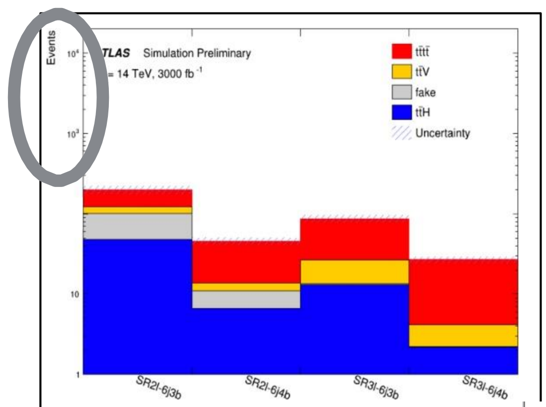
- FCNC: expect improvements by ~1 order of magnitude



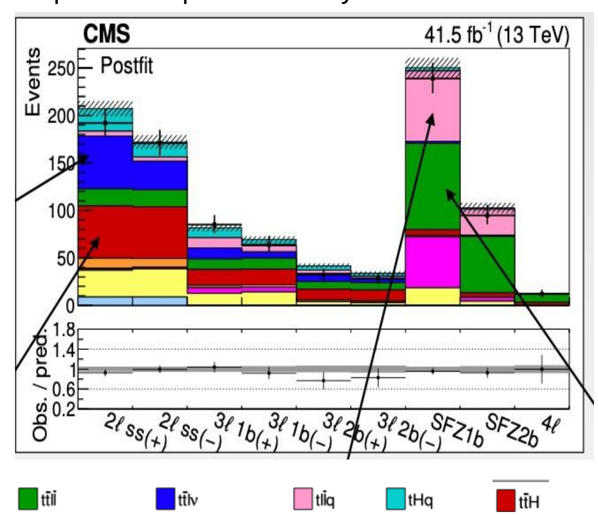
ttgamma:



