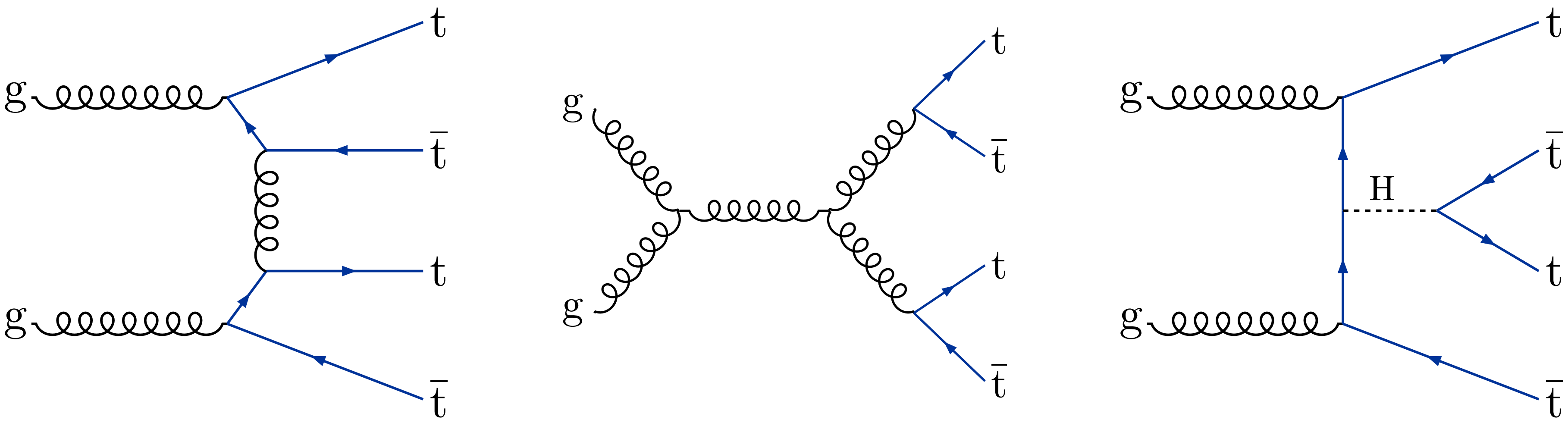
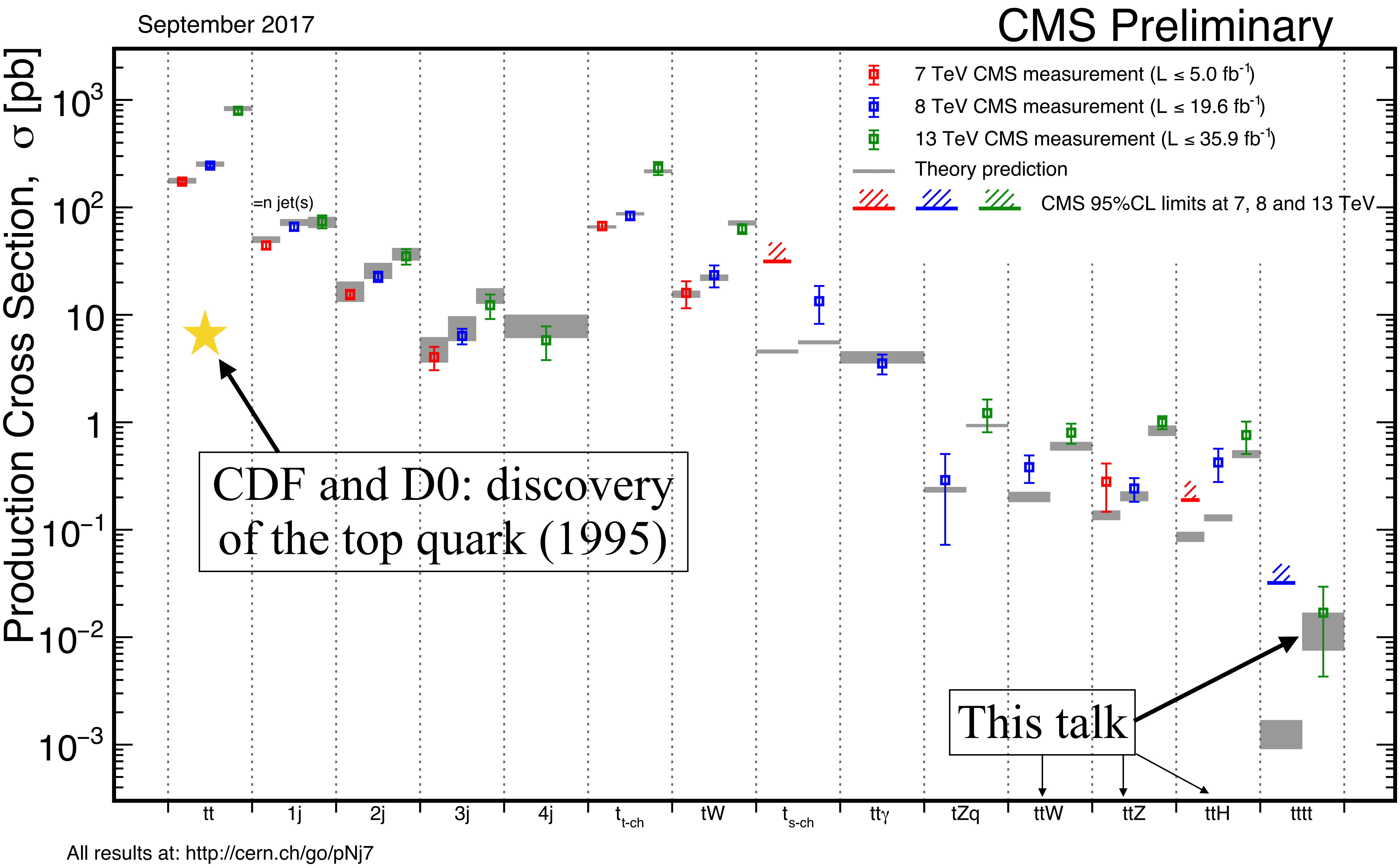
Search for Standard Model production of four top quarks

Giovanni Zevi Della Porta



ttttopic of the week
FNAL, 28 November 2017

A view from the top



CDF and D0: discovery of the top quark (1995)

This talk

Outline

(Beyond) Standard Model tttt Theory

Overview of Experimental Measurements

Focus on latest result:

CMS same-sign and multilepton search, with 35.9 fb^{-1} at 13 TeV

Disclaimer:

Many BSM theories predict boosted tttt or tttt+MET

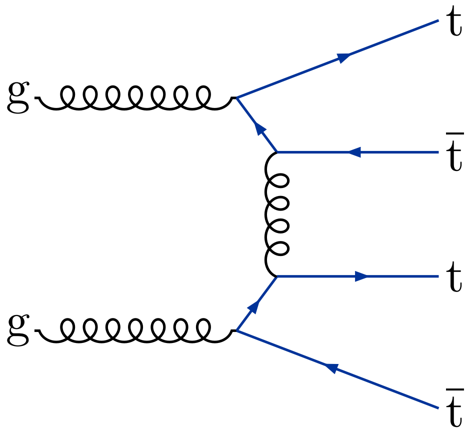
- The featured result grew out of a tttt+MET search for gluino pair-production

I will focus on SM-like tttt production (at rest)

Intro to (B)SM tttt Theory

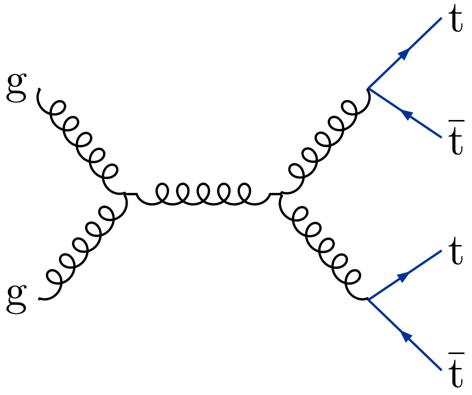
Basic question: what is the tttt cross section?

Scale/PDF choices lead to different NLO/LO k-Factors:



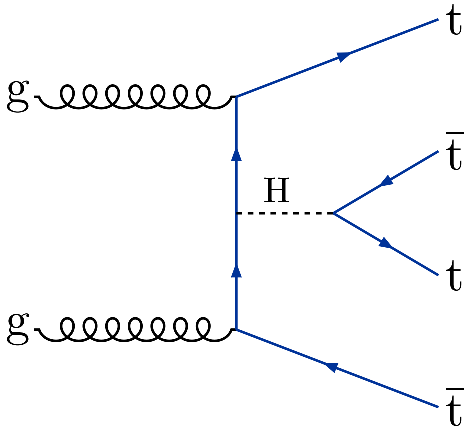
[1] 14 TeV, NLO:

- Scale choice ($\mu = 2m_t$ vs $H_T/4$) gives 20% (10%) variations at LO (NLO)
- NLO/LO k-factor: 1.27 (1.21) for $\mu = 2m_t$ ($H_T/4$)
- $\sigma_{NLO}(tttt) = 15.3^{+4.0}_{-3.8}$ or $16.8^{+4.0}_{-4.2}$ fb



[2] 13 TeV, NLO

- $\mu = H_T/2$. LO and NLO results based on NLO PDF
- NLO/LO k-factor: 2.04
- $\sigma_{NLO}(tttt) = 9.2^{+2.9}_{-2.4}$ fb



[3] 13 TeV, LO including Higgs contribution and interference

- μ = MG default
- $\sigma_{LO}(tttt) = 9.6^{+3.9}_{-3.5}$ fb
  - —> With 1.27 k-factor from [1]: $\sigma_{LO}(tttt)*k = 12.2^{+5.0}_{-4.4}$ fb

Summary:

1) Calculation is not straightforward
2) Measurement might shed some light, and encourage investigation
3) NLO calculation including Higgs contributions is missing

[1] G. Bevilacqua and M. Worek, JHEP 1207, 111 (2012) [arXiv:1206.3064].
[2] J. Alwall et al., JHEP 1407, 079 (2014) [arXiv:1405.0301]
[3] Q.-H. Cao, et al., Phys. Rev. D 95 (2017) 053004 [arXiv:1602.01934]

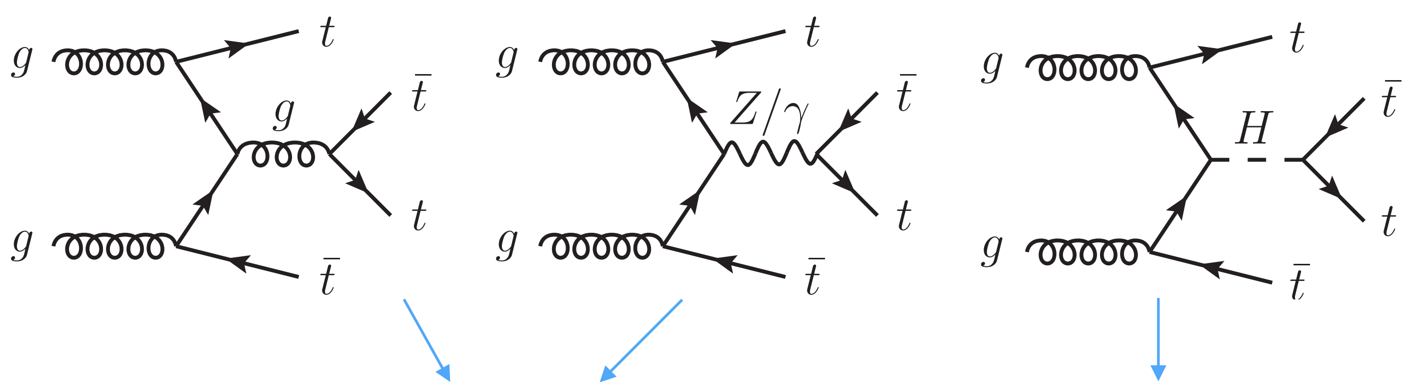
Additional contributions from off-shell Higgs

σ(tttt) includes diagrams with off-shell Higgs bosons

Small, but proportional to 4th power of top-Higgs coupling

- Unique: production and decay through same Yukawa
- $|y_t| > |y_t^{SM}|$ would significantly enhance tttt cross section

$$\boxed{\kappa_t \equiv y_{Htt}/y_{Htt}^{\mathrm{SM}}}$$



$$\sigma(t\bar{t}t\bar{t}) = \sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{g+Z/\gamma} + \kappa_t^2 \sigma_{\mathrm{int}}^{\mathrm{SM}} + \kappa_t^4 \sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_H,$$

	8 TeV	13 TeV	14 TeV
$\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{g+Z/\gamma}$:	1.344 fb,	9.997 fb,	13.140 fb,
$\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_H$:	0.171 fb,	1.168 fb,	1.515 fb,
$\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{\mathrm{int}}$:	−0.224 fb,	−1.547 fb,	−2.007 fb.

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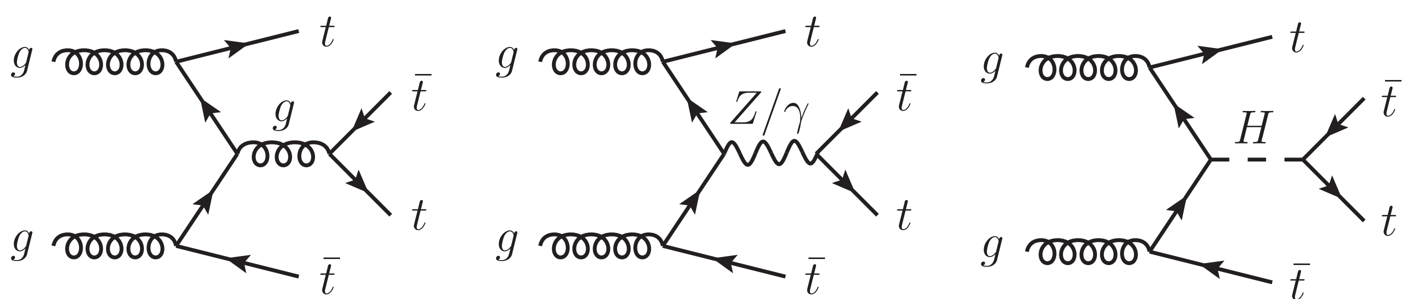
Proposal from Cao et al. [PRD 95, 053004 (2017) and FCC Yellow Report]

Combine tttt and ttH measurements to constrain total Higgs width, assuming SM branching ratio to μμ/ZZ/γγ, or vice-versa

$$\sigma(pp \to t\bar{t}H \to t\bar{t}xx) = \sigma^{SM}(pp \to t\bar{t}H \to t\bar{t}xx) \times \boxed{\kappa_t^2\kappa_x^2 \frac{\Gamma_H^{SM}}{\Gamma_H}}$$



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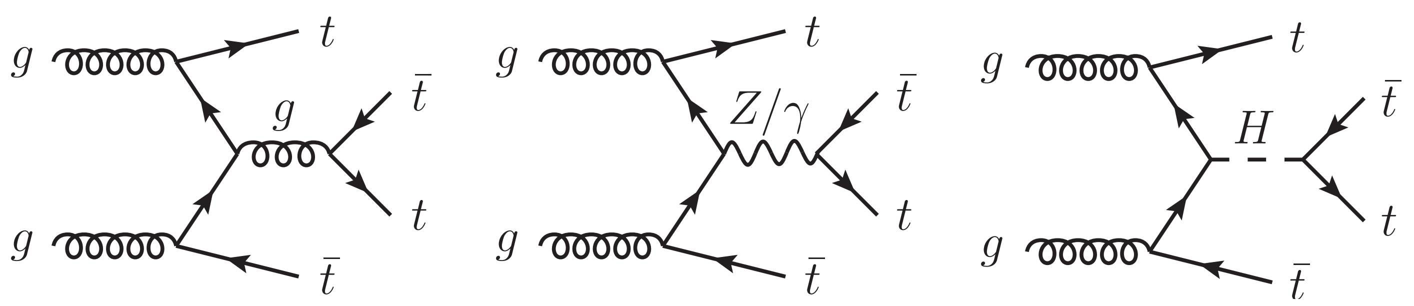

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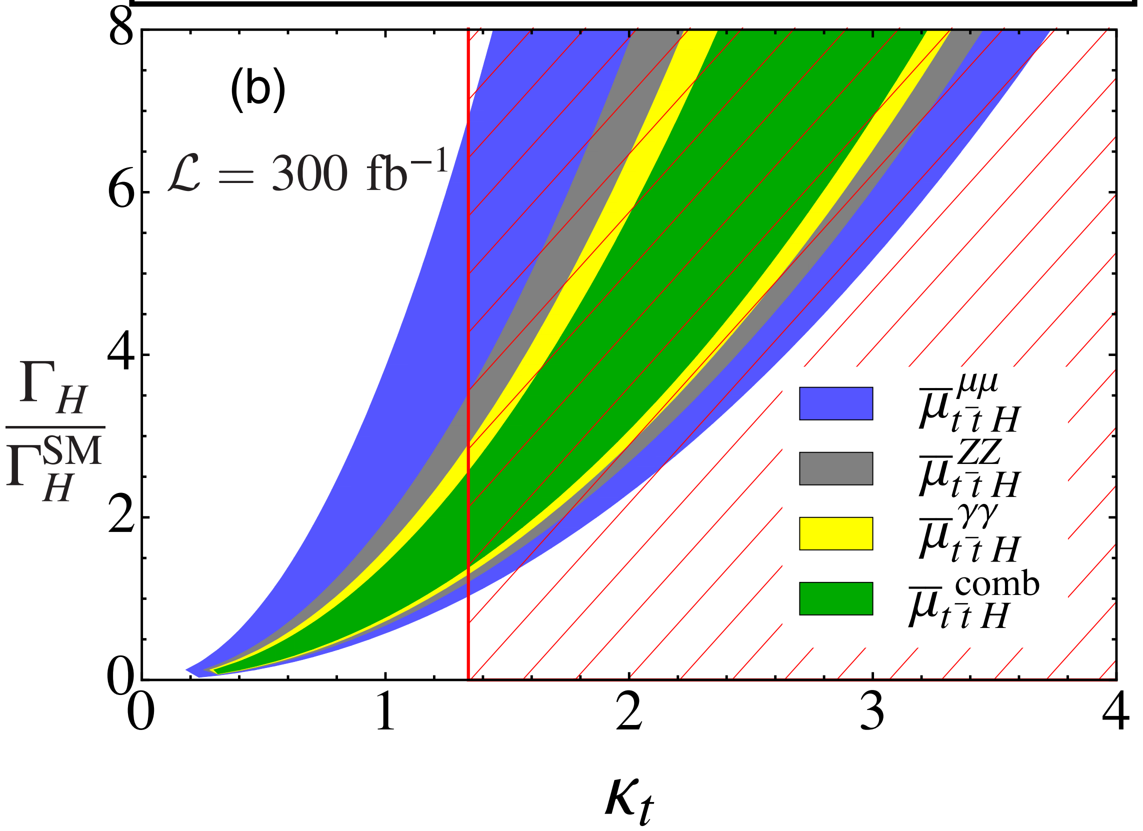


Massive (pseudo) scalars: H/A

Two-Higgs-doublet models (2HDM)

Realized in many new physics scenarios, such as SUSY

Lowest mass scalar can match the SM Higgs (“h”), in the “alignment limit”

Introduce a scalar (H) and a pseudoscalar (A)

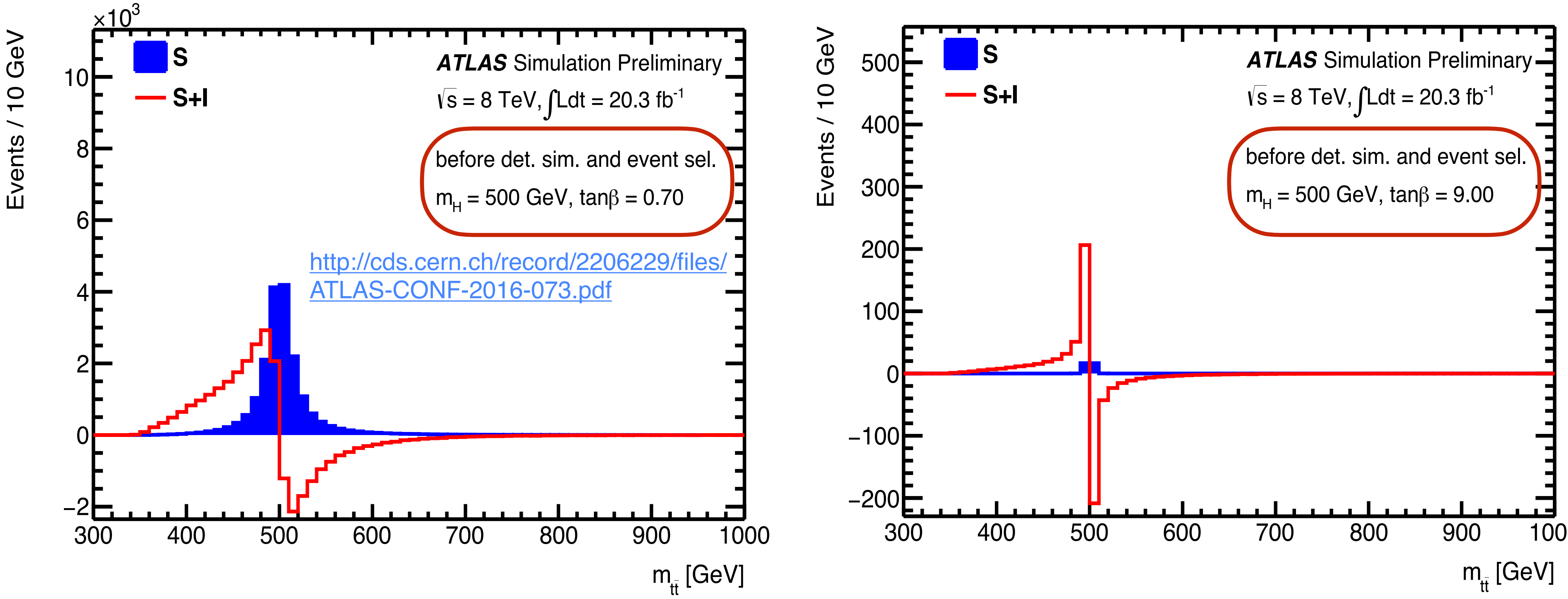
Currently unprobed region (alignment limit, low tanβ, $m_{H/A} \gtrsim 2{*}m_t$) where bb/WW couplings are suppressed, and H/A decays preferentially to tt

Largest cross section is direct production pp→H/A→tt

Problem 1: large background (and interference with) QCD tt production

Problem 2: shape of signal mass peak depends on coupling

Signal shape in m_{tt} for different assumptions of signal strength



http://cds.cern.ch/record/2206229/files/ATLAS-CONF-2016-073.pdf

Constraints from pp→H/A→tt

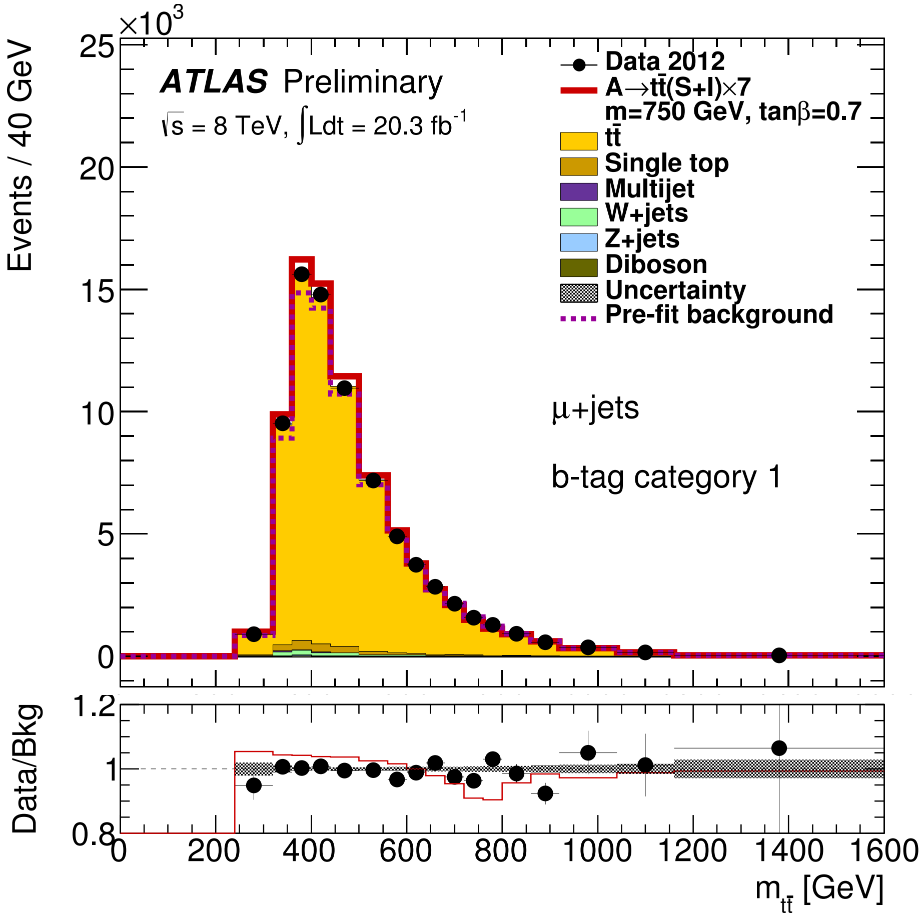
ATLAS search for m_{tt} features in 8 TeV data [CONF-2016-073]

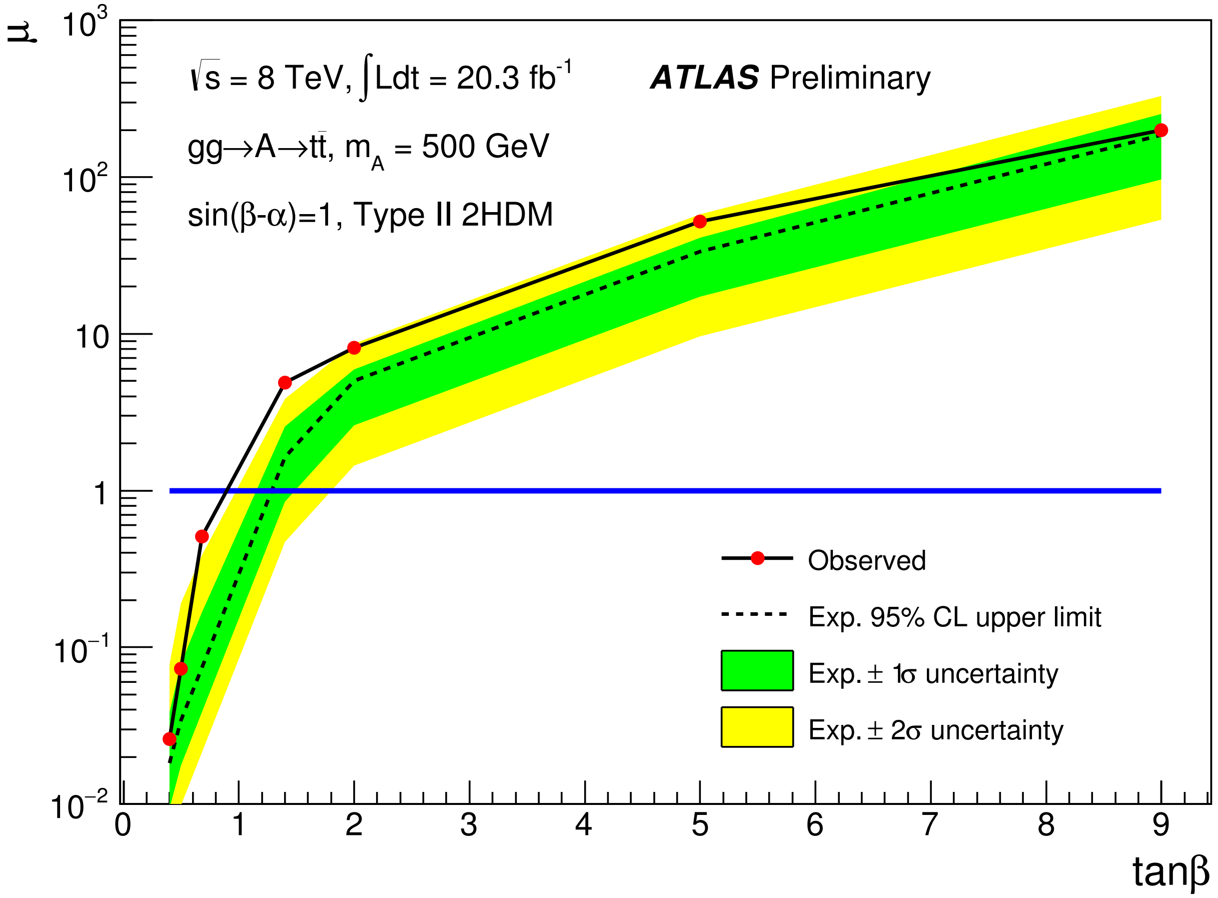
Exclude $m_{A(H)}$~500 GeV for very small values of tanβ<0.85 (0.45)

- Expected sensitivity for tanβ ≲ 1.2 (1.0).

