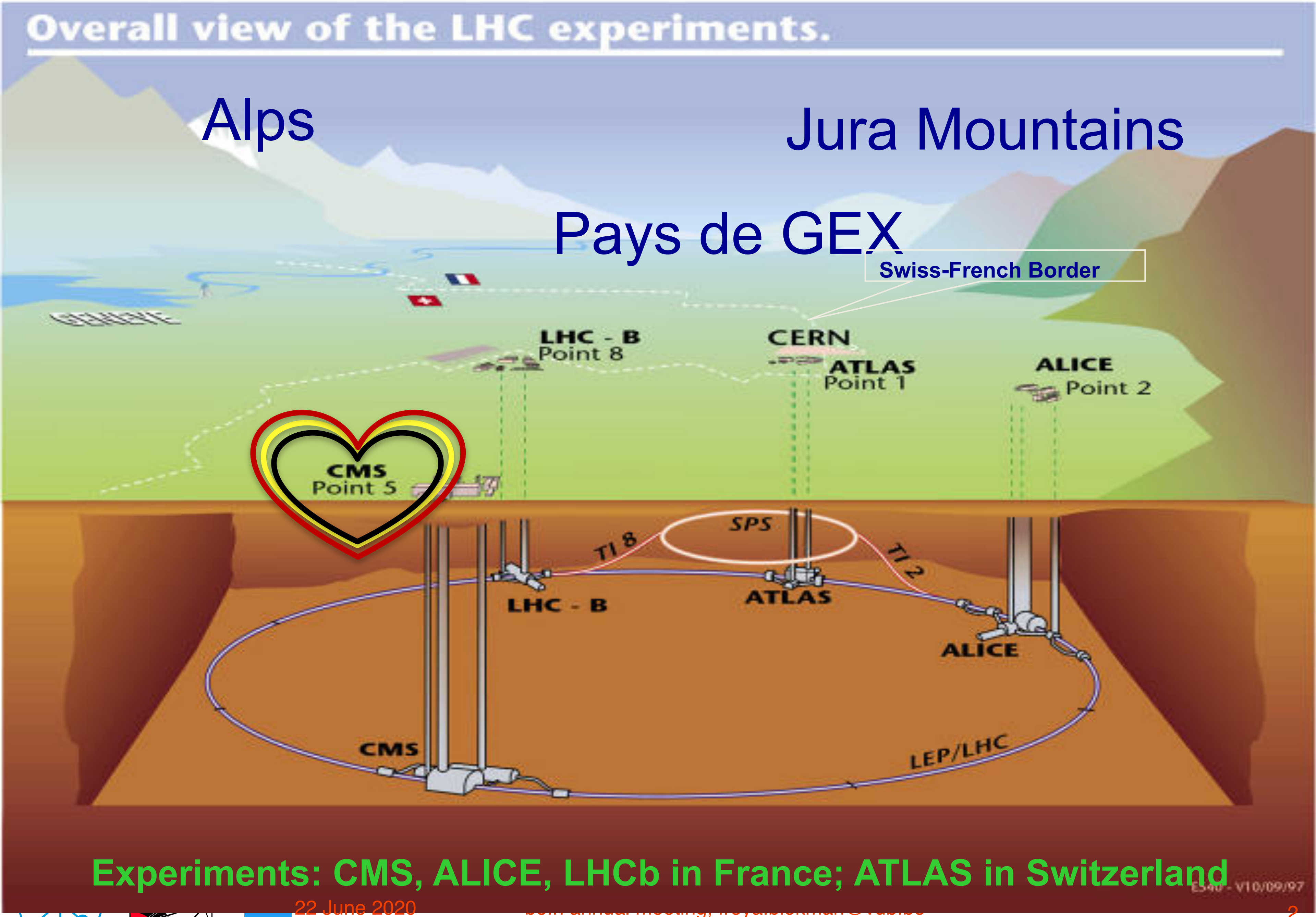
four top quarks

(Experiment)

Slides largely taken also from these talks (both highly recommended):
F. Déliot https://moriond.in2p3.fr/QCD/2023/MondayMorning/Deliot.pdf (ATLAS tttt obs)
K. Skovpen https://indico.cern.ch/event/1231799/attachments/2619648/4528902/kskovpenCERN.pdf (CMS tttt obs)


Overall view of the LHC experiments.
Alps
Jura Mountains
Pays de GEX
Swiss-French Border
GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
Experiments: CMS, ALICE, LHCb in France; ATLAS in Switzerland

LHC: search engine

"Physics beyond the standard model"

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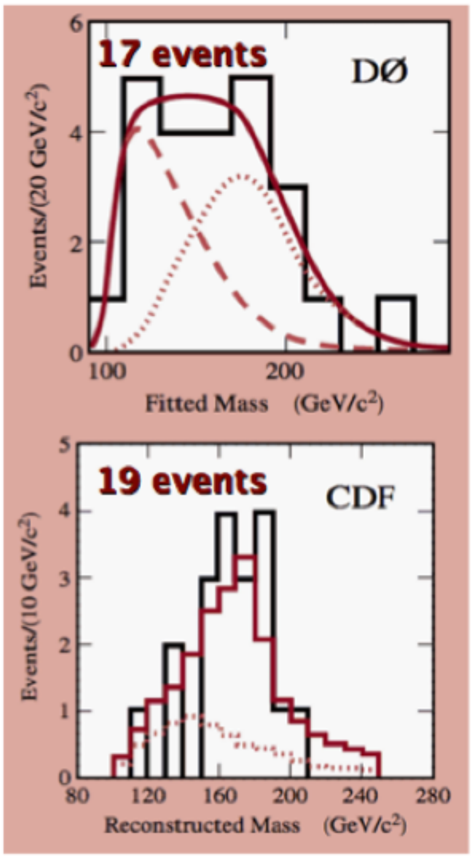
Rates:
Top quark: 600/minute
Higgs boson: 30/minute
BSM: ?

Energy: 7,8,13,14 TeV
Protons/Bunch: 1.5 10^{11}
Bunches/beam: ~3500
Bunch crossing: 40 MHz

History top quark – at the start of LHC

discovery

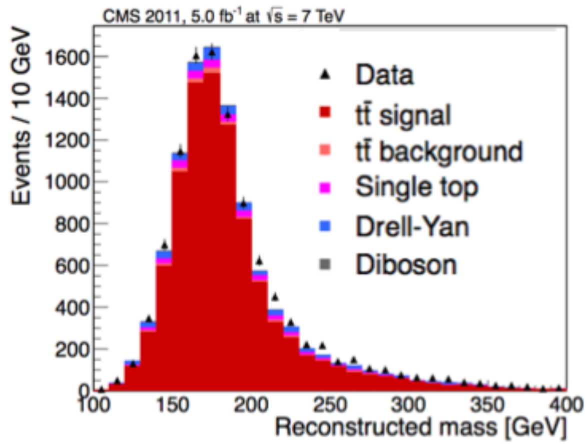
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