4top: improvement up to ~11% possible, constraints on 4-fermion operators

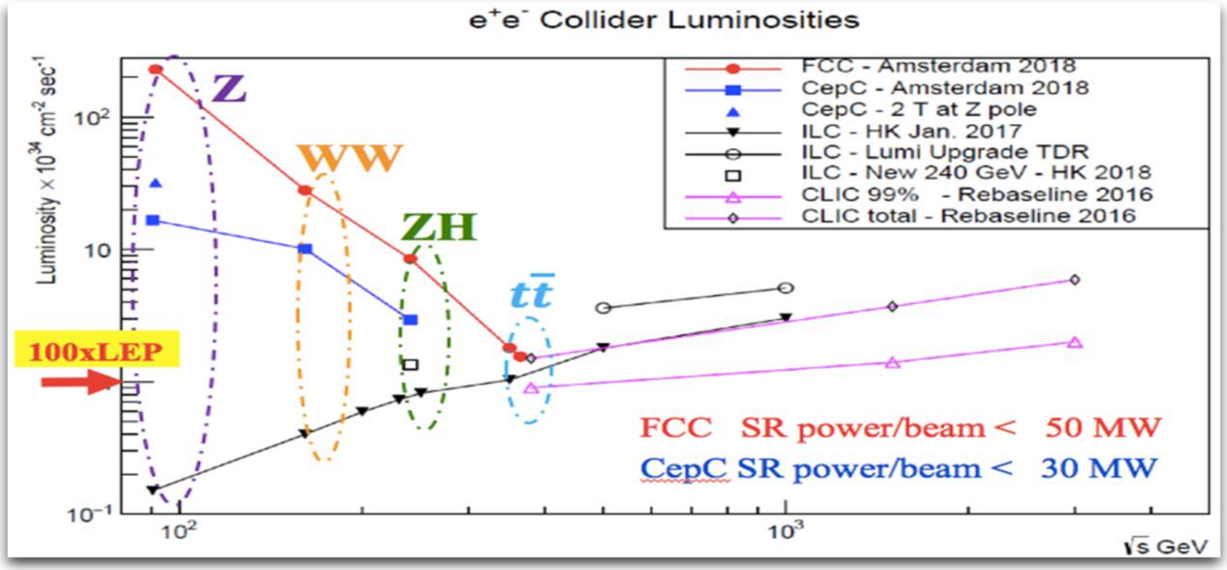


- Exploit multi-process analyses



Top at CEPC

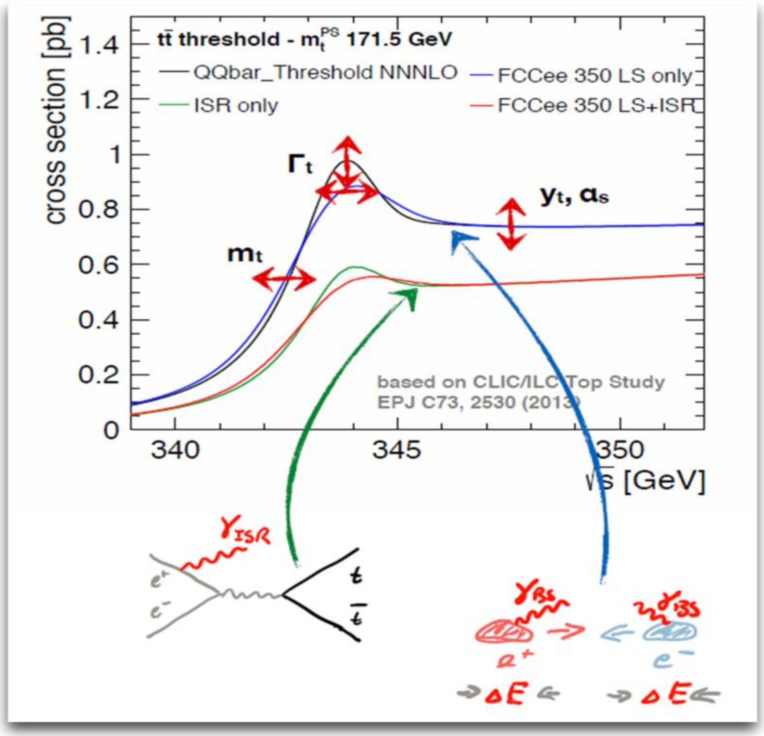
- CEPC will be a versatile machine with many opportunities
  - ✓ Higgs factory @~240 GeV
  - ✓ Diboson factory @~160 GeV
  - ✓ Z factory @~90 GeV



- @~360 GeV it can also be a playground for Top precision measurements, Higgs complementary measurements and also BSM searches

Top Mass at CEPC

- ee-colliders provide not only the top reconstruction method but also the tt threshold scan
- The scan is made against $\sqrt{s}$ and cross-section is the direct observable
- This brings measurements of top mass and a bunch of other parameters
  - Top width
  - Top Yukawa coupling
  - α_S



$\sqrt{s}$ (GeV)	$\Delta\, m_{top}$	$\Delta\, \Gamma_{top}$	$\Delta\, \alpha_S$
342.75	9 MeV	343 MeV	0.00041
344.00	> 50 MeV	26 MeV	0.00047
343.50	15 MeV	40 MeV	0.00040

In the table, 342.75 GeV, 344.00 GeV and 343.50 GeV are optimal energy points for top quark mass, width and α_S, respectively

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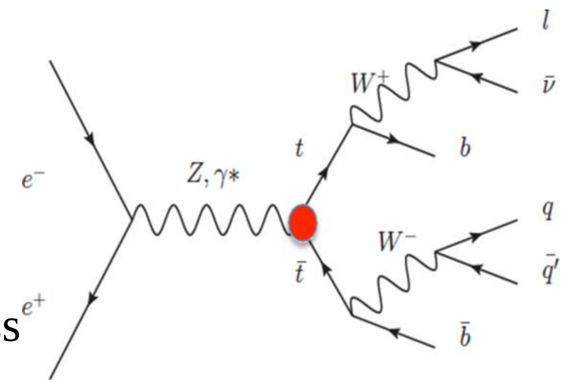
PKU + IHEP