Search loses sensitivity quickly as higher tanβ reduces cross section and narrows width

- Searches for this signature are constrained by systematics on reconstructed m_{tt}
- Difficult to probe 350-450 GeV region due to background shape



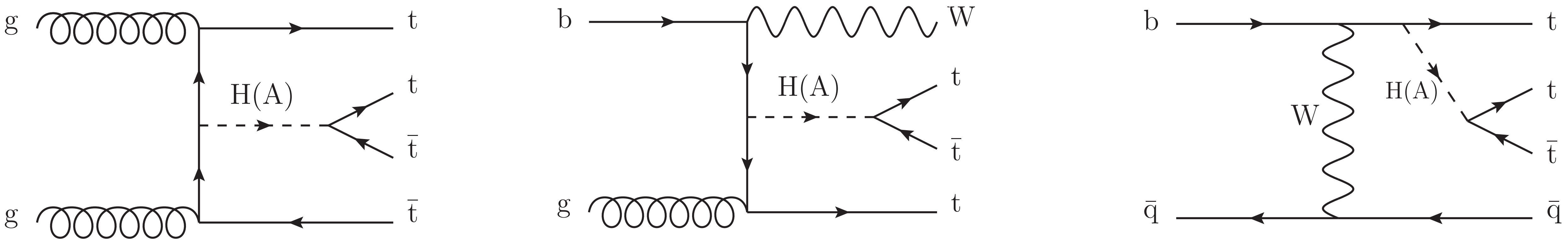


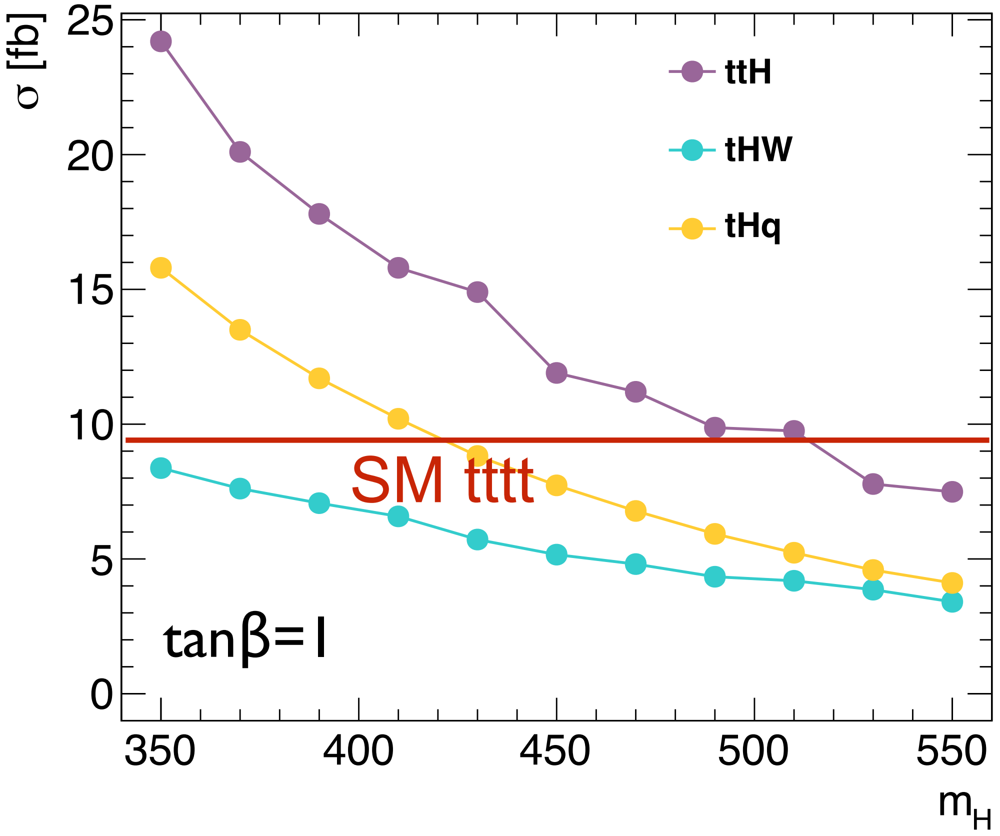
H/A associated production

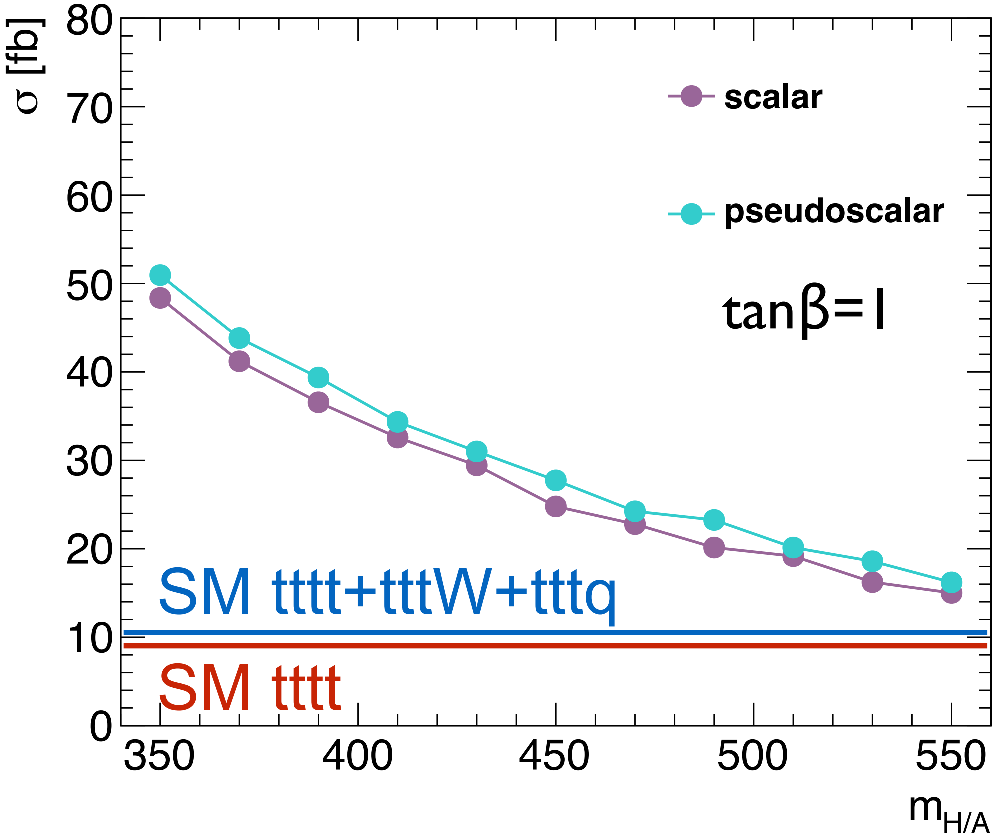
Proposal by N. Craig et al [arXiv:1605.08744]

2HDM predicts enhancement in several top-associated production channels

Can easily probe down to 2^*m_t, where enhancement of σ_{tttt} is a factor of > 2.5




Individual cross sections for H, LO, 13 TeV

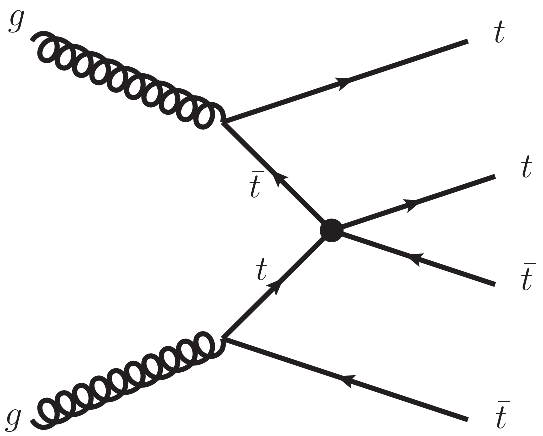

$\sigma_{ttH/A} + \sigma_{tWH/A} + \sigma_{tqH/A}$ (LO, 13 TeV)

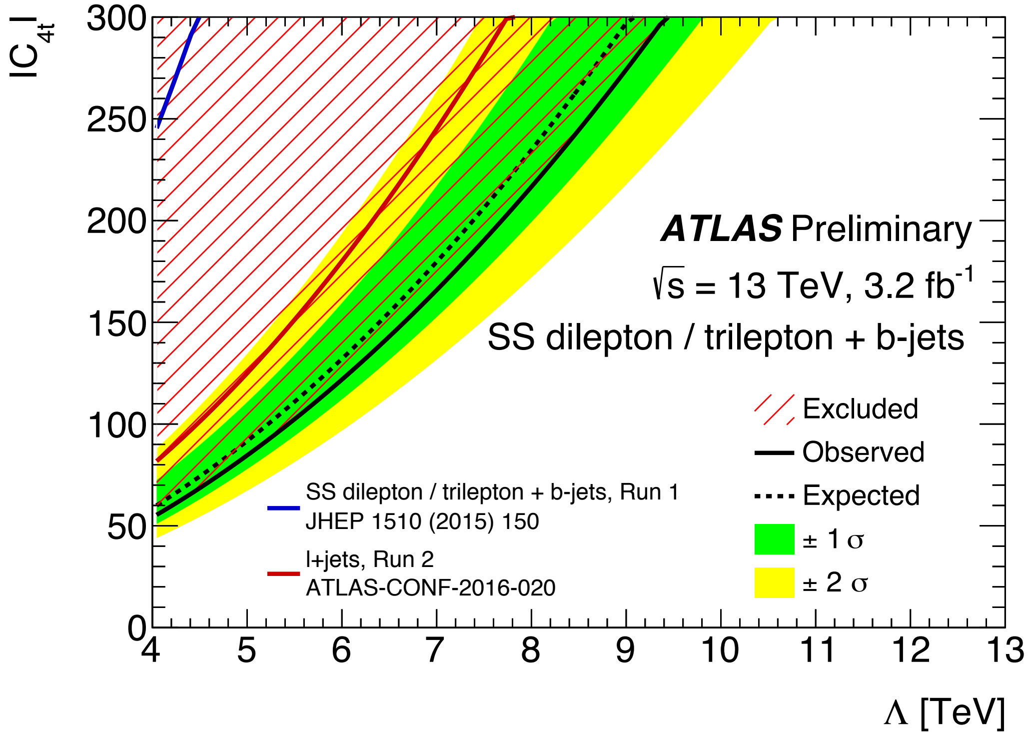
Generic interpretations

Contact interactions (explored by ATLAS-CONF-2016-020 and 032)

Generic non-resonant tttt production, as long as Λ is much larger than the scale of the process

$$\mathcal{L}_{4t} = \frac{C_{4t}}{\Lambda^2} \left(\bar{t}_{\mathrm{R}} \gamma^{\mu} t_{\mathrm{R}}\right) \left(\bar{t}_{\mathrm{R}} \gamma_{\mu} t_{\mathrm{R}}\right)$$





Even more generic: Effective Field Theory operators

- http://feynrules.irmp.ucl.ac.be/wiki/4topEFT

First: can set limits based on cross-section enhancement

Next (300 fb^{-1}): can start studying kinematics

$$\mathcal{O}_R = \left(\bar{t}_R \gamma^{\mu} t_R\right)\left(\bar{t}_R \gamma_{\mu} t_R\right)$$

$$\mathcal{O}_L^{(1)} = \left(\bar{Q}_L \gamma^{\mu} Q_L\right)\left(\bar{Q}_L \gamma_{\mu} Q_L\right)$$

$$\mathcal{O}_L^{(8)} = \left(\bar{Q}_L \gamma^{\mu} T^A Q_L\right)\left(\bar{Q}_L \gamma_{\mu} T^A Q_L\right)$$

$$\mathcal{O}_B^{(1)} = \left(\bar{Q}_L \gamma_{\mu} Q_L\right)\left(\bar{t}_R \gamma_{\mu} t_R\right)$$

$$\mathcal{O}_B^{(8)} = \left(\bar{Q}_L \gamma_{\mu} T^A Q_L\right)\left(\bar{t}_R \gamma_{\mu} T^A t_R\right)$$

Overview of Experimental Measurements

Overview of tttt searches

All-hadronic

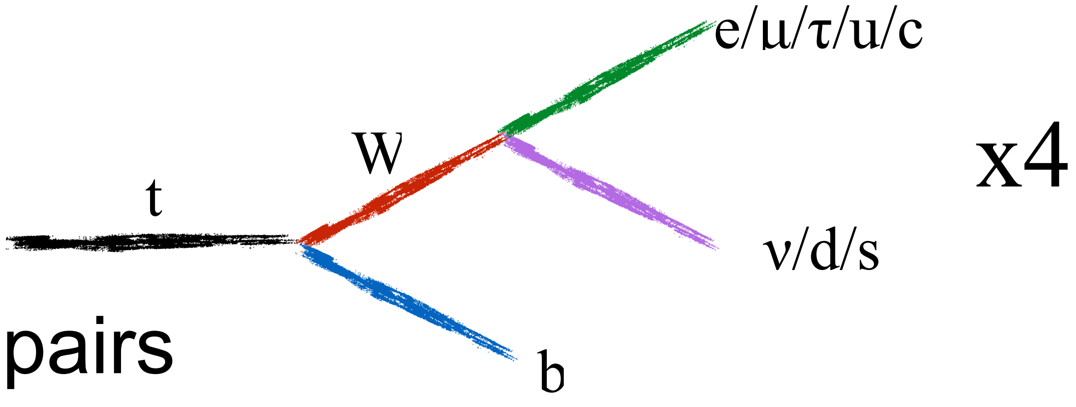
Powerful in boosted searches for new physics, not yet explored at rest

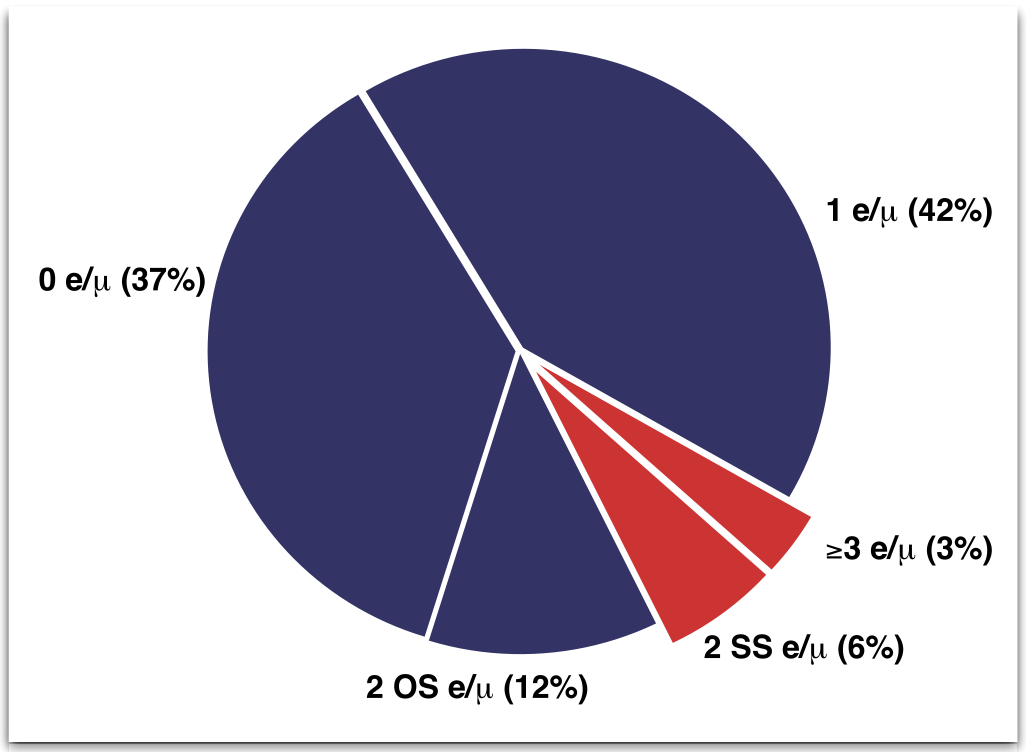
1 lepton and opposite-sign 2 lepton

Large tt pair-production background

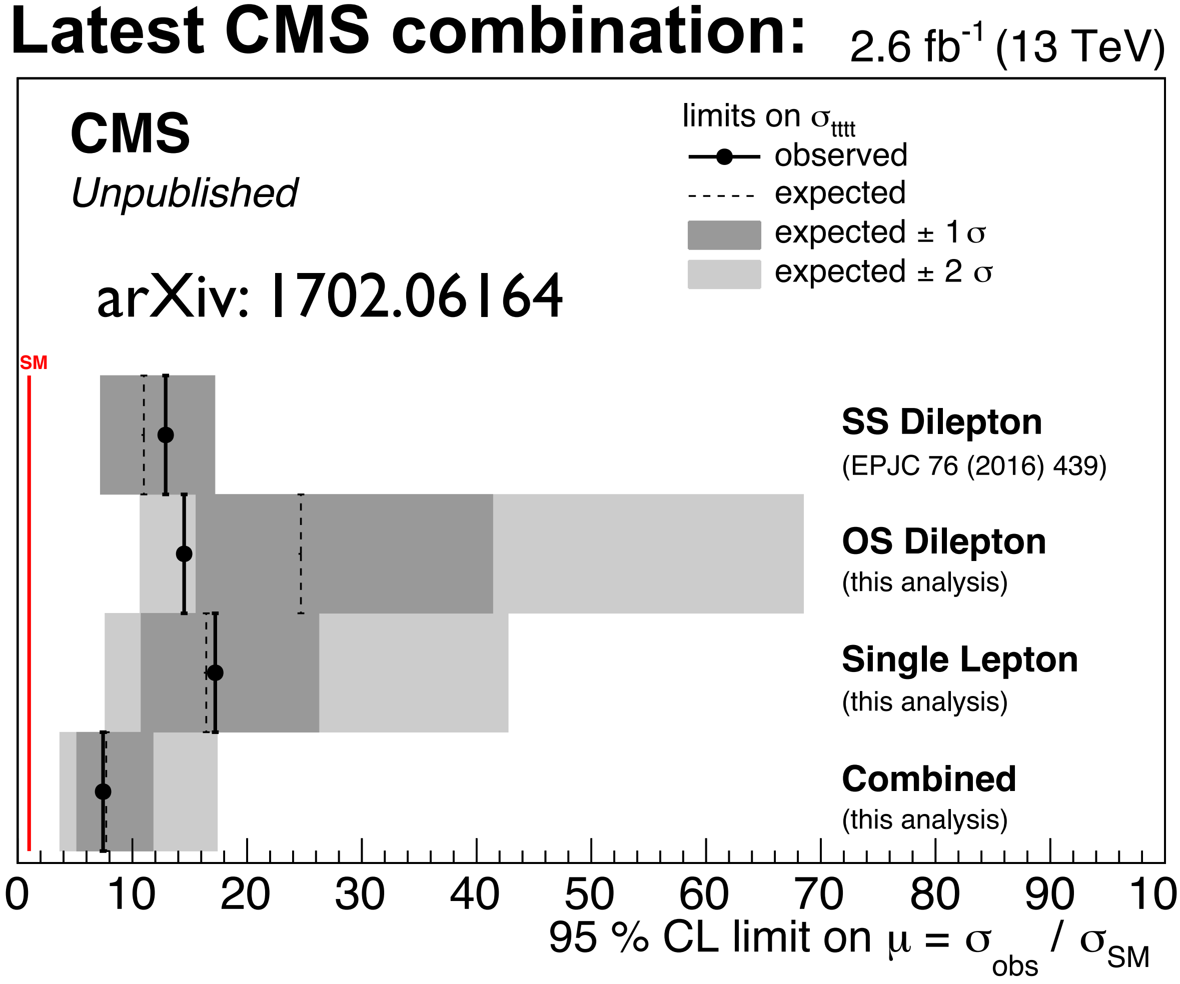
2 same-sign or ≥ 3 leptons

Comparable branching to OS2L, reject top pairs





Latest CMS combination:



CMS 1L and opposite-sign 2L analyses

Huge tt background motivates interesting strategies

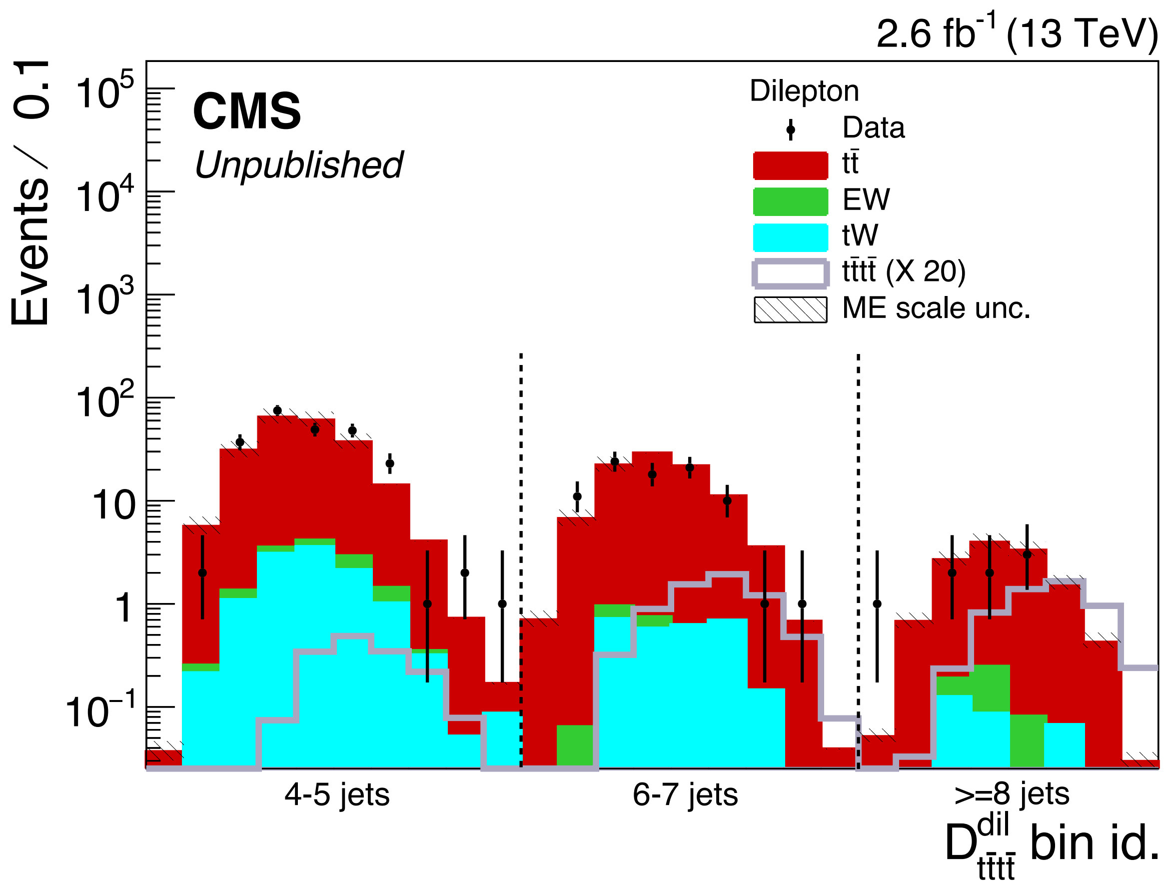
Reconstruct hadronic tops with a BDT, trained on tt:

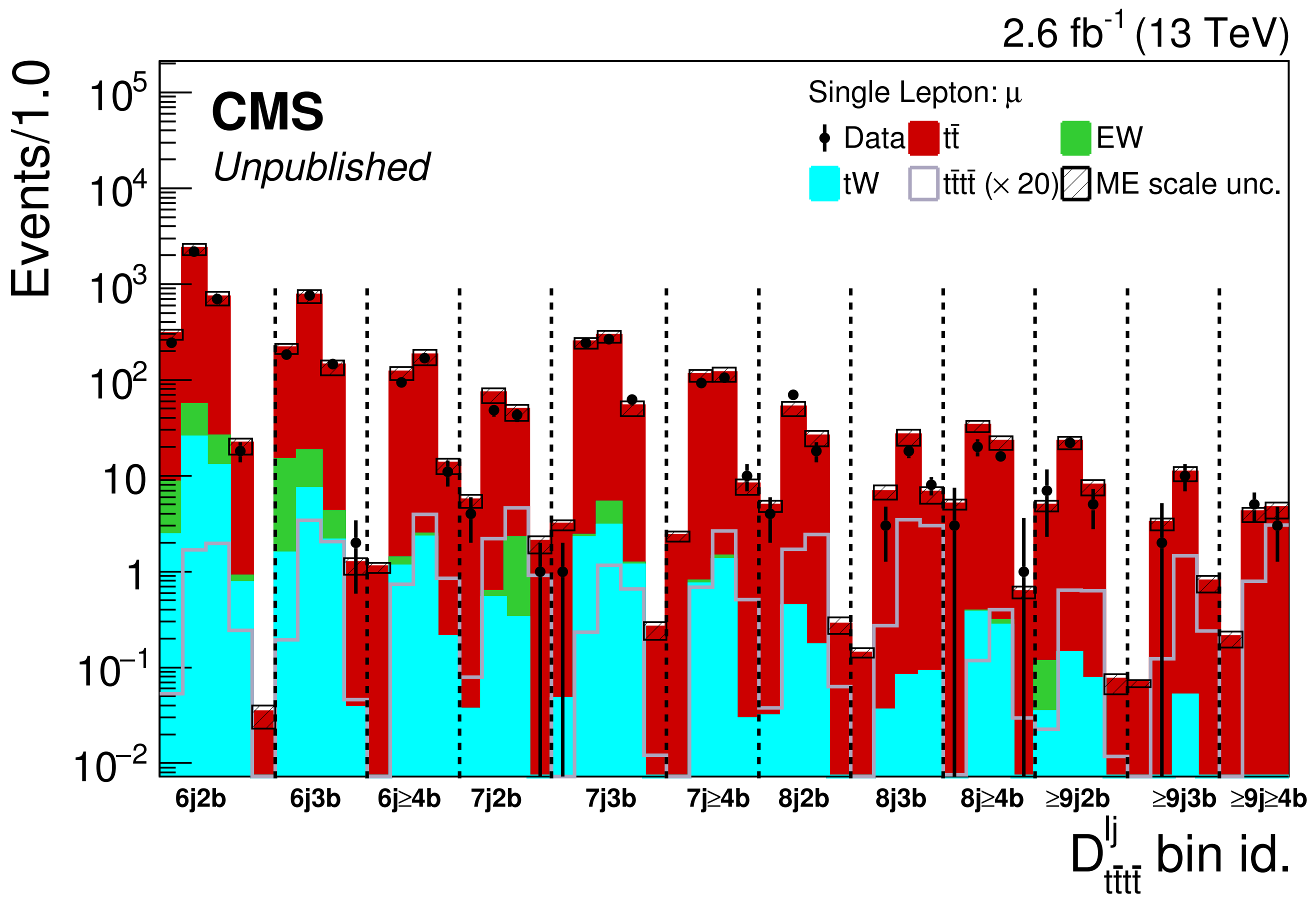
- BDT1 variables: m(jj), m(jjj), b-tag disc.(j), ΔR(jjj, "W"), ΔR(jjj, "b"), $p_T^{jjj}/(\Sigma p_T^{j})$

Use kinematic variables (including BDT1) to train a BDT2: tttt vs tt

Classify according to N(jets), N(b-jets), BDT2

- O(100) signal regions
- Take advantage of high-statistics bins to constrain tt shape systematics





[arXiv:1702.06164]. Results shown on previous slide.

ATLAS analyses

Simpler analysis strategy for single lepton [ATLAS-CONF-2016-020]

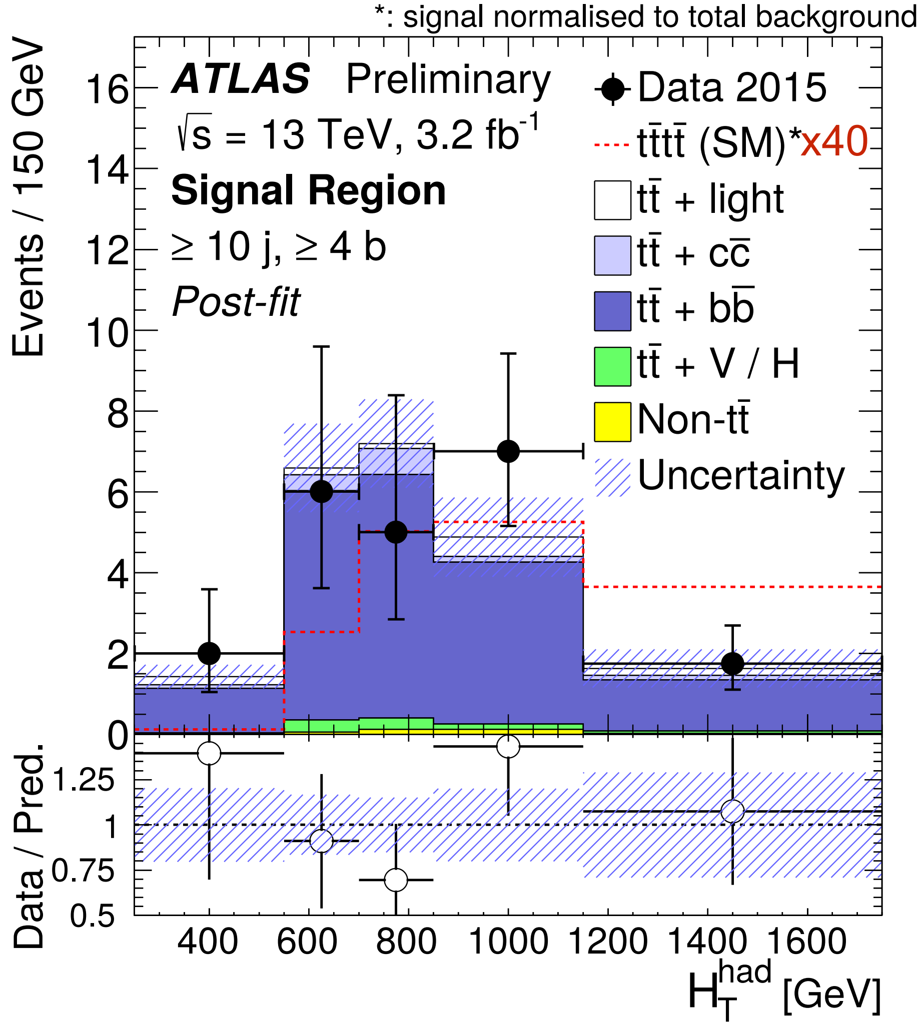
Define SRs using: N_{jets}, N_b, H_T, MET

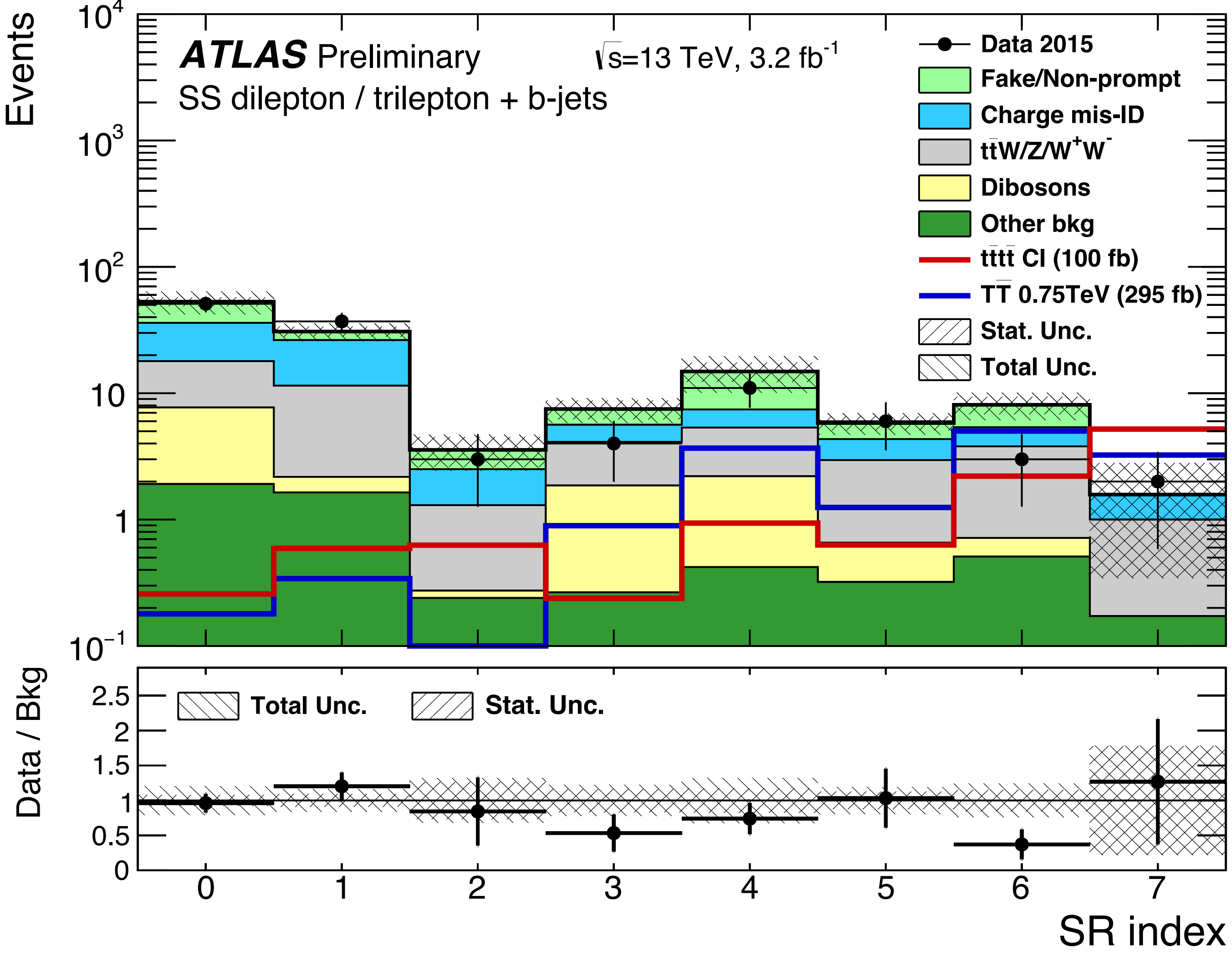
- Upper Limit with 3.2 fb^{-1}: 21*σ^{SM} obs. (16 exp.)
- [CMS with 2.6 fb^{-1}: 17*σ^{SM} obs. (16 exp.)]

Same-sign dilepton [ATLAS-CONF-2016-032]

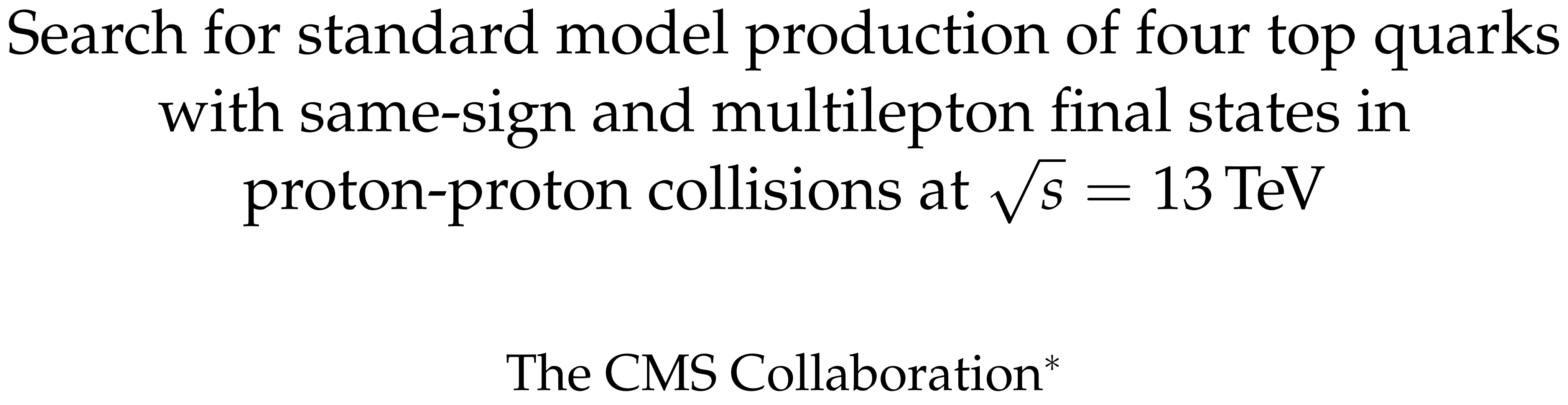
- 95% CL UL: 7*σ^{SM} obs., 12*σ^{SM} exp.