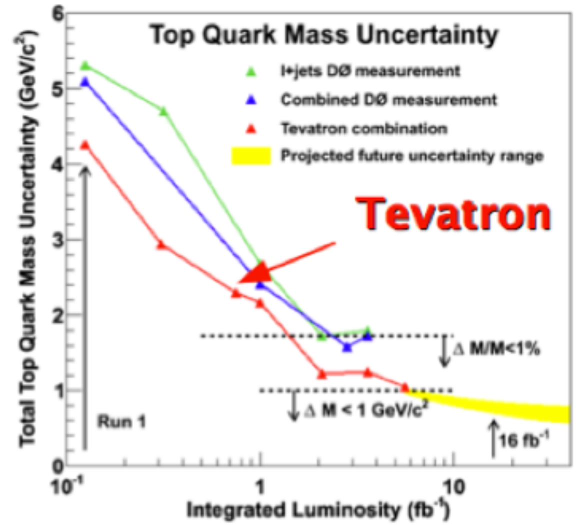
2011

10000s of events



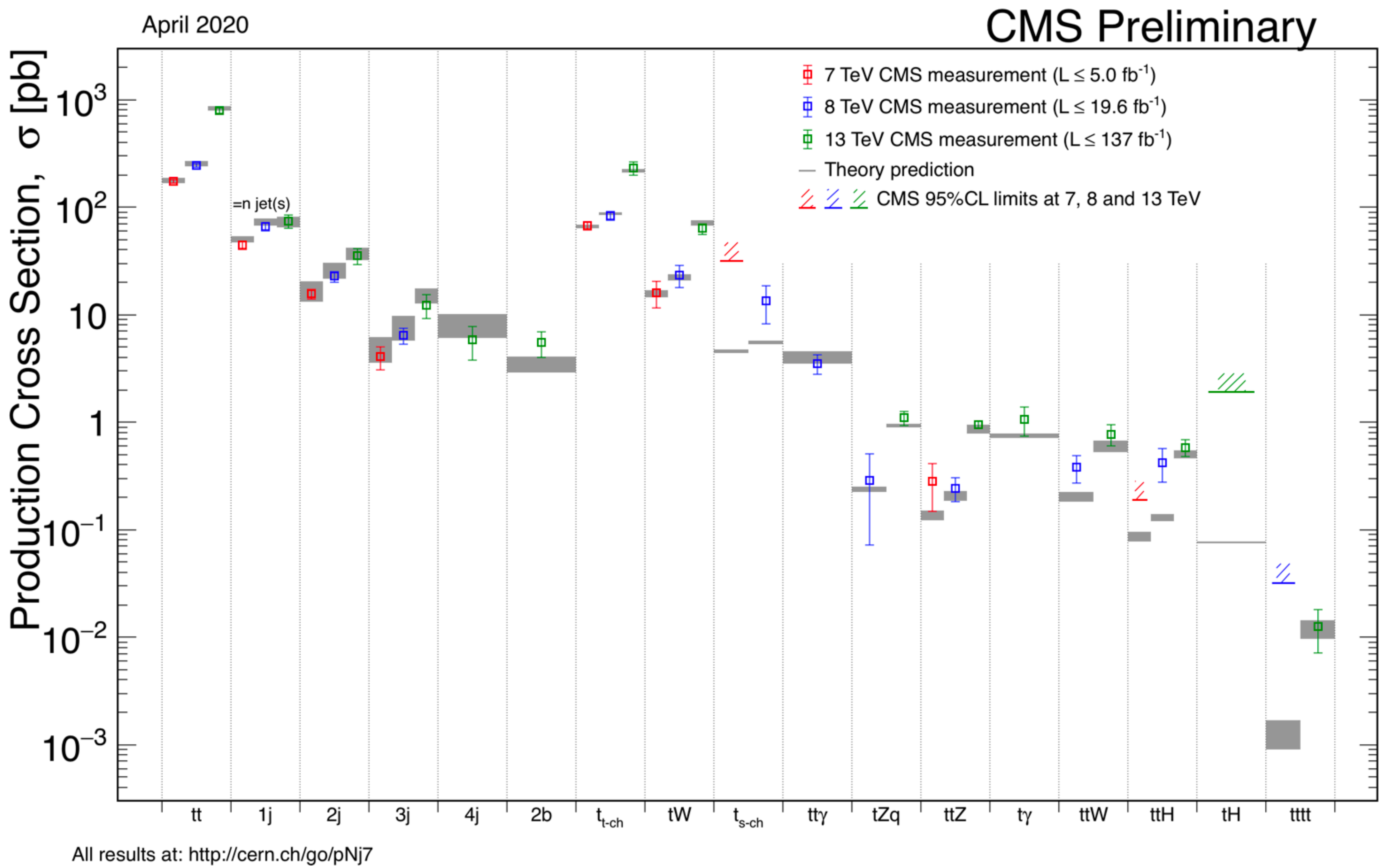
LHC: top quark factory

precision

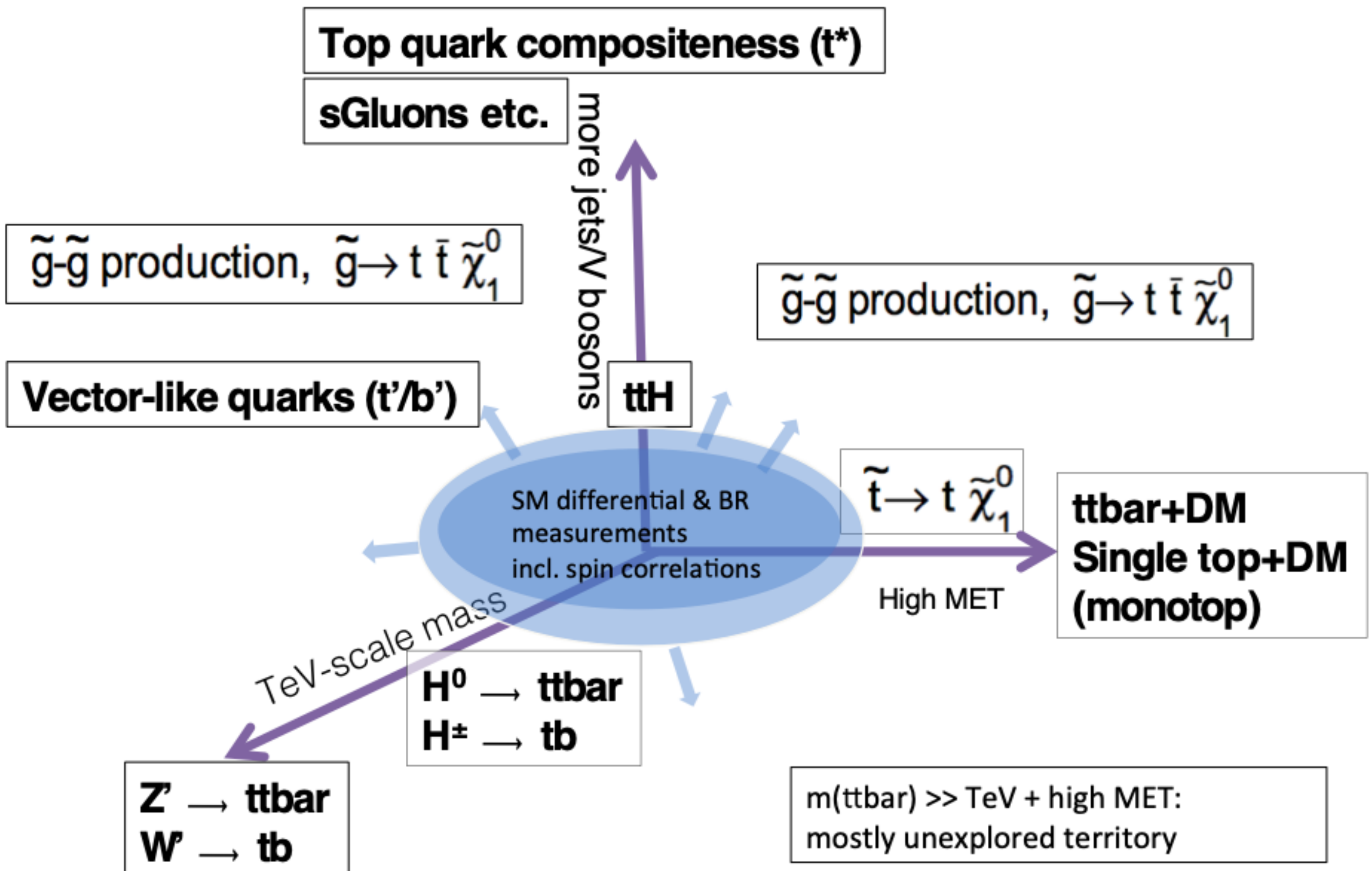


searches

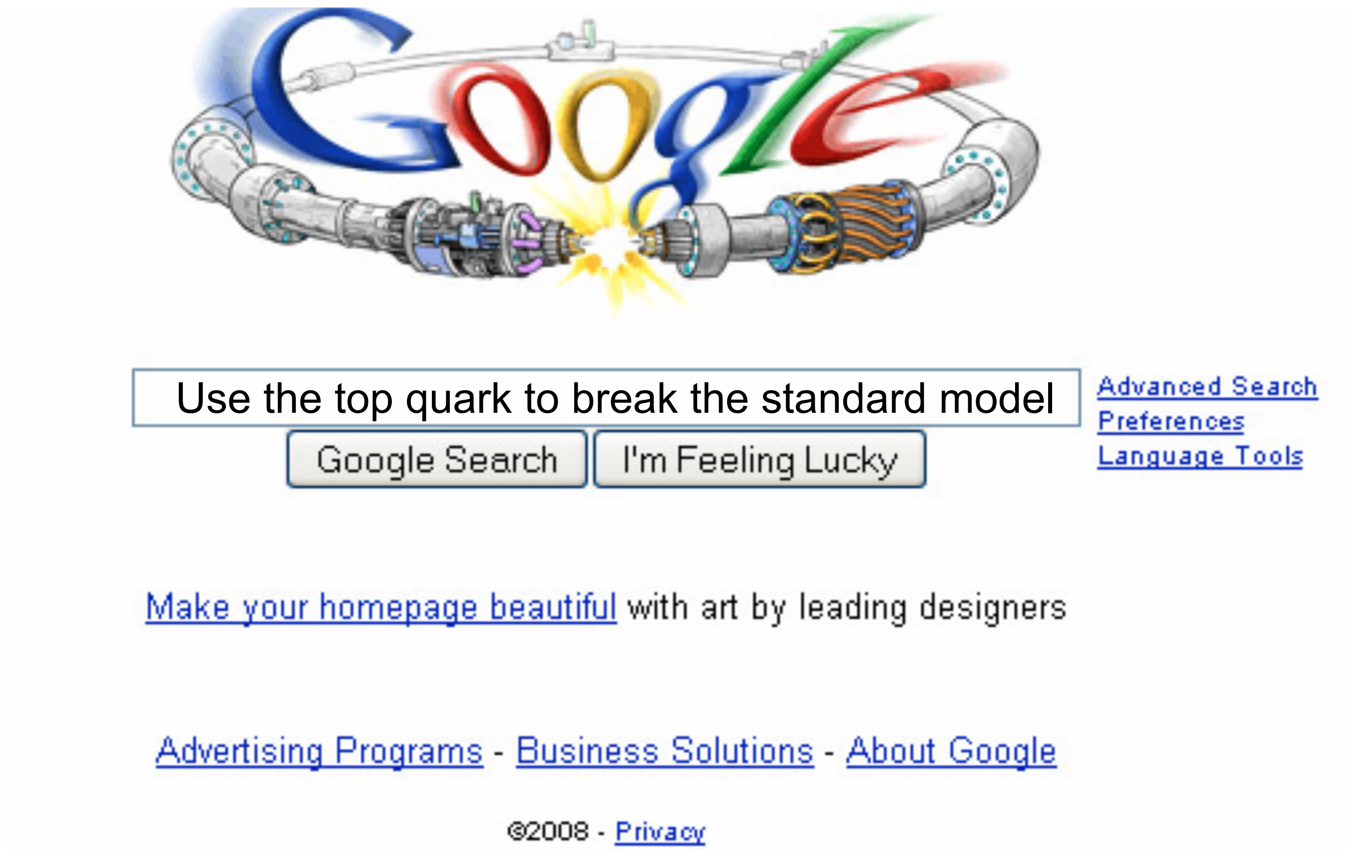
Top quark: now



BSM signatures in the ttbar phase space



See also: Czakon et al. arXiv:1501.01112


Google
Use the top quark to break the standard model
Google Search
I'm Feeling Lucky
Advanced Search
Preferences
Language Tools
Make your homepage beautiful with art by leading designers
Advertising Programs - Business Solutions - About Google
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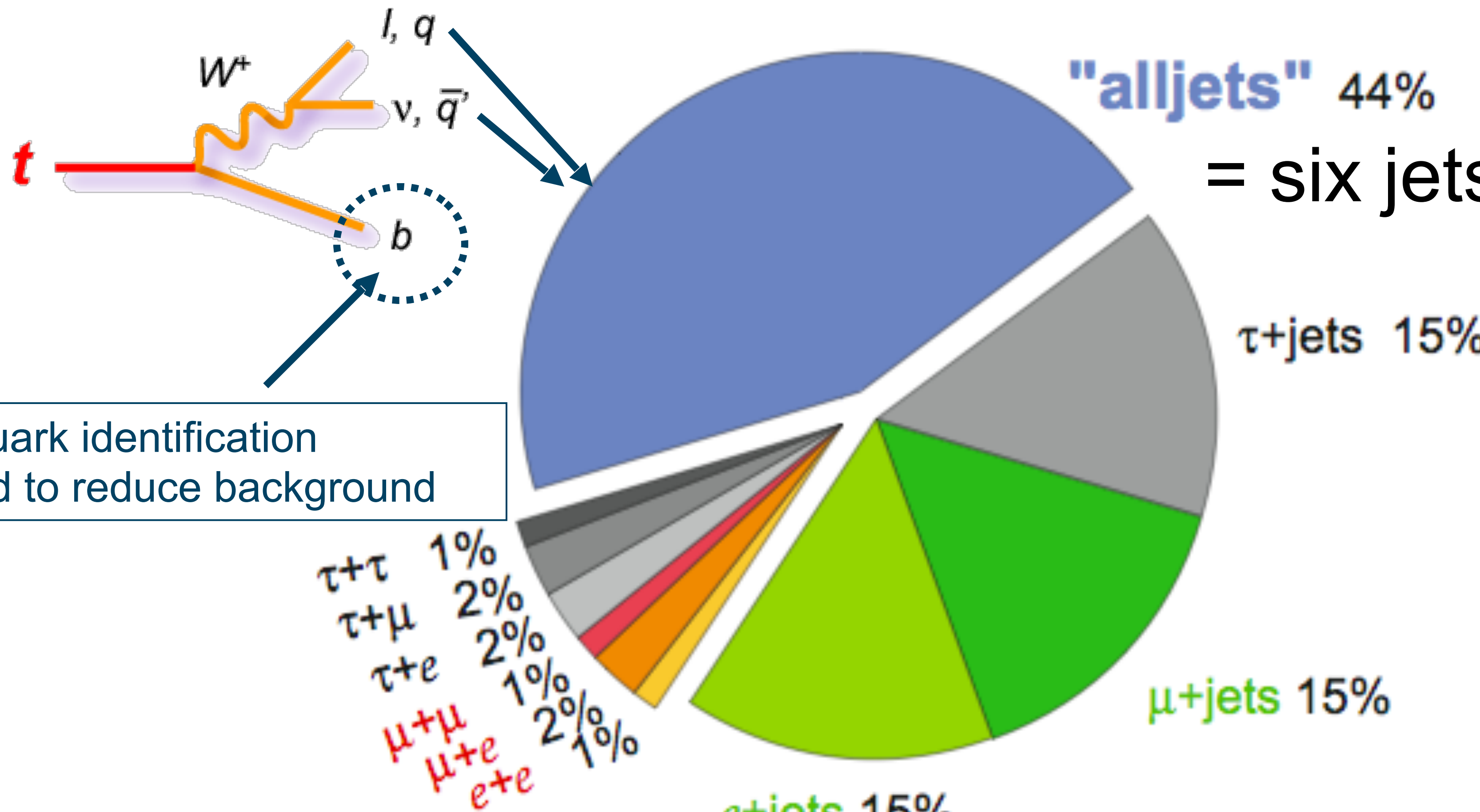
Top pair branching fractions



= six jets

B-quark identification used to reduce background

"dileptons"

= two jets, two leptons, MET

"lepton+jets"

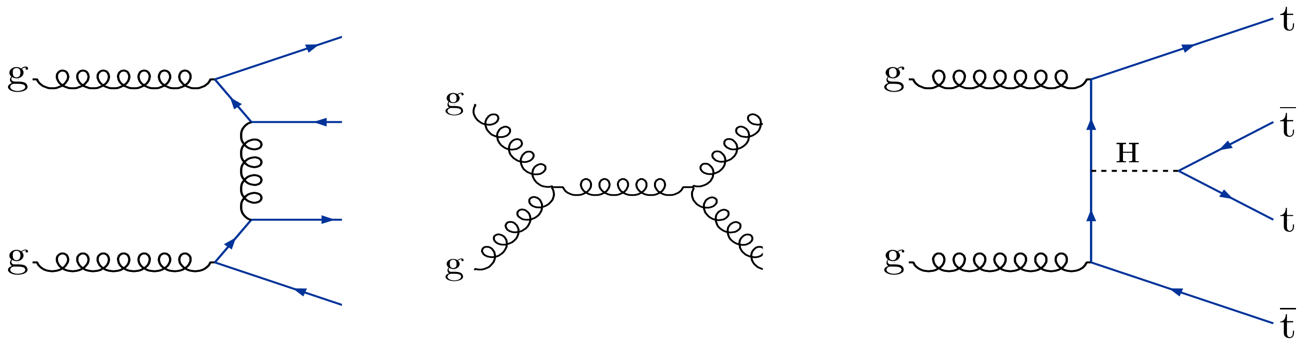
= four jets, lepton, MET

Top physics: decay channel choice

- Difficulty of isolation of top quark events inversely proportional to the complexity of the mass reconstruction

	Isolation signal	Reconstruction
Di-lepton	Relatively easy	Two neutrinos, ambiguities
Lepton+jets	Reasonable	One neutrino, use missing transverse energy
All-hadronic	Very difficult	Possibility to observe top as ‘peak’ in invariant mass spectrum, no energetic neutrinos

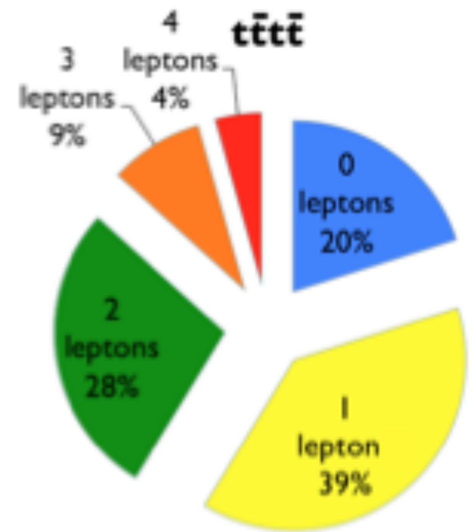
tttt: theory and strategy



Cross section ~1 order of magnitude smaller than ttH

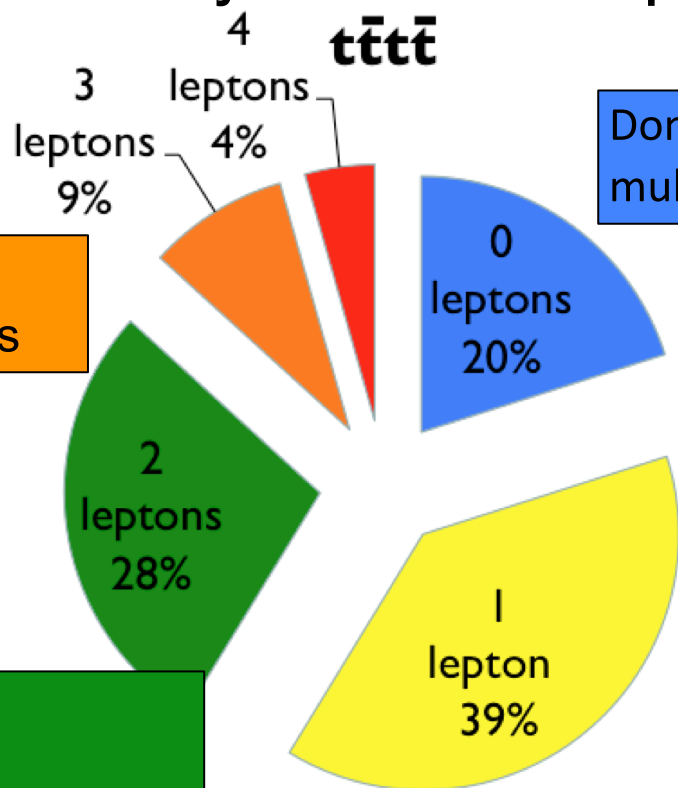
Signatures: 4leptons4b - 3leptons4b2j – 2leptons4b4j -1lepton4b6j – 4b8j

Experimental results don't always use the the newest cross section - fb comparison always better than mu/signal strength



Analysis strategy

- Depends on final state
  - (similar ttH analysis: fewer leptons = more work)



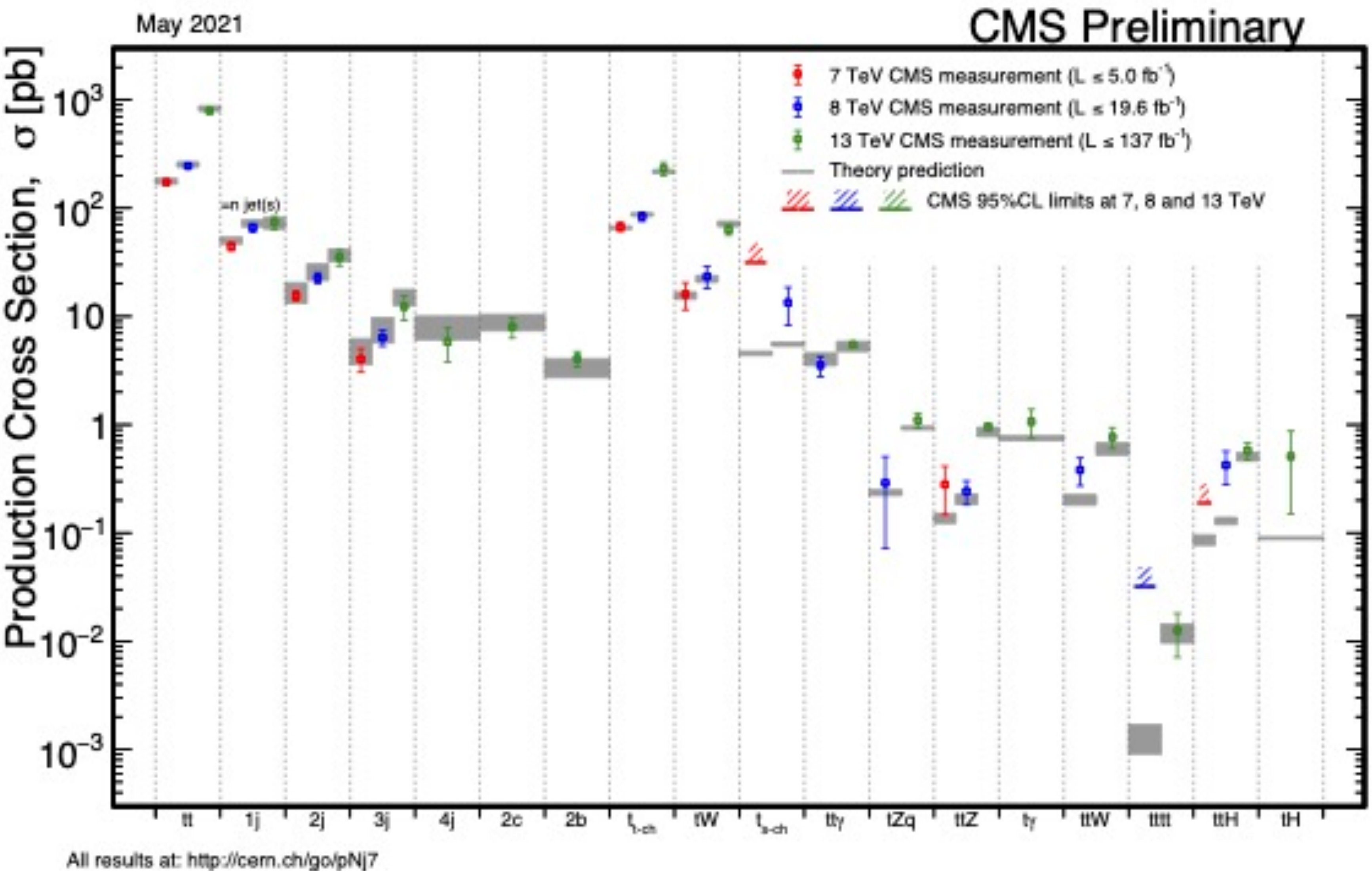
Dominant background:
multijet QCD, ttbar+HF

Dominant background:
ttW/Z/H, dibosons, fakes

Dominant background:
OS dileptons: ttbar+HF
SS dileptons: ttW/Z/H, dibosons, fakes

Dominant background:
ttbar+HF

The top quark ladder



Four top quark cross section - what is it?