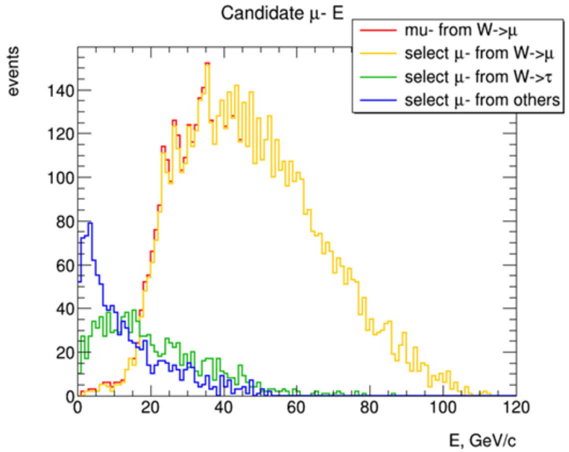
Top electroweak couplings at CEPC

- ✓ Set constraints on new physics scale
- ✓ Very sensitive to BSM Physics
- ✓ Test of composite Higgs models

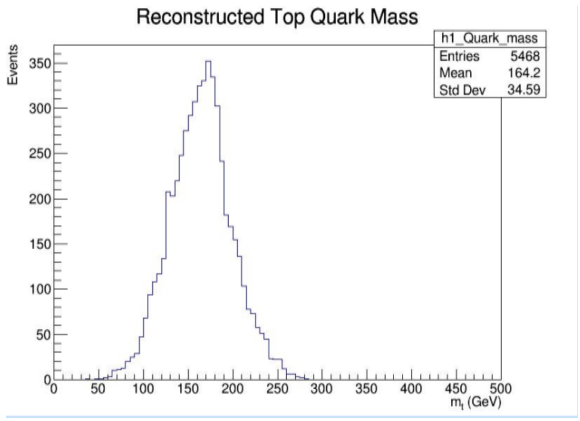
At the CEPC, the ttV (V = γ, Z) couplings could be probed directly through the top pair production process



- ☐ The energy and the angular distributions of the decay products, in particular, the charged lepton and the b-quark,… are powerful tools to disentangle and access different components of the ttZ and ttγ.



Xiaoxu Zhang (NJU)



Mustapha Biyabi (IHEP)

In progress
NJU + IHEP

Summary I

- ✓ Top is the heaviest fundamental particle discovered so far
- ✓ ATLAS and CMS provided many results with full Run2 dataset:
  - ➢ High precision measurements
  - ➢ Searching for very rare processes
  - ➢ Measuring the top properties and couplings
  - ➢ Setting constraints to new physics
- ✓ The very first look of the Run-3 data gives the results at the highest CM energy in record!
- ✓ So far, all measurements of top quark showed good agreement with SM predictions

Summary II

✓ What can we learn from Run2?

- Theoretical advancements are still necessary to improve simulation and to understand / reduce uncertainties
- Machine learning has significant role in top physics!

✓ What do we expect for Run3?

- Statistical limited Measurements and searches will be improved
- More data will allow for reaching higher region (pT or masses) sensitive to BSM
- Advanced algorithms will enhance the sensitivity: –Higgs, multi-top, boosted objects, SUSY, Dark matter, etc.

More results with more data are coming…..