Definition			Name
$e^\pm e^\pm + e^\pm\mu^\pm + \mu^\pm\mu^\pm + eee + ee\mu + e\mu\mu + \mu\mu\mu$, $N_{\text{jets}} \geq 2$			
$400 < H_T < 700GeV$	$N_b = 1$	$E_T^{\text{miss}} > 40$ GeV	SR0
	$N_b = 2$		SR1
	$N_b \geq 3$		SR2
$H_T \geq 700$ GeV	$N_b = 1$	$40 < E_T^{\text{miss}} < 100GeV$	SR3
		$E_T^{\text{miss}} \geq 100$ GeV	SR4
	$N_b = 2$	$40 < E_T^{\text{miss}} < 100GeV$	SR5
		$E_T^{\text{miss}} \geq 100$ GeV	SR6
	$N_b \geq 3$	$E_T^{\text{miss}} > 40$ GeV	SR7





Focus on latest results



Search for standard model production of four top quarks with same-sign and multilepton final states in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$

The CMS Collaboration*

arXiv:1710.10614 [hep-ex]

Same-sign and multilepton CMS search with 2016 data: 35.9 fb at 13 TeV

Object Selection (leptons and b-jets)

Triggers and Event Selection

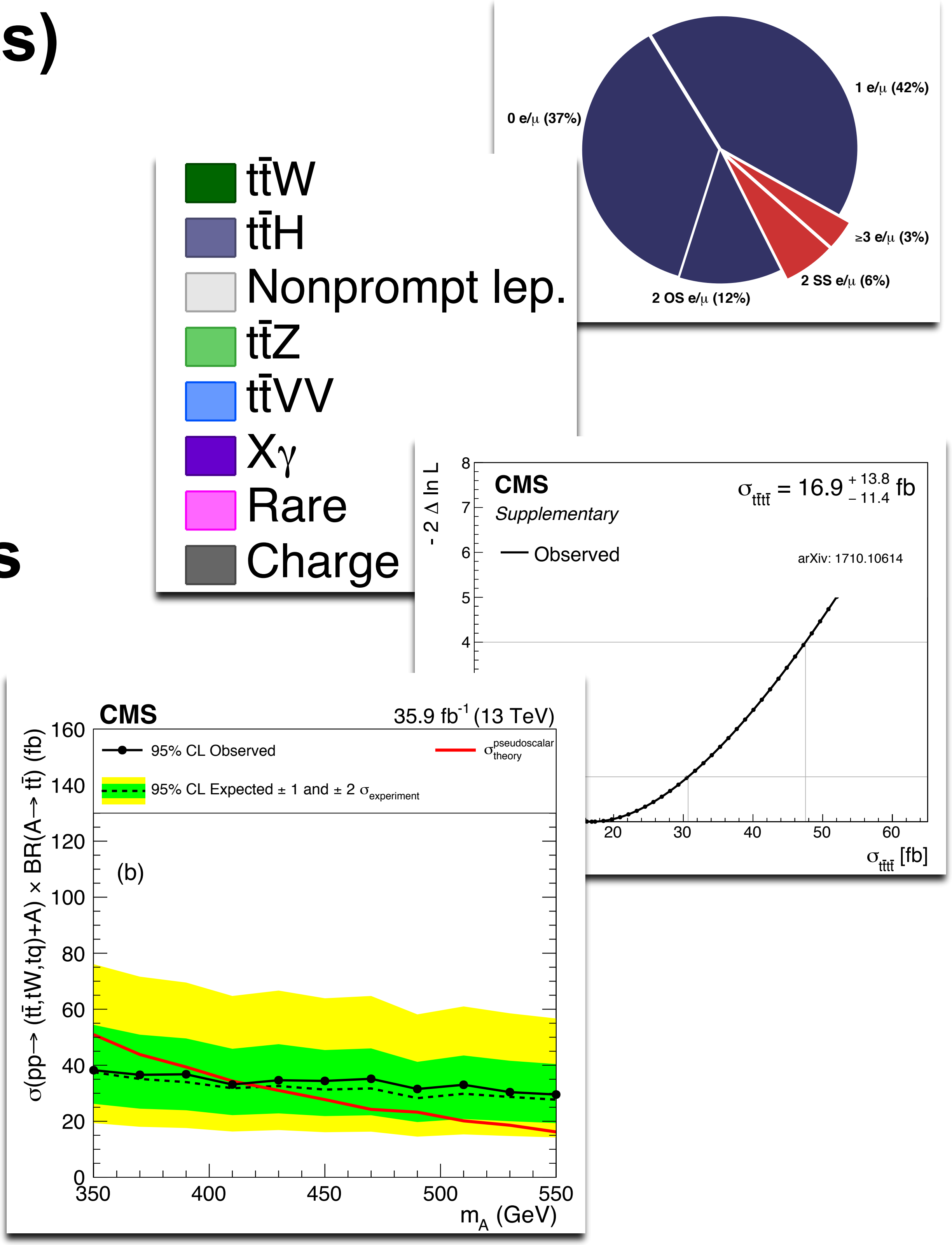
Background Estimates

Signal and Background Kinematics

Definition of Signal Regions

Results and Discussion

Additional Interpretations



Leptons and jets

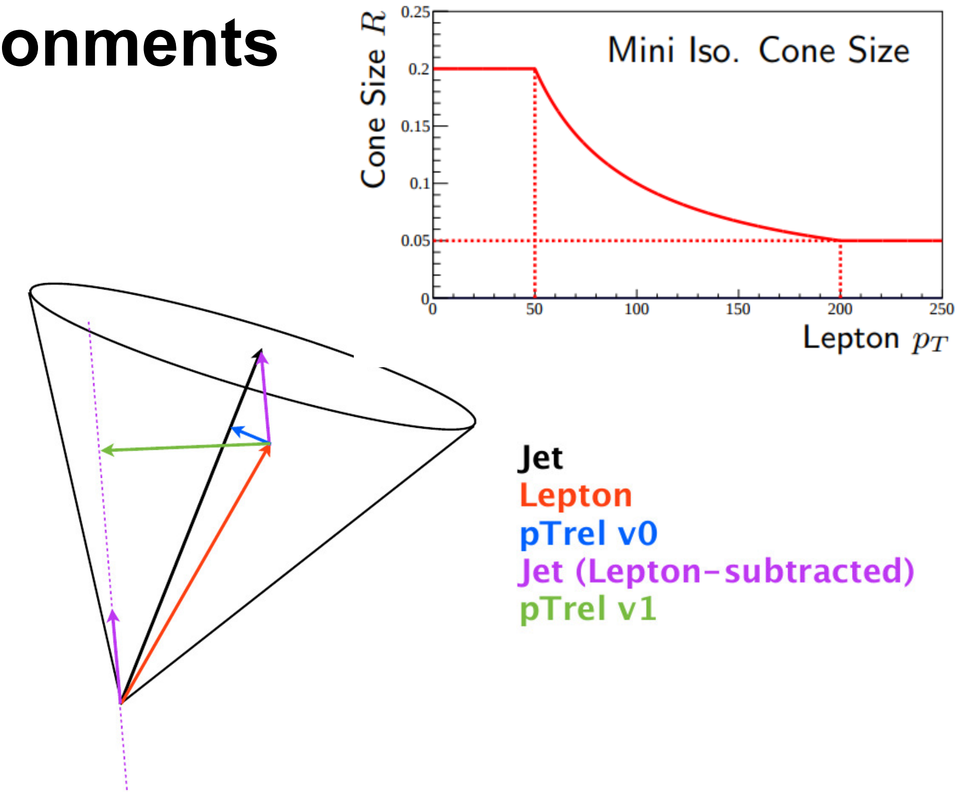
Lepton selection optimized for high multiplicity environments

Optimize isolation by defining 3 variables:

- A) Mini-isolation (cone [0.2, 0.05], shrinking with p_T)
- B) Large cone isolation: cone = jet in which lepton is clustered
- C) Lepton momentum transverse to the lepton-subtracted jet

A is always required, then B OR C

- B rejects most fake/nonprompt leptons
- C recovers leptons overlapping with jets due to boost/multiplicity



Latest b-tagging of jets, using deep learning

Based on standard tagger (CSV), but using more tracks and featuring 4 hidden layers

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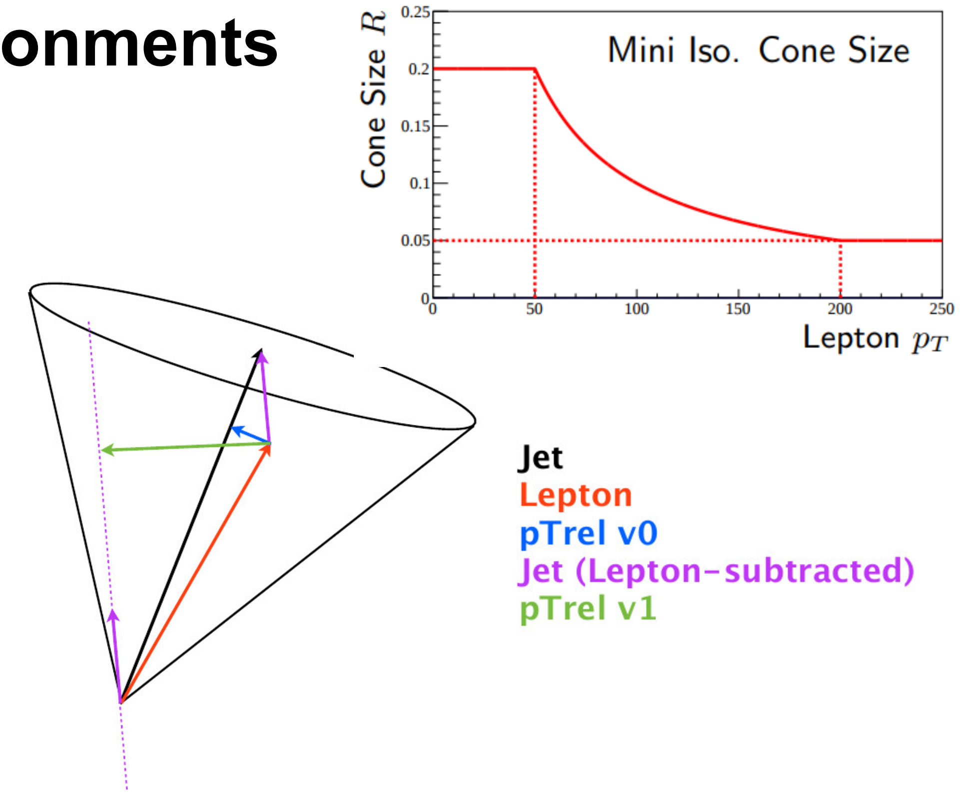

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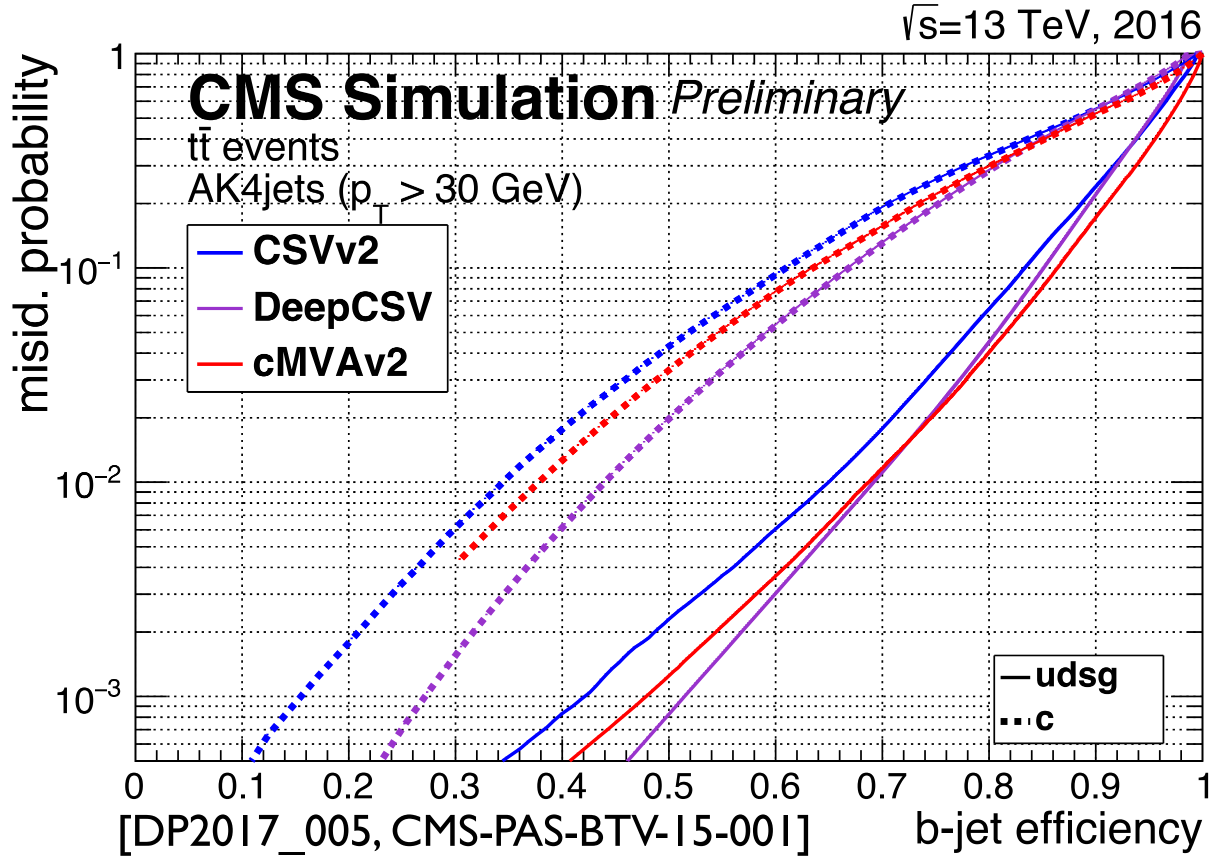


[DP2017_005, CMS-PAS-BTV-15-001]

Efficiencies w.r.t truth:

e (20-60 GeV): 45–70%

μ (20-60 GeV): 70–90%

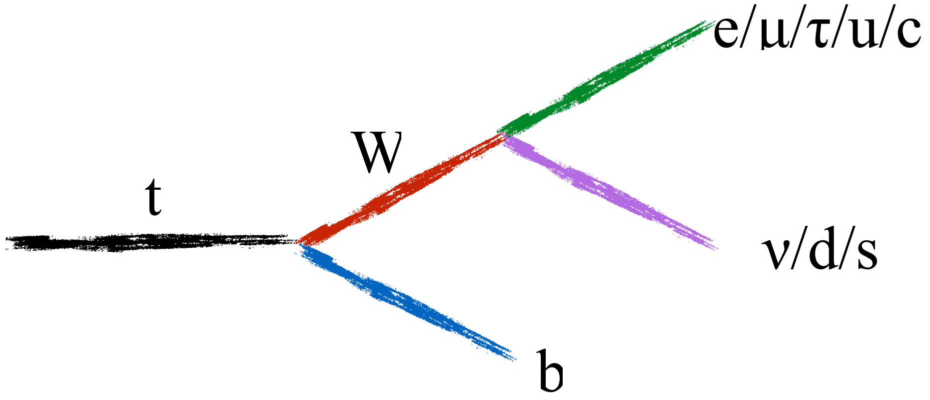
b-jets (20-400 GeV): 55–70%

Trigger and Baseline selection

Dilepton triggers: ee, μμ, eμ

Use non-isolated triggers with $p_T^{lep} > 8$ GeV, $H_T > 300$ GeV

- > 95% (92%) for ee, eμ (μμ)



Object kinematics:

Object	p_T	η
Electrons	$p_T > 20$ GeV	$\|\eta\| < 2.5$
Muons	$p_T > 20$ GeV	$\|\eta\| < 2.4$
Jets	$p_T > 40$ GeV	$\|\eta\| < 2.4$
b-tagged jets	$p_T > 25$ GeV	$\|\eta\| < 2.4$

Baseline selection:

2 same-sign or ≥ 3 leptons

- DY veto: $m_{ll} > 12$ GeV and $|m_{ll} - m_Z| > 15$ GeV with $p_T^{lep3} >$ 5(7) GeV for e(μ)

Njets ≥ 2, Nb ≥ 2

HT > 300, MET > 50 GeV

tttt: Branching Ratio ~ 9% Baseline Selection ~ 1.5%

Main Backgrounds

Processes with same-sign WW (or WZ with a lost Z lepton) and b-jets

- ttW, ttZ, ttH (H to WW, ZZ), “ttVV”
- “Rare”: VV, VVV, tWZ, tZq

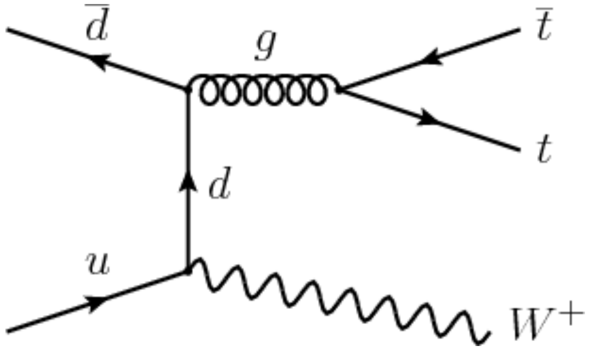
Processes with Wγ/Zγ, and an untagged γ conversion

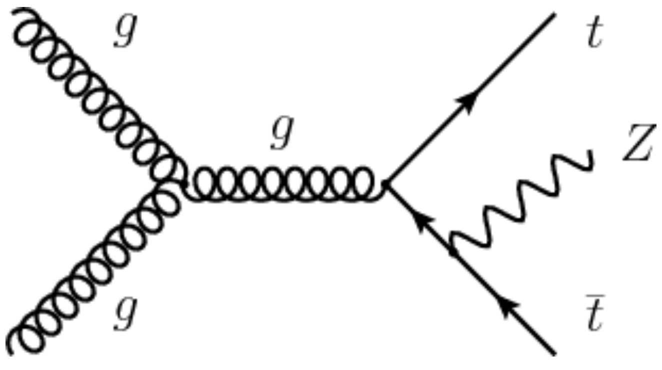
- “Xγ”: tγ, ttγ

Single-lepton or opposite-sign dilepton processes

1) with an additional fake/nonprompt lepton
2) with a charge-misidentified electron

Main diagrams for ttW and ttZ:





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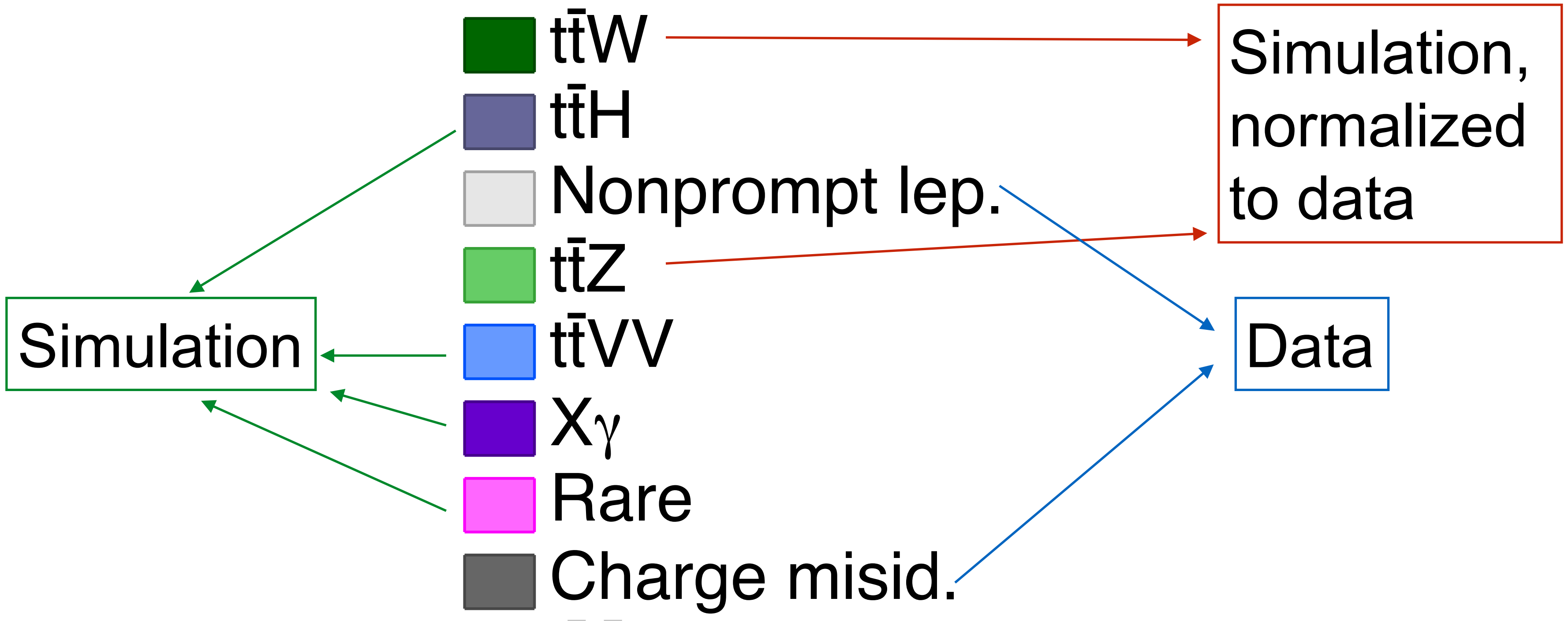


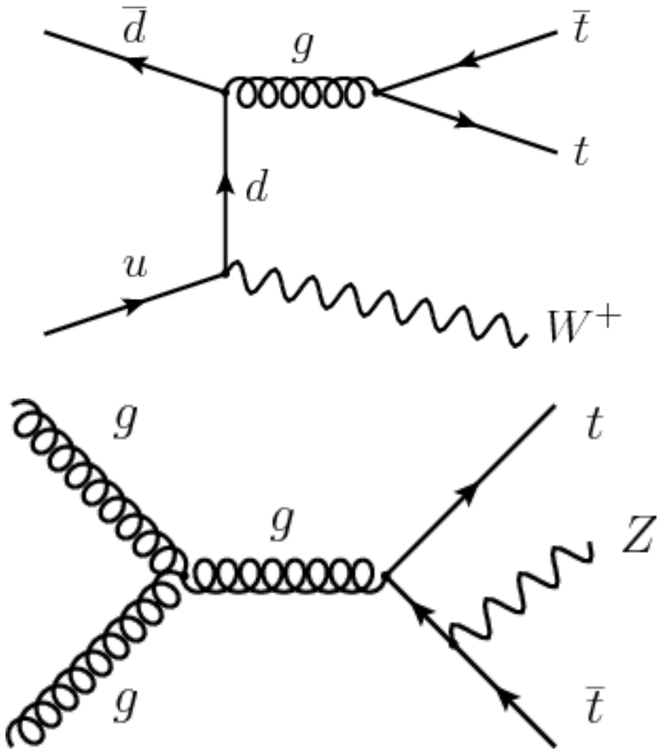
🟩 $t\bar{t}W$
🟦 $t\bar{t}H$
⬜ Nonprompt lep.
🟩 $t\bar{t}Z$
🟦 $t\bar{t}VV$
🟪 Xγ
🟪 Rare
⬛ Charge misid.

Simulation

Simulation, normalized to data

Data

Main diagrams for ttW and ttZ:

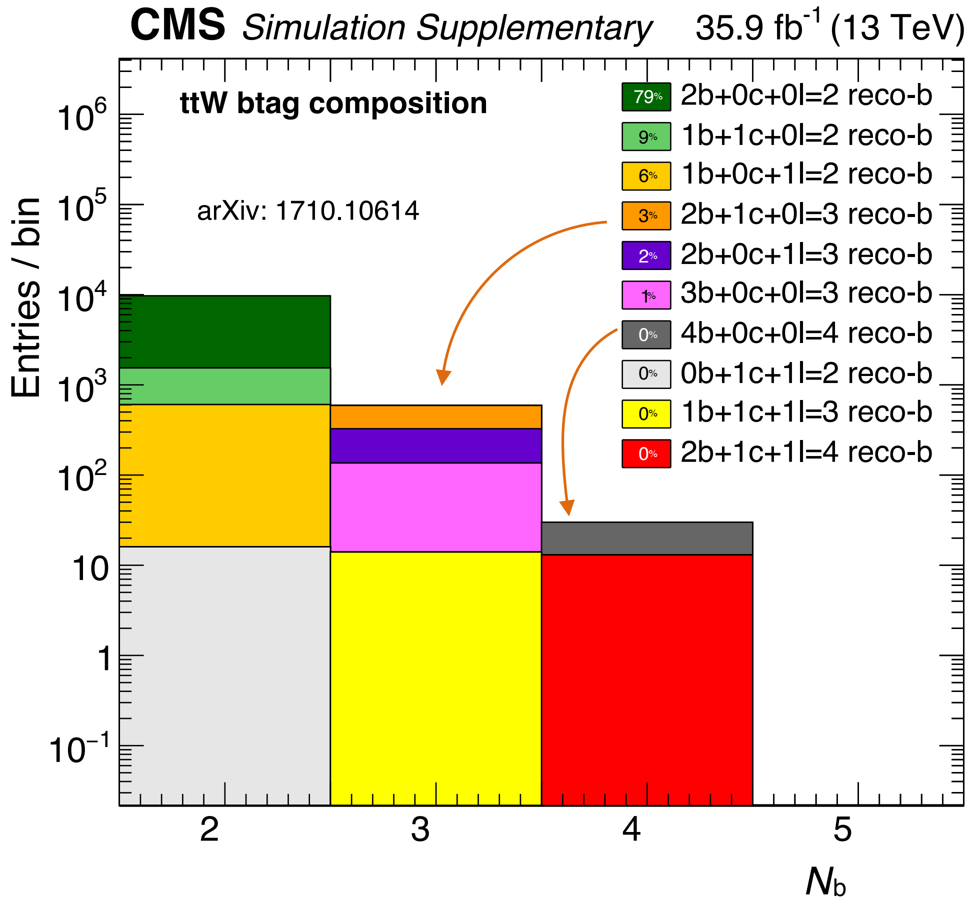


Where do the extra (b-)jets come from?

Main backgrounds, ttW, ttZ, ttH(WW) have 2 b-jets: why 3 b-tags?

Check ttW at generator level:

- N_b = 3 region dominated by ttW+c
- N_b = 4 region dominated by ttW+bb

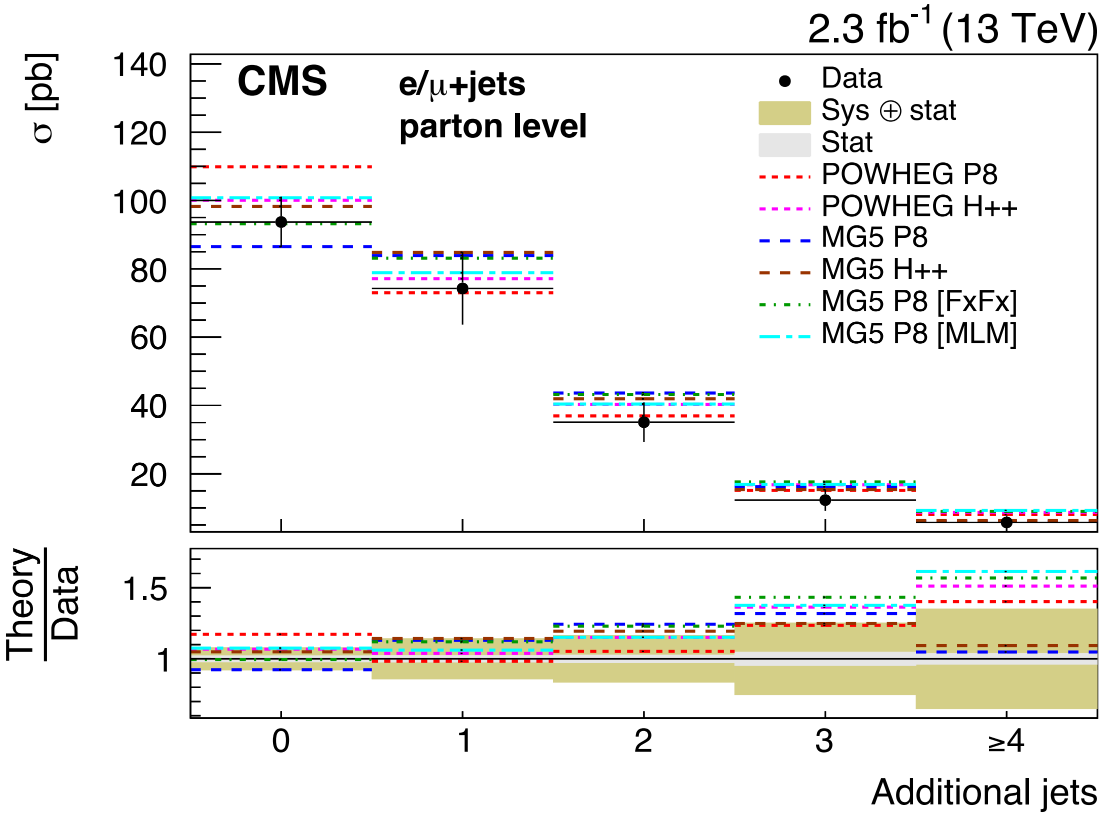


Are ttV+jets and ttV+bb well understood?