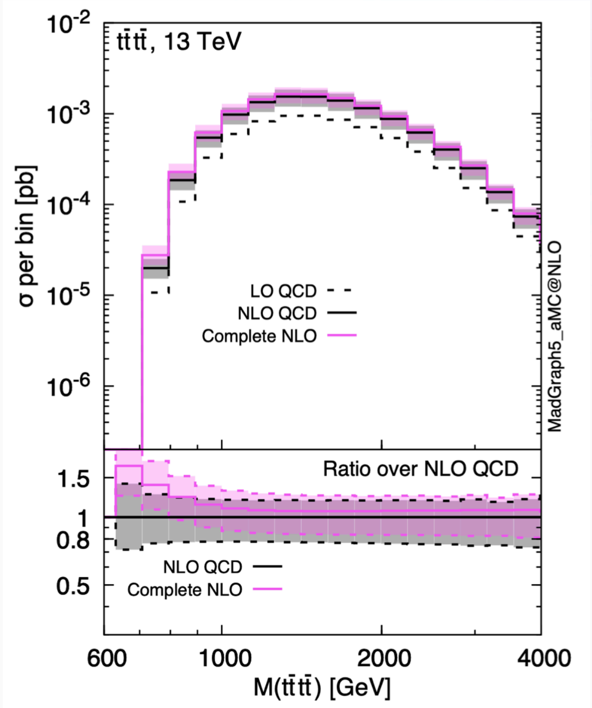
Complete NLO

- Substantial **cancellation** at tree level between QCD and subdominant EW contributions

  ➡ **Large NLO corrections**

- **NLO EW** corrections are subdominant but can be considerably enhanced at differential level

- **Full NLO accuracy** including one-loop and real emission corrections with terms of $\mathcal{O}(\alpha_s\alpha^2)$, $\mathcal{O}(\alpha^3)$, $\mathcal{O}(\alpha_s\alpha)$, $\mathcal{O}(\alpha^2)$



σ[fb]	$\mathrm{LO_{QCD}}$	$\mathrm{LO_{QCD}+NLO_{QCD}}$	LO	LO + NLO	$\frac{\mathrm{LO(+NLO)}}{\mathrm{LO_{QCD}(+NLO_{QCD})}}$
$\mu = H_T/4$	$6.83^{+70\%}_{-38\%}$	$11.12^{+19\%}_{-23\%}$	$7.59^{+64\%}_{-36\%}$	$11.97^{+18\%}_{-21\%}$	1.11 (1.08)

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K. Skovpen

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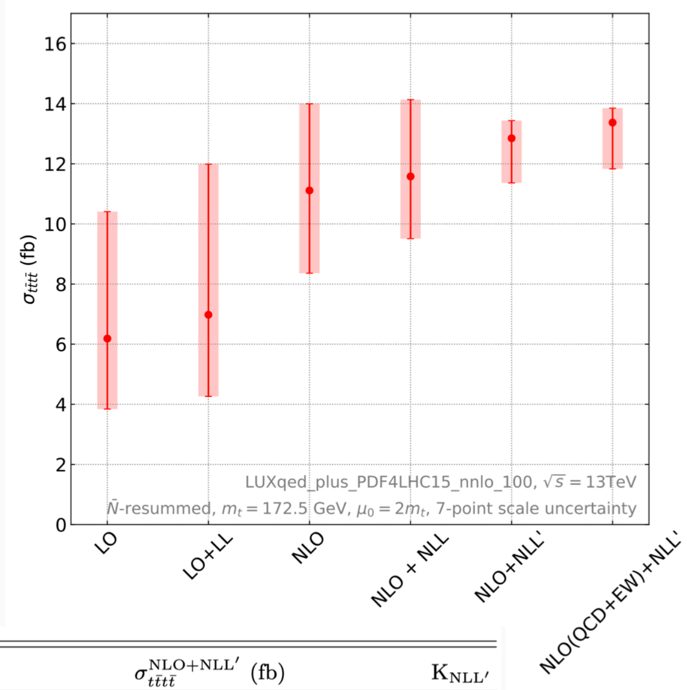
Four top quark cross section - what is it?

NLO + NLL′

- Recent calculations at **next-to-leading logarithmic (NLL′)** accuracy
- Resummation of **soft gluon emissions** for four colored particles (for the first time)
- Increase in cross section by **15%**
- Decrease in scale uncertainties by **50%**

arXiv:2212.03259



$\sqrt{s}$ (TeV)	$\sigma^{\mathrm{NLO}}_{t\bar{t}t\bar{t}}$ (fb)	$\sigma^{\mathrm{NLO+NLL}}_{t\bar{t}t\bar{t}}$ (fb)	$\sigma^{\mathrm{NLO+NLL'}}_{t\bar{t}t\bar{t}}$ (fb)	$\mathrm{K}_{\mathrm{NLL'}}$
13	$11.00(2)^{+25.2\%}_{-24.5\%}$ fb	$11.46(2)^{+21.3\%}_{-17.7\%}$ fb	$12.73(2)^{+4.1\%}_{-11.8\%}$ fb	1.16
13.6	$13.14(2)^{+25.1\%}_{-24.4\%}$ fb	$13.81(2)^{+20.7\%}_{-20.1\%}$ fb	$15.16(2)^{+2.5\%}_{-11.9\%}$ fb	1.15
$\sqrt{s}$ (TeV)	$\sigma^{\mathrm{NLO(QCD+EW)}}_{t\bar{t}t\bar{t}}$ (fb)	$\sigma^{\mathrm{NLO(QCD+EW)+NLL}}_{t\bar{t}t\bar{t}}$ (fb)	$\sigma^{\mathrm{NLO(QCD+EW)+NLL'}}_{t\bar{t}t\bar{t}}$ (fb)	$\mathrm{K}_{\mathrm{NLL'}}$
13	$11.64(2)^{+23.2\%}_{-22.8\%}$ fb	$12.10(2)^{+19.5\%}_{-16.3\%}$ fb	$13.37(2)^{+3.6\%}_{-11.4\%}$ fb	1.15
13.6	$13.80(2)^{+22.6\%}_{-22.9\%}$ fb	$14.47(2)^{+18.5\%}_{-19.1\%}$ fb	$15.82(2)^{+1.5\%}_{-11.6\%}$ fb	1.15

K. Skovpen

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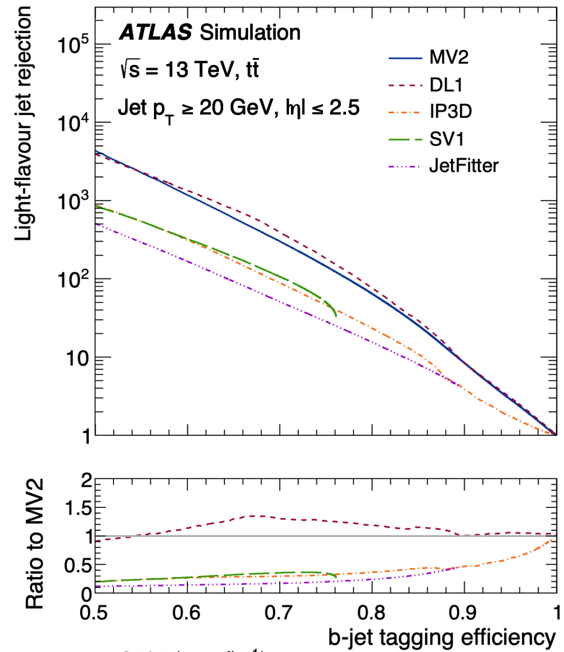
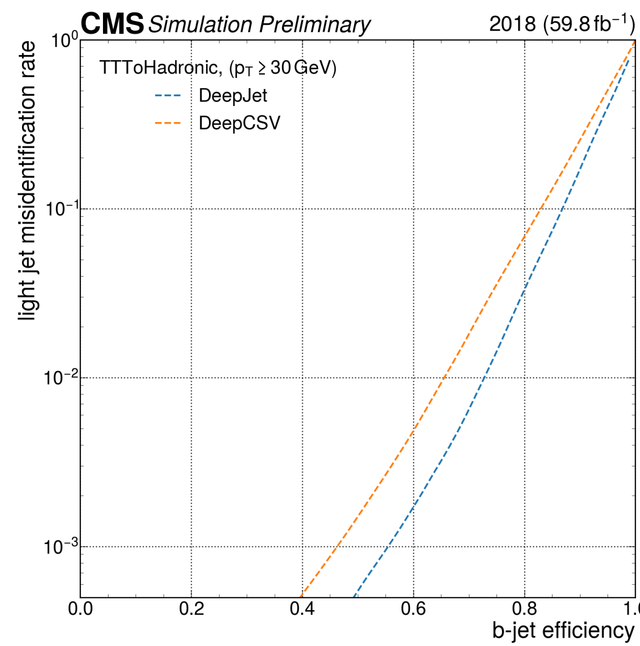
On ttbar+HF

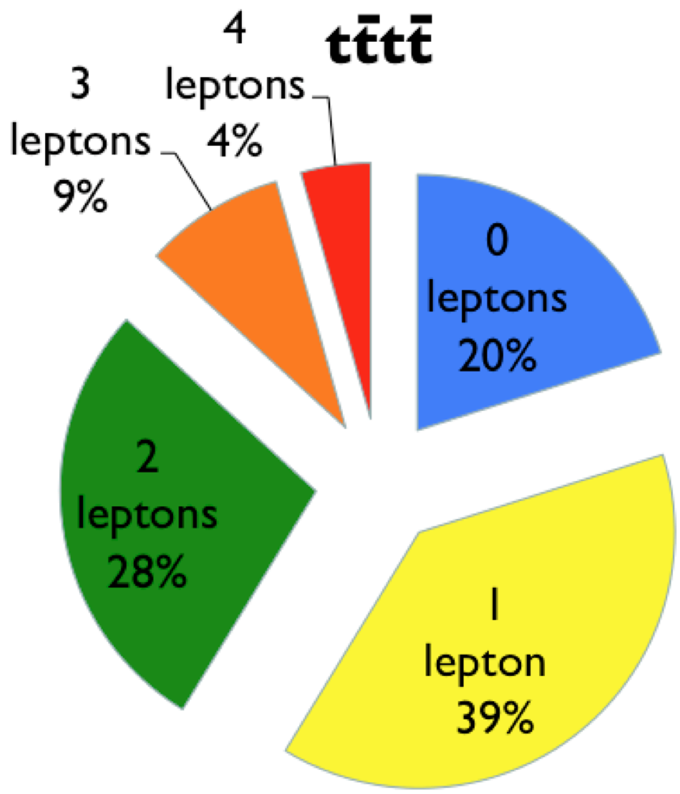
- Entire topic by itself
  - With theory considerations!
  - Also very relevant for ttH production

- Important to remember for four-top production: these are real b quarks
  - so just using (tight) b-tagging to reject QCD background is typically not the most beneficial strategy as it cuts (just as) hard into signal





Different final states



CMS all-hadronic, l+jets, OSDL: TOP-21-005 (accepted arXiv:2303.03864)

ATLAS l+jets, OSDL: arXiv:1811.02305

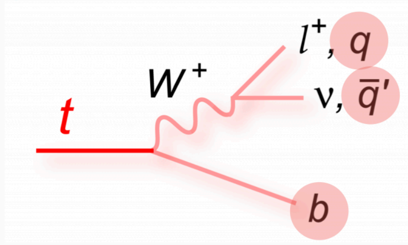
CMS: evidence for tttt (l+jets input)

More details: CMS TOP-21-005 arXiv:2303.03864 (Accepted PLB)

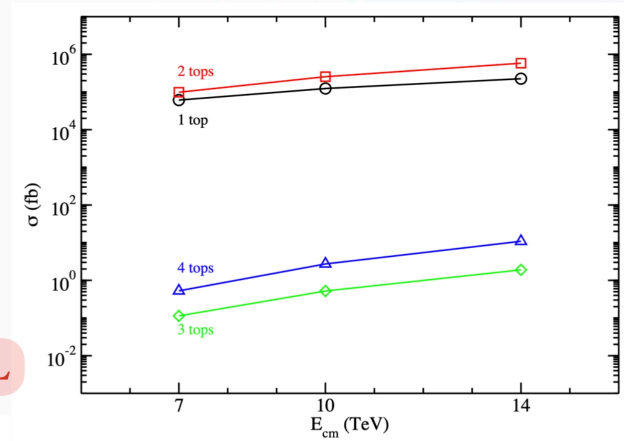
Lepton+jets

JHEP 11 (2014) 154

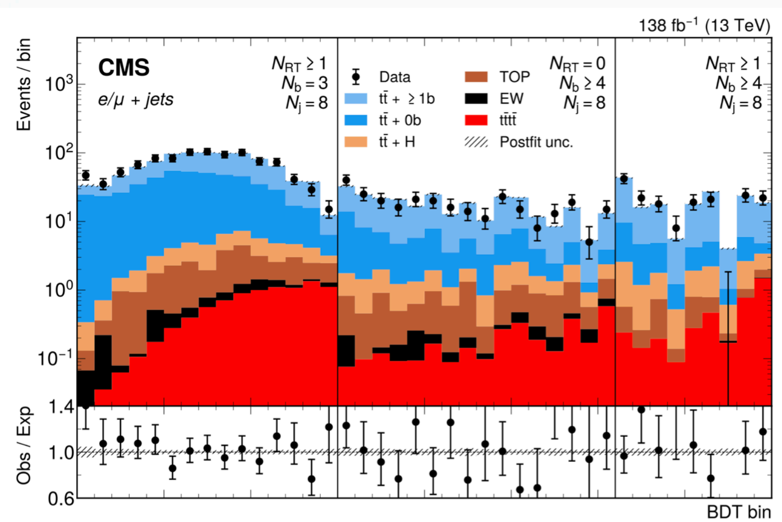
- First studied at **8 TeV, 20 fb^{-1}**
- Production cross section ≈ **1 fb**
- Introduce a « **trijet** » tagger in a **BDT**



$\sigma_{t\bar{t}t\bar{t}} < 32$ fb @95 % CL



PLB 687 (2010) 70



arXiv:2303.03864 (Submitted to PLB)

- Followed by the study at **13 TeV, 138 fb^{-1}**
- Apply **H_T > 500 GeV**
- **Categorize** events based on lepton flavor, jet and b-tagged jet multiplicities, number of resolved top quark candidates

$S = 1.4\,(1.2)\,\sigma$

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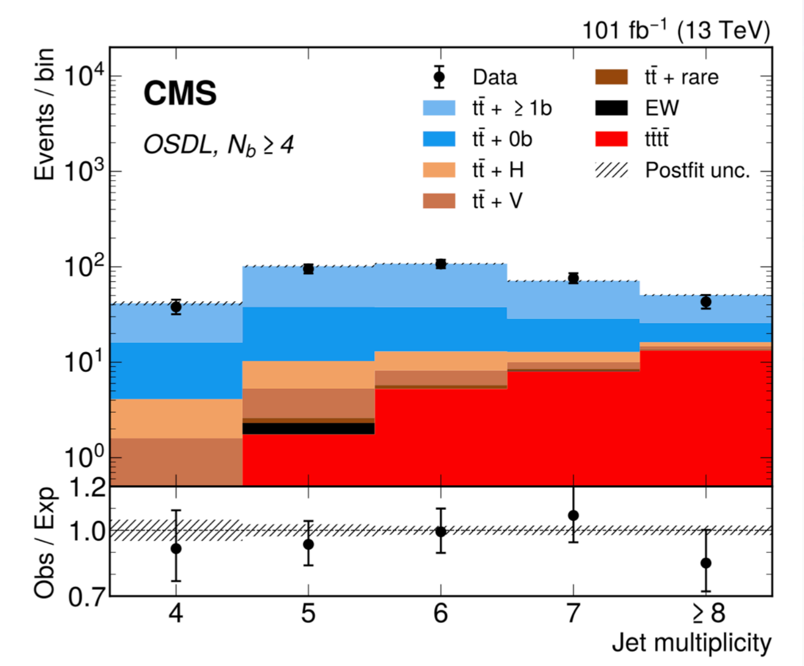
CMS: evidence for tttt (OS leptons input)

OS leptons+jets

arXiv:2303.03864 (Submitted to PLB)

- Done with **101 fb^{-1}** of **13 TeV** data
- Use the **H_T > 500 GeV** spectrum in the fit
- **Categorize** by lepton flavors, also by jet and b-tagged jet multiplicities



$S = 1.8\,(0.6)\,\sigma$

More details: CMS TOP-21-005 arXiv:2303.03864

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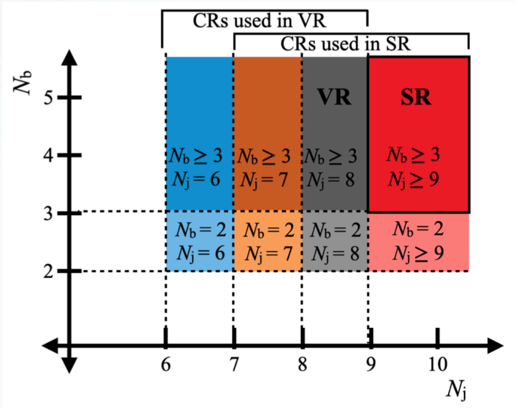
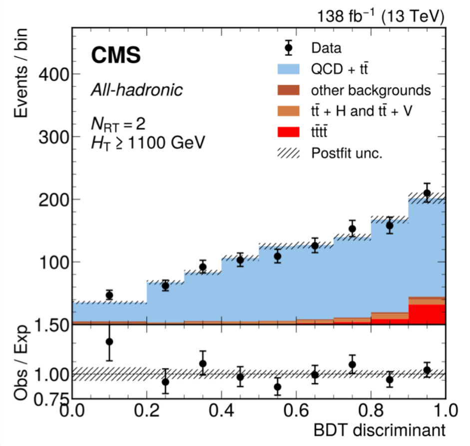
CMS: evidence for tttt (all-hadronic input)