As the future: 3B ttbar at HL-LHC and XX ttbar at CEPC

基本粒子的发现(加速器)

1932 Cockcroft-Walton直线质子加速器
1929 Lawrence 回旋加速器
1939 Lawrence 回旋加速质子至100 MeV
1950 Berkeley 质子6.3 GeV 1953 Brookhaven 3.3 GeV质子 同步加速器
1954.9.29 11个西欧国家批准成立CERN
1959 CERN 26 GeV 质子同步加速器
1962 Stanford建造直线电子加速器(20 GeV)
1967 达到设计指标=> 深度非弹，结构函数，
1973 夸克"登台亮相"（渐进自由发现）
1974 丁肇中(Brookhaven) Richter(SLAC)发现J/ψ(十一月革命)
1977 Martin Perl(SLAC) 发现τ
1977 Lederman在费米实验室(E288)发现Y (b-夸克)
1983.1 鲁比亚(CERN SPS UA1/UA2) 发现W
1983.6 UA1发现Z

1960-70's

- ✓ 1968 FNAL开始建造LINAC
- ✓ 1973-1979 Tevatron对撞机研发
- ✓ 1976 开始研发CDF探测器

- ✓ 1971.2.19 CERN开始建造SPS
- ✓ 1976 提议改建为对撞机
- ✓ 1978.6.29 UA1实验获批

1980's

- ✓ 1981 CDF 概念设计完成
- ✓ 1981 提议D0实验
- ✓ 1982.7.1 开始建造CDF
- ✓ 1983 FNAL建成Tevatron
- ✓ 1984.11 D0实验设计完成
- ✓ 1986.11.30 1.8 TeV $p\bar{p}$对撞
- ✓ 1989 CDF 开始 Run 1升级

- ✓ 1981.7.10 SPS 第一次$p\bar{p}$对撞，$\sqrt{s}$ = 540 GeV
- ✓ 1983.1.25,UA1发现W(新闻发布)
- ✓ 1984.10.17, Carlo Rubbia, Simon van der Meer获诺奖

- ✓ 1981 LEP 立项
- ✓ 1983.9.13 LEP破土动工
- ✓ 1988.2.8 LEP隧道竣工
- ✓ 1989.8.13 LEP开始对撞(Ecm = 91 GeV)

- ✓ 1981 KEK建造TRISTAN对撞机
- ✓ 1989 KEK关闭TRISTAN对撞机

1990's

- ✓ 1991 D0建造完成
- ✓ 1992.2 D0安装完成
- ✓ 1992.5 D0开始取数
- ✓ **1995 CDF/D0 发现顶夸克**
- ✓ 1992 LHC Expression of Interest
- ✓ 1995.10 LHC完成设计报告
- ✓ 1999.5 LEP质心能量达到192 GeV
- ✓ 2000 LEP质心能量达到200 GeV
- ✓ 2000.11.2 LEP 关机

2000's

- ✓ 2001 Tevatron Run 2
- ✓ 2009.11 LHC $\sqrt{s} = 900$ GeV pp 对撞

2010's

2010.2 LHC 7 TeV pp对撞

2011.9.30 Tevatron 停机

2011 CMS/ATLAS 取得 5/fb 对撞数据

2012 CMS/ATLAS取得20/fb 对撞数据

2012.7.2 CDF/D0 发布希格斯粒子迹象

2012.7.4 CERN新闻发布:CMS/ATLAS发现希格斯粒子

2010.2 LHC 7 TeV pp对撞

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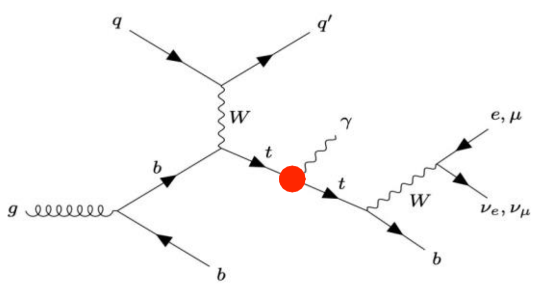
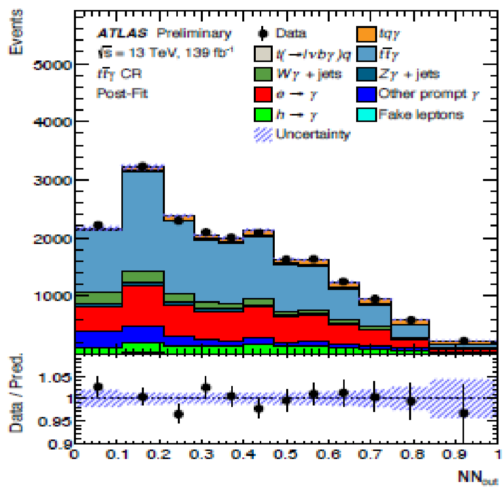
tqγ production