Use tt+jets and tt+bb as proxy for ttV

- tt+jets measurement is below theory
- σ(ttbb)/σ(ttjj) measurement is 1 σ above theory (1.7 ± 0.6) [arXiv:1705.10141]

Correct ttV simulation using tt Data/MC



[tt+bb: arXiv:1705.10141, tt+jets: arXiv:1610.04191]

ttW

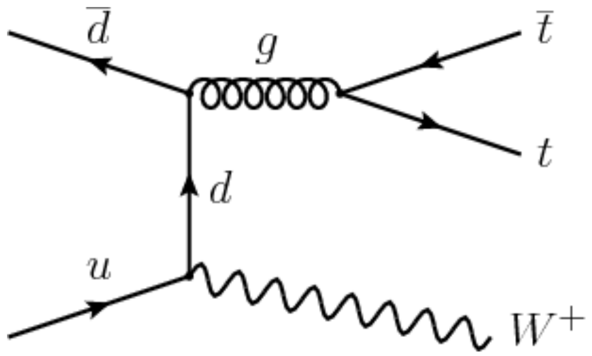
🟩 $t\bar{t}$W

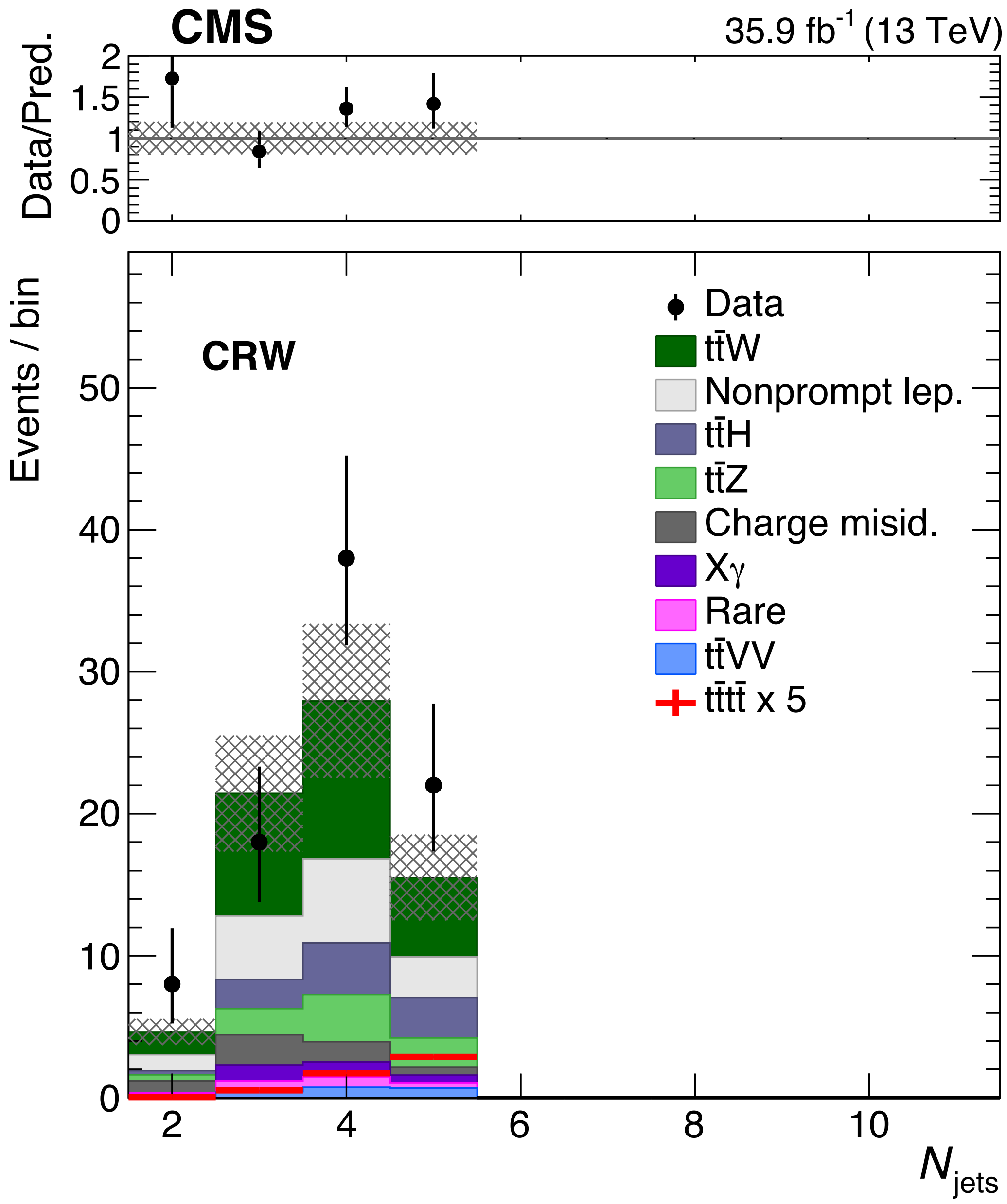
Define a Control Region (CRW) to normalize the simulation

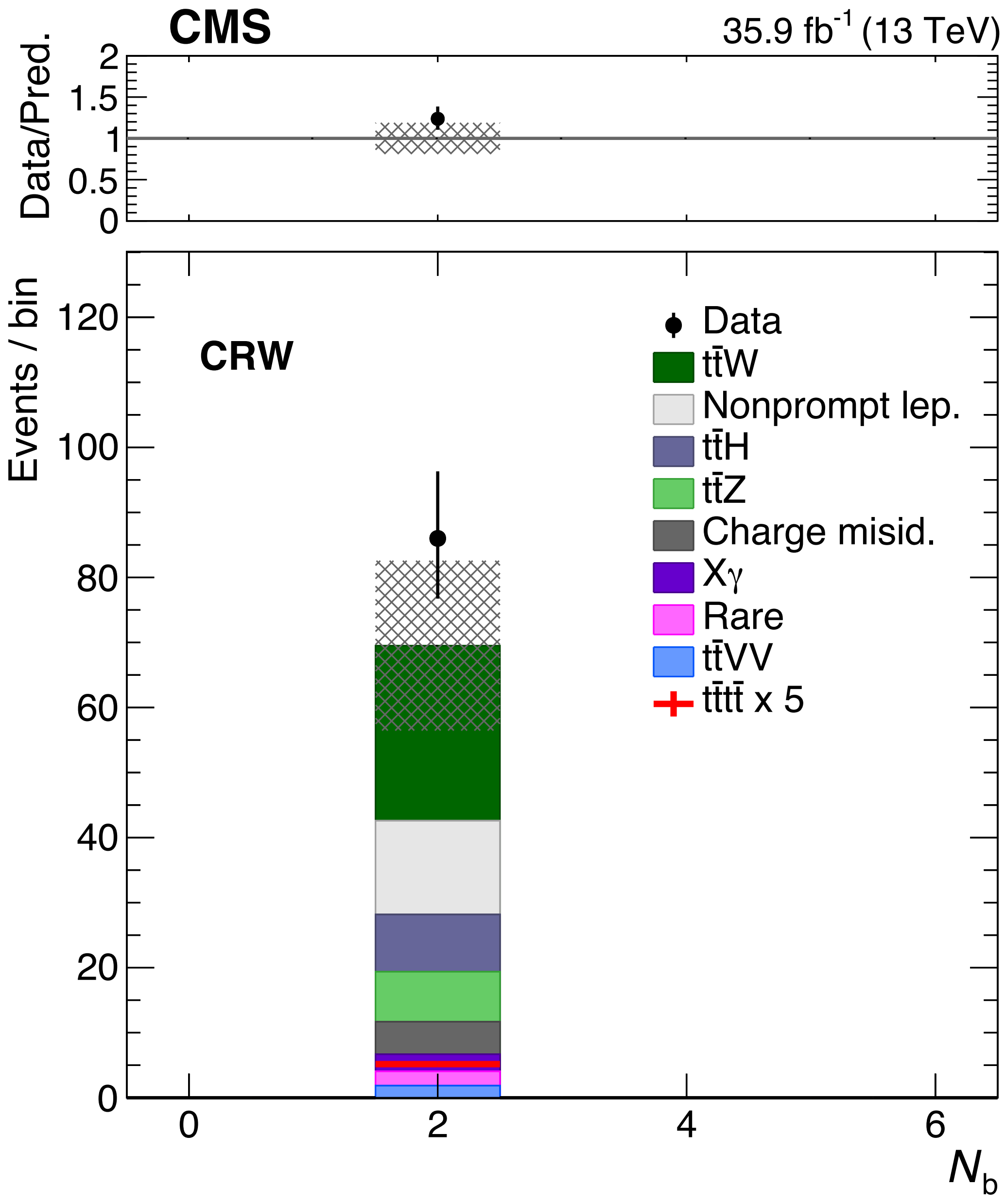
Baseline selection, with: $N_{lep} = 2$, $N_{jets} \leq 5$, $N_b = 2$

- ttW purity ~ 40%

Scaling (post-fit): 1.2 ± 0.3







ttZ

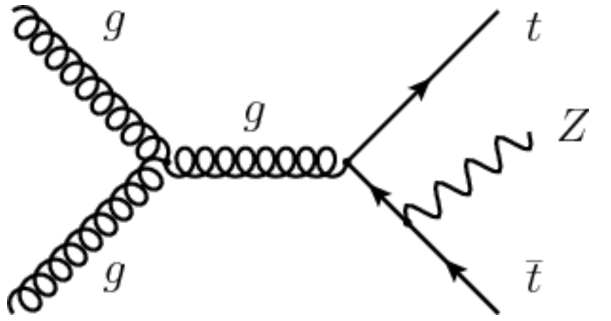
🟩 $t\bar{t}Z$

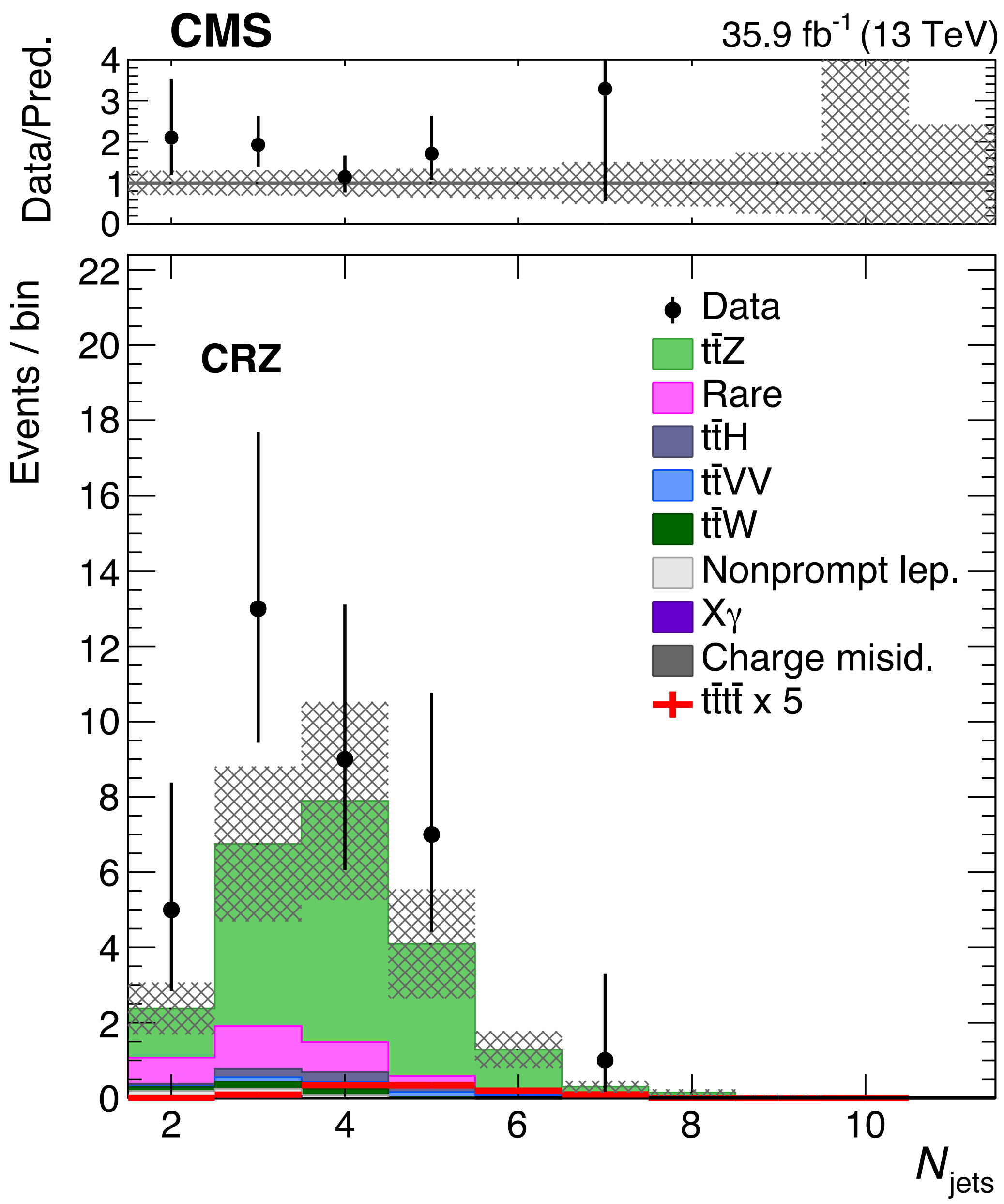
Do the same for ttZ, inverting the DY veto

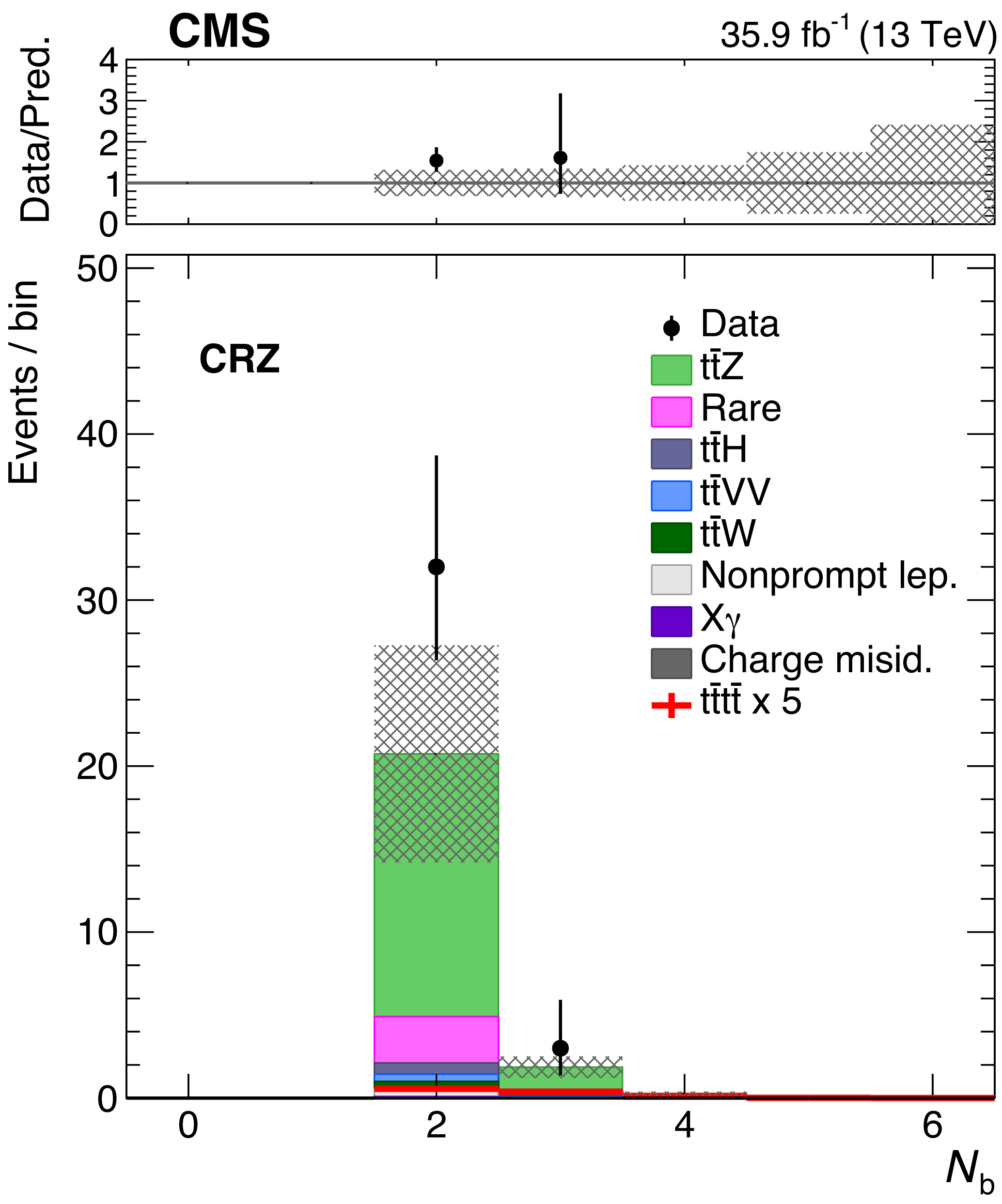
Baseline selection, $N_{lep} = 3$, $|m_{ll} - m_Z| < 15$ GeV

- ttZ purity ~ 75%

Scaling (post-fit): 1.3 ± 0.3







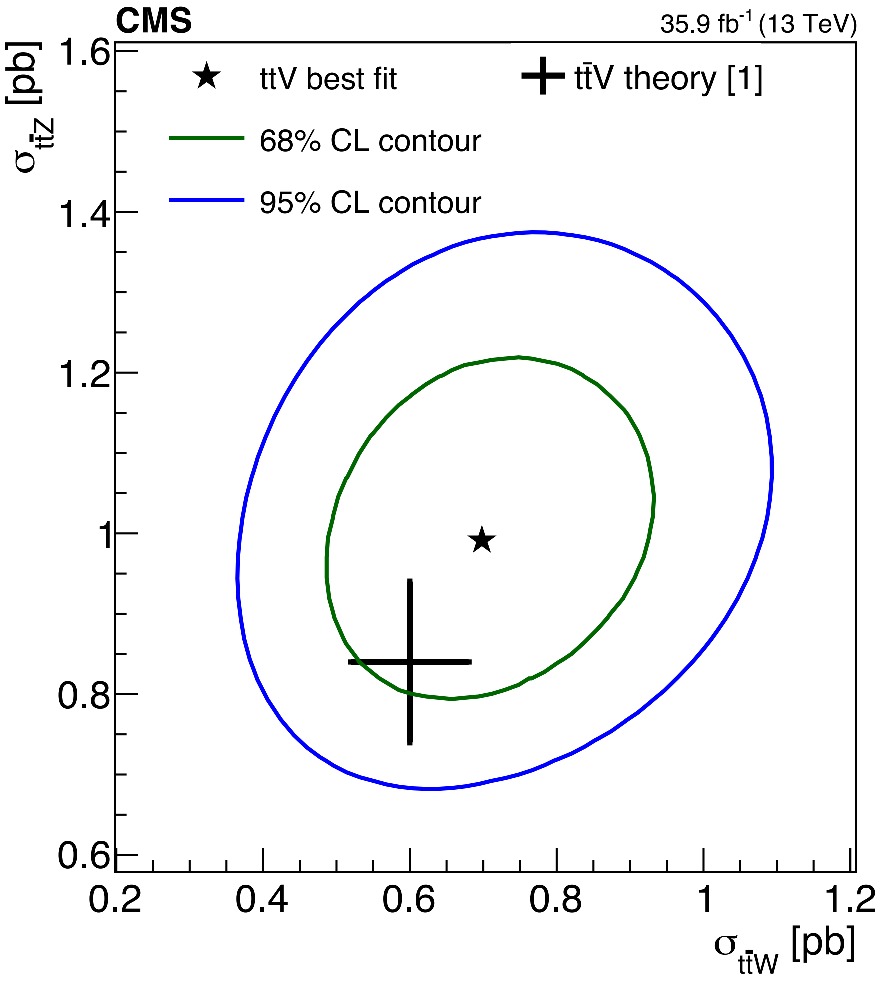
Compare to ttW and ttZ measurements

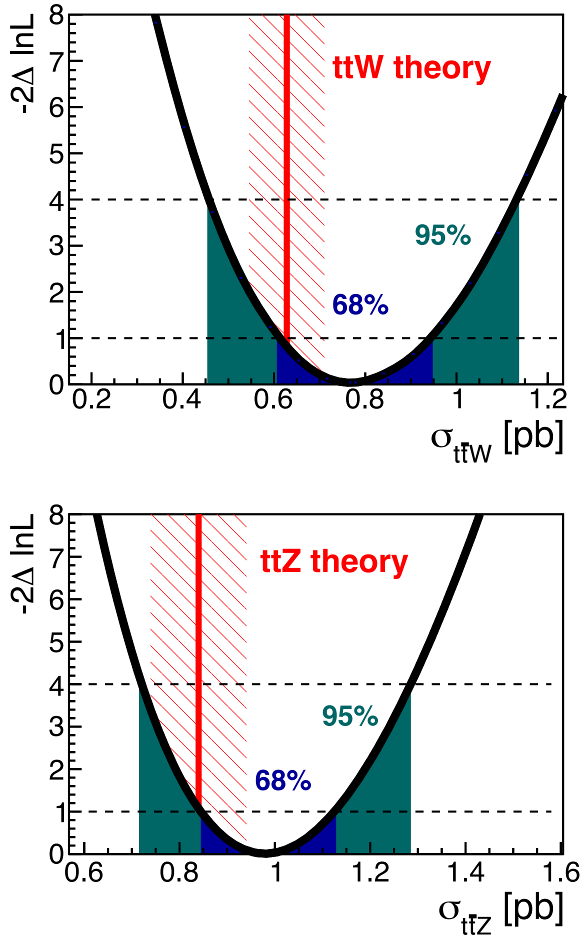
CMS measures ttW and ttZ with the same dataset

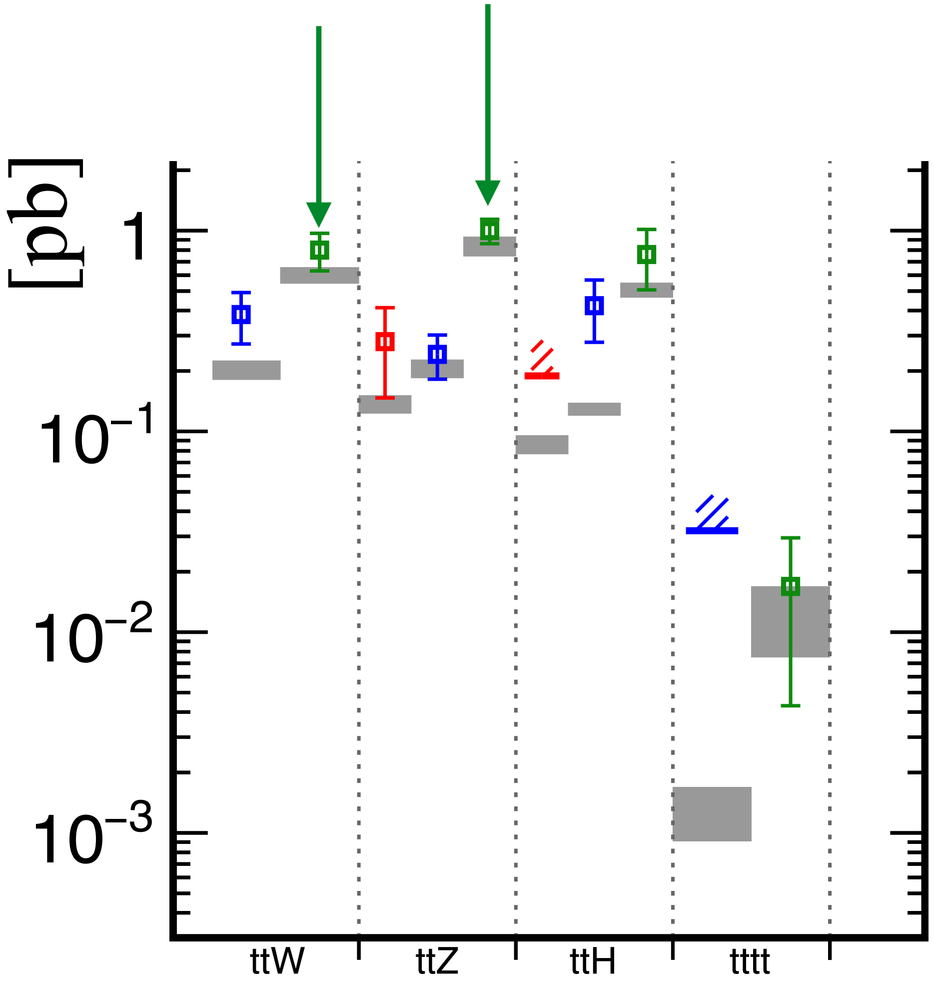
Cannot use directly, as they use the same events (2LSS, ≥3L)

Main result is consistent with our estimates: 1.2 (1.3) ± 0.3 for ttW (ttZ)

- ttW signal strength: $1.23^{+0.19}_{-0.18}\,(\mathrm{stat})^{+0.20}_{-0.18}\,(\mathrm{syst})^{+0.13}_{-0.12}\,(\mathrm{theo})$
- ttZ signal strength: $1.17\,^{+0.11}_{-0.10}\,(\mathrm{stat})^{+0.14}_{-0.12}\,(\mathrm{syst})^{+0.11}_{-0.12}\,(\mathrm{theo})$







ttH

▨ $t\bar{t}H$

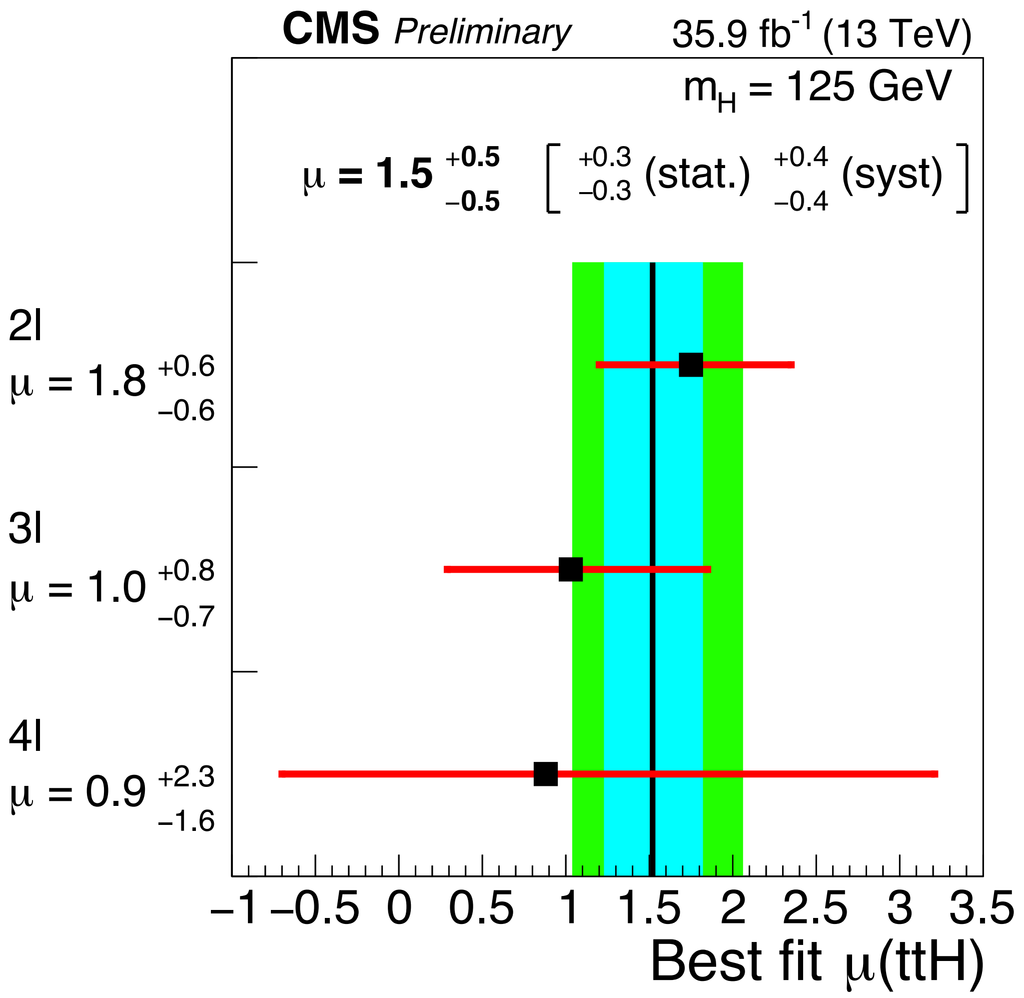
Second largest background (after ttW) and less well known

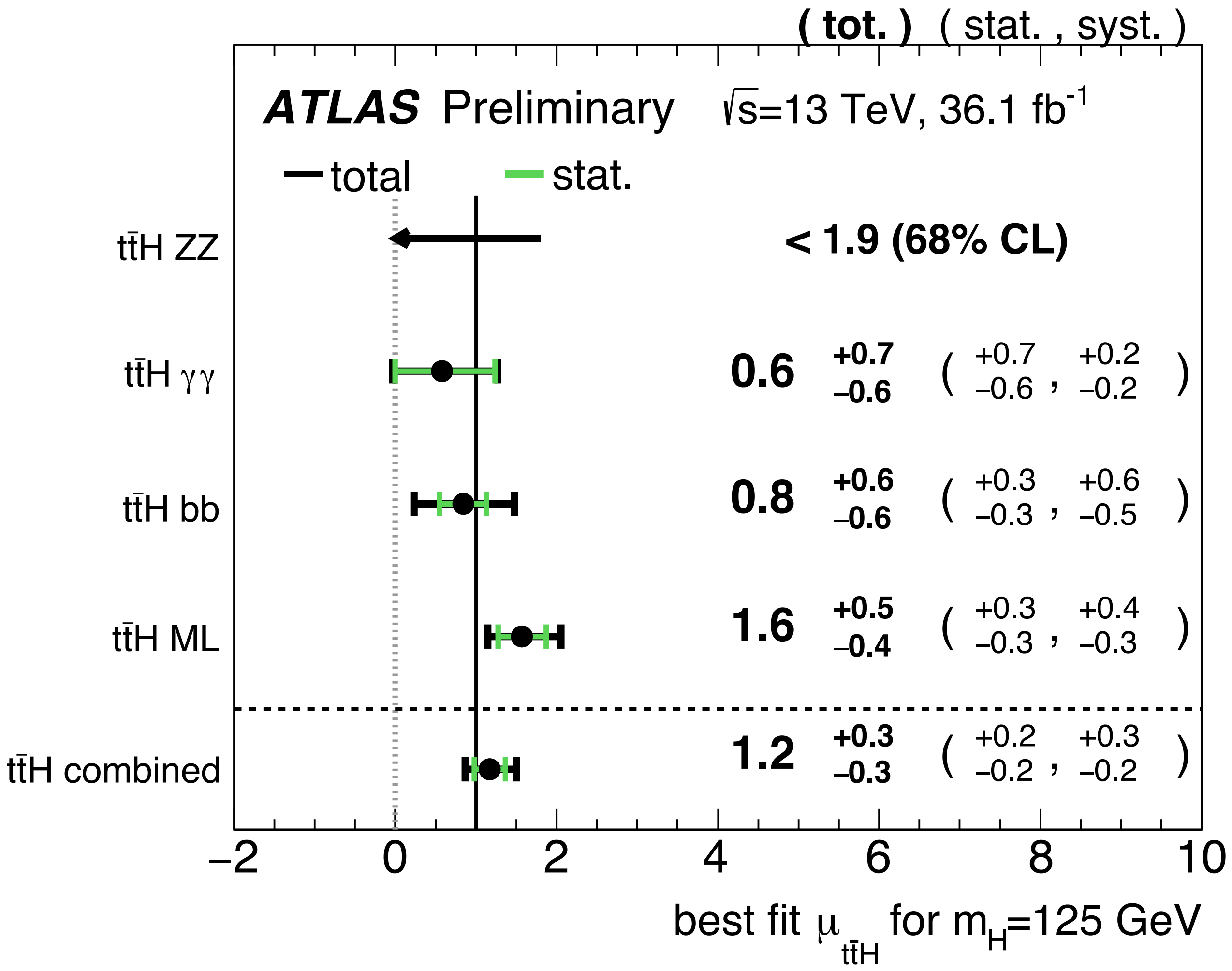
Mainly enters signal regions through H(WW): 500 fb * 20% ~ 100 fb

Latest measurements motivate a 50% uncertainty (rather than ~10% theory unc.)