All-hadronic





arXiv:2303.03864 (Submitted to PLB)

- Done for the first time with **138 fb^{-1}** of **13 TeV** data
- Select events with **no prompt isolated leptons** in $H_T > 700$ GeV
- Use the improved **DeepJet** b-tagger
- **Categorize** events in H_T, the number of boosted top quark candidates, jet and b-tagged jet multiplicities
- **BDT** to separate signal from QCD and $t\bar{t}$ backgrounds
- **ABCD** method to estimate background

$S = 2.5\,(0.4)\,\sigma$

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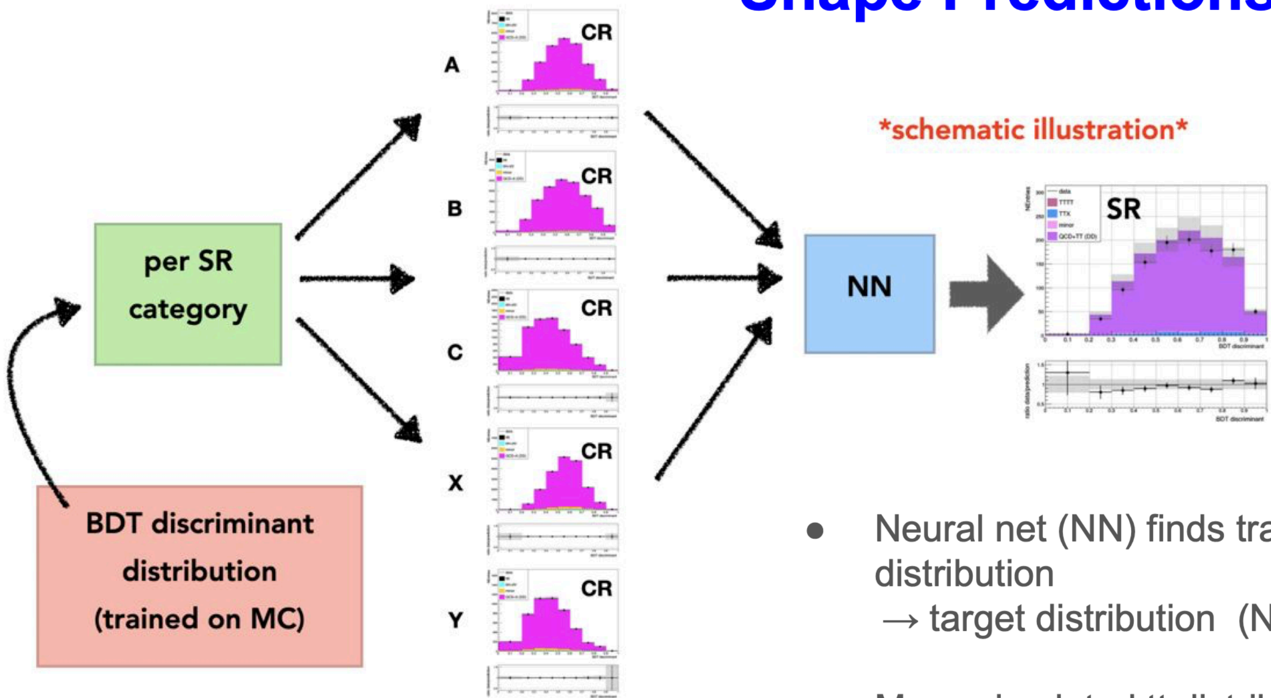
Innovative ML intermezzo

Shape Predictions for BDT and H_T

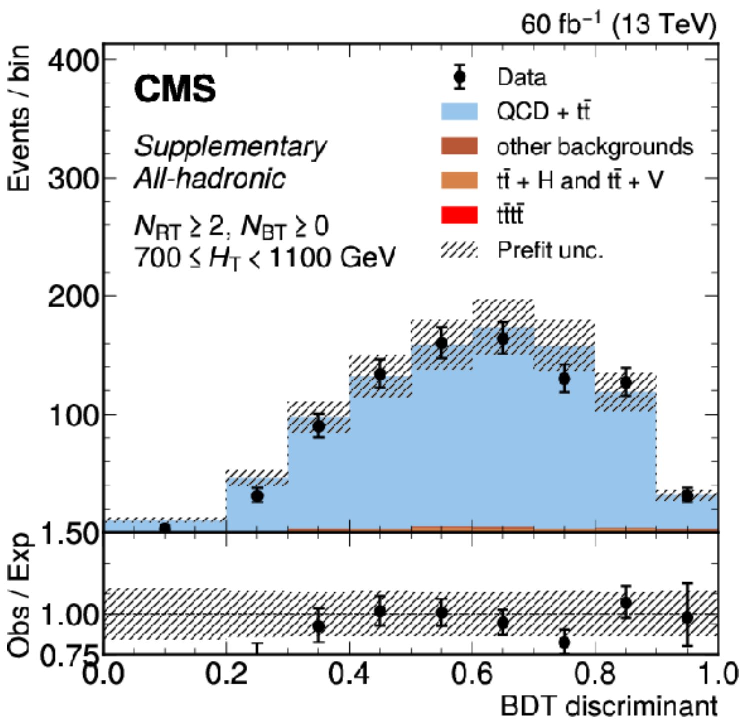


- Neural net (NN) finds transformation from input distribution
  → target distribution (Neural autoregressive flow)
- Maps simulated tt distributions onto tt + QCD distributions in 5 CR distributions for BDT & H_T simultaneously

*Huang, Krueger, Lacoste, Courville. *Neural Autoregressive Flows.* arXiv:1804.00779
*S. Choi. arXiv:2008.0363

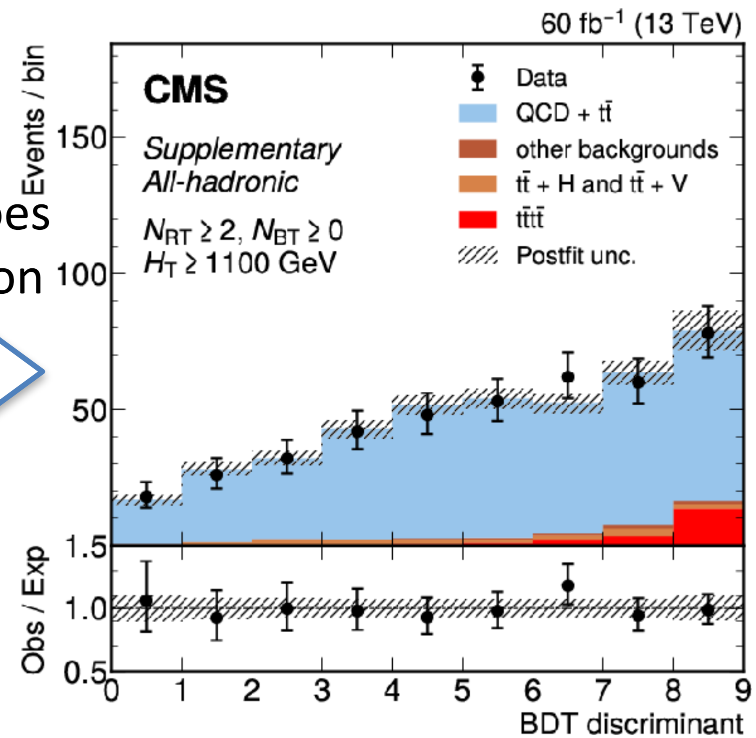
15th Int. Conf. on Top-quark Physics (TOP2022) Nicholas Manganelli - UC Riverside 14