arXiv:2302.01283
Submitted to PRL

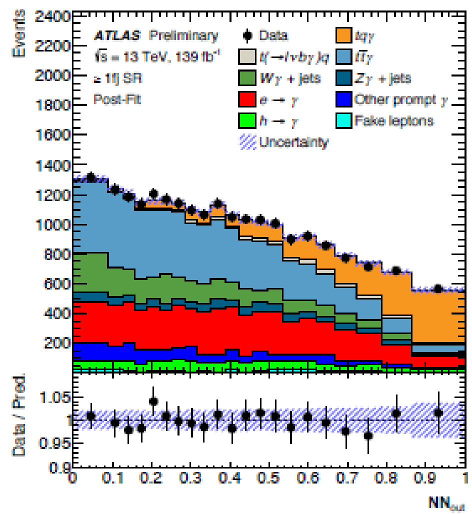


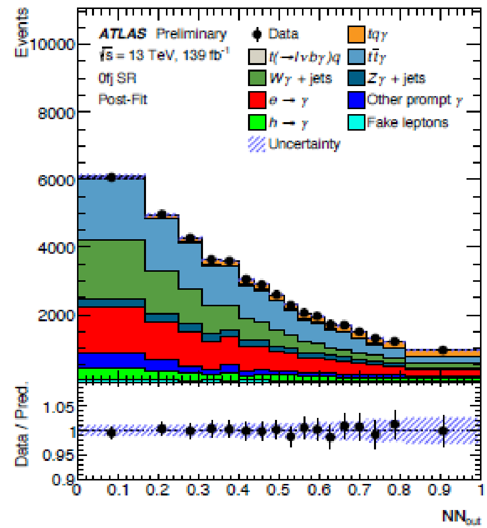
- ✓ **First evidence from CMS using ~36/fb of data**
- ✓ **New ATLAS analysis with full run 2 data**

Largest background from ttγ



Signal regions (NN)





Observed (expected) significance is 9.1σ (6.7σ)

~40% higher that prediction

Parton level cross section: $\sigma(tq\gamma)\,\mathcal{B}(t \to \ell\nu b) = 580 \pm 19(\text{stat.}) \pm 63(\text{syst.})\text{fb}$

Particle level cross section $\sigma(tq\gamma)\,\mathcal{B}(t \to \ell\nu b) + \sigma(t \to \ell\nu b\gamma)q = 287 \pm 8(\text{stat.})^{+32}_{-31}(\text{syst.})\text{fb}$