CMS multileptons: HIG-17-004 —> Signal strength μ = 1.5 ± 0.5

ATLAS multilep. (including tau): ATLAS-CONF-2017-077: μ = 1.2 ± 0.3





ttVV

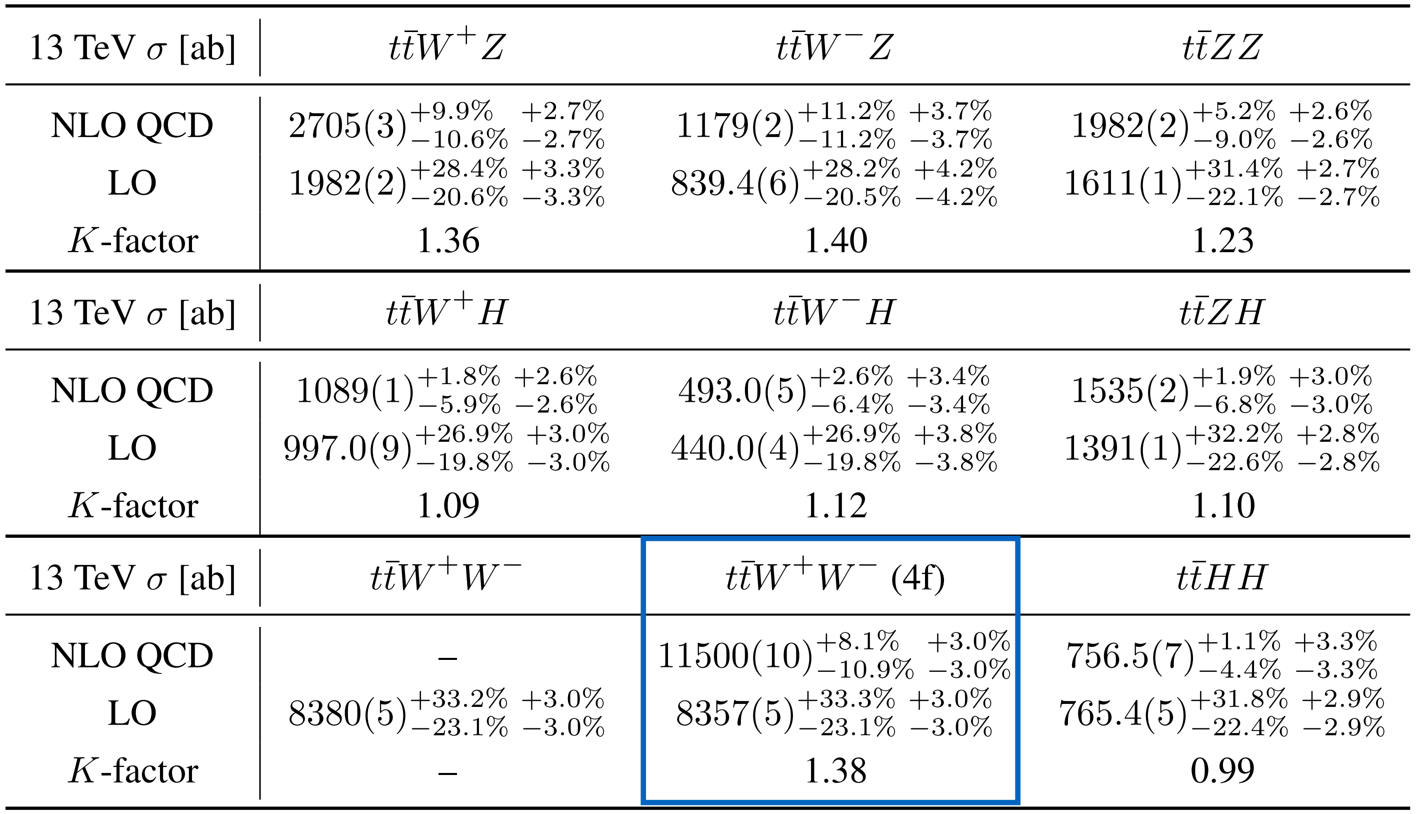
🟦 $t\bar{t}$VV

Several not-yet-observed rare backgrounds with t's and V's

Generate LO samples, use NLO cross-sections

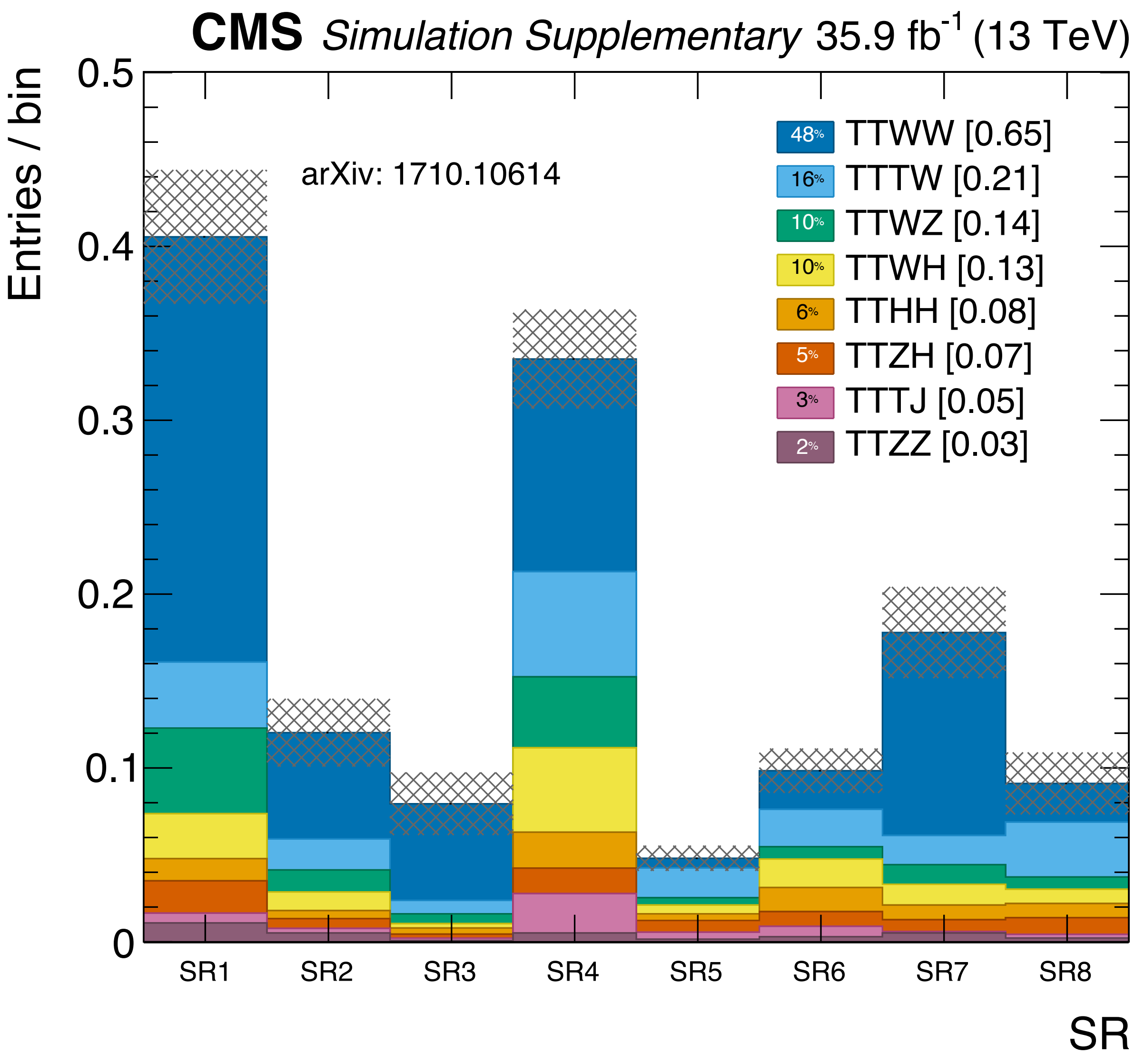
- Largest contribution: ttWW (σ ~ 10 fb)

Interesting measurements for Run 3 and beyond!



13 TeV σ [ab]	$t\bar{t}W^+Z$	$t\bar{t}W^-Z$	$t\bar{t}ZZ$
NLO QCD	$2705(3)^{+9.9\%}_{-10.6\%}\ ^{+2.7\%}_{-2.7\%}$	$1179(2)^{+11.2\%}_{-11.2\%}\ ^{+3.7\%}_{-3.7\%}$	$1982(2)^{+5.2\%}_{-9.0\%}\ ^{+2.6\%}_{-2.6\%}$
LO	$1982(2)^{+28.4\%}_{-20.6\%}\ ^{+3.3\%}_{-3.3\%}$	$839.4(6)^{+28.2\%}_{-20.5\%}\ ^{+4.2\%}_{-4.2\%}$	$1611(1)^{+31.4\%}_{-22.1\%}\ ^{+2.7\%}_{-2.7\%}$
K-factor	1.36	1.40	1.23
13 TeV σ [ab]	$t\bar{t}W^+H$	$t\bar{t}W^-H$	$t\bar{t}ZH$
NLO QCD	$1089(1)^{+1.8\%}_{-5.9\%}\ ^{+2.6\%}_{-2.6\%}$	$493.0(5)^{+2.6\%}_{-6.4\%}\ ^{+3.4\%}_{-3.4\%}$	$1535(2)^{+1.9\%}_{-6.8\%}\ ^{+3.0\%}_{-3.0\%}$
LO	$997.0(9)^{+26.9\%}_{-19.8\%}\ ^{+3.0\%}_{-3.0\%}$	$440.0(4)^{+26.9\%}_{-19.8\%}\ ^{+3.8\%}_{-3.8\%}$	$1391(1)^{+32.2\%}_{-22.6\%}\ ^{+2.8\%}_{-2.8\%}$
K-factor	1.09	1.12	1.10
13 TeV σ [ab]	$t\bar{t}W^+W^-$	$t\bar{t}W^+W^-$ (4f)	$t\bar{t}HH$
NLO QCD	–	$11500(10)^{+8.1\%}_{-10.9\%}\ ^{+3.0\%}_{-3.0\%}$	$756.5(7)^{+1.1\%}_{-4.4\%}\ ^{+3.3\%}_{-3.3\%}$
LO	$8380(5)^{+33.2\%}_{-23.1\%}\ ^{+3.0\%}_{-3.0\%}$	$8357(5)^{+33.3\%}_{-23.1\%}\ ^{+3.0\%}_{-3.0\%}$	$765.4(5)^{+31.8\%}_{-22.4\%}\ ^{+2.9\%}_{-2.9\%}$
K-factor	–	1.38	0.99

arXiv:1610.07922 (Handbook of LHC cross-sections 4)



X+γ and Rares

■ Xγ
■ Rare

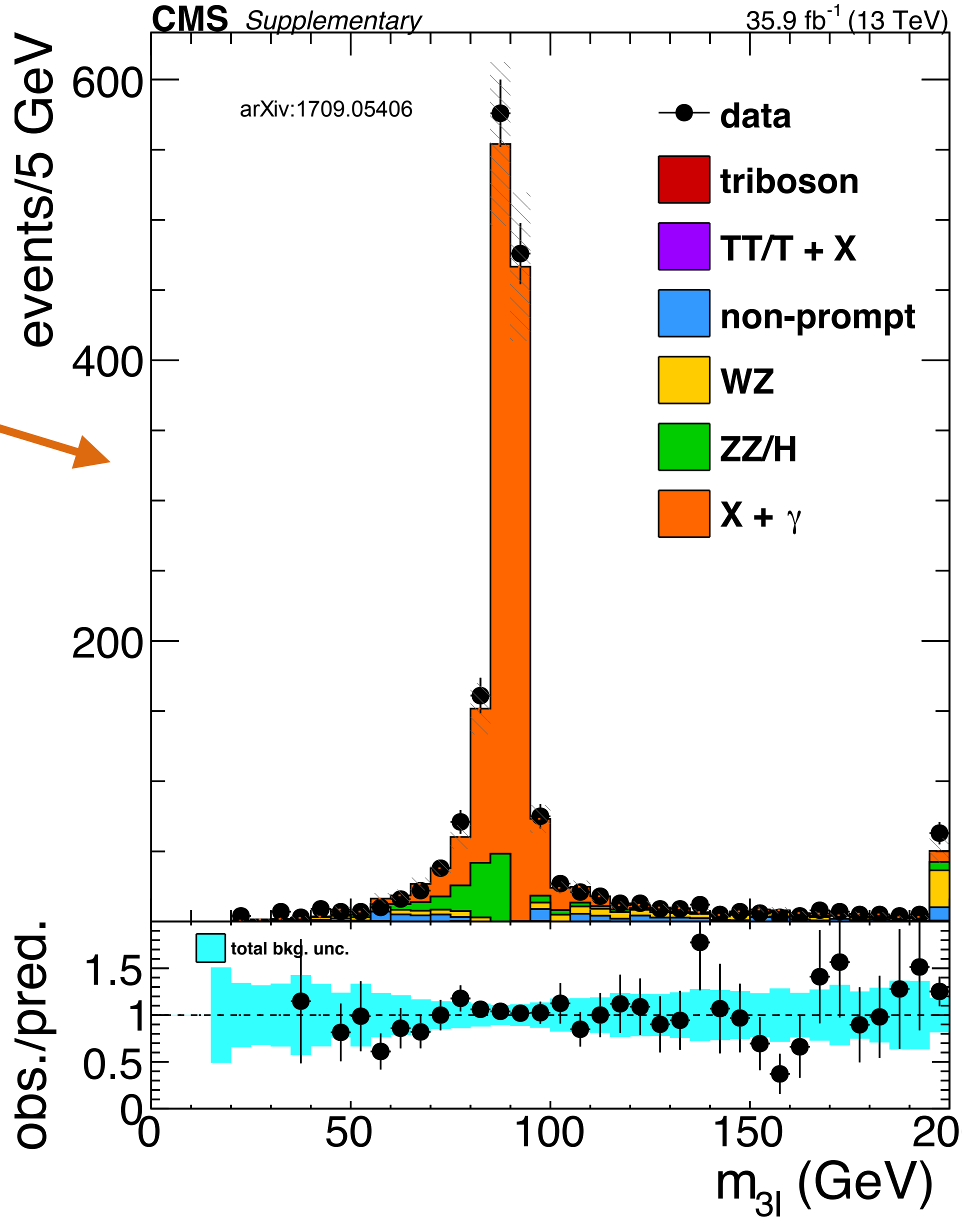
X+γ: ttγ, tγ

Asymmetric prompt γ —> dilepton, with one lepton lost

- Internal conversions: γ* —> e^+e^-, $\mu^+\mu^-$
- External conversions: γ —> e^+e^- interacting with the detector

Estimated from simulation in tttt analysis

- But could also define a Z—>llγ* and γ*—> ll CR, as in arXiv:1709.05406
- CR: $N_{lep} = 3$, $m_{ll} < 75$ GeV, MET < 50 GeV



Rares:

- VVV: WWW, WWZ, WZZ, ZZZ, WWγ, WZγ
- tZq, ggH, WH, ZH, $W^{\pm}W^{\pm}$, tttV, tttq
- Estimated from simulation

Nonprompt leptons

▢ Nonprompt lep.

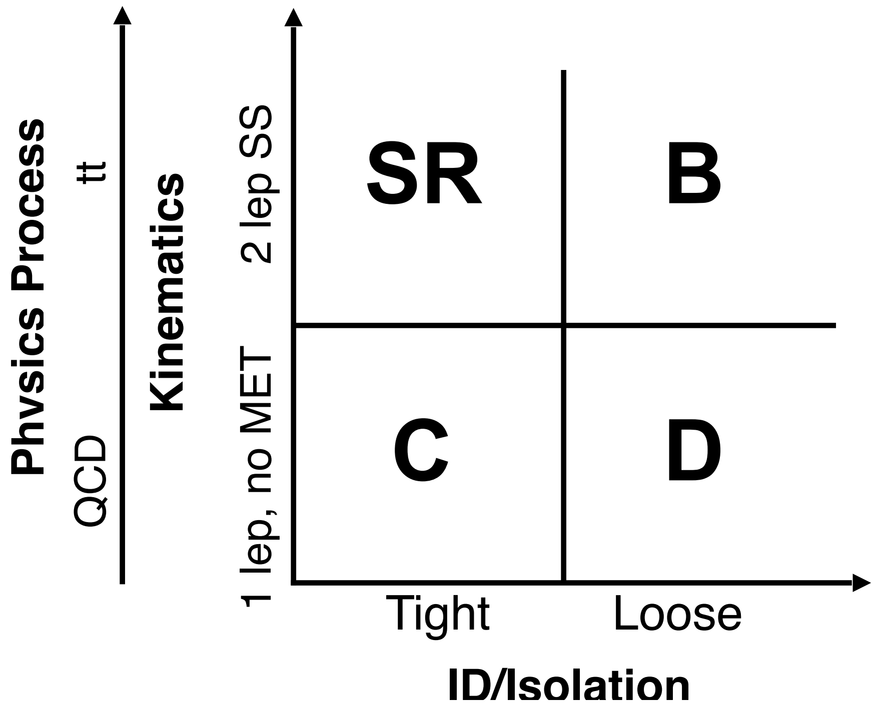
Different sources of “nonprompt” leptons

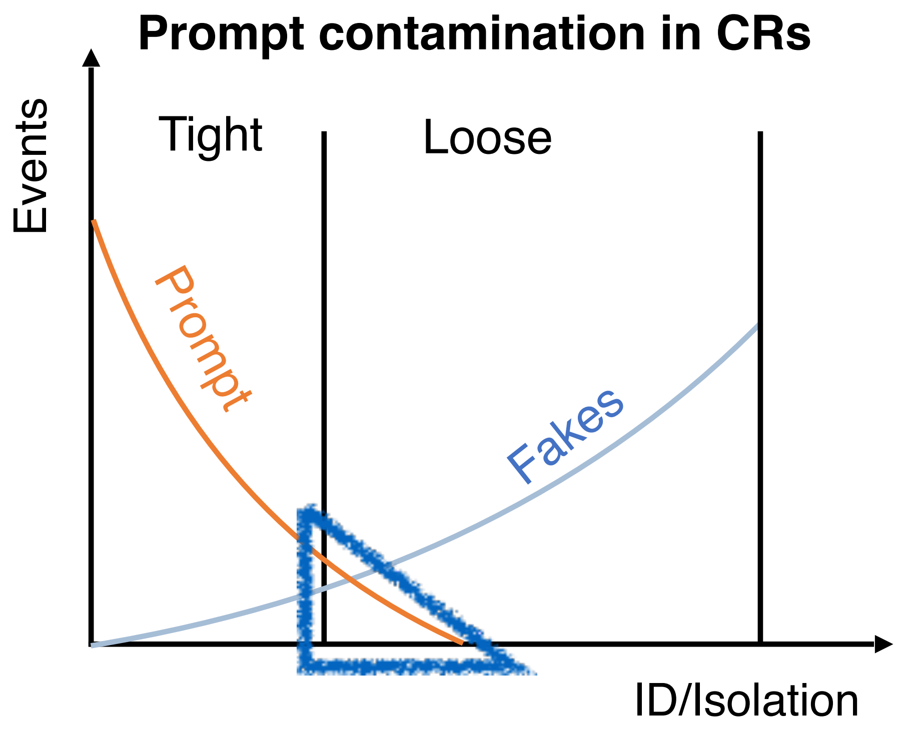
1) Leptons from decays of heavy-flavor and light-flavor hadrons
2) Hadrons misidentified as leptons
3) Conversions of γ in jets (Note: prompt photons included in X+γ)

Due to the huge tt cross-section, this should be the main background in the same sign final state

We use dedicated IDs to reduce it, and dedicated methods to understand it

Basic estimate based on “fake rate” method (aka ABCD)

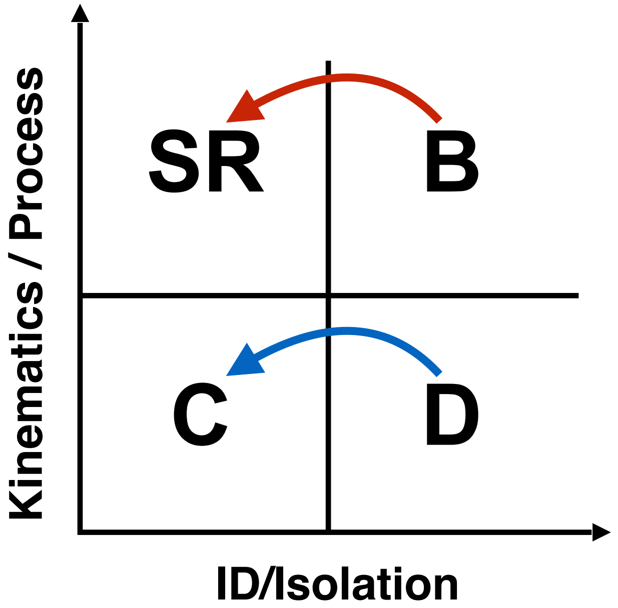




Nonprompt leptons (2)

ABCD works well, as long as two variables are uncorrelated and the transfer factor applies to SR:

$$TF \equiv \boxed{\frac{C}{D}} \overset{?}{=} \boxed{\frac{SR}{B}}$$



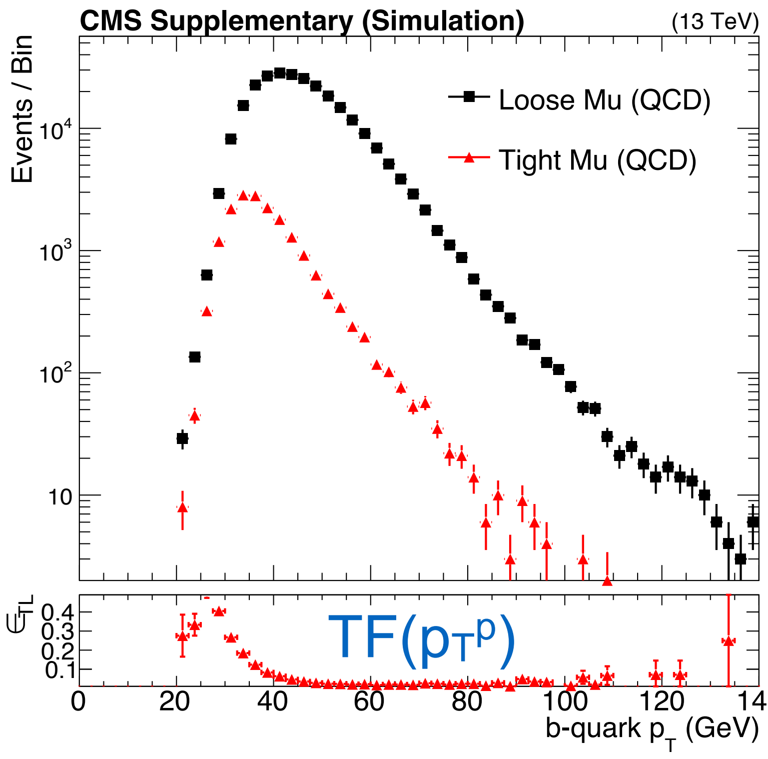
Differences can be understood and parametrized

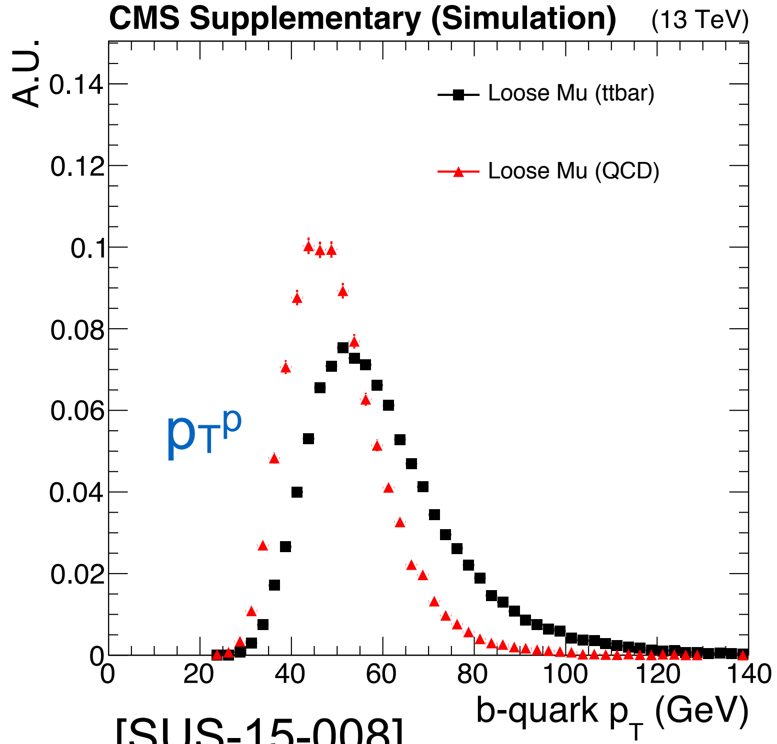
- 1st cause of difference: lepton kinematics: $TF(p_T^l, \eta^l)$
- 2nd: p_T and flavor (b/c/light) of lepton's <u>parton parent</u> (p)
  - Could be solved by: $TF(p_T^l, \eta^l, p_T^p, f^p)$

Example: pick muons with: $20 < p_T^l < 25 \text{ GeV}, \ |\eta^l| < 0.9, \ f^p = b$

$TF(p_T^p)$ plot shows clear dependence

And p_T^p is different for QCD and tt



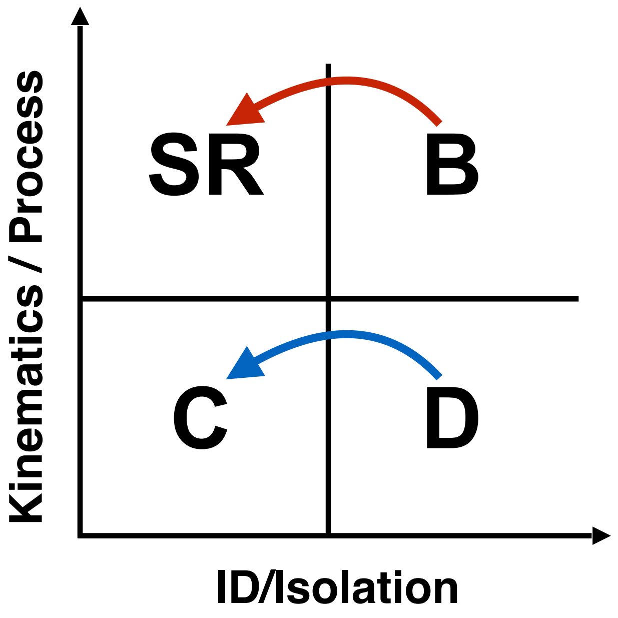


[SUS-15-008]

Nonprompt leptons (2)

ABCD works well, as long as two variables are uncorrelated and the transfer factor applies to SR:

$$TF \equiv \boxed{\frac{C}{D}} \overset{?}{=} \boxed{\frac{SR}{B}}$$



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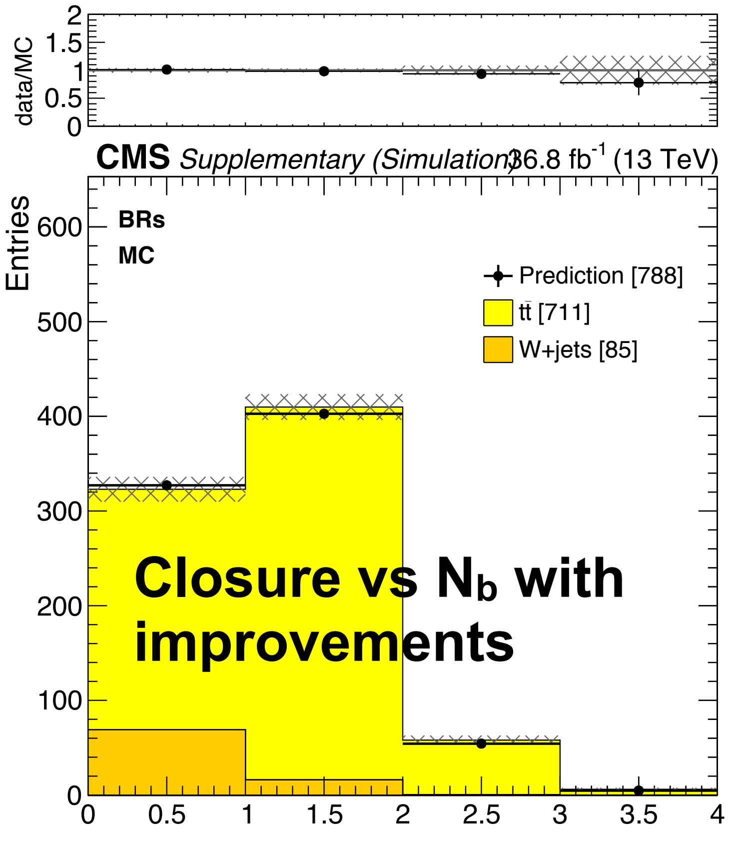
  - Could be solved by: $TF(p_T^l, \eta^l, p_T^p, f^p)$

Two ideas to avoid a 4D TF:

- Tune the "Loose" selection: $TF|_b = TF|_c = TF|_l$
- Combine p_T^l and p_T^p: $p_T^{cone} = \text{Tight} \ ? \ p_T^l : p_T^l(1 + \text{RelIso})$
- Use $TF(p_T^{cone}, \eta^l)$

Improvements bring "closure" of ABCD well within ±30%, across sample kinematics



Closure vs N_b with improvements

[SUS-16-035]

Charge misidentification

■ Charge misid.

Charge misidentification is negligible for muons, and for electrons we reduce it by requiring "triple-charge agreement"

Agreement between 3 available charge measurements

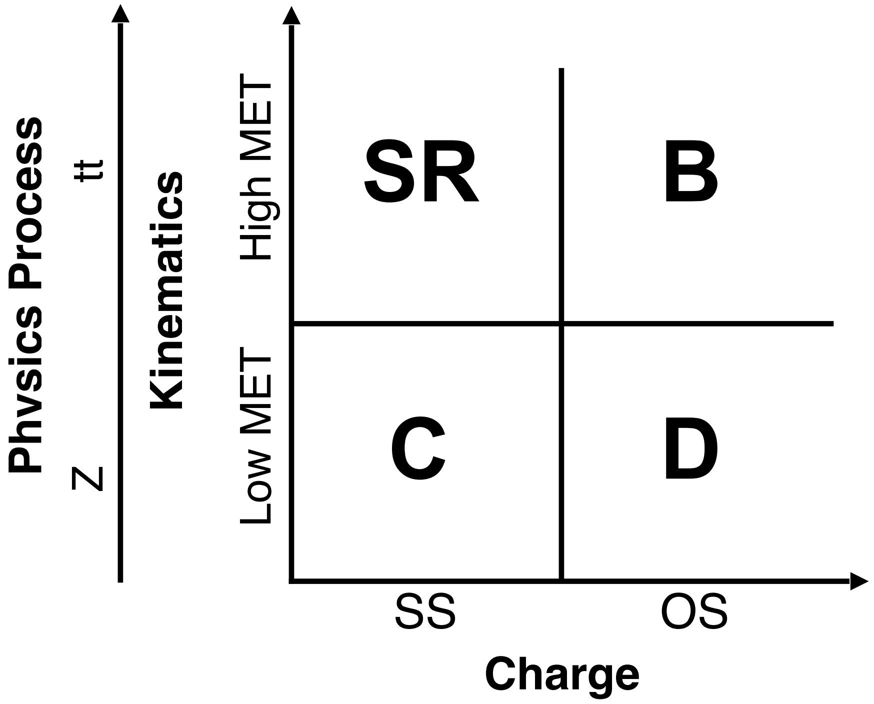
- Pion-like track, Electron-like track (with Brehm), Δφ(Pixel hits, Supercluster)

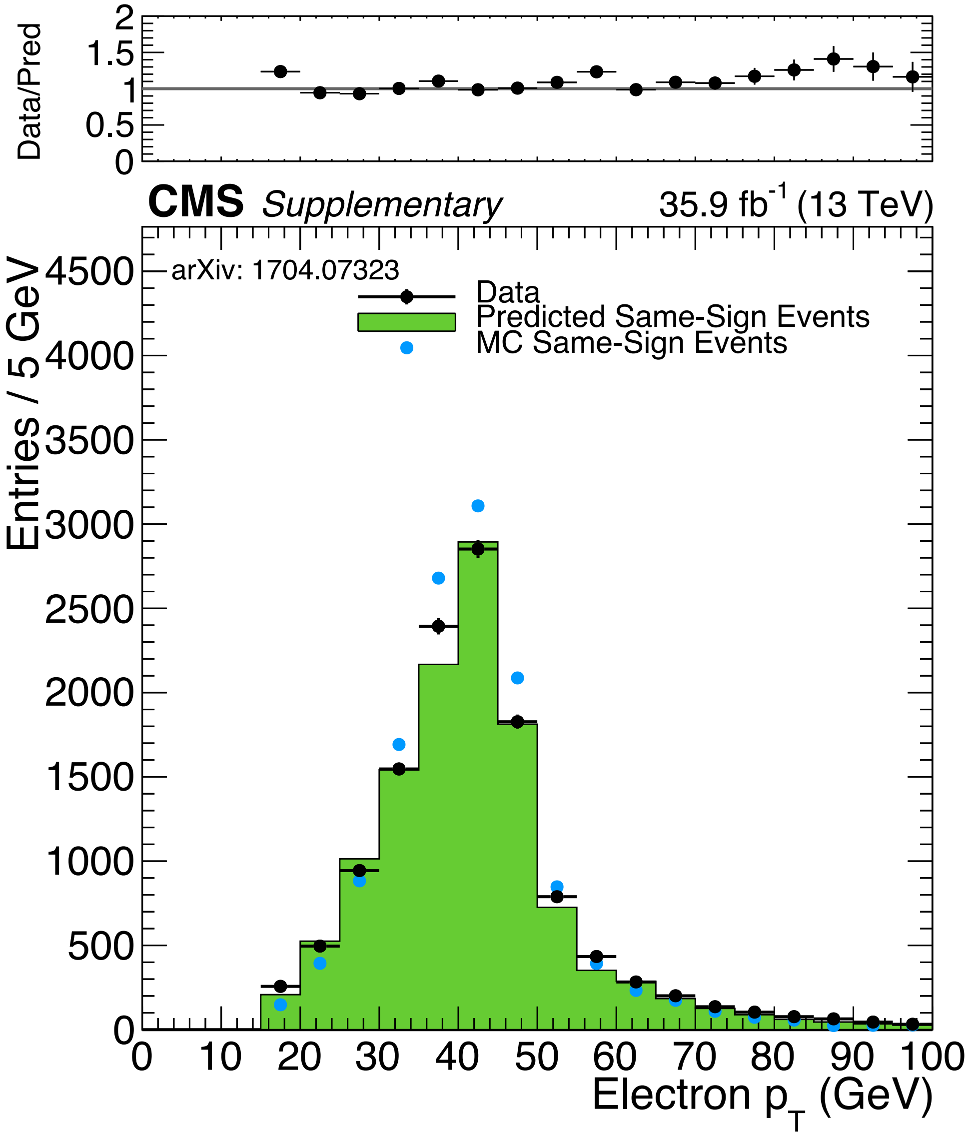
Estimate based on "ABCD-like" method

Use Z MC to estimate $TF(p_T^l, \eta^l)$

- Validate TF in Z-enriched (low-MET) data

Apply TF to OS events in data





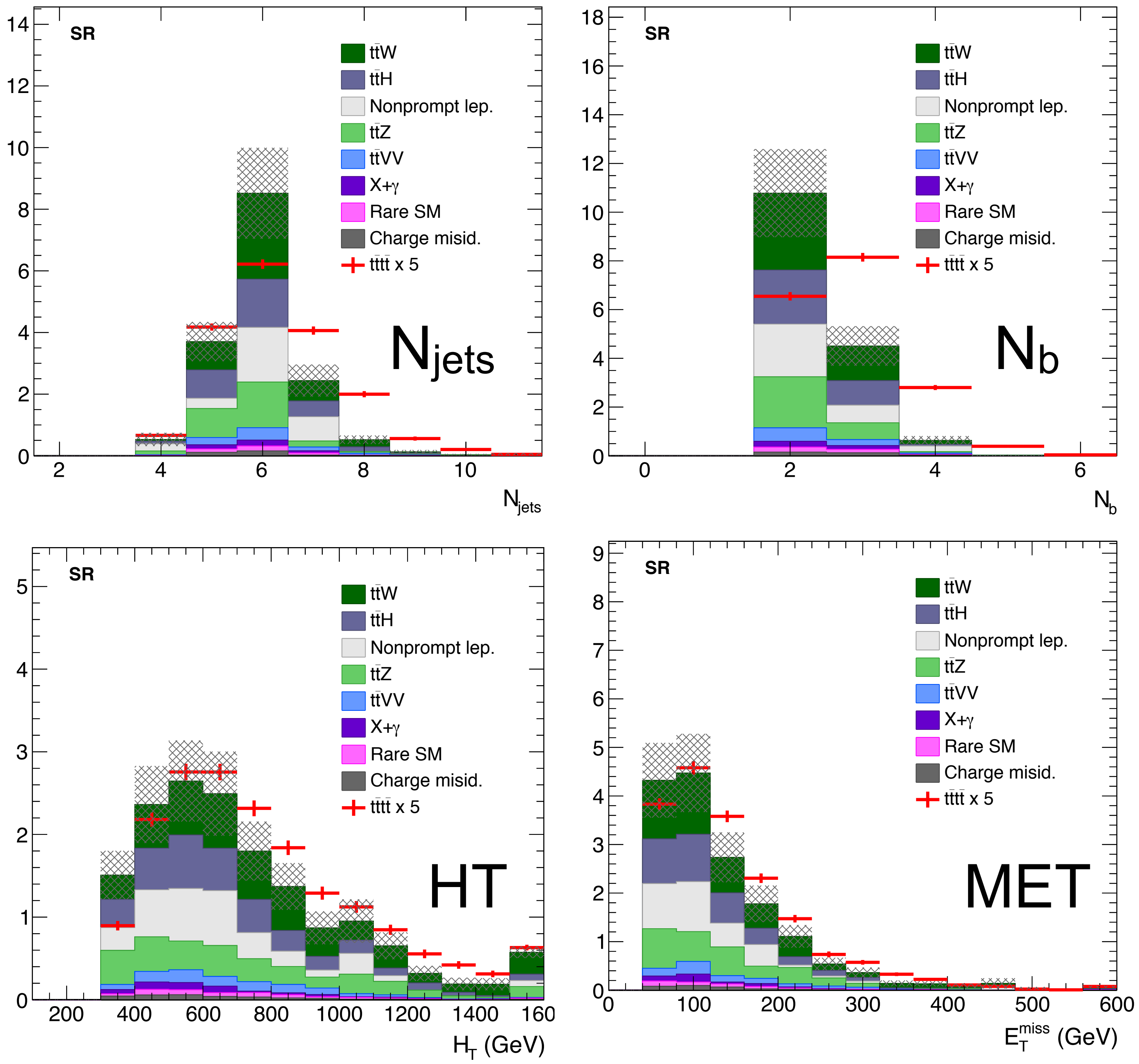
Signal and Background Kinematics

Signal peaks at $N_{jets} = 6$

- Expect 8 jets from dilepton tttt
- Lost jets: acceptance, overlaps
- Extra jets: ISR