Innovative ML intermezzo



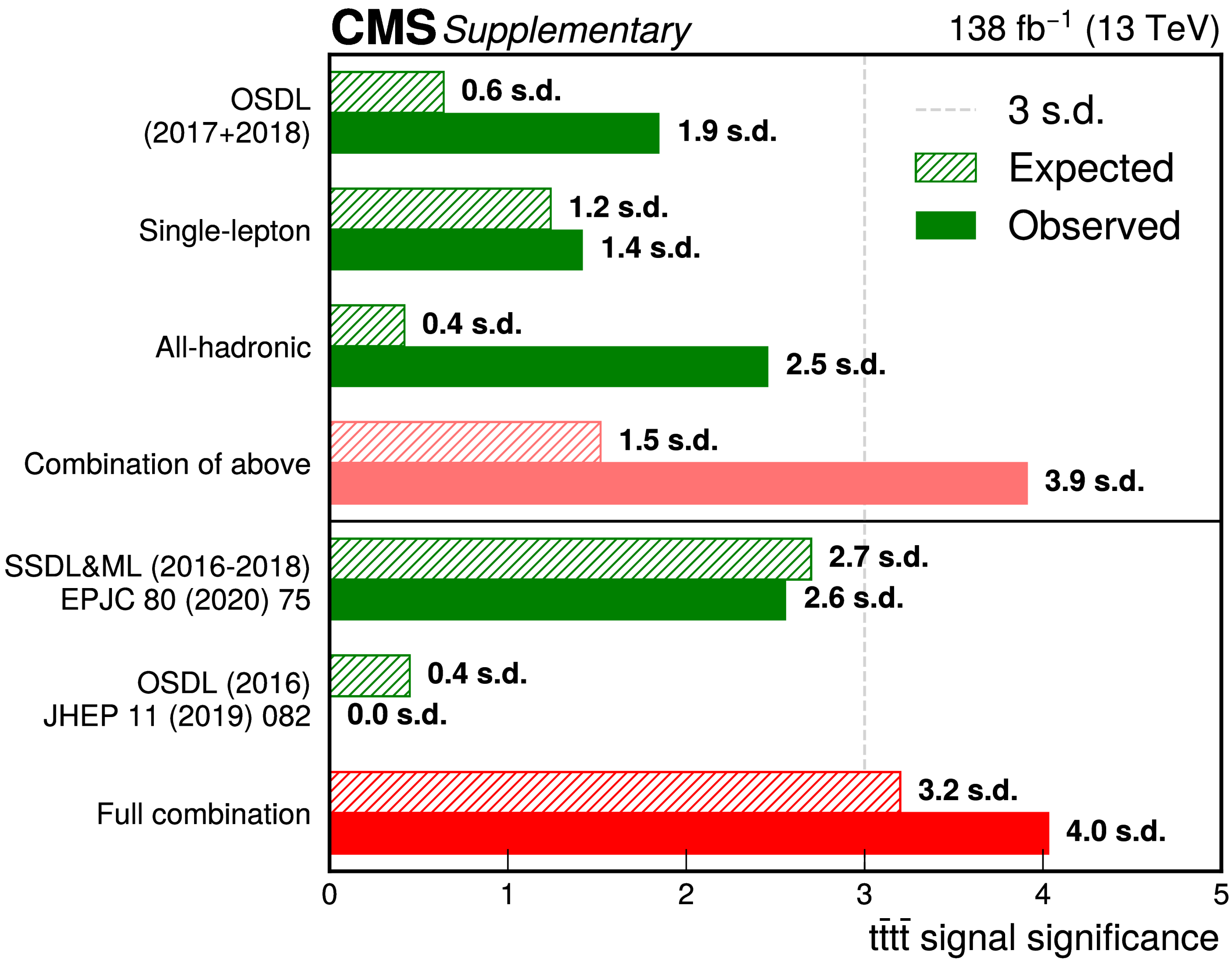
Neural net does transformation

auto-regressive flow DNN

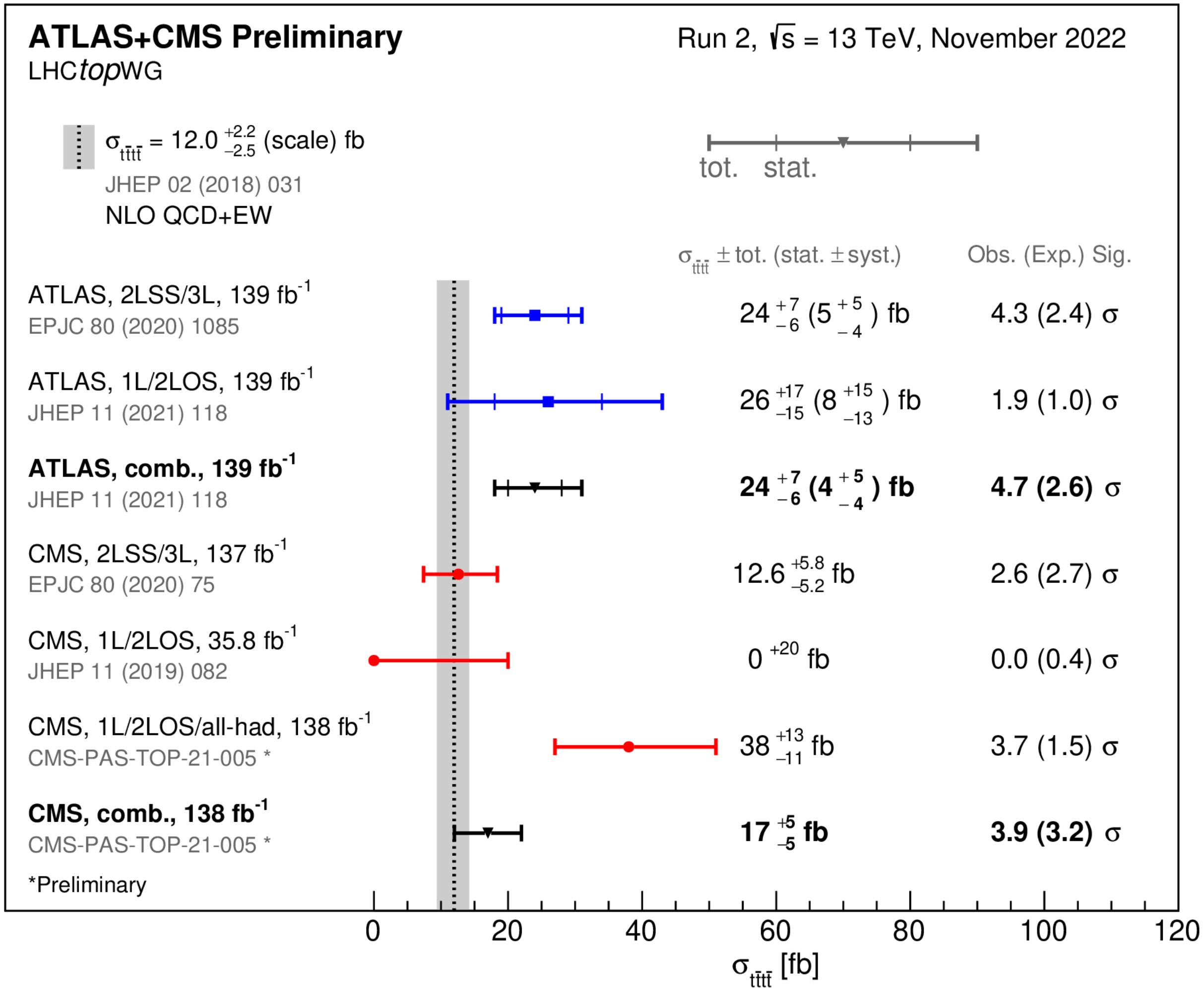


More details: CMS TOP-21-005 arXiv:2303.03864

CMS: evidence for tttt in 0,1,2(OS) leptons

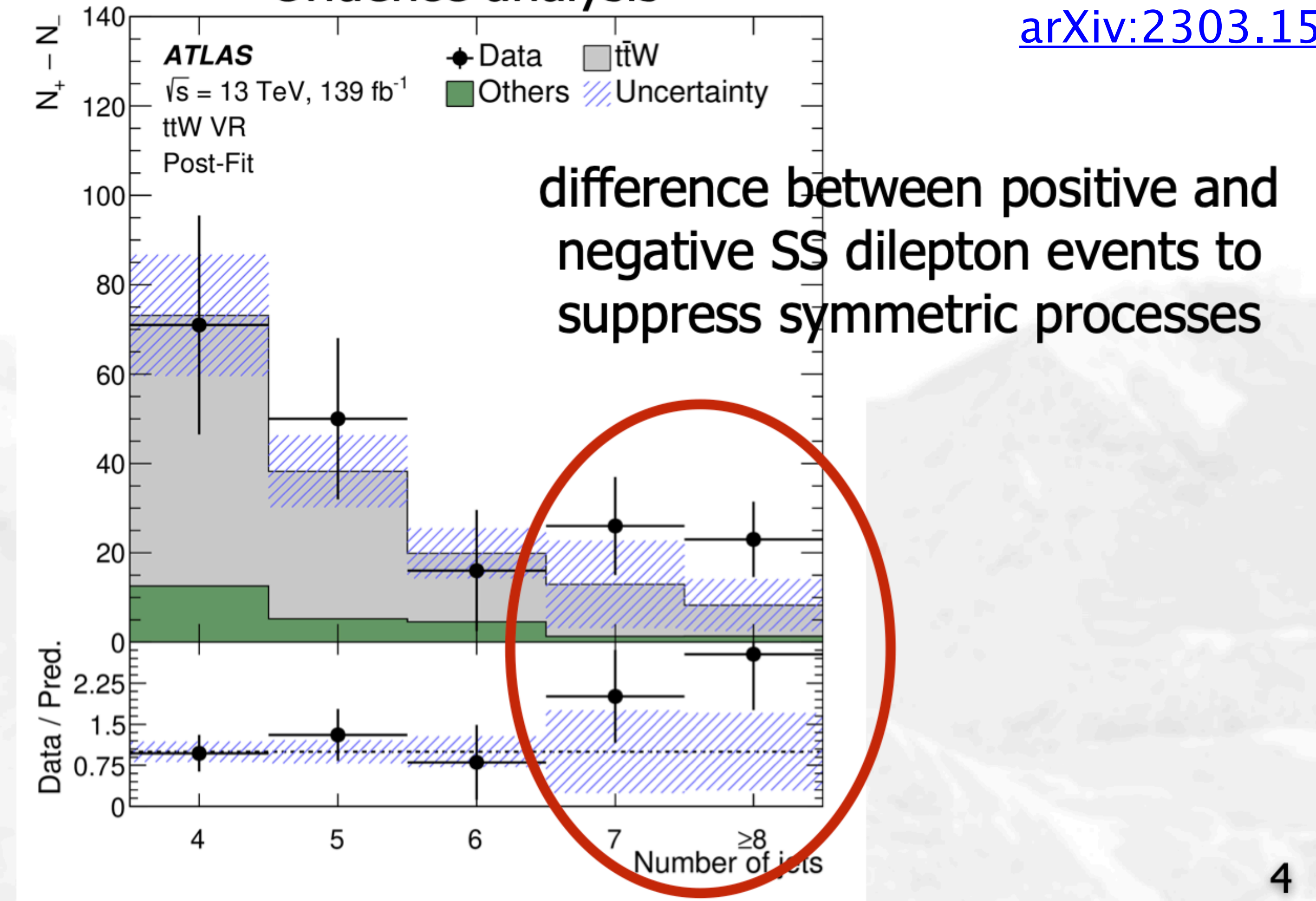


Why re-analysis?



ATLAS: SSDL, ML (motivation)

$t\bar{t}W$ validation region in the evidence analysis



Re-analysis (just like CMS)
Submitted to EPJC
[arXiv:2303.15061](https://arxiv.org/abs/2303.15061)

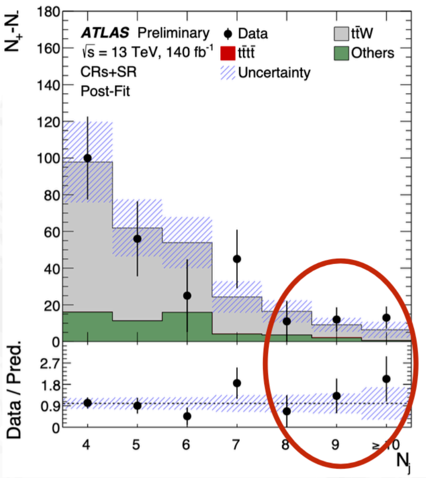
ATLAS: SSDL, ML (backgrounds)

Background estimation in the four top cross section measurement

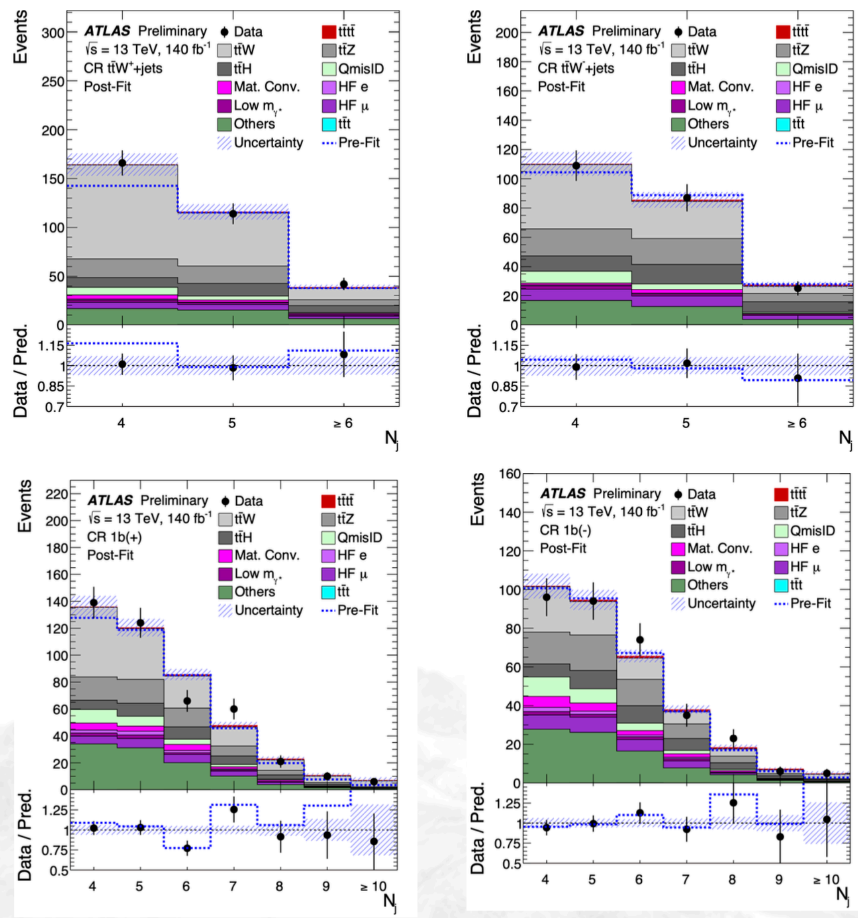
- $t\bar{t}Z$+jets and $t\bar{t}H$+jets background:
  - From simulation

- $t\bar{t}W$+jets background:
  - Njets dependence fitted to data using 4 free parameters
  - 4 control regions with 1 b-tag jet and with low Ht , split by charge

$t\bar{t}W$ background	a_0	a_1	$\mathrm{NF}_{t\bar{t}W^{+}(4\mathrm{jet})}$	$\mathrm{NF}_{t\bar{t}W^{-}(4\mathrm{jet})}$
Value	$0.51^{+0.10}_{-0.10}$	$0.22^{+0.25}_{-0.22}$	$1.27^{+0.25}_{-0.22}$	$1.11^{+0.31}_{-0.28}$



Fitted $t\bar{t}W$ compatible with the measurement in the previous slide



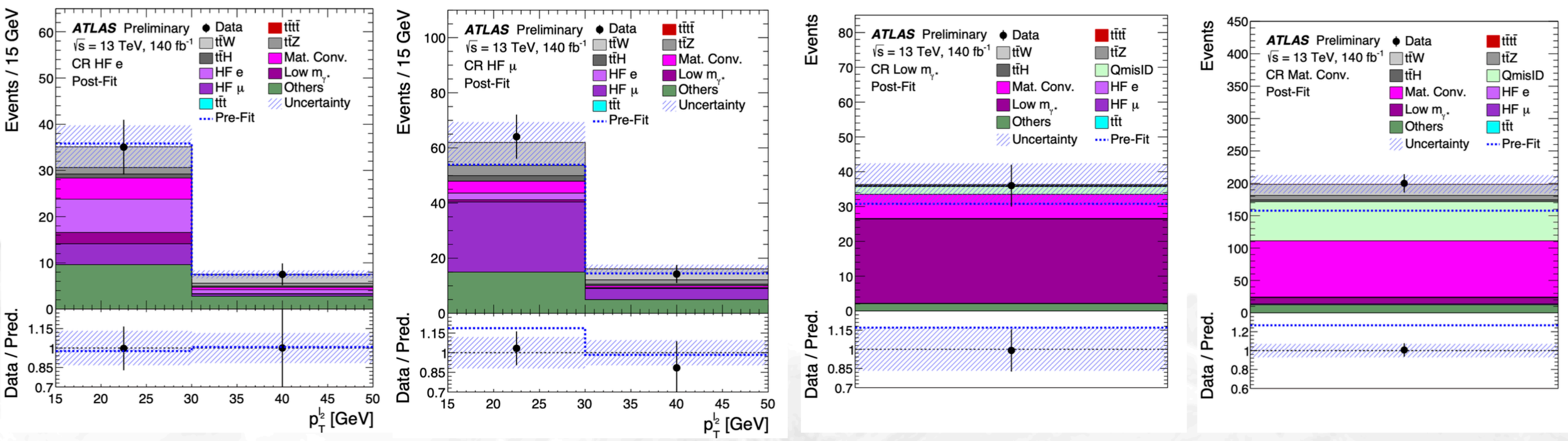
Submitted to EPJC arXiv:2303.15061

ATLAS: SSDL, ML (backgrounds)

Background estimation in the four top cross section measurement

- Fake/non prompt lepton background
  - Shape from MC, normalisation from data using control regions enriched in fake (low jets multiplicity, low Ht)
- Charges mid-ID
  - Charge flip rate from data

$NF_{HFe} = 0.66 \pm 0.61$ $NF_{HF\mu} = 1.27 \pm 0.50$ $NF_{Low\ m\gamma*} = 1.08 \pm 0.34$ $NF_{Mat.Conv.} = 1.80 \pm 0.44$



Submitted to EPJC arXiv:2303.15061

ATLAS: SSDL, ML: Signal region

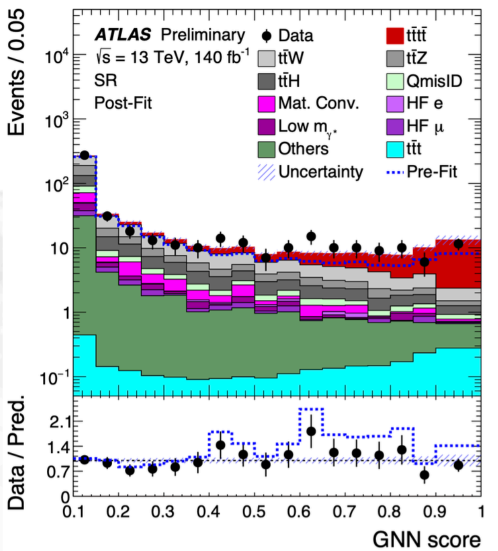
Four top cross section measurement

- Graph neural network (GNN) to separate signal from backgrounds
- Simultaneous profile likelihood fit to data in the signal region and the 8 control regions

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

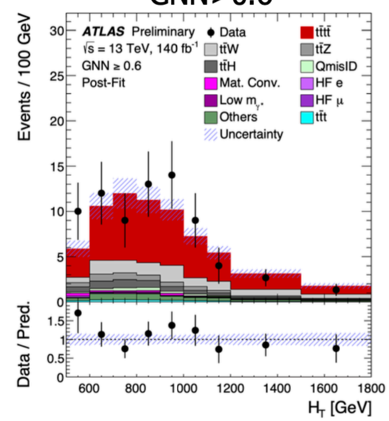
$$\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}(\text{stat})\,^{+4.6}_{-3.4}(\text{syst})\ \text{fb}$$

compatible at 1.8 σ with the SM prediction (wrt 12 fb)
Largest systematic uncertainties on signal modelling

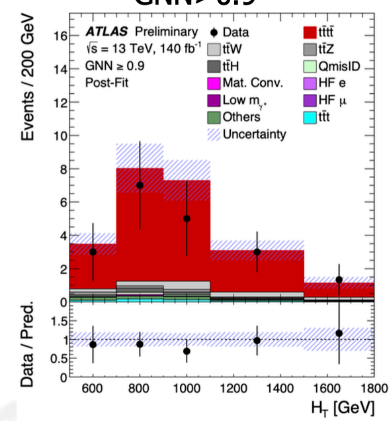


Expected significance: 4.3 σ (wrt 12 fb) /4.7σ (wrt 13.4 fb)
Observed significance: 6.1σ

GNN>0.6



GNN>0.9



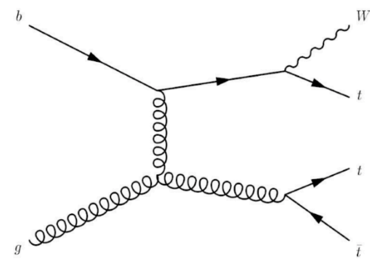
- Main gain in sensitivity thanks to
  - updated lepton and jet selection and uncertainties
  - use of the GNN discriminant
  - improved treatment of the tt̄t background

Submitted to EPJC arXiv:2303.15061

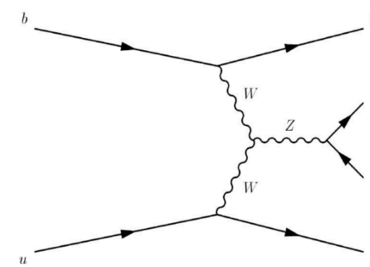
ATLAS: three tops?

Four top as a path to three top

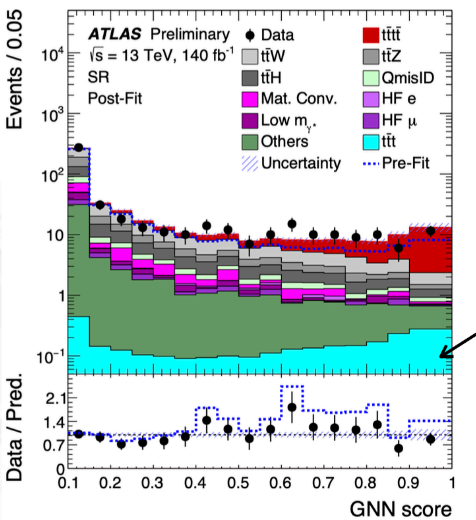
- SM three top production
  - Cross section ~ 10 times smaller than the four top process
  - Still very signal like
  - Currently no experimental constraints
- Free floating both $t\bar{t}t\bar{t}$ and $t\bar{t}t$ in the fit
  - Very large correlation between the 2 processes : - 93%