Compatible with the SM within 2.5(1.9)σ at parton(particle) level

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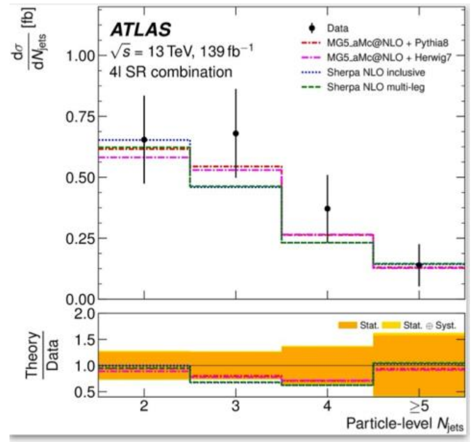
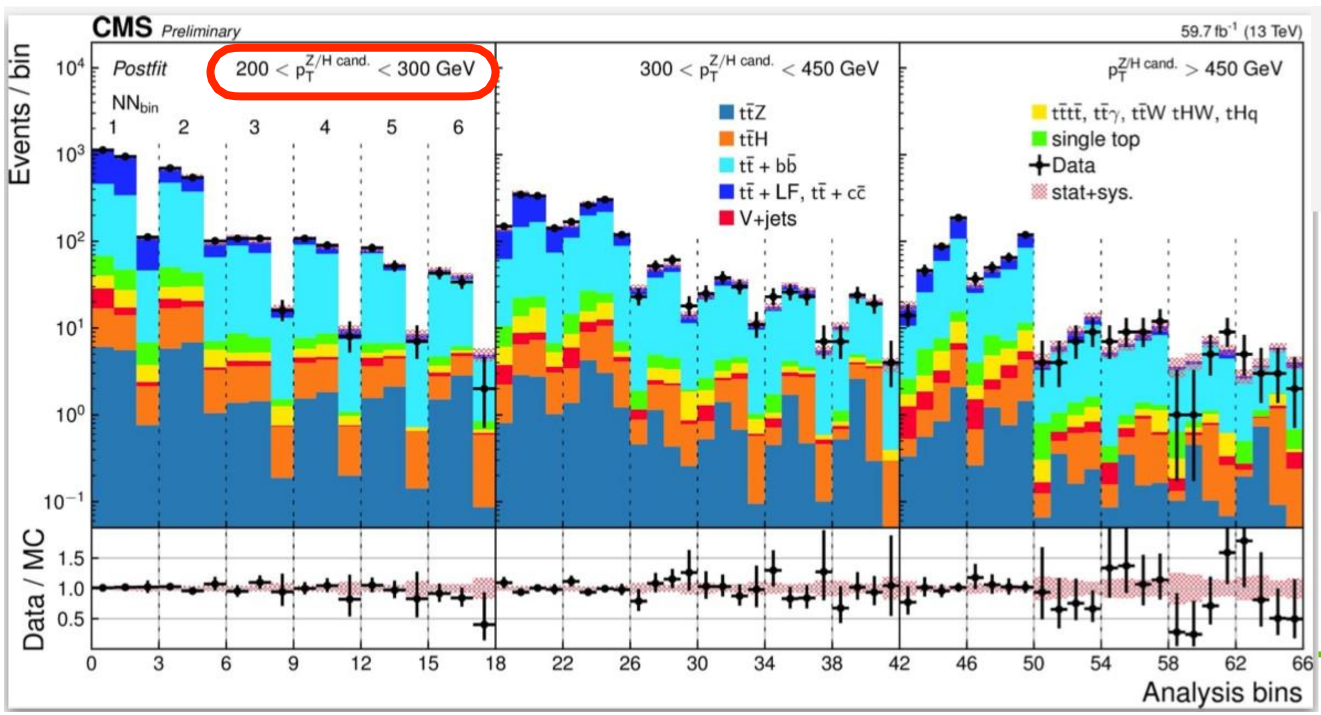
ttZ measurements

Channel	$\mu_{t\bar{t}Z}$
Trilepton	$1.17 \pm 0.07\,(\text{stat.})\ ^{+0.12}_{-0.11}\,(\text{syst.})$
Tetralepton	$1.21 \pm 0.15\,(\text{stat.})\ ^{+0.11}_{-0.10}\,(\text{syst.})$
Combination ($3\ell + 4\ell$)	$1.19 \pm 0.06\,(\text{stat.})\ \pm 0.10\,(\text{syst.})$