Signal peaks at $N_b = 3$

- Expect 4 b-jets
- Loss due to b-tagging efficiency (55-70%)



In any case, N_{jets} and N_b are the most discriminant variables

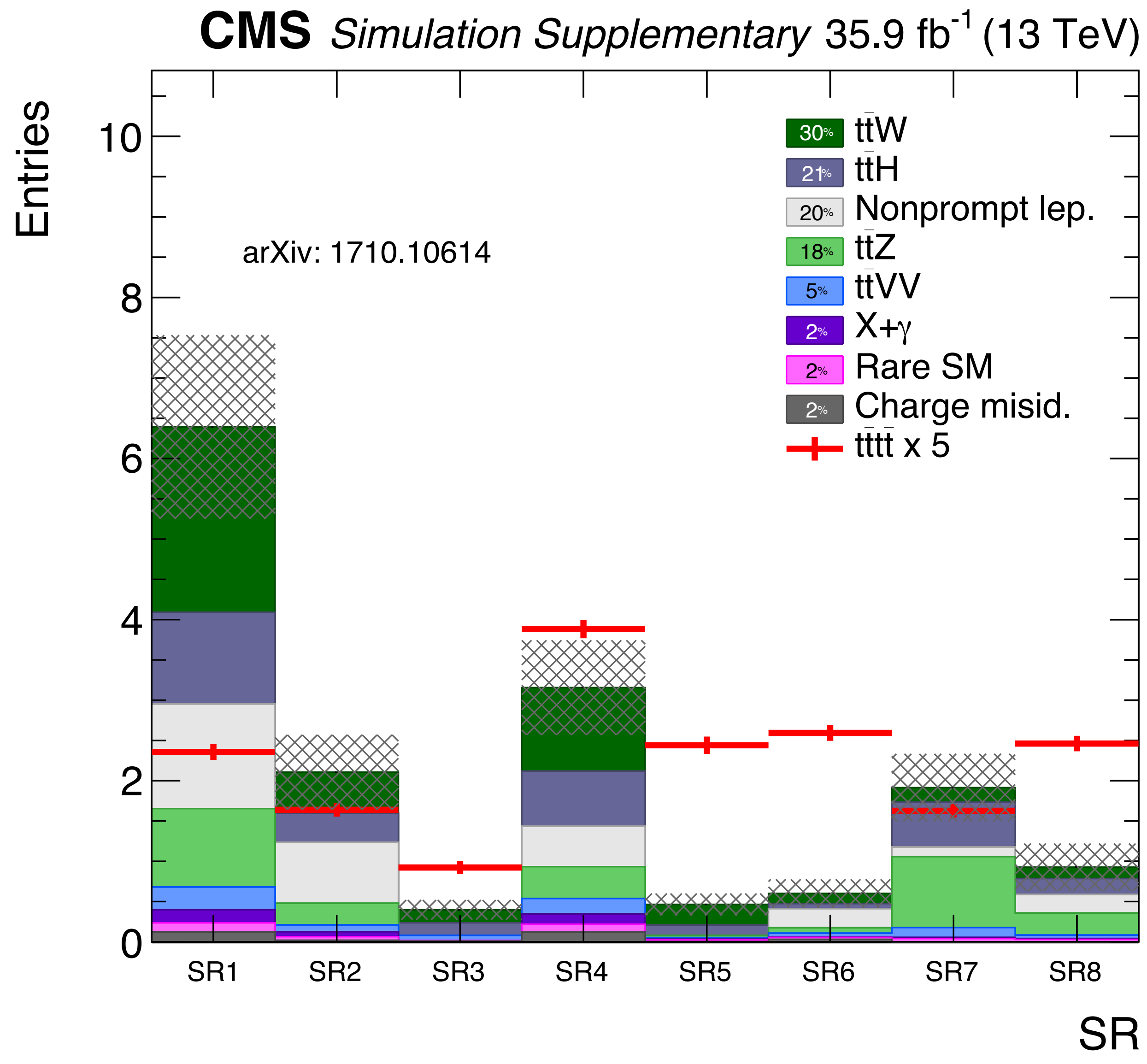
Signal Region definitions

Use N_{jets}, N_b, and separate 2 lepton and ≥3 lepton events

Group regions with similar S/B

Avoid empty regions, or regions with << 1 signal event expected

N_leps	N_b	N_jets	Region
2	2	≤ 5	CRW
		6	SR1
		7	SR2
		≥ 8	SR3
	3	5, 6	SR4
		≥ 7	SR5
	≥ 4	≥ 5	SR6
≥ 3	2	≥ 5	SR7
	≥ 3	≥ 4	SR8
inverted Z-veto			CRZ



Statistics and Systematics

In current setup, few events expected in each signal region

- Combining all SRs, expect ~5.5 tttt and 16 background events
- Statistically limited: Systematics only account for 10% of tot. unc.

Results (limit, significance, cross-section) obtained through a maximum-likelihood fit to all CRs and SRs

- Systematic uncertainties profiled as nuisance parameters

	Source	Uncertainty (%)
Signals and Backgrounds	Integrated luminosity	2.5
	Pileup	0–6
	Trigger efficiency	2
	Lepton selection	4–10
	Jet energy scale	1–15
	Jet energy resolution	1–5
	b tagging	1–15
	Size of simulated sample	1–10
	Scale and PDF variations	10–15
	ISR/FSR (signal)	5–15
Backgrounds	$t\bar{t}$H (normalization)	50
	Rare, Xγ, $t\bar{t}$VV (norm.)	50
	$t\bar{t}$Z, $t\bar{t}$W (normalization)	40
	Charge misidentification	20
	Nonprompt leptons	30–60

Expected results of the fit:

- ttW constrained to ±30%
- ttZ constrained to ±30%
- ttH stays at ±50%

other nuisances unconstrained

tttt constrained to ~ ±100%

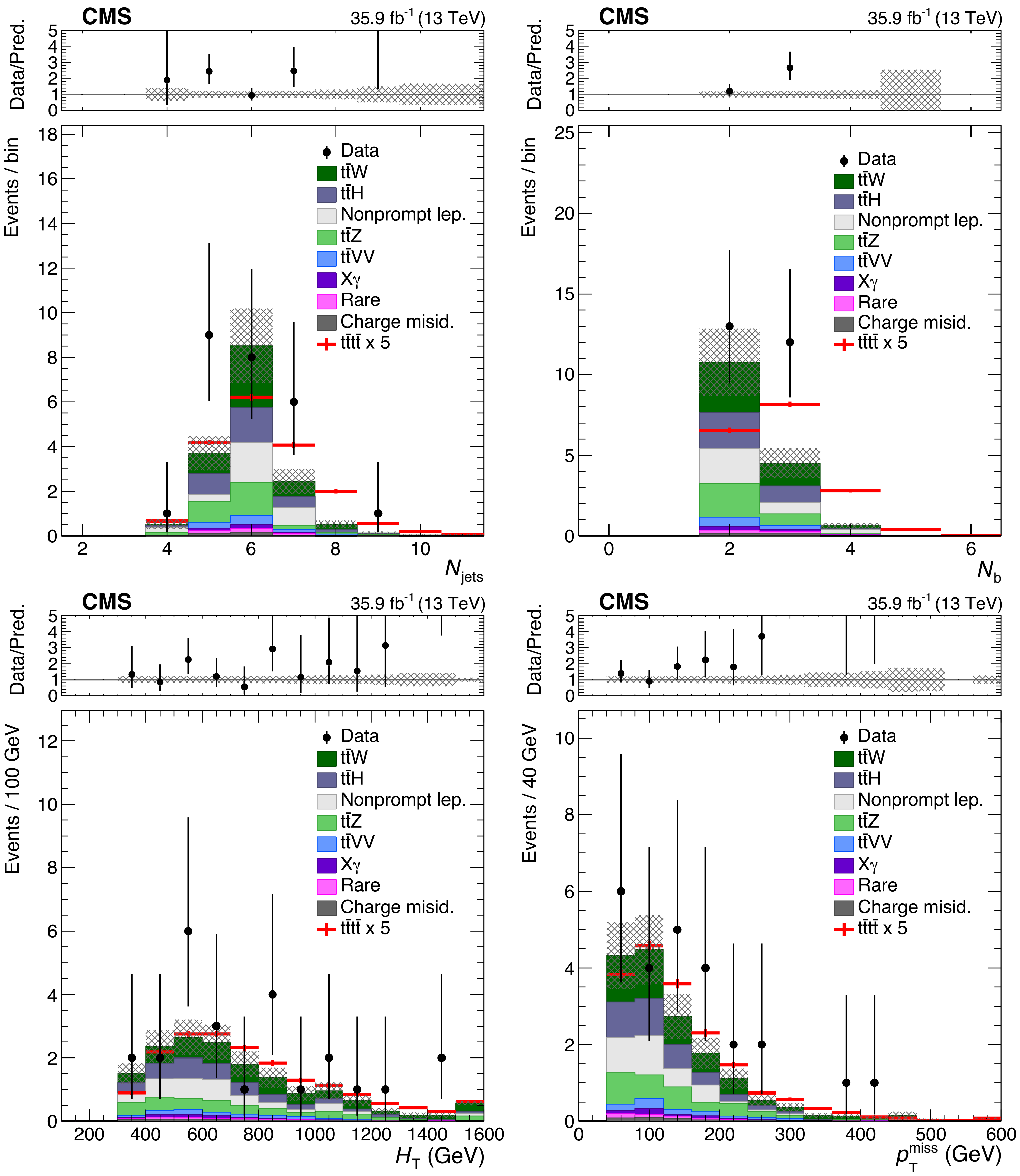
in other words, 1.0 sigma expected significance

Opening the box (pre-fit)

Small underestimate when using pre-fit ttW, ttZ

Interesting excess in $N_b = 3$ bin

Checked individual events, found no suspicious behavior



Full Post-Fit results

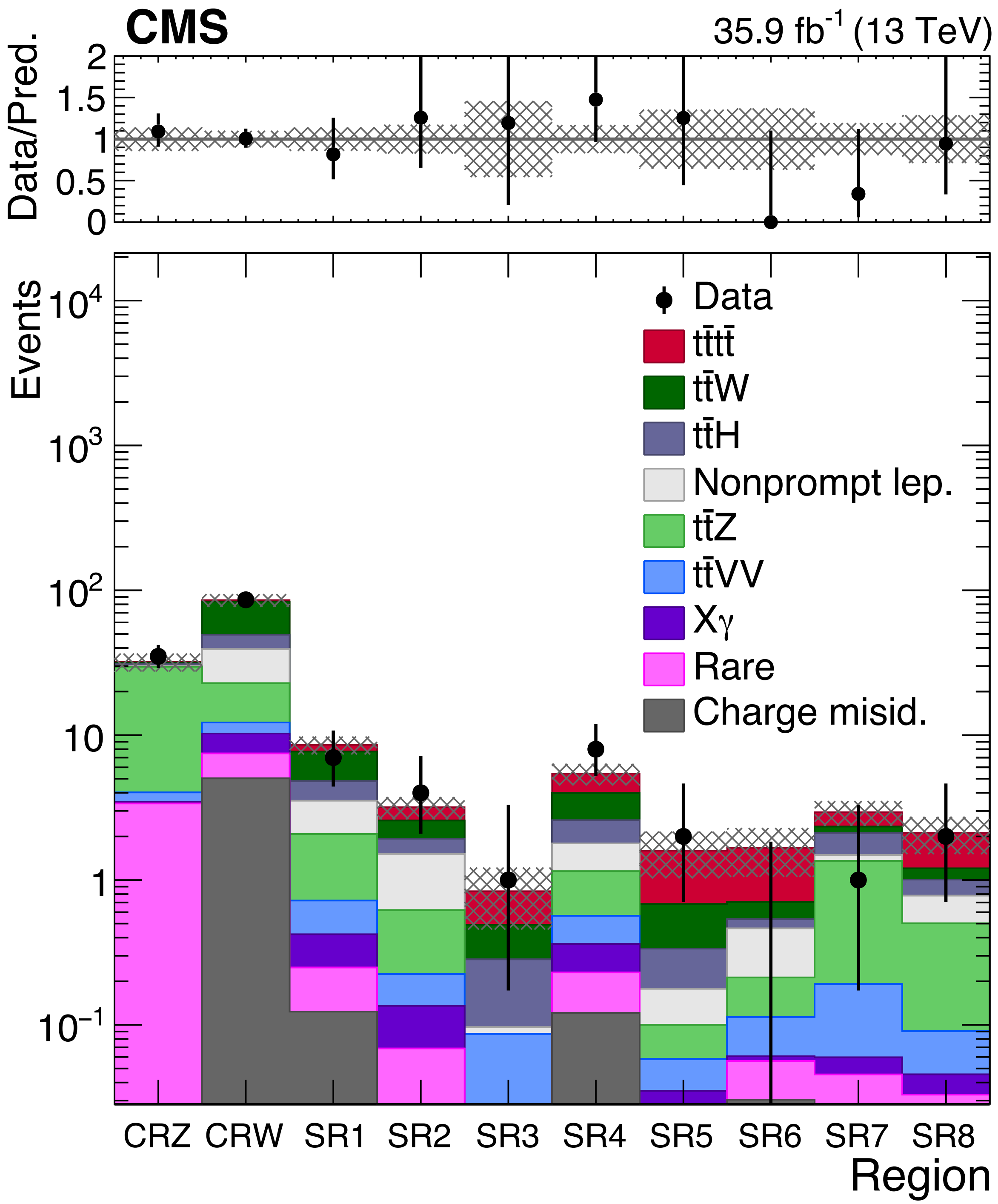
Post-fit normalization parameters:

ttW: 1.2 ± 0.3

ttZ: 1.3 ± 0.3

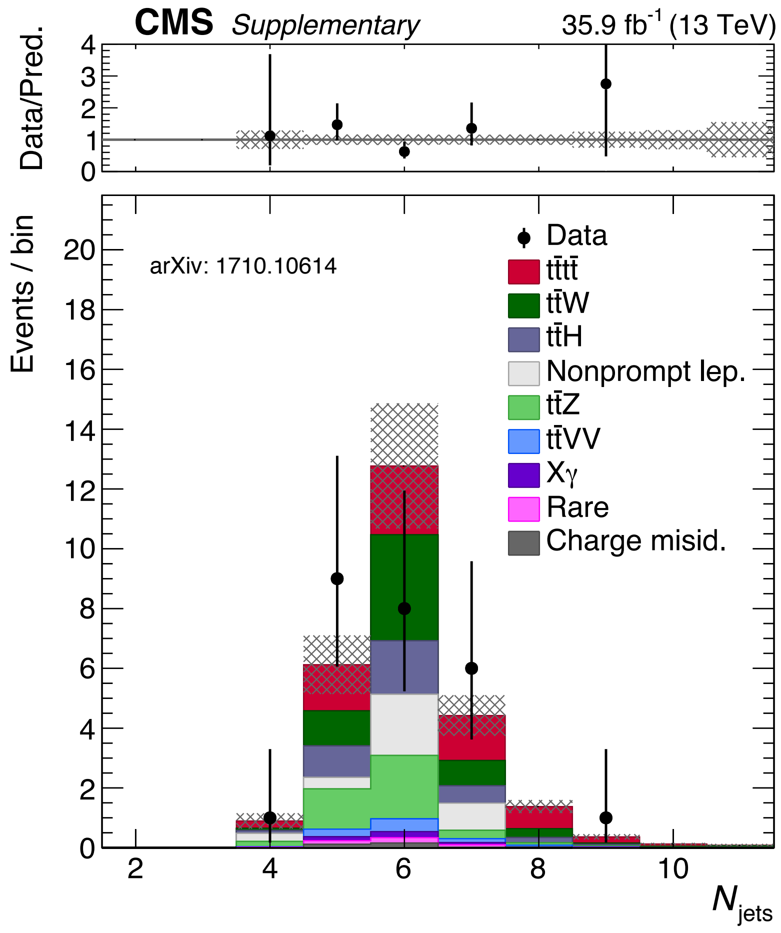
ttH: 1.1 ± 0.5

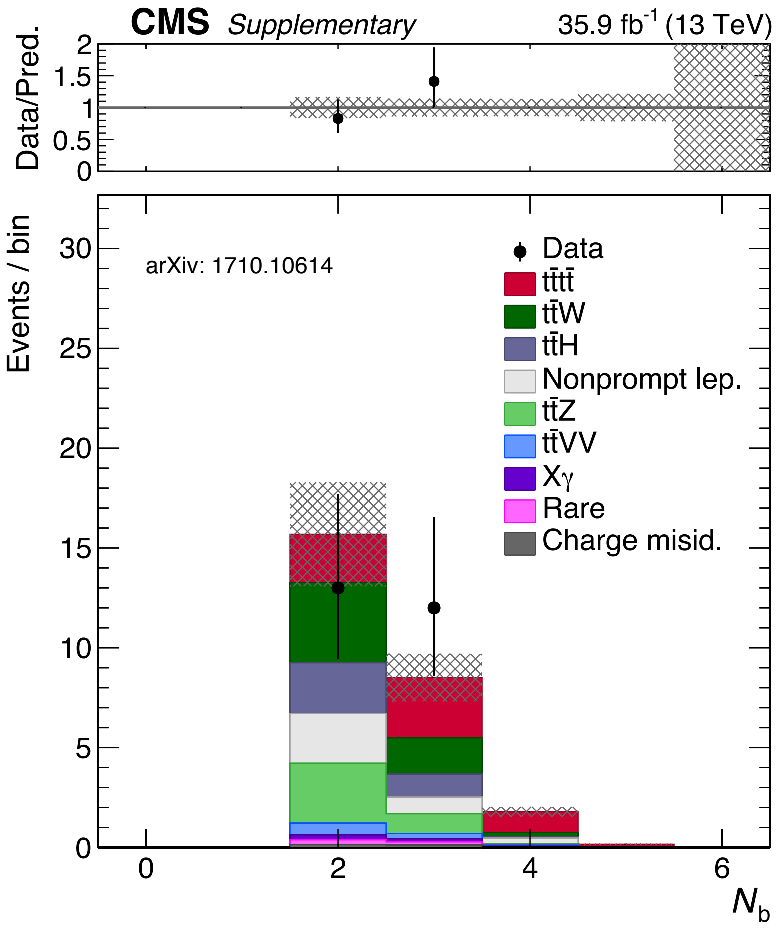
N_{leps}	N_{b}	N_{jets}	Region
2	2	≤ 5	CRW
		6	SR1
		7	SR2
		≥ 8	SR3
	3	5, 6	SR4
		≥ 7	SR5
	≥ 4	≥ 5	SR6
≥ 3	2	≥ 5	SR7
	≥ 3	≥ 4	SR8
inverted Z-veto			CRZ

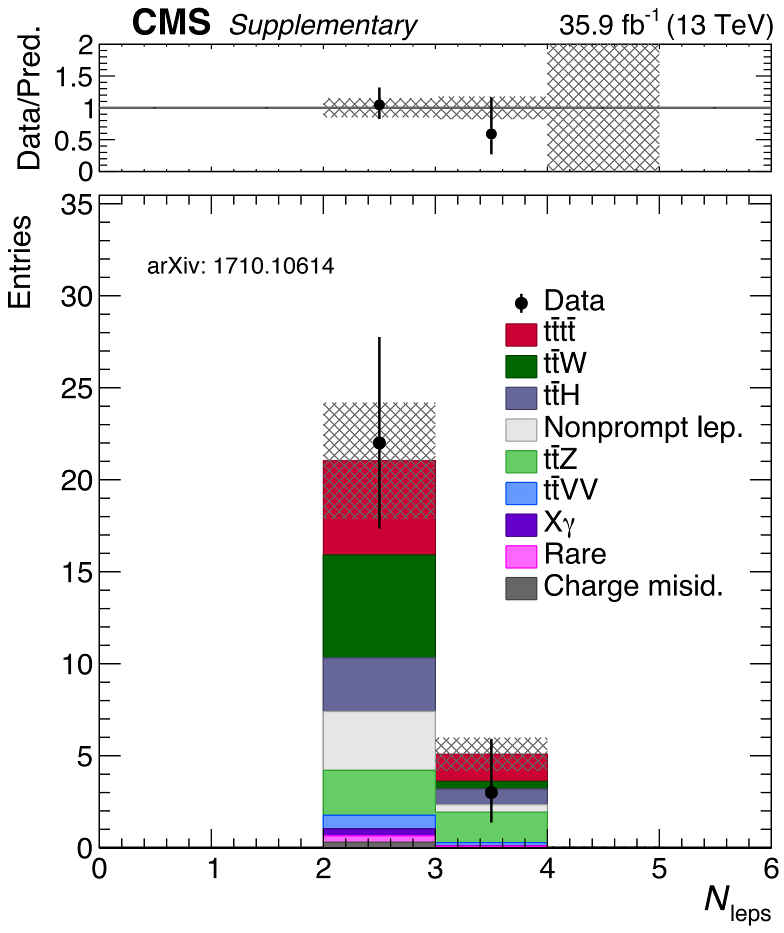


Post-fit kinematics

Reduced tension in Nb=3 region. Good agreement for leptons.







μμ μe eμ ee

Results: tttt

95% Confidence Level Upper Limit

Expected (assuming no SM tttt) : $20.8^{+11.2}_{-6.9}$ fb

Observed : 41.7 fb

Signal significance w.r.t. background-only hypothesis:

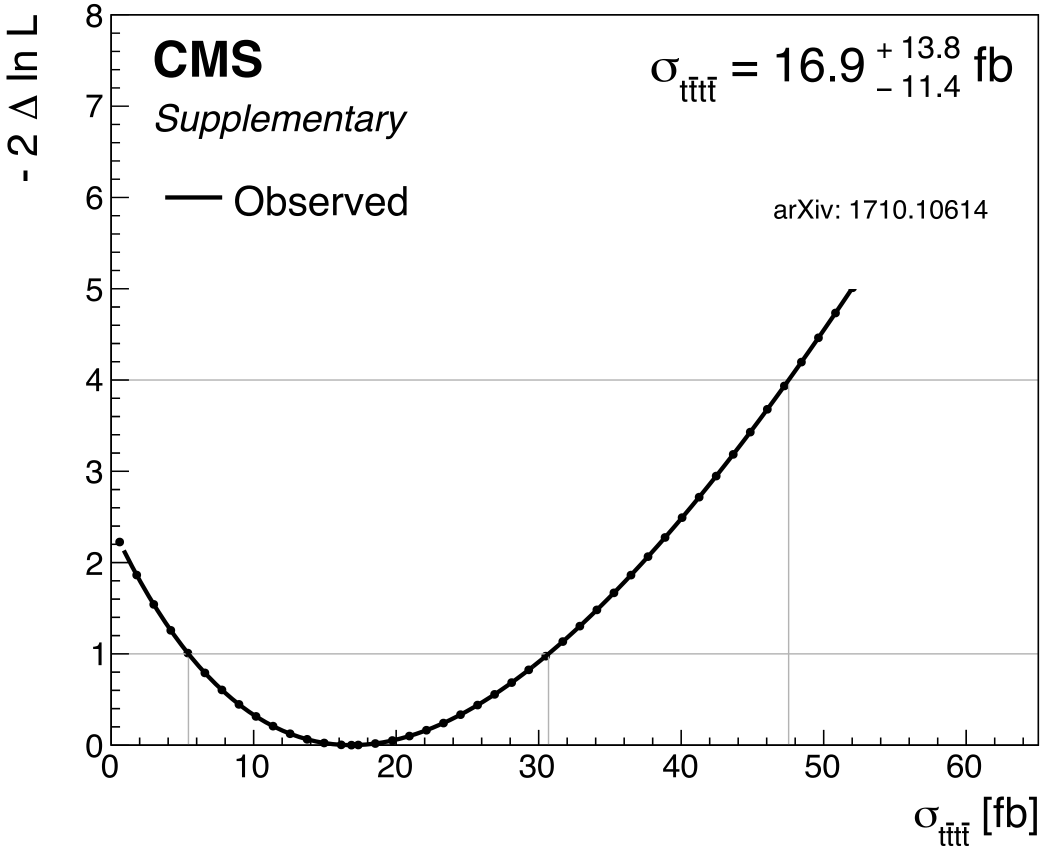
Expected : 1.0

Observed : 1.6

Cross section measurement:

Expected (based on 9.2 fb theory): $9.2^{+11}_{-8.6}$ fb

Observed : $16.9^{+13.8}_{-11.4}$ fb



Reminder of theory predictions:

NLO: $9.2^{+2.9}_{-2.4}$ fb

LO*k-Factor: $12.2^{+5.0}_{-4.4}$ fb

Measured cross-section is high, but well within experimental uncertainty

Results: 2HDM heavy (pseudo)scalar *

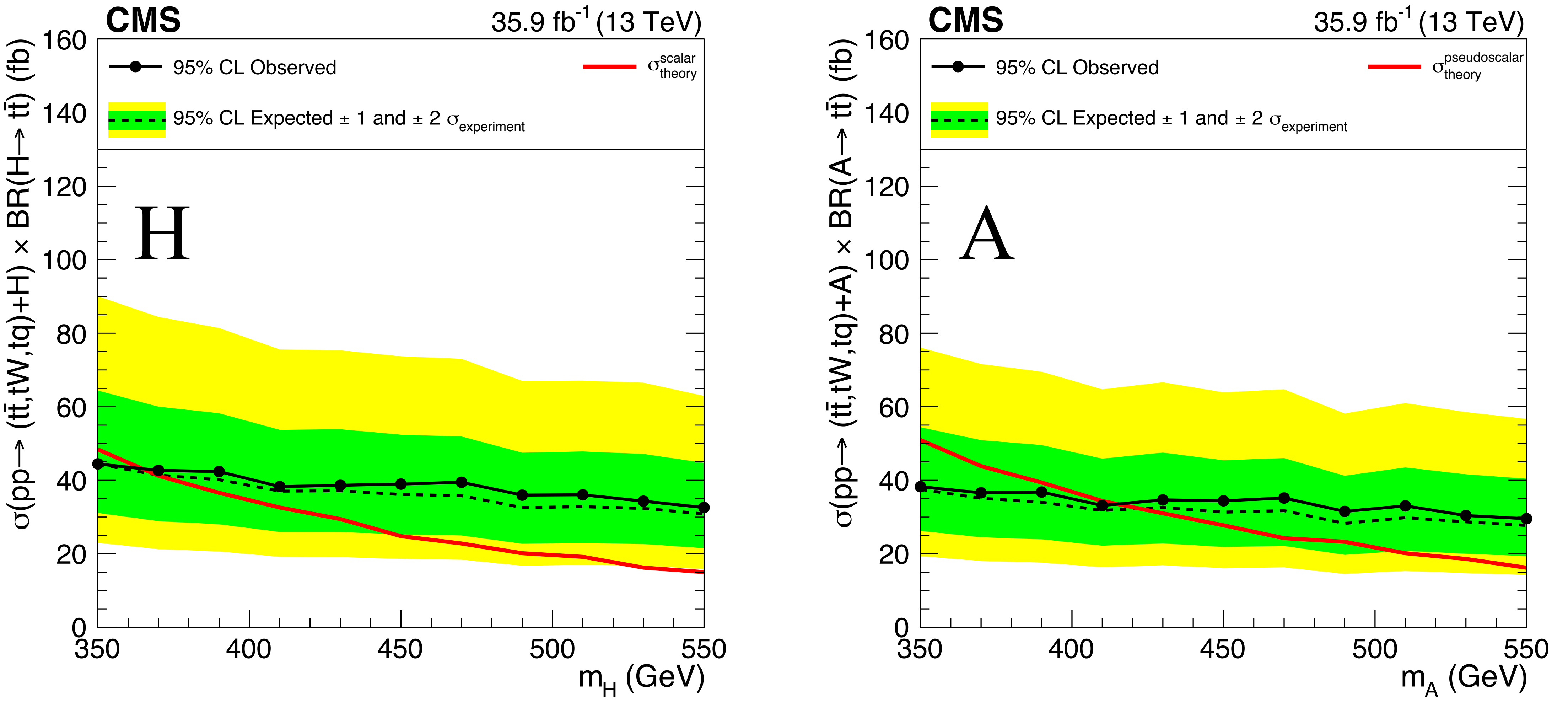
Exclude $m_{A(H)}$ < 430 (360) GeV for tanβ = 1

Several advantages over m_{tt} interference search:

(1) statistics limited, large enhancement over SM tttt

(2) no dependence on H(tt) width —> can extend sensitivity to higher tanβ

(3) can probe H/A masses at the low end of m_{tt} spectrum (350 GeV)



* From generic 2016 same-sign analysis, arXiv:1704.07323, which inspired the dedicated tttt analysis

Results: Top-Higgs Yukawa

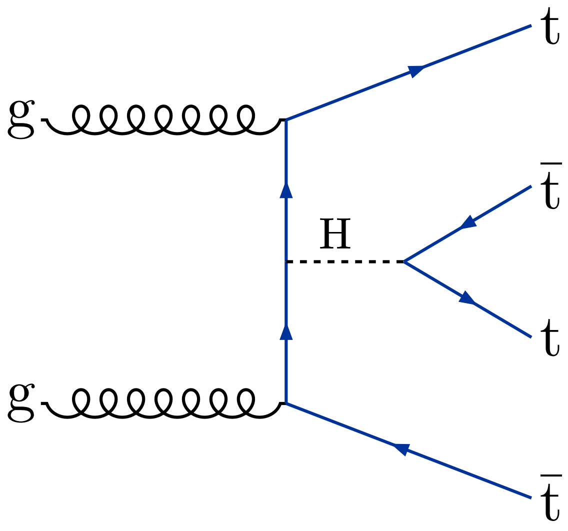
First simplified attempt:

Compare measurement with σ(tttt) as a function of $\kappa_t = |y_t/y_t^{SM}|$

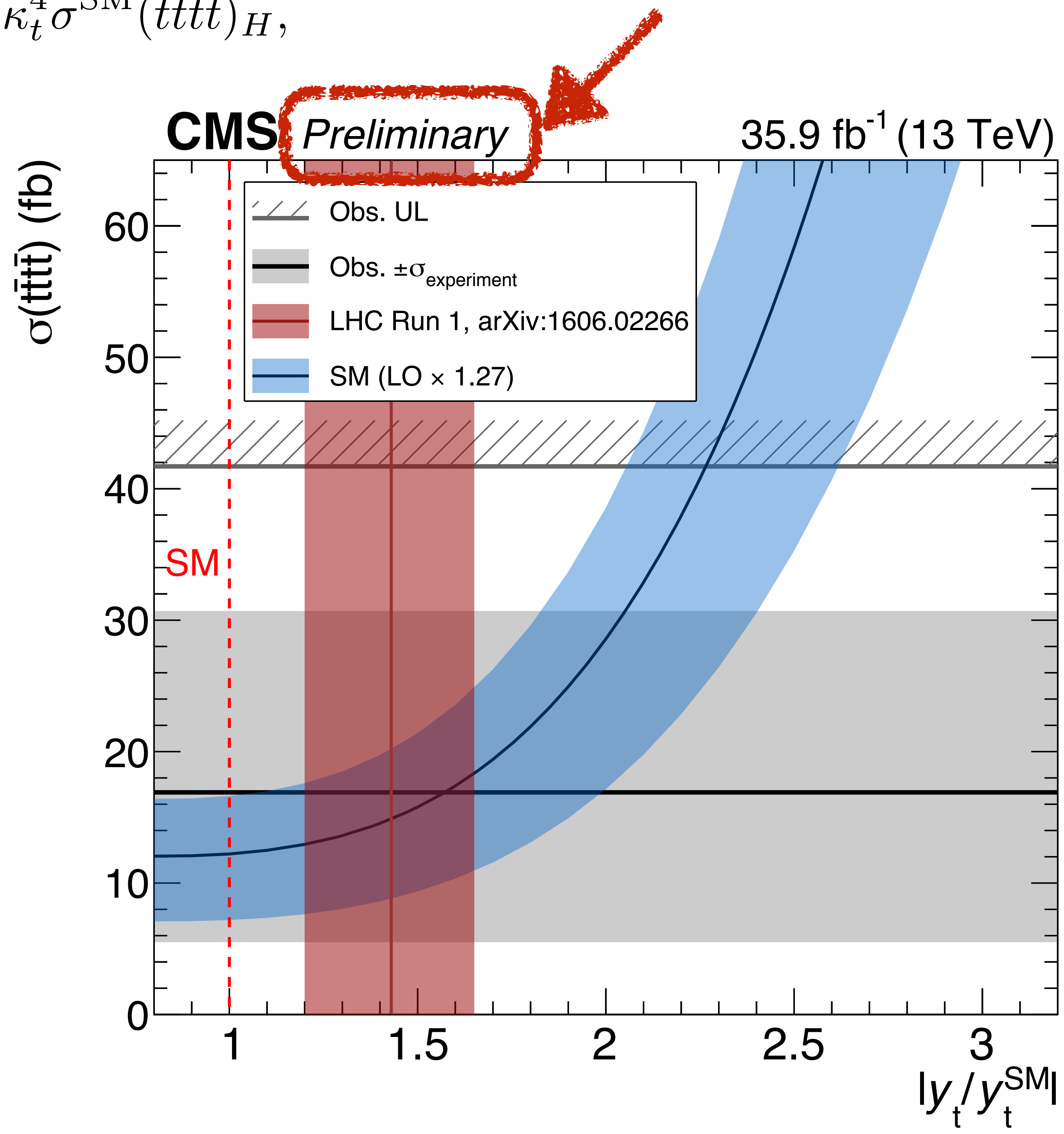
$$\sigma(t\bar{t}t\bar{t}) = \sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma} + \kappa_t^2\sigma^{\rm SM}_{\rm int} + \kappa_t^4\sigma^{\rm SM}(t\bar{t}t\bar{t})_H,$$

- Assume that tttt acceptance is not affected by production

… but not the whole story…



	13 TeV
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma}$:	9.997 fb,
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_H$:	1.168 fb,
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{\rm int}$:	−1.547 fb,



Results: Top-Higgs Yukawa (2)

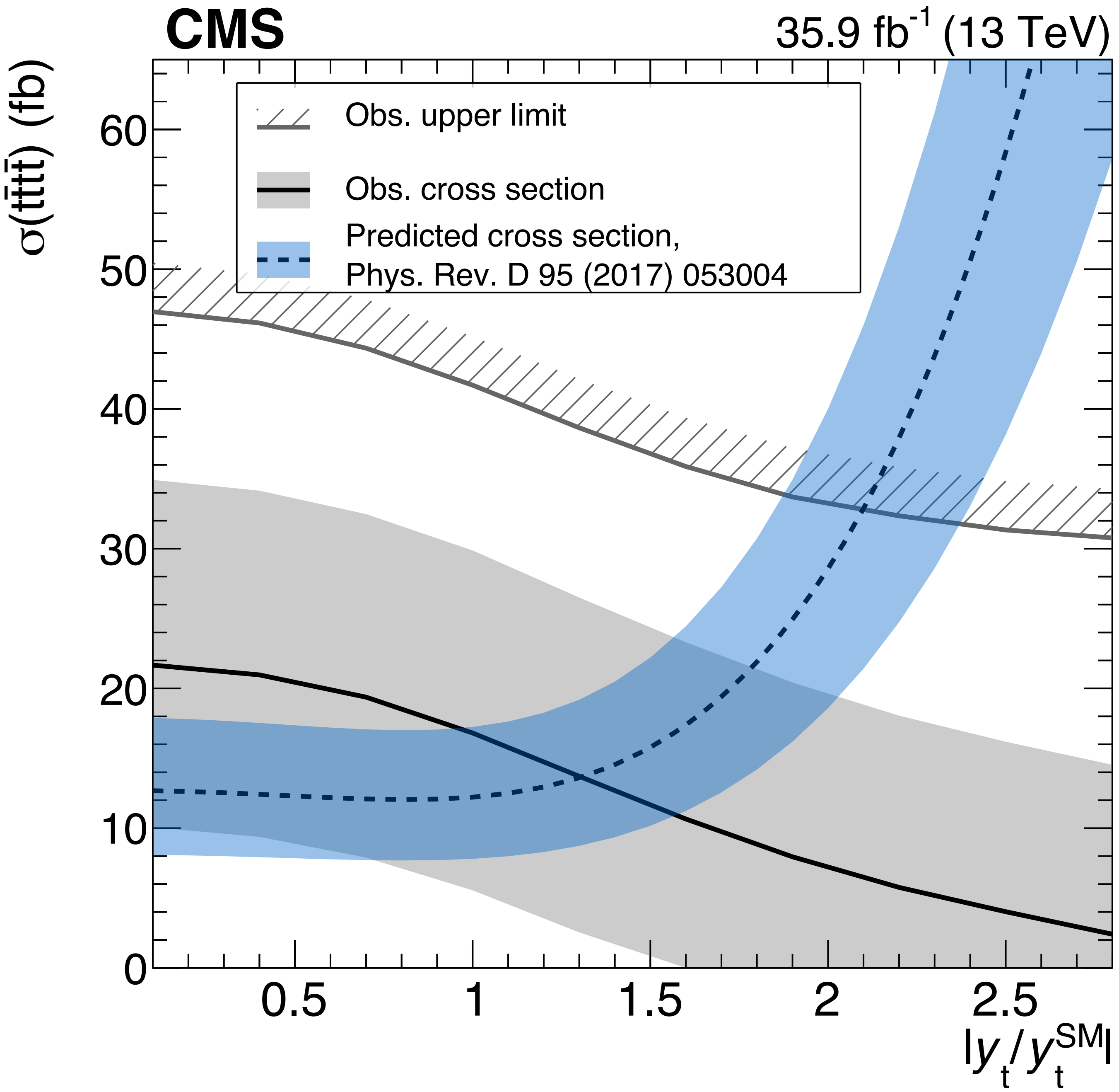
More accurate treatment of ttH background

ttH cross section also depends on y_t (proportional to y_t^2)

—> Need to adapt ttH normalization when testing y_t hypotheses

Result:

$|y_t| < 2.1$ based on the 95% CL upper limit on σ(tttt)



Conclusions

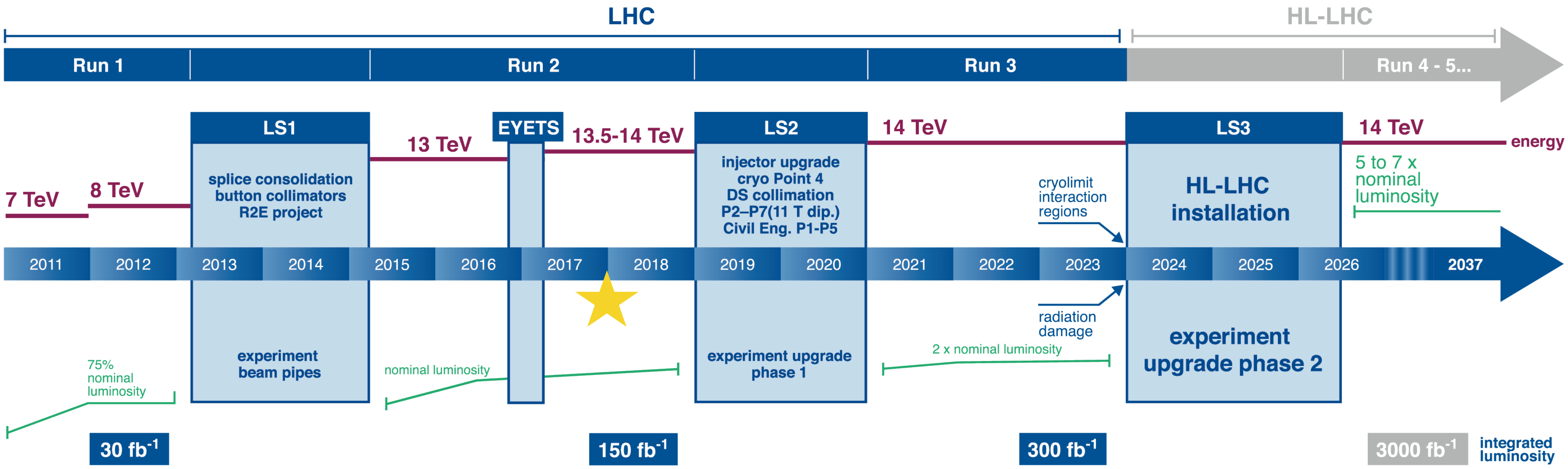
σ(tttt) is enhanced in many New Physics models

- 4th power of top-Higgs yukawa opens a new window towards the Higgs
- tt-associated production can help to probe heavy neutral particles (H/A)
- Effective Field Theory framework not yet fully explored

The search for SM tttt is finally starting to see a signal

Still a long way to go: we might reach 3σ significance in 2018, after combining with the other tttt channels (1L, 2LOS)

- Same-sign/multilepton dedicated search is young, there is plenty of of room for improvements: more signal regions, looser selection, MVA, τ, top-tagging…



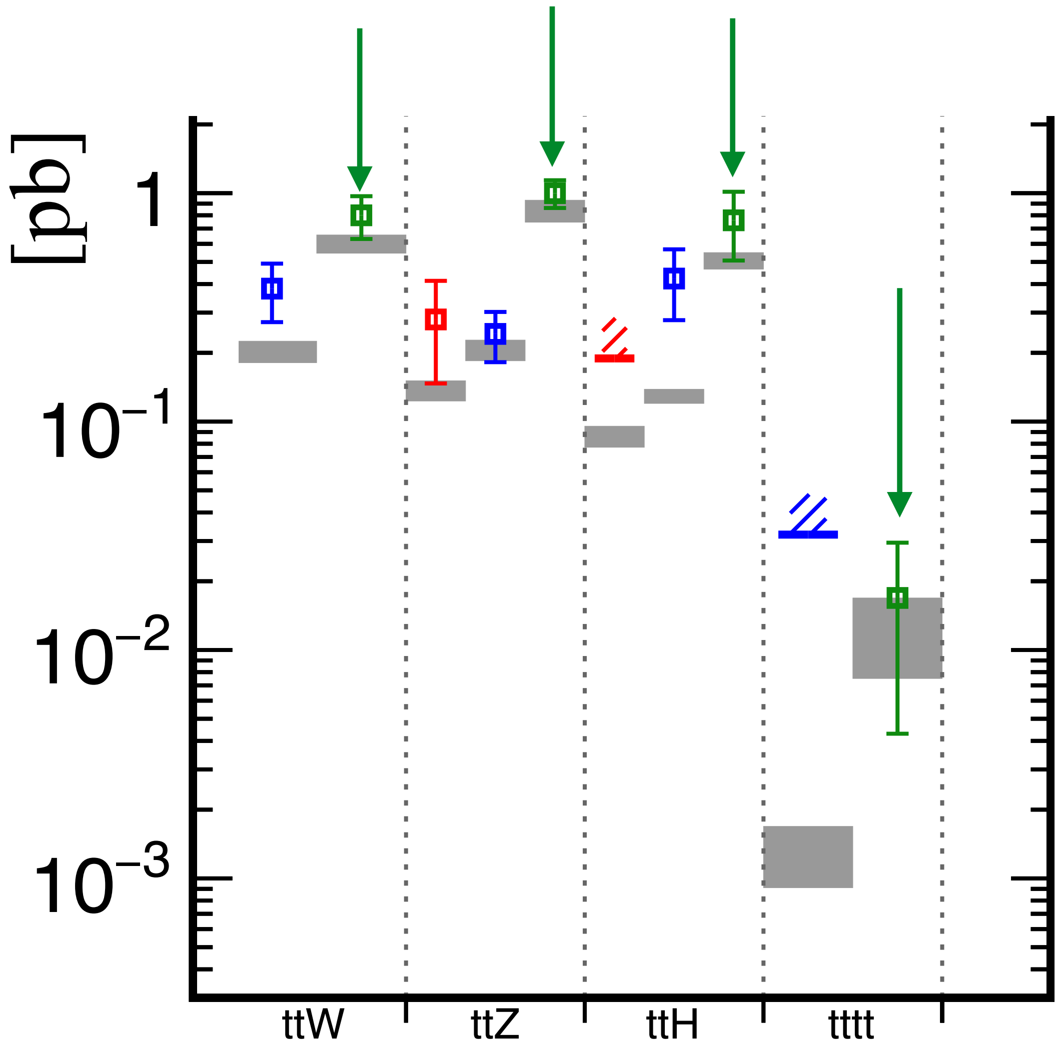
Conclusions (2)

As luminosity grows (and energy does not), interesting and challenging to probe rare SM processes (ttVV, tttV, ttt)

We will need HL-LHC to get through this list…

Closing quiz: why are tt+X measurements ~1σ (20-50%) high?

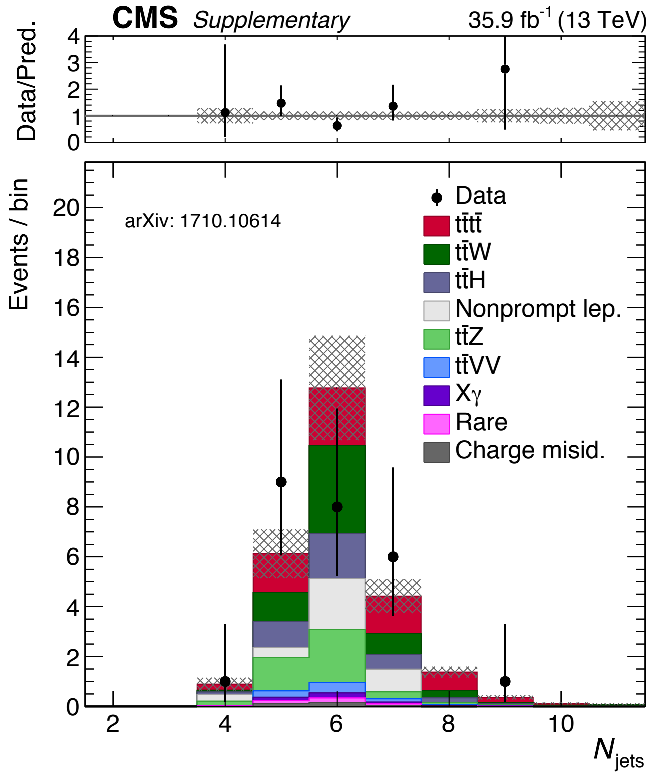
13 TeV σ [ab]	$t\bar{t}W^+Z$	$t\bar{t}W^-Z$	$t\bar{t}ZZ$
NLO QCD	$2705(3)^{+9.9\%\ +2.7\%}_{-10.6\%\ -2.7\%}$	$1179(2)^{+11.2\%\ +3.7\%}_{-11.2\%\ -3.7\%}$	$1982(2)^{+5.2\%\ +2.6\%}_{-9.0\%\ -2.6\%}$
LO	$1982(2)^{+28.4\%\ +3.3\%}_{-20.6\%\ -3.3\%}$	$839.4(6)^{+28.2\%\ +4.2\%}_{-20.5\%\ -4.2\%}$	$1611(1)^{+31.4\%\ +2.7\%}_{-22.1\%\ -2.7\%}$
K-factor	1.36	1.40	1.23
13 TeV σ [ab]	$t\bar{t}W^+H$	$t\bar{t}W^-H$	$t\bar{t}ZH$
NLO QCD	$1089(1)^{+1.8\%\ +2.6\%}_{-5.9\%\ -2.6\%}$	$493.0(5)^{+2.6\%\ +3.4\%}_{-6.4\%\ -3.4\%}$	$1535(2)^{+1.9\%\ +3.0\%}_{-6.8\%\ -3.0\%}$
LO	$997.0(9)^{+26.9\%\ +3.0\%}_{-19.8\%\ -3.0\%}$	$440.0(4)^{+26.9\%\ +3.8\%}_{-19.8\%\ -3.8\%}$	$1391(1)^{+32.2\%\ +2.8\%}_{-22.6\%\ -2.8\%}$
K-factor	1.09	1.12	1.10
13 TeV σ [ab]	$t\bar{t}W^+W^-$	$t\bar{t}W^+W^-$ (4f)	$t\bar{t}HH$
NLO QCD	–	$11500(10)^{+8.1\%\ +3.0\%}_{-10.9\%\ -3.0\%}$	$756.5(7)^{+1.1\%\ +3.3\%}_{-4.4\%\ -3.3\%}$
LO	$8380(5)^{+33.2\%\ +3.0\%}_{-23.1\%\ -3.0\%}$	$8357(5)^{+33.3\%\ +3.0\%}_{-23.1\%\ -3.0\%}$	$765.4(5)^{+31.8\%\ +2.9\%}_{-22.4\%\ -2.9\%}$
K-factor	–	1.38	0.99

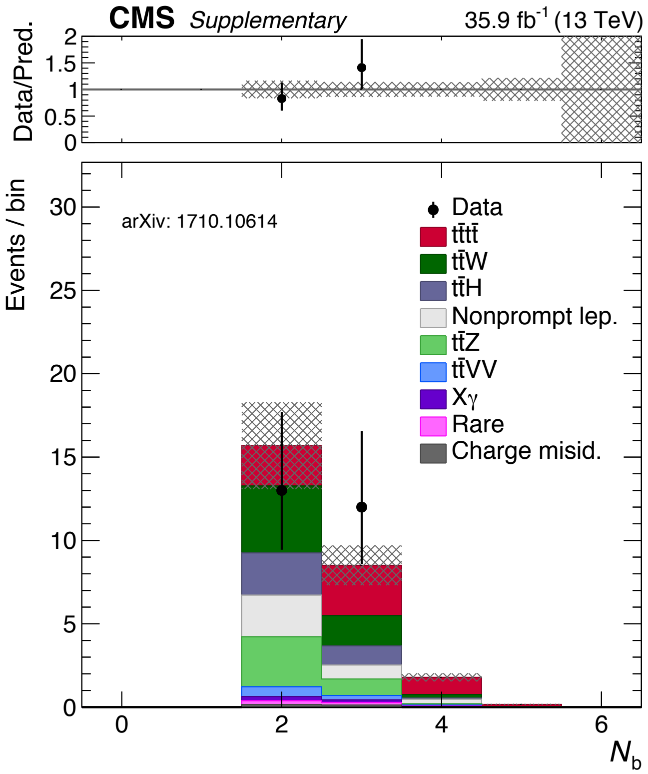


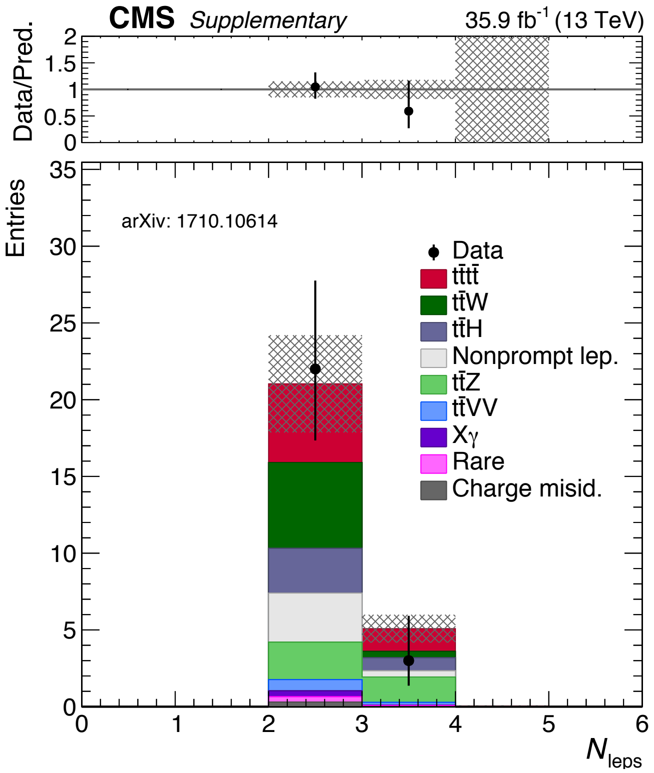
Backup

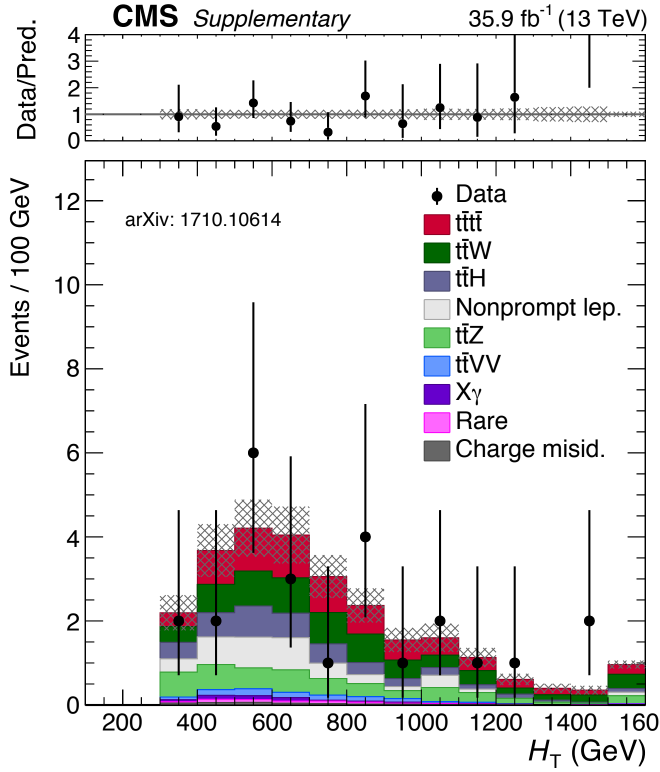
Post-fit kinematics

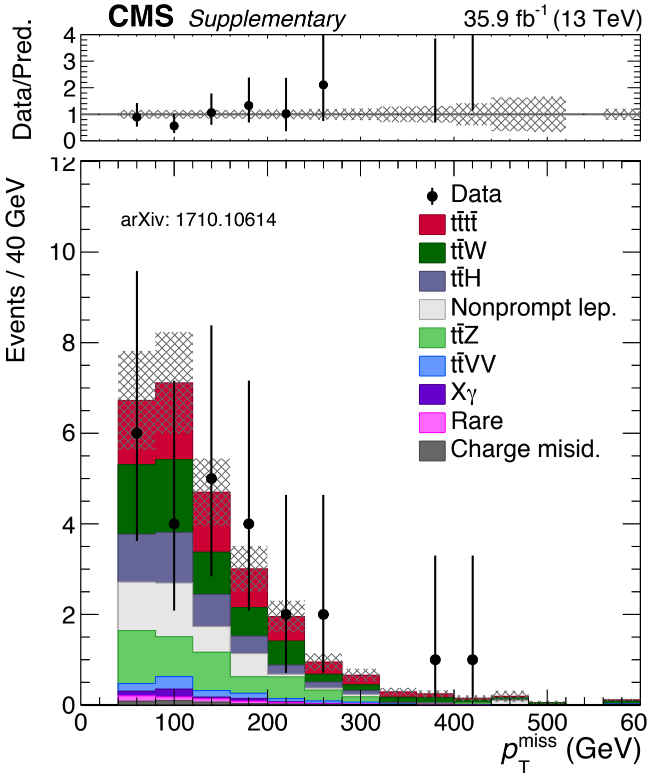
Reduced tension in Nb=3 region. Good agreement for leptons.

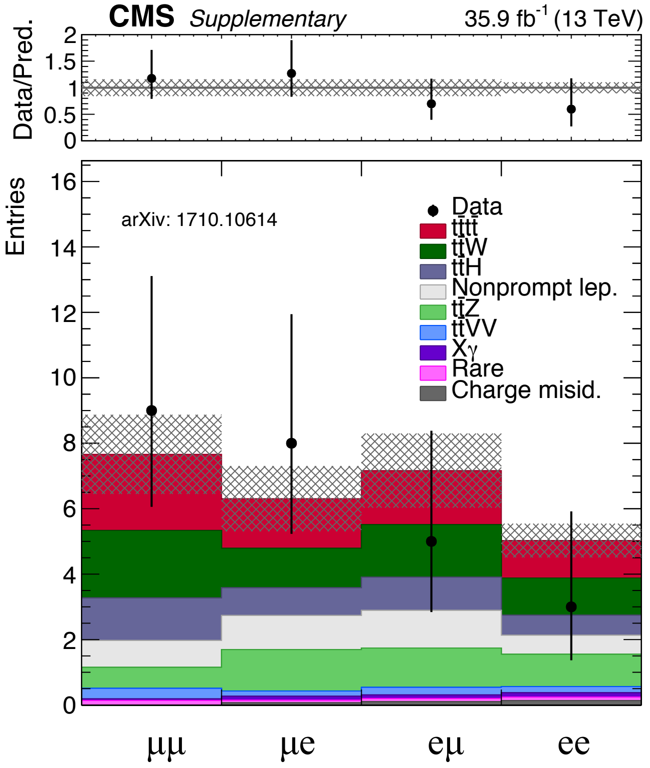




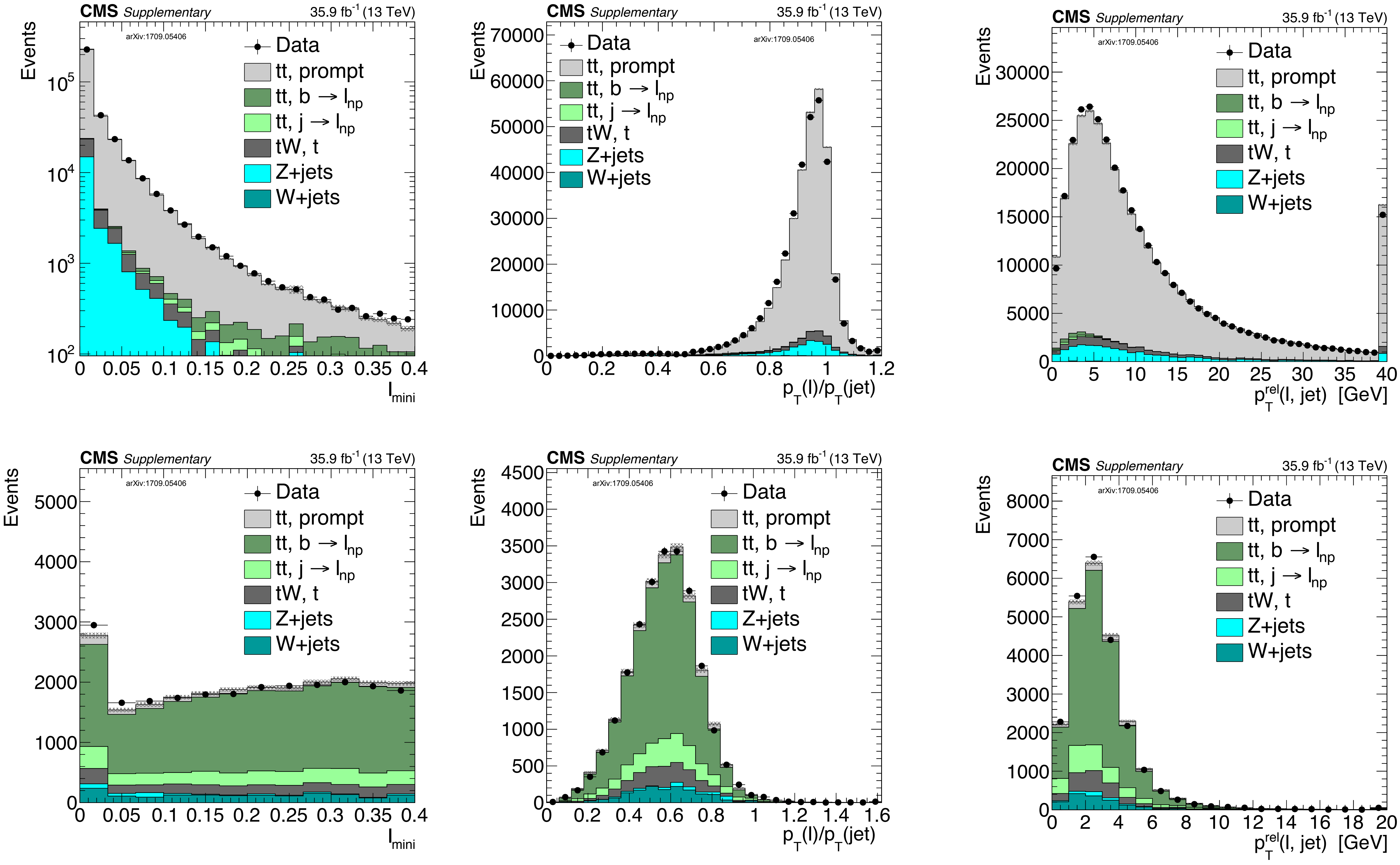








Isolation components in prompt and nonprompt leptons



Multi-Isolation details

$$\Delta R\left(p_{\mathrm{T}}(\ell)\right) = \frac{10\,\mathrm{GeV}}{\min\left[\max\left(p_{\mathrm{T}}(\ell), 50\,\mathrm{GeV}\right), 200\,\mathrm{GeV}\right]}$$

$$p_{\mathrm{T}}^{\mathrm{ratio}} = \frac{p_{\mathrm{T}}(\ell)}{p_{\mathrm{T}}(\mathrm{jet})},$$

$$p_{\mathrm{T}}^{\mathrm{rel}} = \frac{|(\vec{p}(\mathrm{jet}) - \vec{p}(\ell)) \times \vec{p}(\ell)|}{|\vec{p}(\mathrm{jet}) - \vec{p}(\ell)|}$$

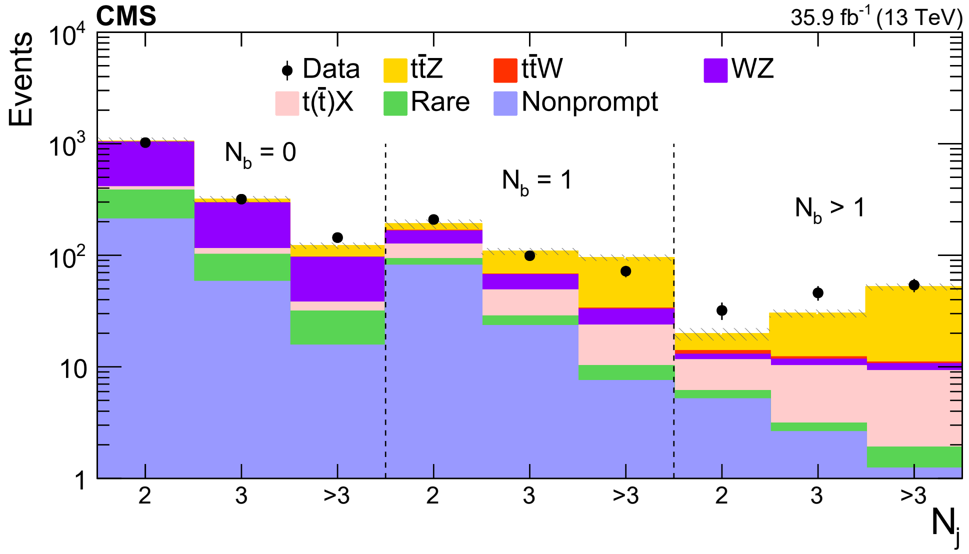
$$I_{\mathrm{mini}} < I_1 \text{ AND } (p_{\mathrm{T}}^{\mathrm{ratio}} > I_2 \text{ OR } p_{\mathrm{T}}^{\mathrm{rel}} > I_3).$$