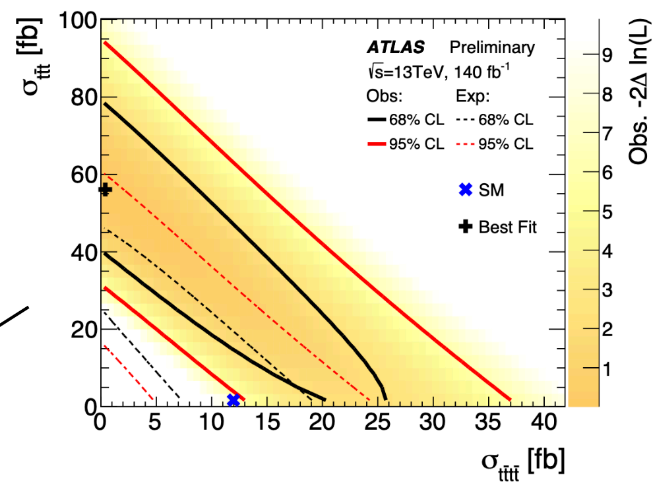


σ($t\bar{t}t$ W) ~ 1 fb



σ($t\bar{t}t$ q) ~ 0.6 fb





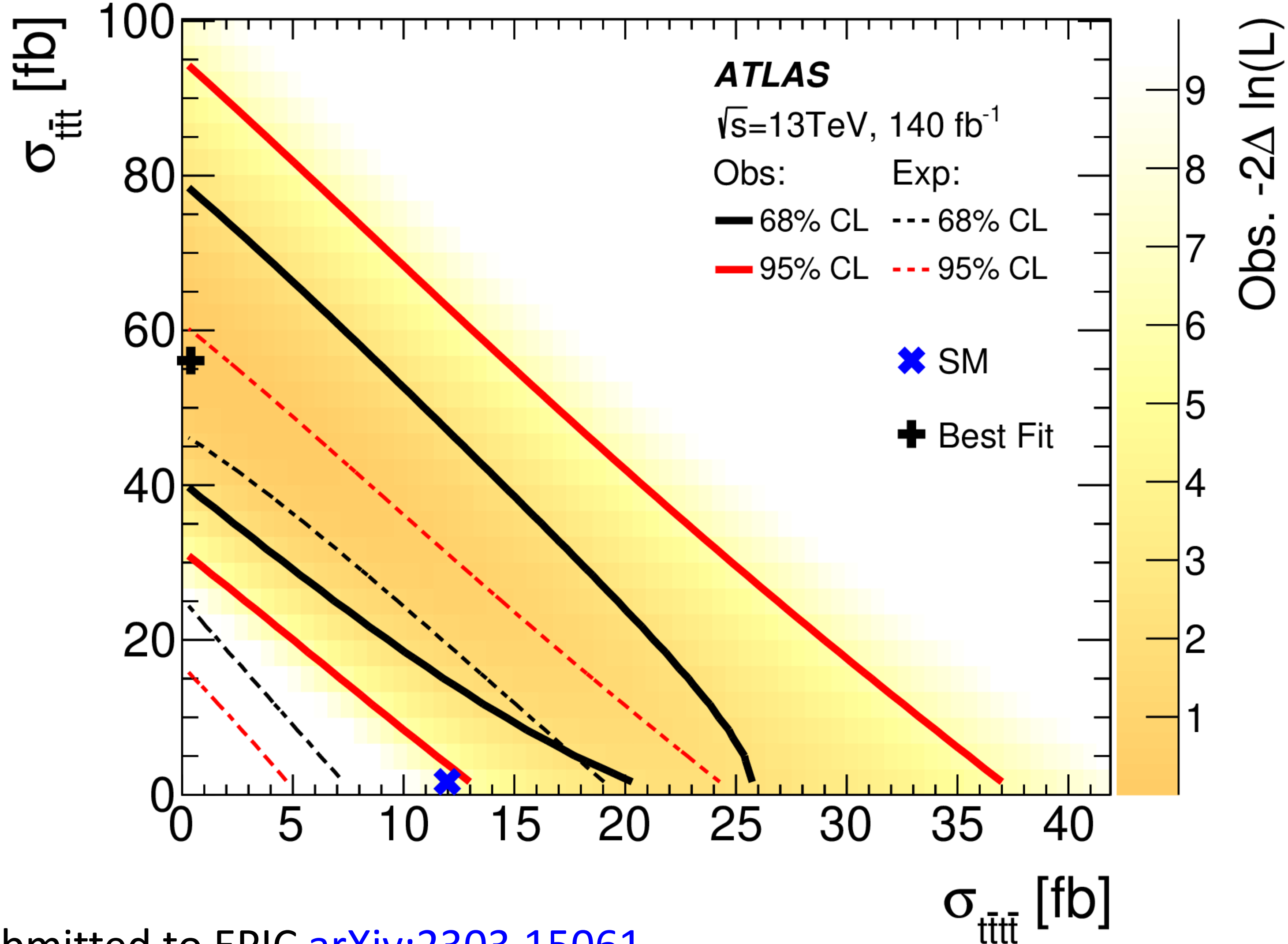
Use the 2D likelihood scan to set limit on $t\bar{t}t$ production

Processes	95% CL cross section interval [fb] with $\mu_{t\bar{t}t\bar{t}} = 1$	95% CL cross section interval [fb] with $\mu_{t\bar{t}t\bar{t}} = 1.9$
$t\bar{t}t$	[4.7, 60]	[0, 41]
$t\bar{t}tW$	[3.1, 43]	[0, 30]
$t\bar{t}tq$	[0, 144]	[0, 100]

Frédéric Déliot, MoriondQCD 23, 27-MAR-23 14

Submitted to EPJC arXiv:2303.15061

ATLAS: three tops?



Submitted to EPJC arXiv:2303.15061

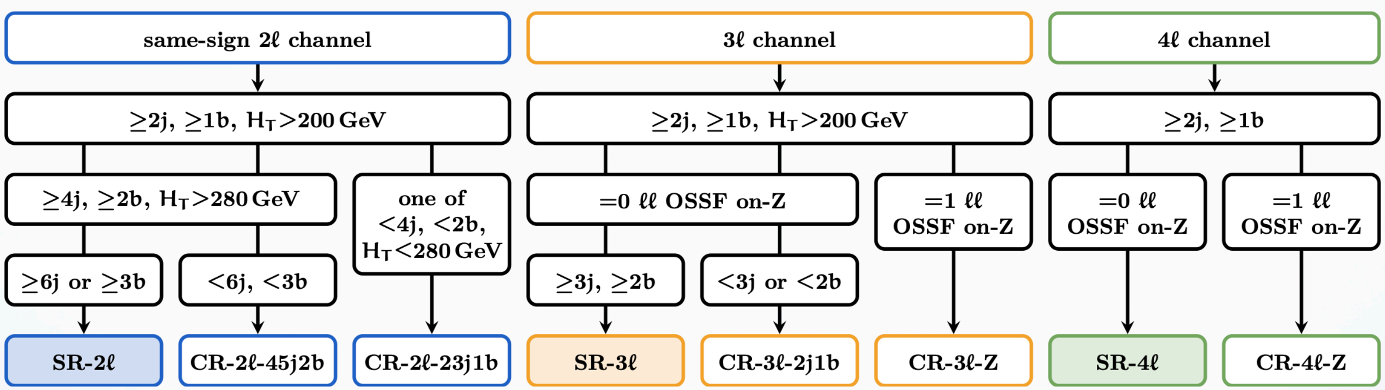
CMS: SSDL, ML: analysis strategy

CMS TOP-22-013 - arXiv:2305.13439 (submitted to PLB)

- **Analyze** multi lepton channels: **2LSS**, **3L**, **4L**
- **Event categorization** based on jet and b-tagged jet multiplicities, H_T

- **Electrons** (**muons**):
  - $p_T > 10$ GeV, $|\eta| < 2.5$ (2.4)
  - LeptonMVA ID
  - $p_T > 25, 20, 10, 10$

- **Jets**:
  - $p_T > 25$ GeV, $|\eta| < 2.4$
  - DeepJet b tagging ($\varepsilon = 90\%$)
  - Use DeepJet score in MVA

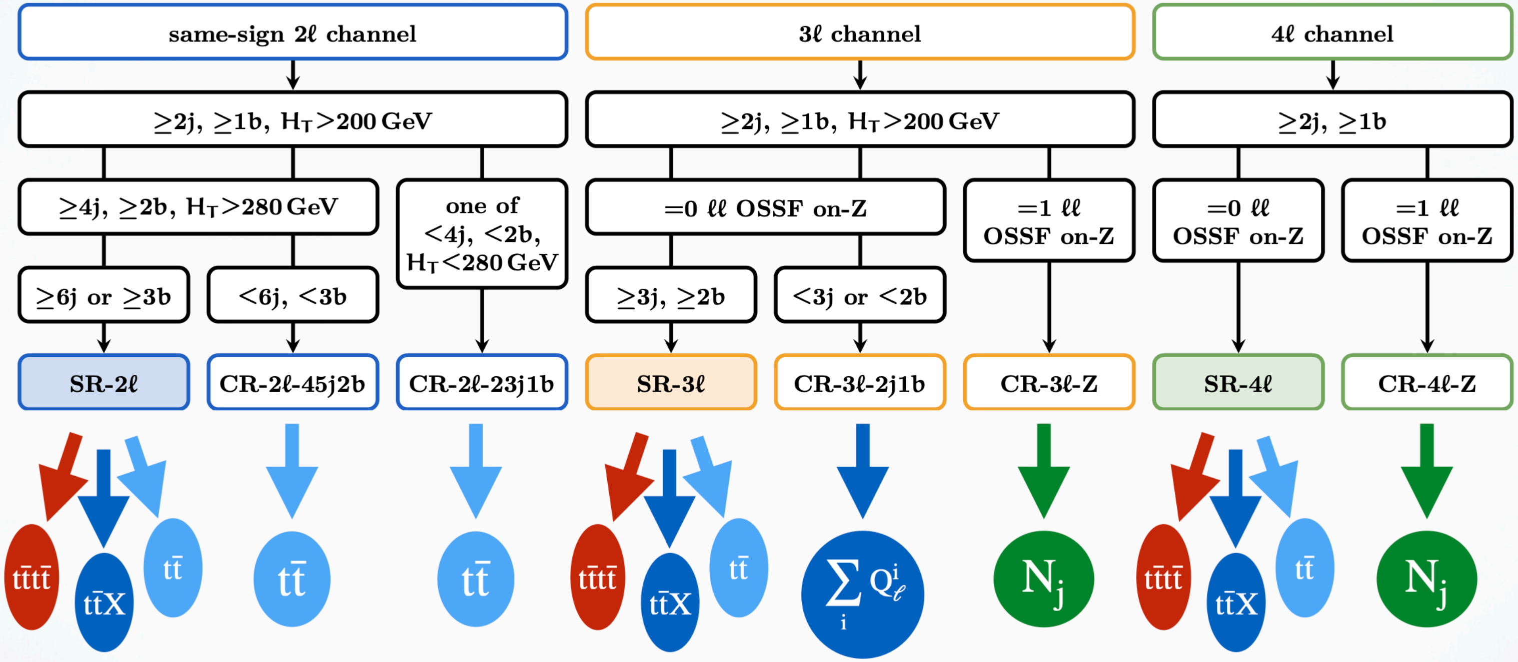


25

CMS: SSDL, ML: analysis strategy

Final fit

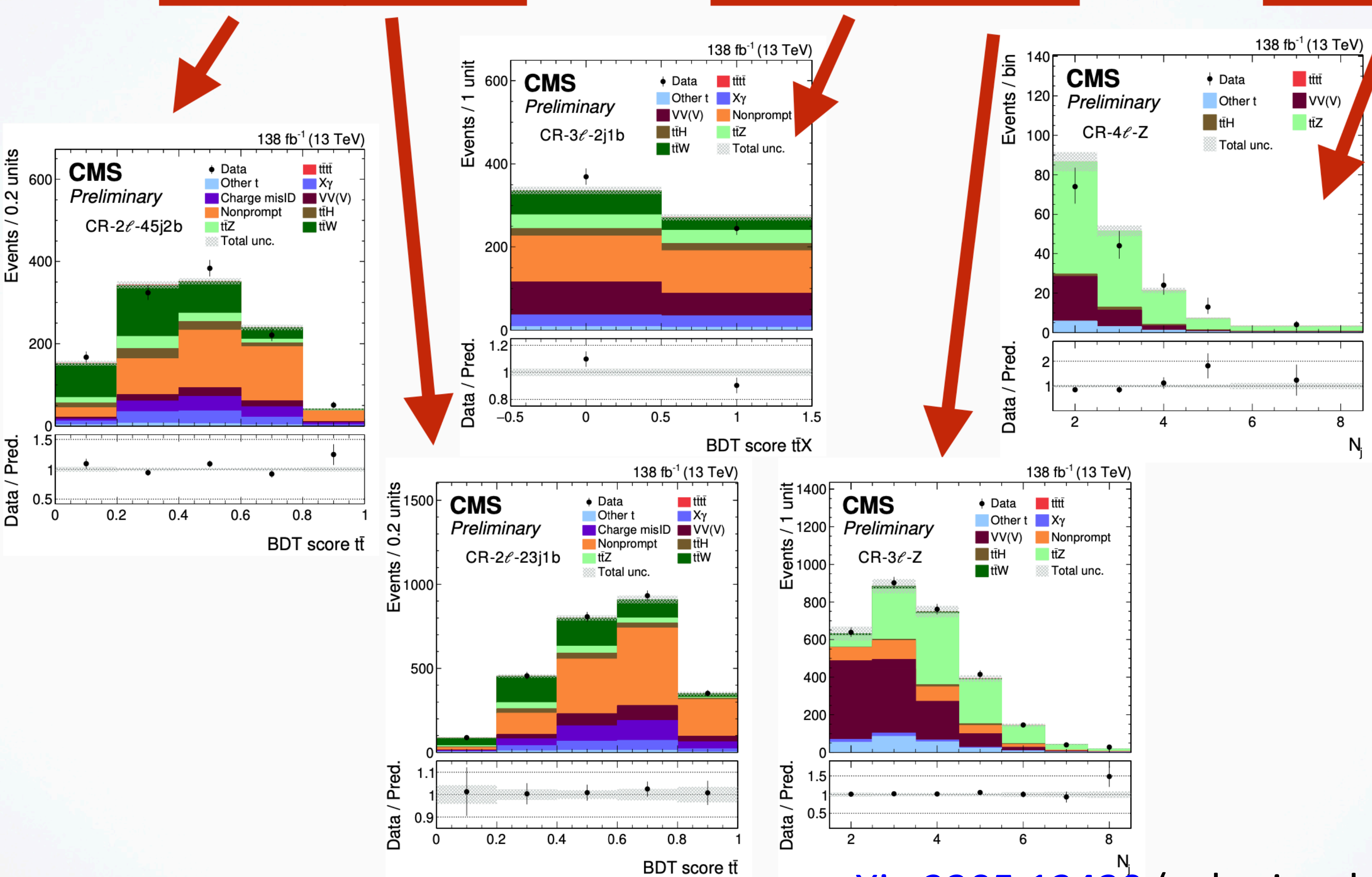
- **All SRs and CRs** are included in a binned profile likelihood fit
- Additionally **split SRs into three subregions** ($t\bar{t}t\bar{t}$, $t\bar{t}V$, and $t\bar{t}$) based on the highest value of three BDT scores



arXiv:2305.13439 (submitted to PLB)

CMS: SSDL, ML (backgrounds)

SR-2ℓ | CR-2ℓ-45j2b | CR-2ℓ-23j1b | SR-3ℓ | CR-3ℓ-2j1b | CR-3ℓ-Z | SR-4ℓ | CR-4ℓ-Z



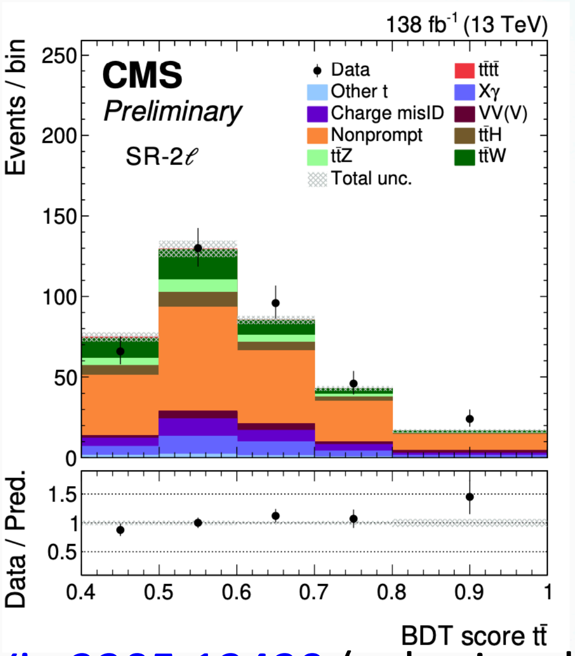
arXiv:2305.13439 (submitted to PLB)