- ✓ Precision 10%
- ✓ Slightly higher than prediction

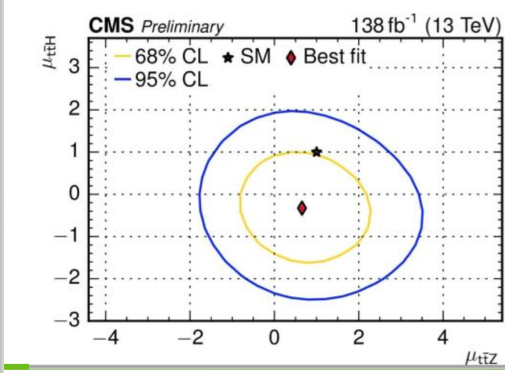


➢ Measurement of ttZ(bb) and ttH(bb) in boosted regime arXiv:2208.12837



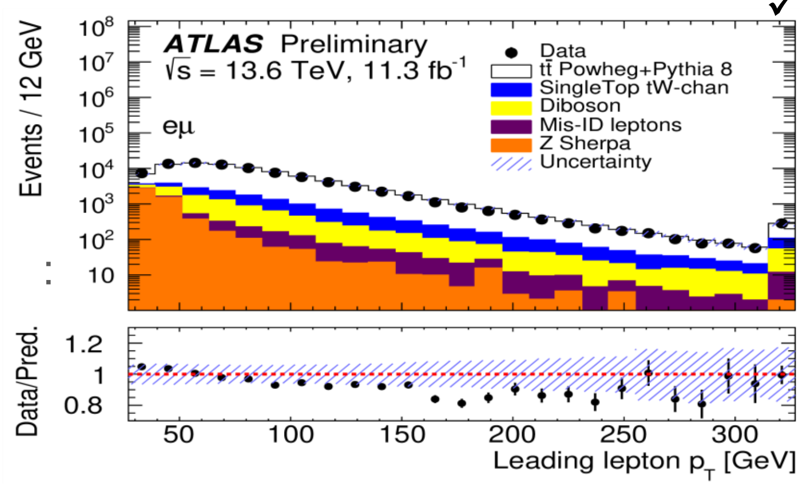
Signal strength	Observed	Stat.
$\mu_{t\bar{t}Z}$	$0.65\ ^{+1.04}_{-0.98}$	$^{+0.80}_{-0.75}$
$\mu_{t\bar{t}H}$	$-0.27\ ^{+0.86}_{-0.83}$	$^{+0.72}_{-0.65}$

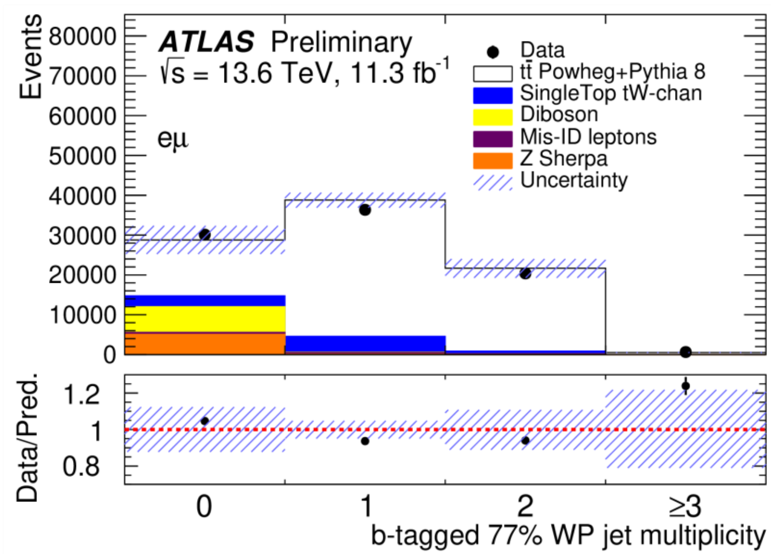
Limited by statistics



Top pair & Z boson production at new energy

Top enriched eμ events





✓ **ATLAS measured inclusive ttbar, fiducial Z boson cross-sections, and the ratio at 13.6 TeV**

- Limited by the preliminary luminosity, but cancelled for the ratio!
- Measured values are consistent with the SM prediction using the PDF4LHC21 PDF set.

$$\sigma(t\bar{t}) = 859 \pm 4\ _{(\text{stat})} \pm 22\ _{(\text{syst})} \pm 19\ _{(\text{lumi})}\ \text{pb}$$

$$R_{t\bar{t}/Z} = 1.144 \pm 0.006\ _{(\text{stat})} \pm 0.022\ _{(\text{syst})} \pm 0.003\ _{(\text{lumi})}$$

ATLAS-CONF-2023-006