CMS: SSDL, ML

Signal region: 2LSS

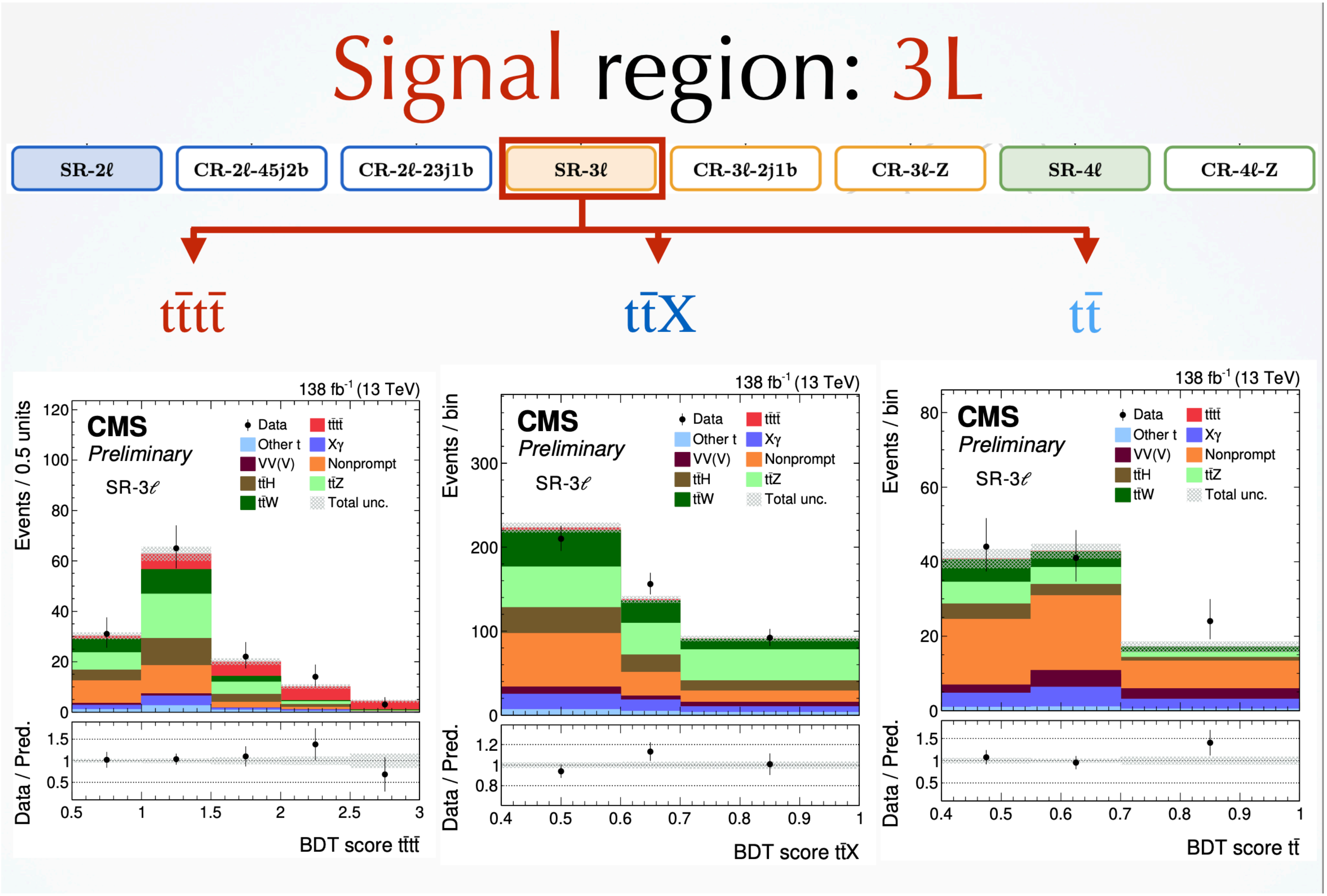
SR-2ℓ | CR-2ℓ-45j2b | CR-2ℓ-23j1b | SR-3ℓ | CR-3ℓ-2j1b | CR-3ℓ-Z | SR-4ℓ | CR-4ℓ-Z

$t\bar{t}$



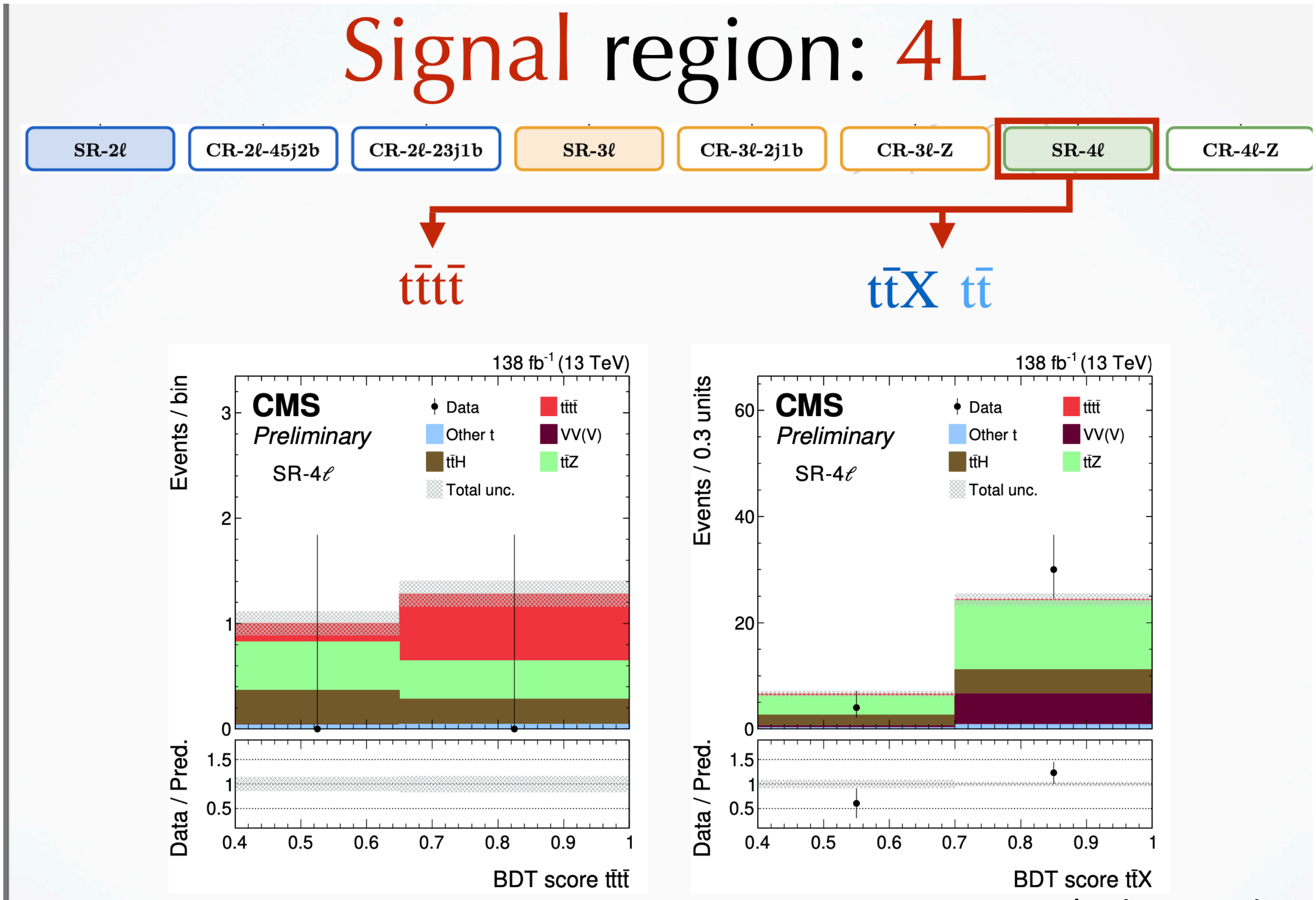
arXiv:2305.13439 (submitted to PLB)

CMS: SSDL, ML



arXiv:2305.13439 (submitted to PLB)

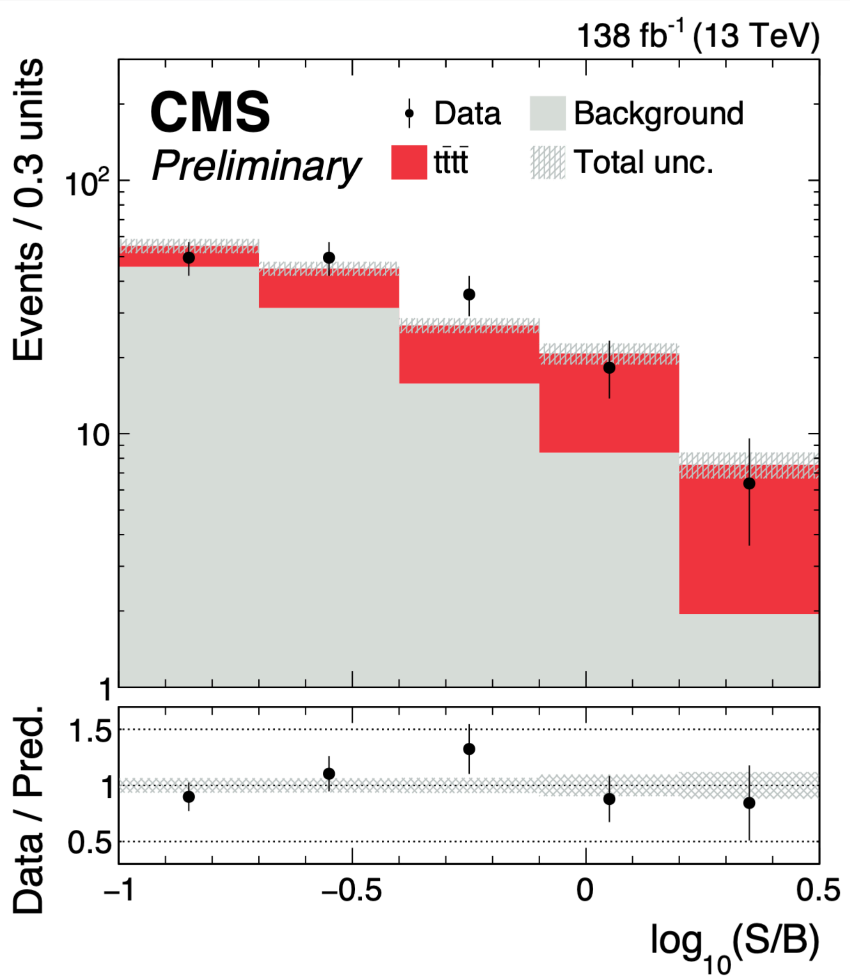
CMS: SSDL, ML



[arXiv:2305.13439](https://arxiv.org/abs/2305.13439) (submitted to PLB)

CMS: SSDL, ML: result

arXiv:2305.13439 (submitted to PLB)



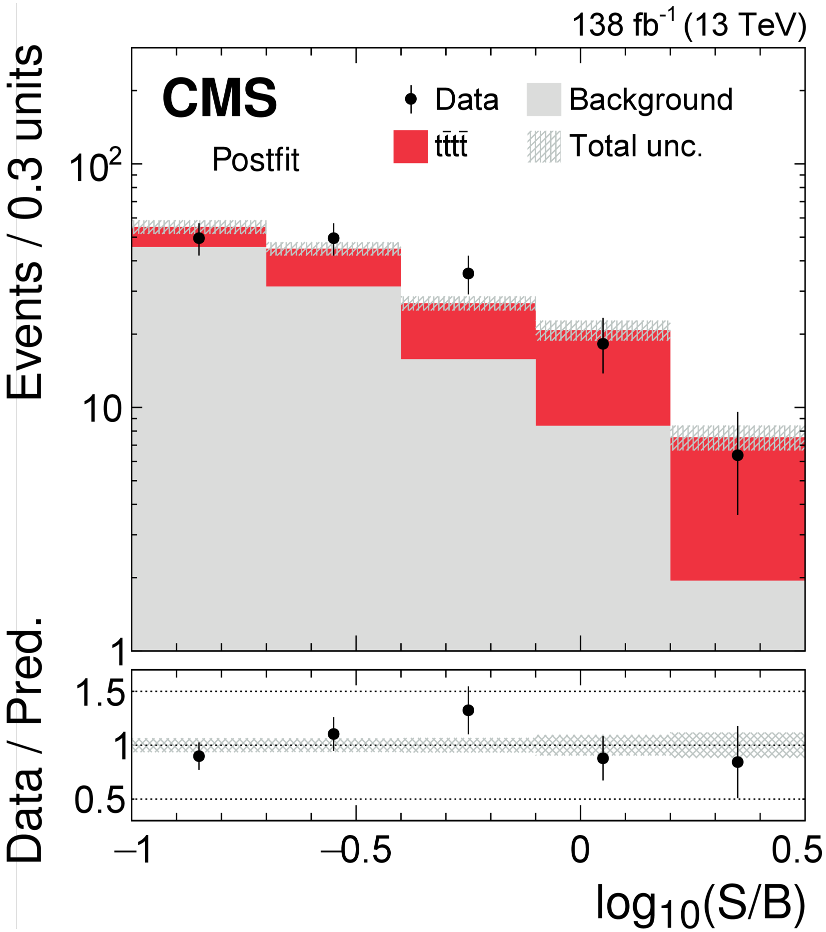
- Clearly **need** something like four tops to exist to be able to describe the data
- $\sigma_{\mathrm{t\bar{t}t\bar{t}}}/\sigma^{\mathrm{th.}}_{\mathrm{t\bar{t}t\bar{t}}} = 1.3 \pm 0.3$
- $\sigma_{\mathrm{ttW}}/\sigma^{\mathrm{th.}}_{\mathrm{ttW}} = 1.4 \pm 0.1$
- $\sigma_{\mathrm{ttZ}}/\sigma^{\mathrm{th.}}_{\mathrm{ttZ}} = 1.3 \pm 0.1$
- Measured **ttW** and **ttZ** cross sections are in agreement with SM within 2.3 σ and 2.2 σ, respectively
- $S_{\mathrm{t\bar{t}t\bar{t}}} = 5.5\ (4.9)\ \sigma$

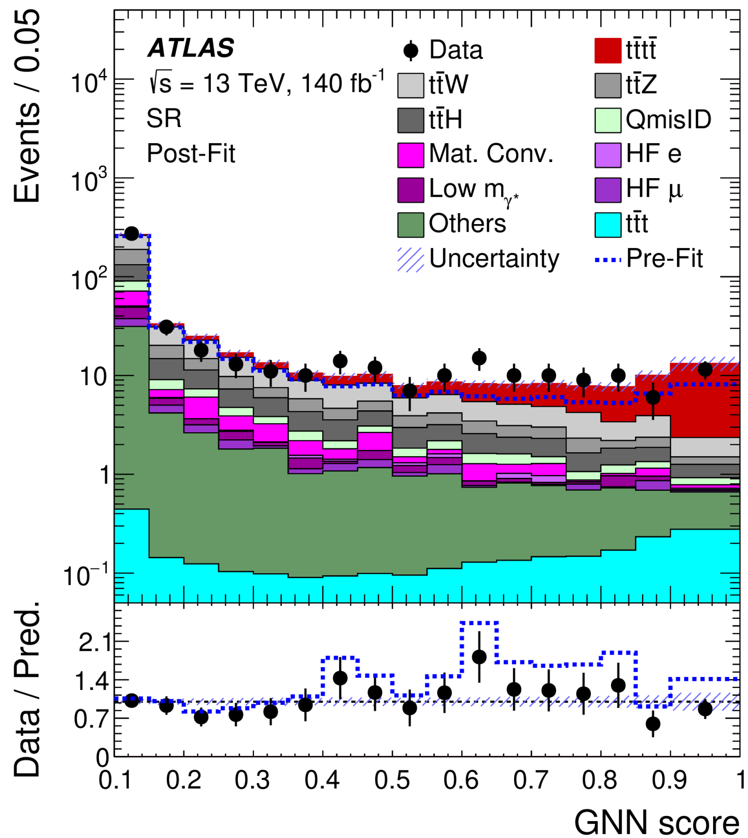
in agreement with SM

$\sigma_{\mathrm{t\bar{t}W}} = 997\,^{+98}_{-92}$ fb $\quad \sigma_{\mathrm{t\bar{t}Z}} = 1134\,^{+100}_{-96}$ fb $\quad \sigma_{\mathrm{t\bar{t}t\bar{t}}} = 17.9\,^{+3.7}_{-3.5}$ (stat.) $^{+2.4}_{-2.1}$ (syst.) fb

Four-tops now really established in multi lepton final states!

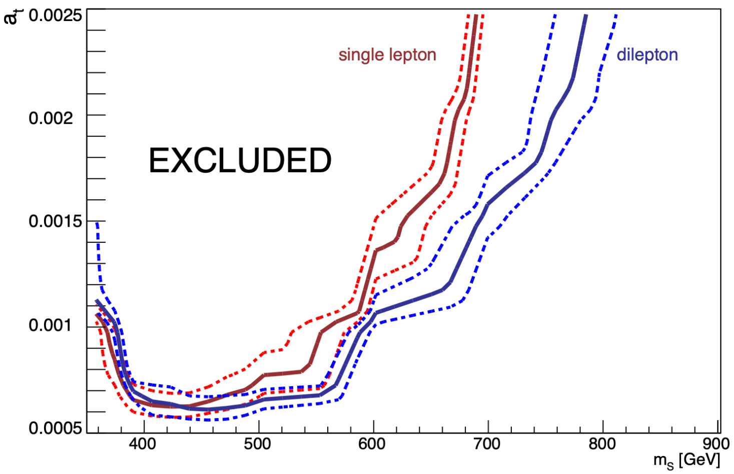
Also shows power of well-understood data!





Some thoughts on interpretation

- The CMS and ATLAS tttt results are all very ML heavy
- The various ML methods are trained on (N)LO tttt MC (typically even with many diagrams turned off on purpose!)
- See for example 1501.07580 for example of the consequences
  - (executive summary: ML results cannot necessarily be directly interpretated in BSM context if scale >4*mtop TeV)



Different approaches to EFT

- ATLAS: BSM-like EFT looking for dramatic changes in shape at high scale
- CMS: SM-like EFT trying to constrain small changes cross section limit/ uncertainties and mapping fit cross section limits to Wilson coefficients

- Both have pros and cons

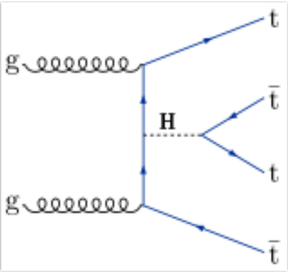
EFT interpretations

- Like many rare processes involving loop diagrams, four-top production is extremely sensitive to new physics
- SM effective field theory at order 6

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)}\mathcal{O}_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)}\mathcal{O}_k^{(6)} + o\left(\frac{1}{\Lambda^2}\right)$$

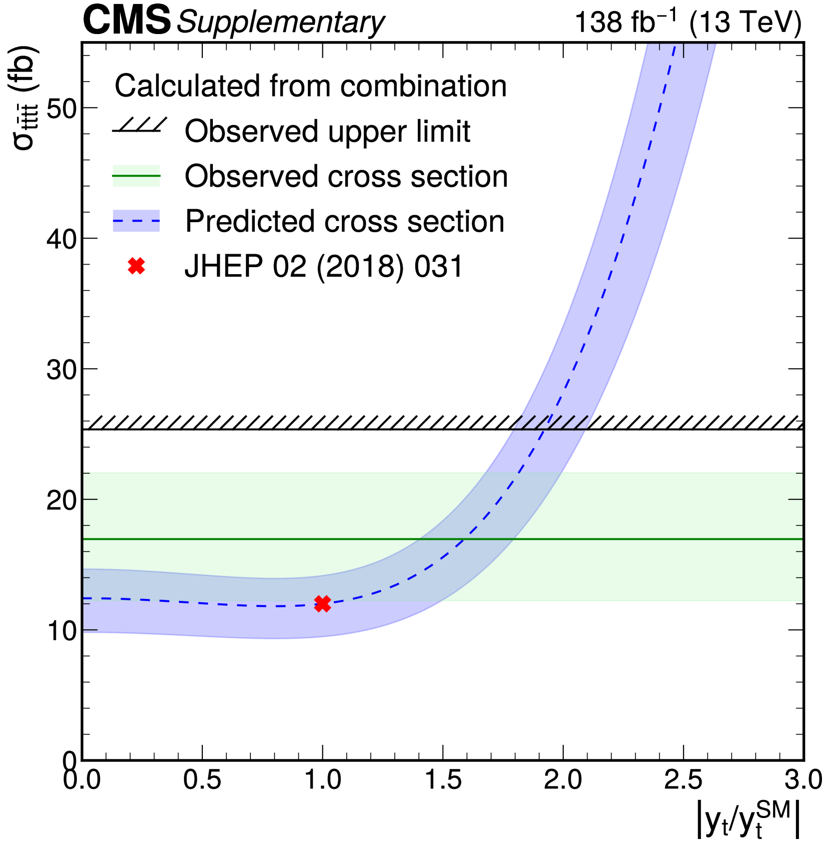
- ATLAS previous Run 2: use $\mathcal{L}_{\mathrm{EFT}}$ - $\mathcal{L}_{\mathrm{SM}}^{(4)}$ as signal model, constrain Λ
- CMS FTR/Run 2(2016): constrain $\mathcal{L}_{\mathrm{EFT}}$ / $\mathcal{L}_{\mathrm{SM}}^{(4)}$ with $\Delta\sigma_{tttt}/\ \sigma_{tttt}$, fix Λ, constrain C_k
- HL-LHC yellow report has lookup tables to map cross section uncertainties to EFT parameters!

Yukawa coupling from y_t



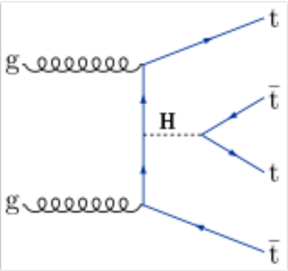
- About 20% of tttt production diagrams contain H, and y_t has substantial influence on value σ_{tttt}

- Interpreting more than just cross section: not easy (as many diagrams involved) with current MC - will be very ML heavy goal



CMS-TOP-21-005 arXiv:2303.03864 (see additional material)

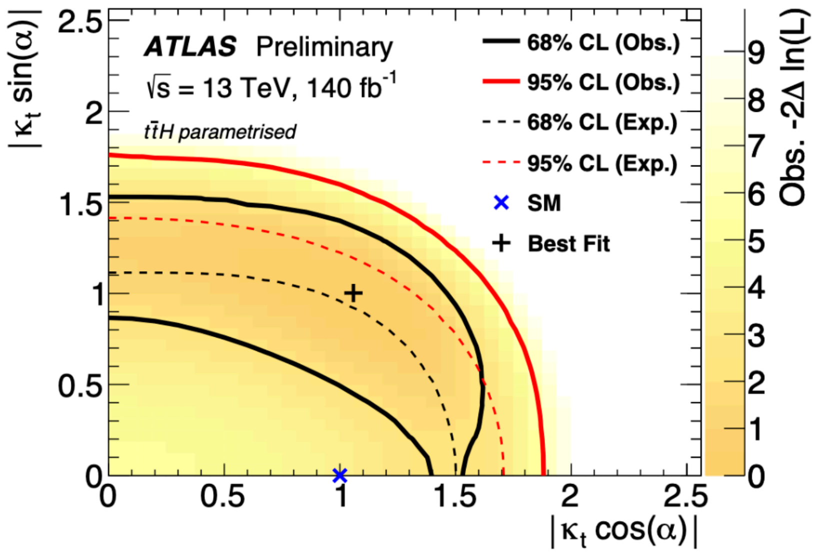
Yukawa coupling from y_t



- About 20% of tttt production diagrams contain H, and y_t has substantial influence on value σ_{tttt}

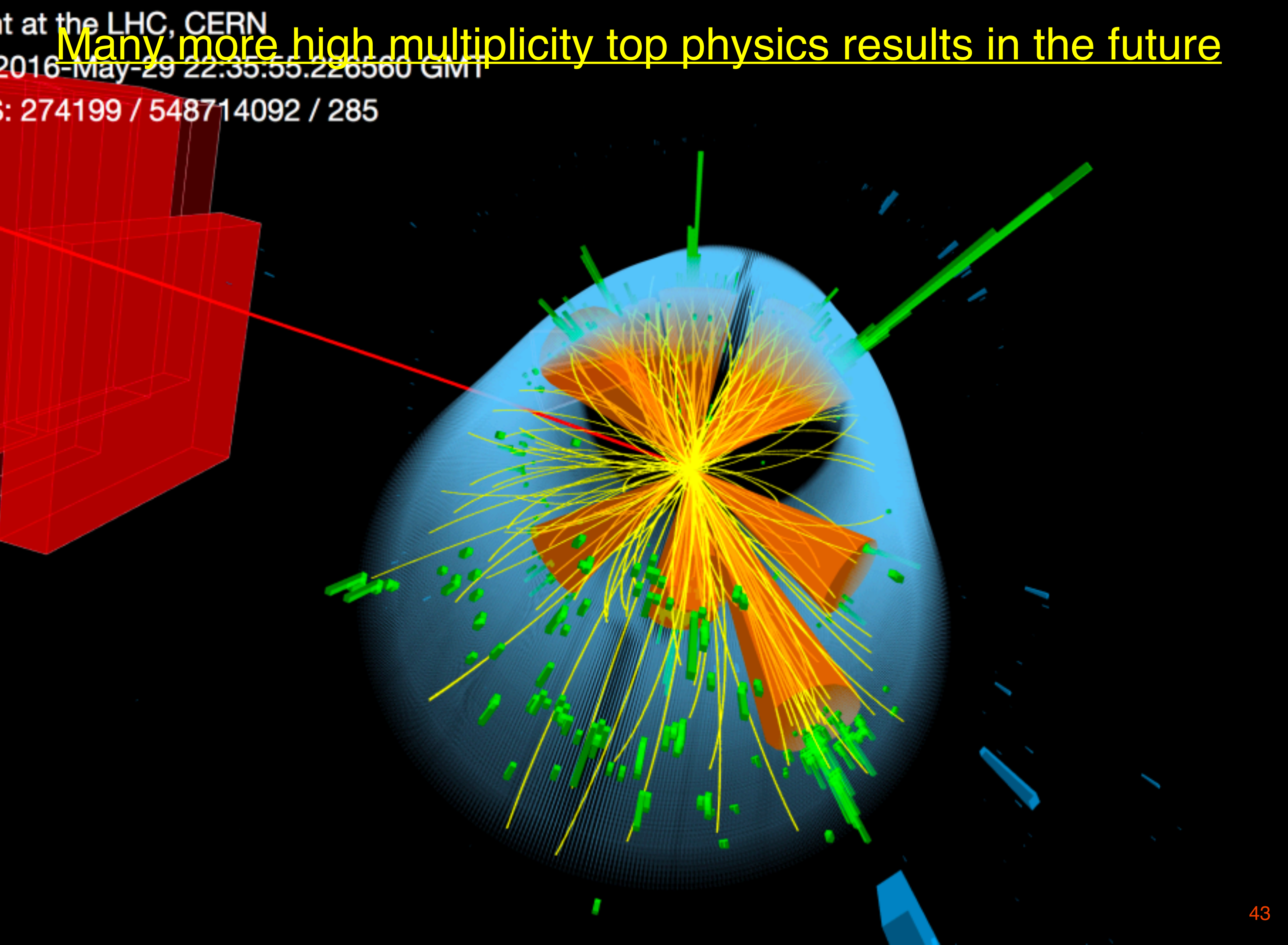
- ATLAS mad an attempt in the context of the CP even/odd H yukawa
  - ttH dependence other important effect

Obs (exp) limit with α= 0: $|\kappa_t| < 1.8$ (1.6)

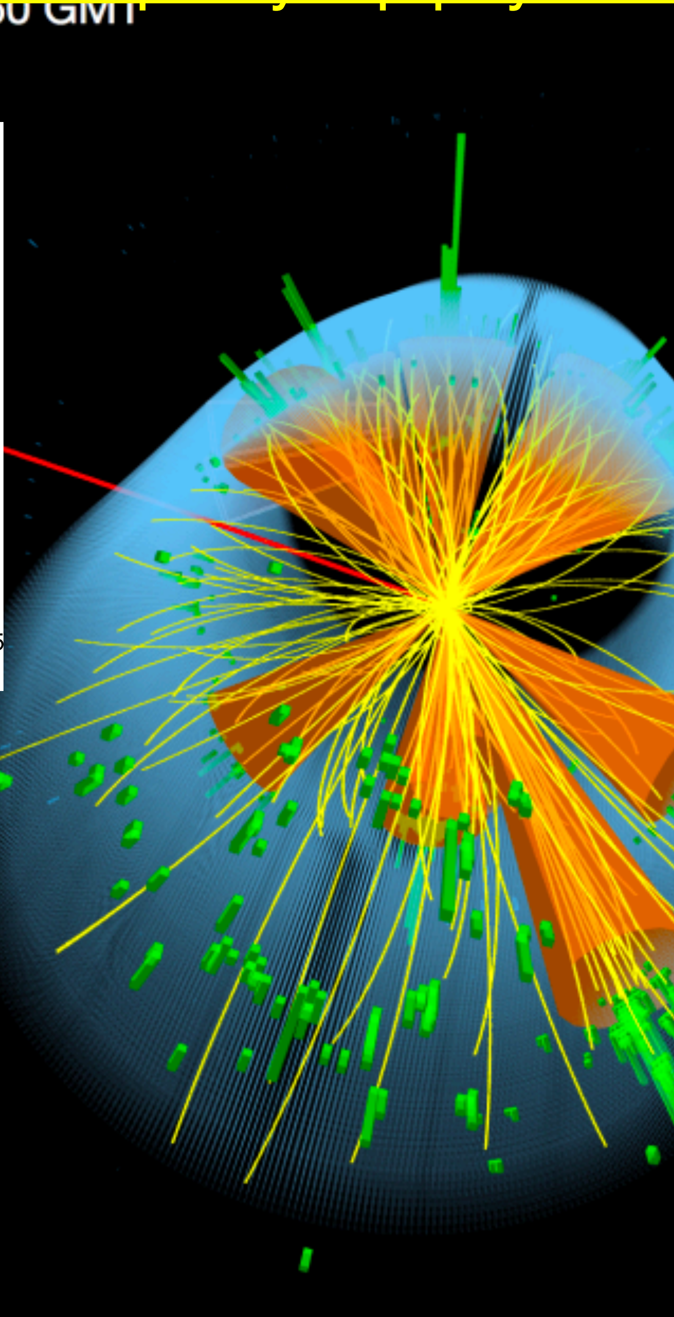


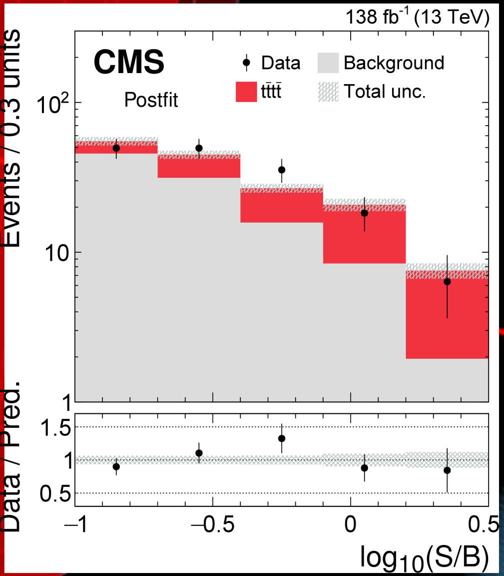
Submitted to EPJC arXiv:2303.15061

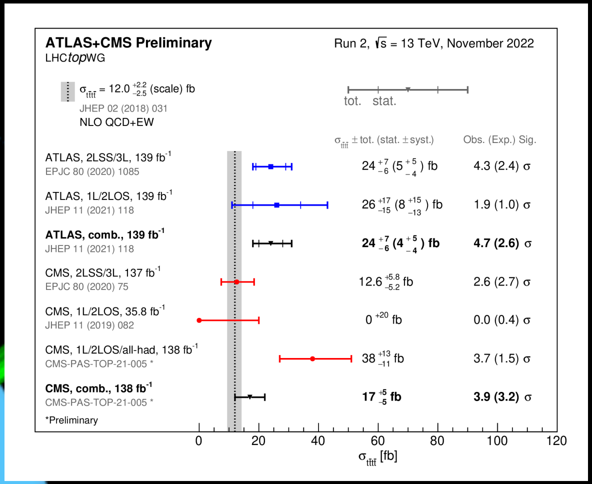
Many more high multiplicity top physics results in the future

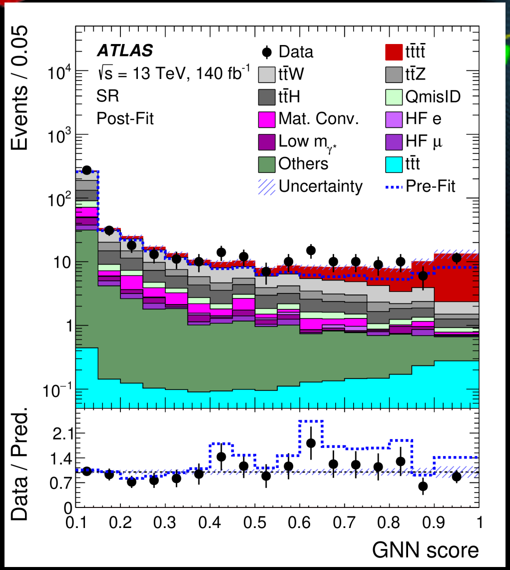


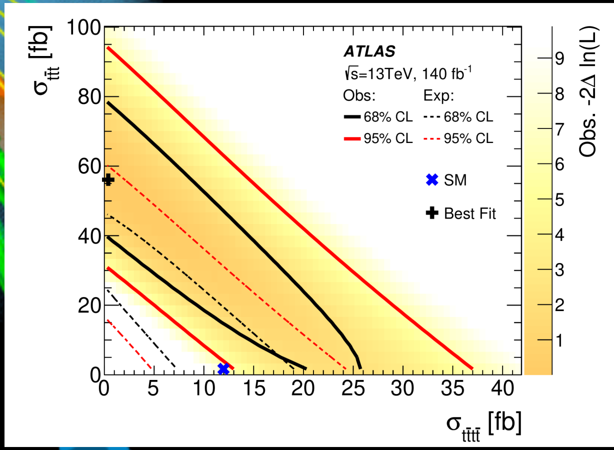
Many more high multiplicity top physics results in the future











Systematic impacts