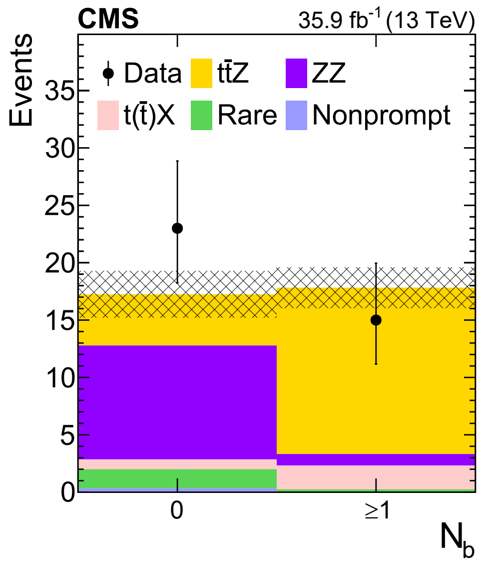
Isolation variable	Muons	Electrons
I_1	0.16	0.12
I_2	0.76	0.80
I_3 (GeV)	7.2	7.2

CMS ttW and ttZ Results

https://arxiv.org/pdf/1711.02547.pdf, TOP-17-005

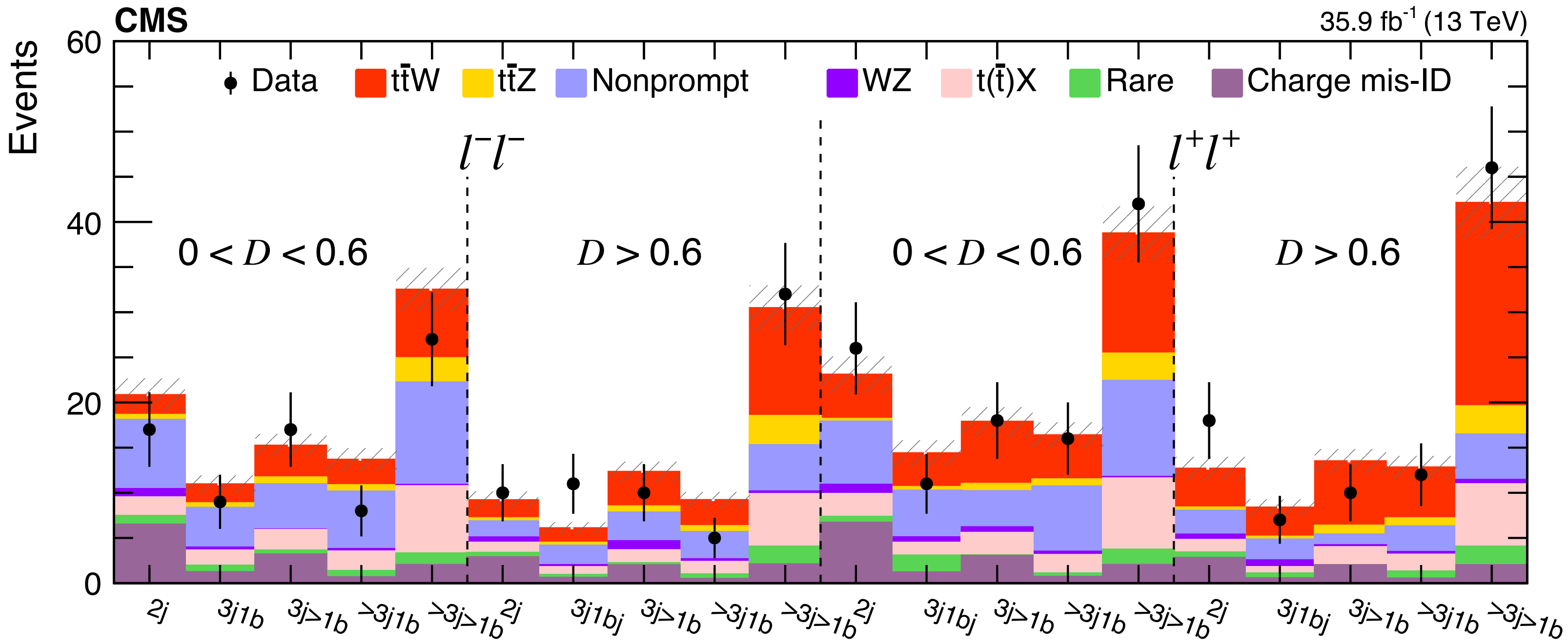
The measured signal strength parameters are found to be $1.23^{+0.19}_{-0.18}$ (stat)$^{+0.20}_{-0.18}$ (syst)$^{+0.13}_{-0.12}$ (theo) for $t\bar{t}W$, and $1.17\ ^{+0.11}_{-0.10}$ (stat)$^{+0.14}_{-0.12}$ (syst)$^{+0.11}_{-0.12}$ (theo) for $t\bar{t}Z$. These parameters are used to multiply the corresponding theoretical cross sections for $t\bar{t}W$ and $t\bar{t}Z$ mentioned in Section 1, to obtain the measured cross sections for $t\bar{t}W$ and $t\bar{t}Z$:

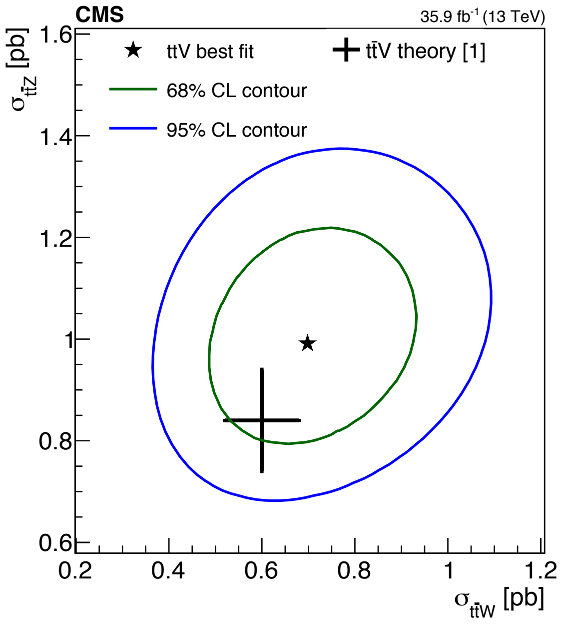


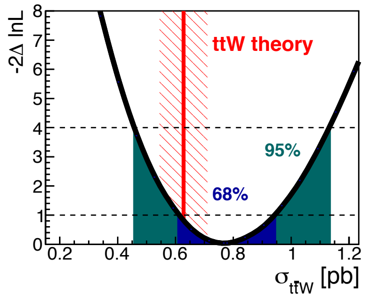


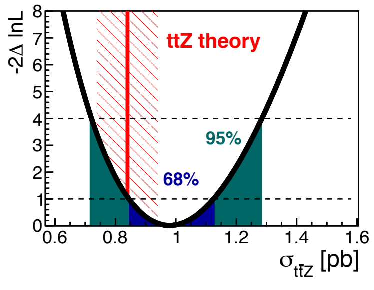
$$\sigma(pp \to t\bar{t}W) = 0.77^{+0.12}_{-0.11}\,(\text{stat})^{+0.13}_{-0.12}\,(\text{syst})\,\text{pb},$$

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

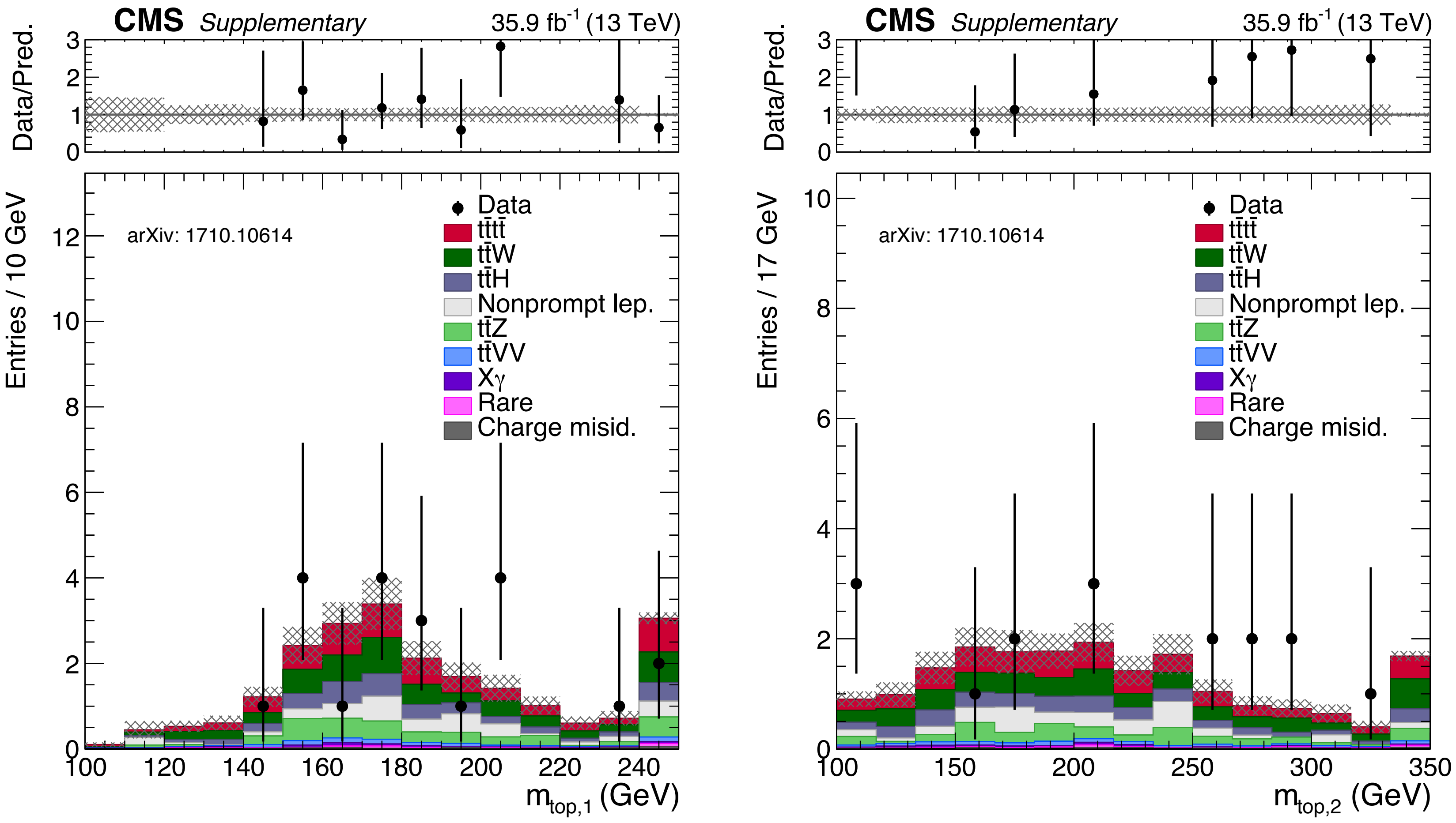






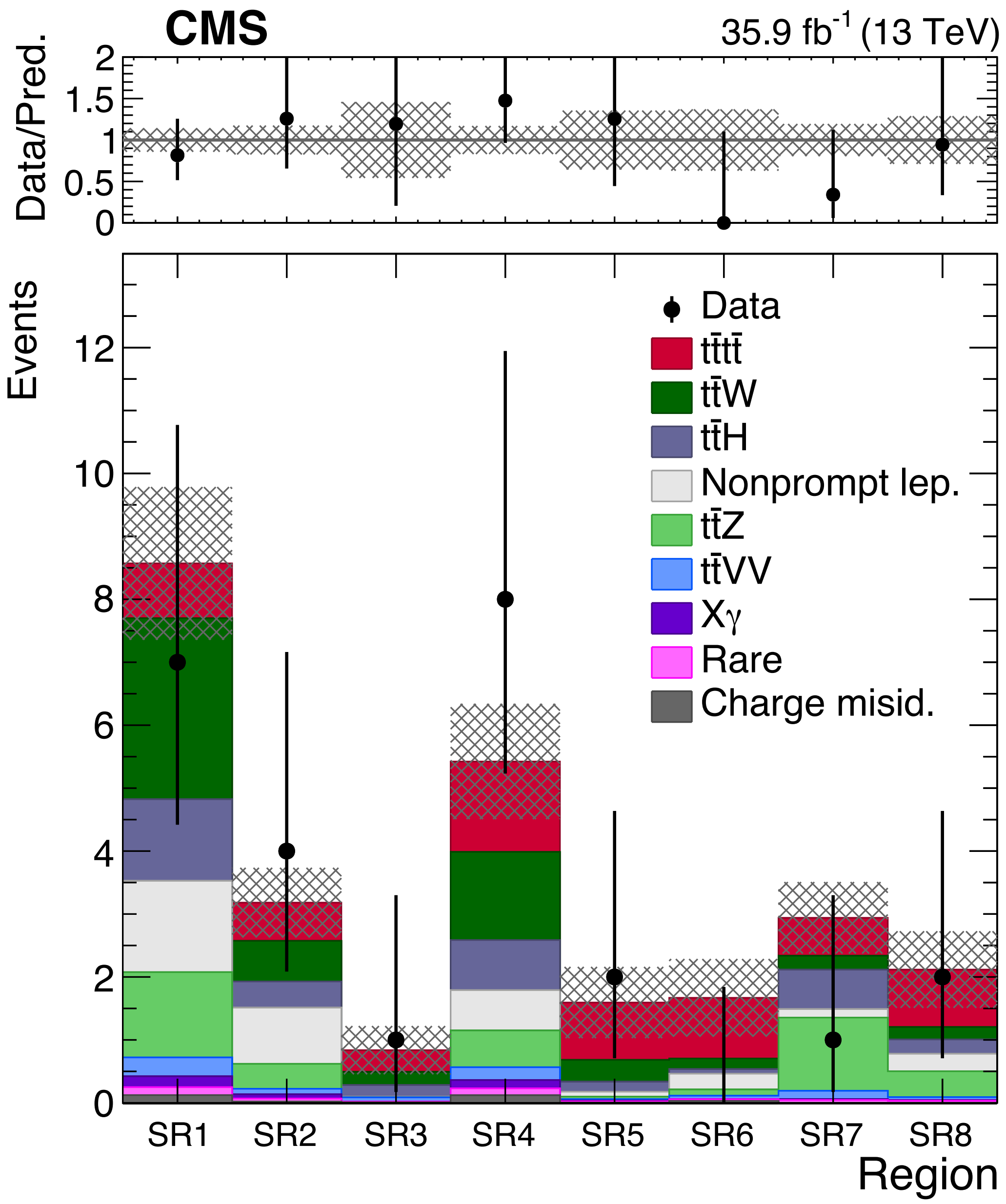


Reconstructing hadronic tops



Post-fit table

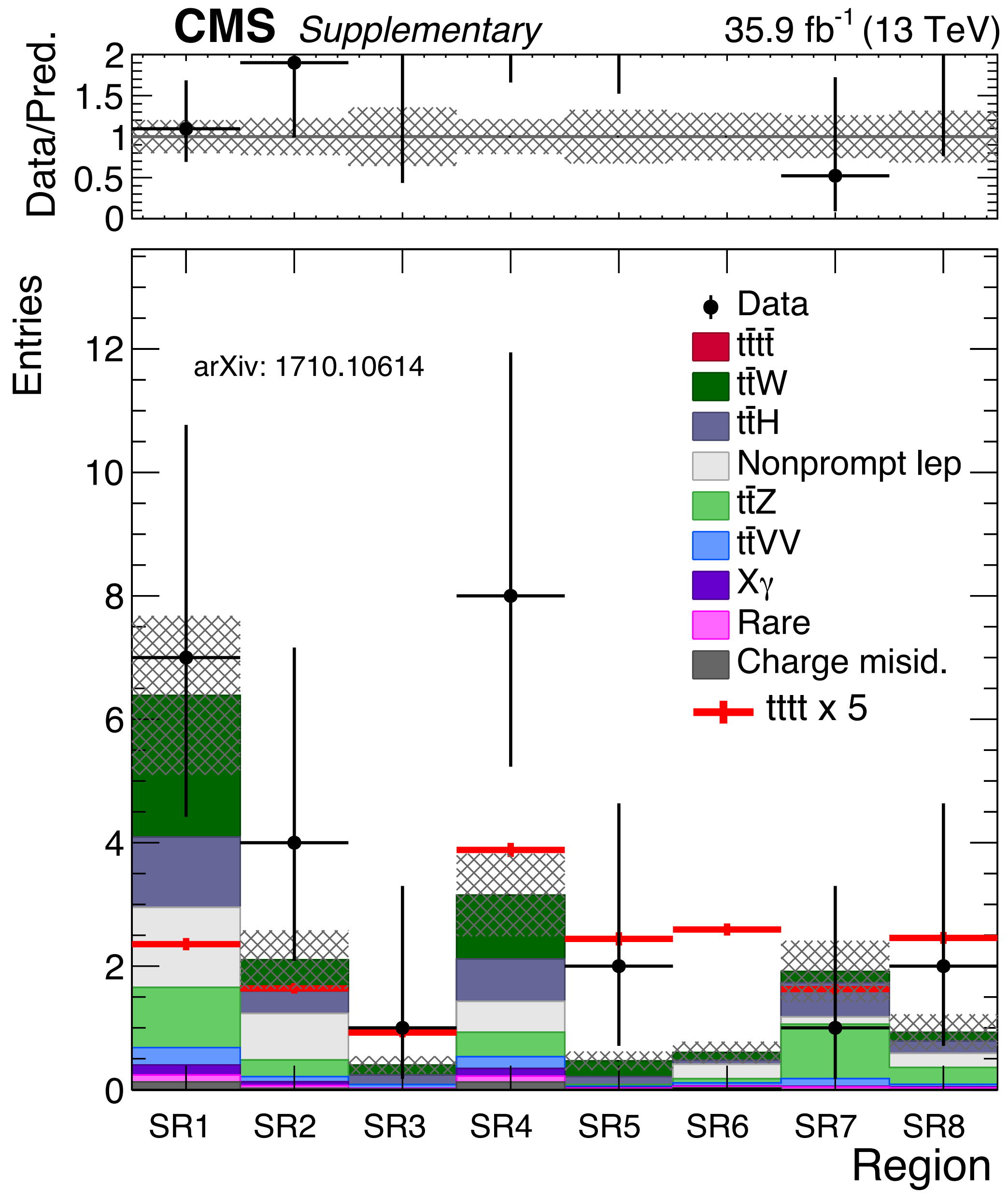
	SM background	$t\bar{t}t\bar{t}$	Total	Observed
CRZ	31.7 ± 4.6	0.4 ± 0.3	32.1 ± 4.6	35
CRW	83.7 ± 8.8	1.9 ± 1.2	85.6 ± 8.6	86
SR1	7.7 ± 1.2	0.9 ± 0.6	8.6 ± 1.2	7
SR2	2.6 ± 0.5	0.6 ± 0.4	3.2 ± 0.6	4
SR3	0.5 ± 0.3	0.4 ± 0.2	0.8 ± 0.4	1
SR4	4.0 ± 0.7	1.4 ± 0.9	5.4 ± 0.9	8
SR5	0.7 ± 0.2	0.9 ± 0.6	1.6 ± 0.6	2
SR6	0.7 ± 0.2	1.0 ± 0.6	1.7 ± 0.6	0
SR7	2.3 ± 0.5	0.6 ± 0.4	2.9 ± 0.6	1
SR8	1.2 ± 0.3	0.9 ± 0.6	2.1 ± 0.6	2



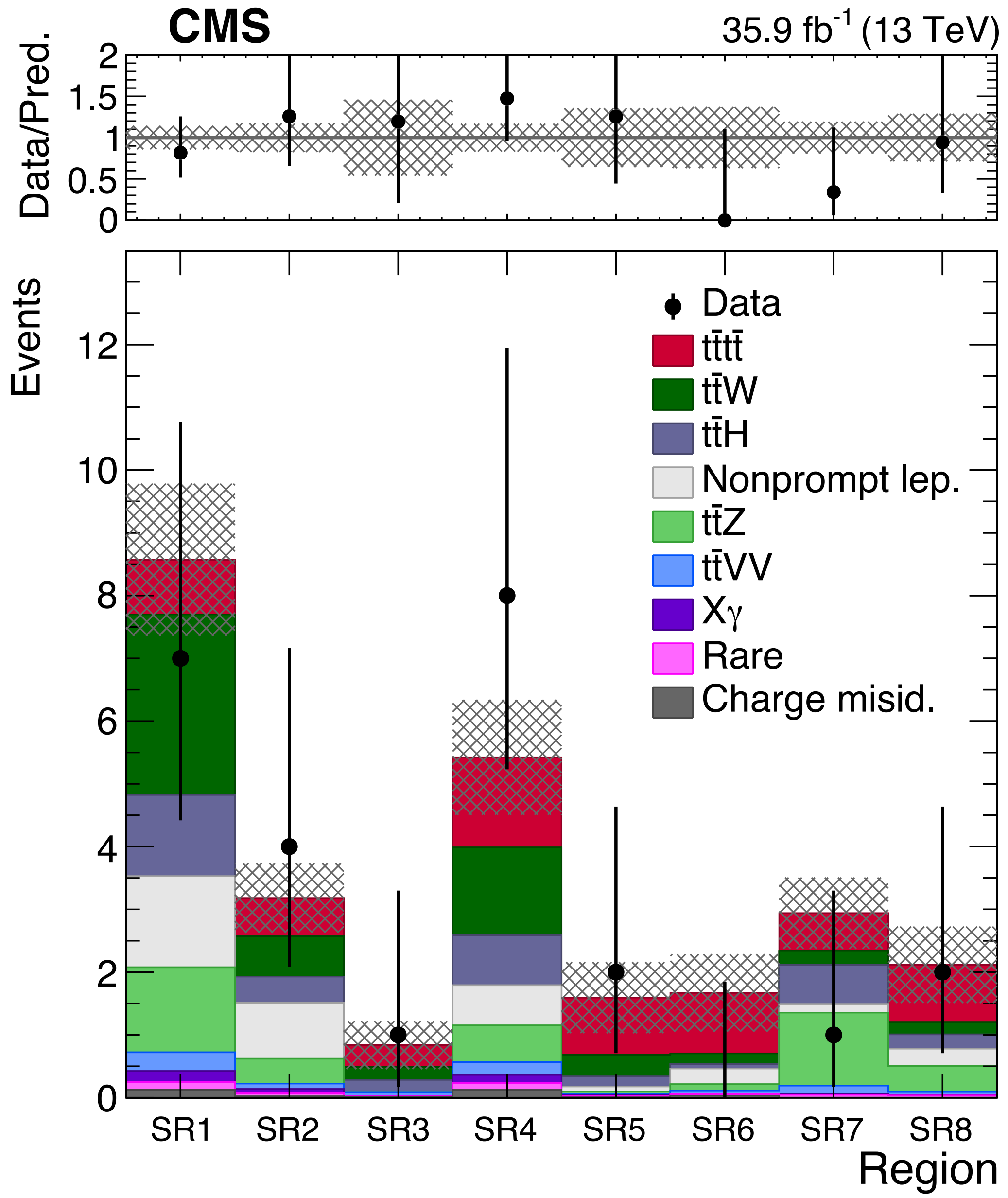
Pre vs Post SRs

N_{leps}	N_{b}	N_{jets}	Region
2	2	6	SR1
		7	SR2
		≥ 8	SR3
	3	5, 6	SR4
		≥ 7	SR5
	≥ 4	≥ 5	SR6
≥ 3	2	≥ 5	SR7
	≥ 3	≥ 4	SR8

Pre-fit, tttt overlaid

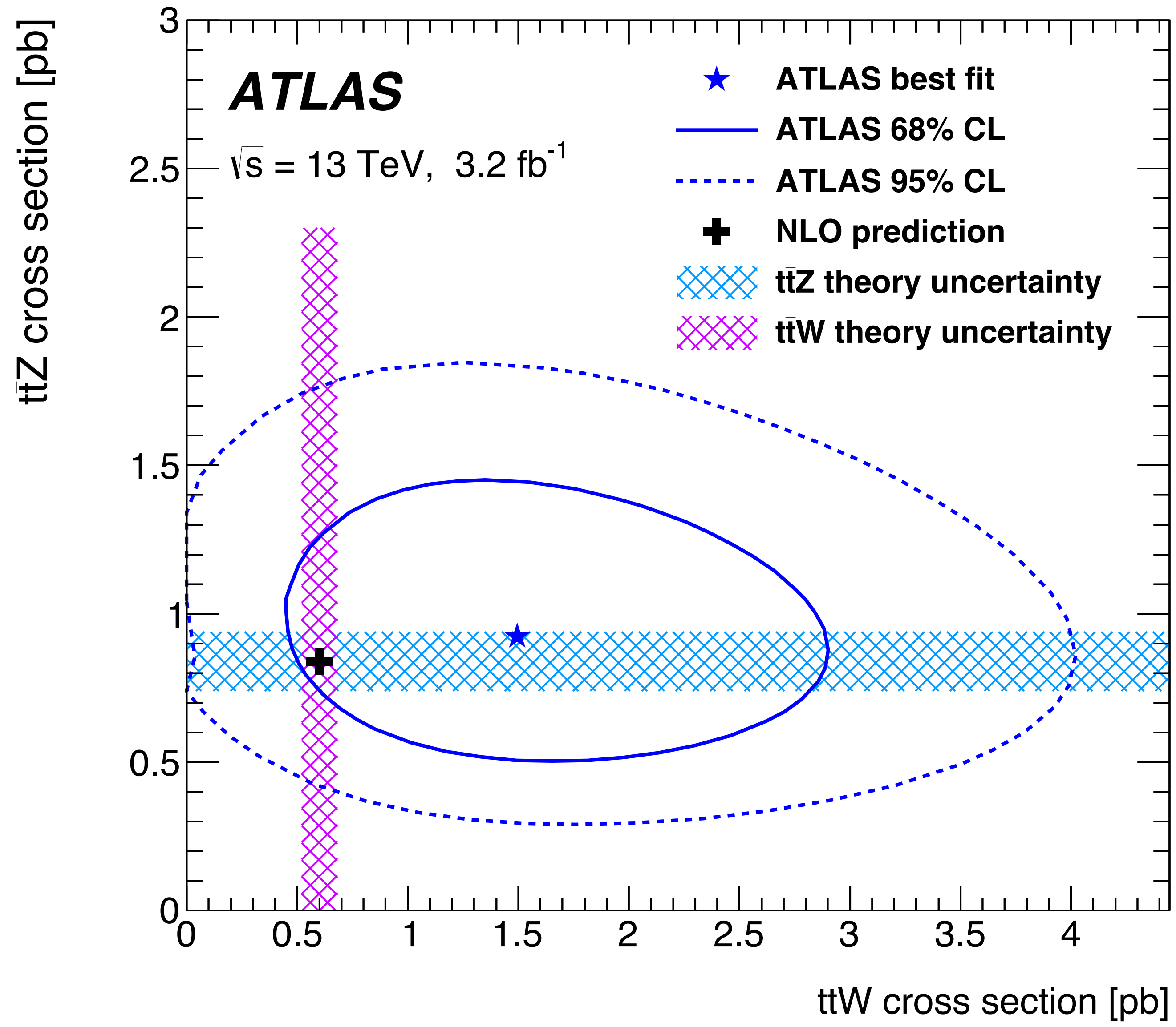


Post-fit, tttt stacked



ATLAS ttW and ttZ

arXiv:1609.01599



2HDM: from PDG and arXiv:1605.08744

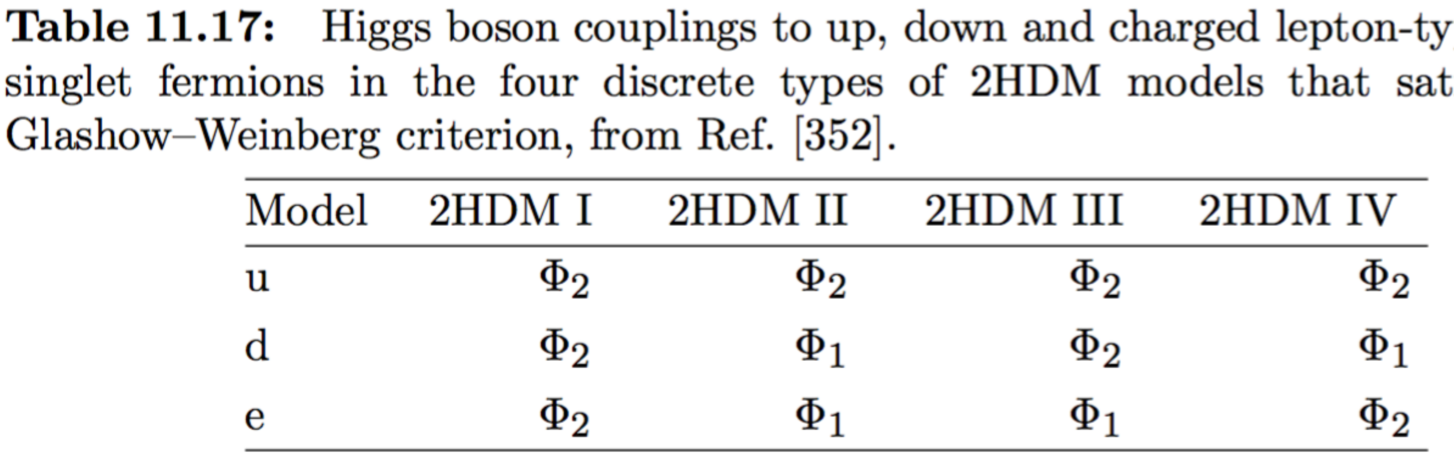
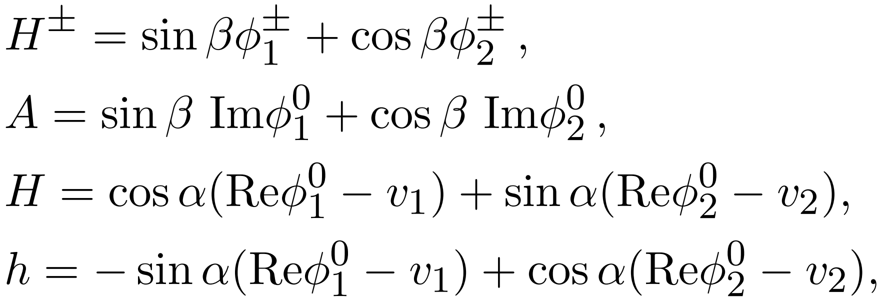


Table 11.17: Higgs boson couplings to up, down and charged lepton-type $SU(2)_L$ singlet fermions in the four discrete types of 2HDM models that satisfy the Glashow–Weinberg criterion, from Ref. [352].

Model	2HDM I	2HDM II	2HDM III	2HDM IV
u	Φ_2	Φ_2	Φ_2	Φ_2
d	Φ_2	Φ_1	Φ_2	Φ_1
e	Φ_2	Φ_1	Φ_1	Φ_2

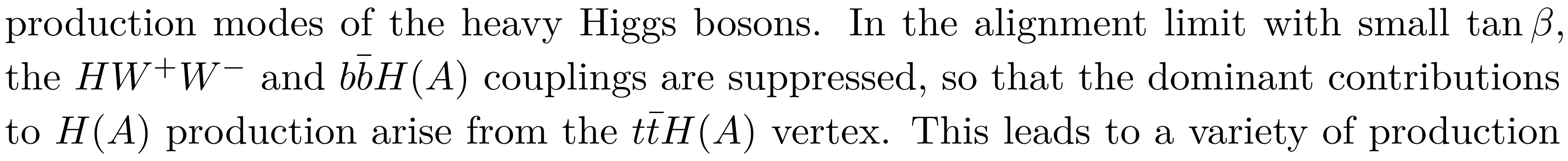
$\tan\beta = v_2/v_1.$

$$\Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1^0 + ia_1^0 \\ \sqrt{2}\phi_1^-\end{pmatrix}, \qquad \Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix}\sqrt{2}\phi_2^+ \\ \phi_2^0 + ia_2^0\end{pmatrix},$$

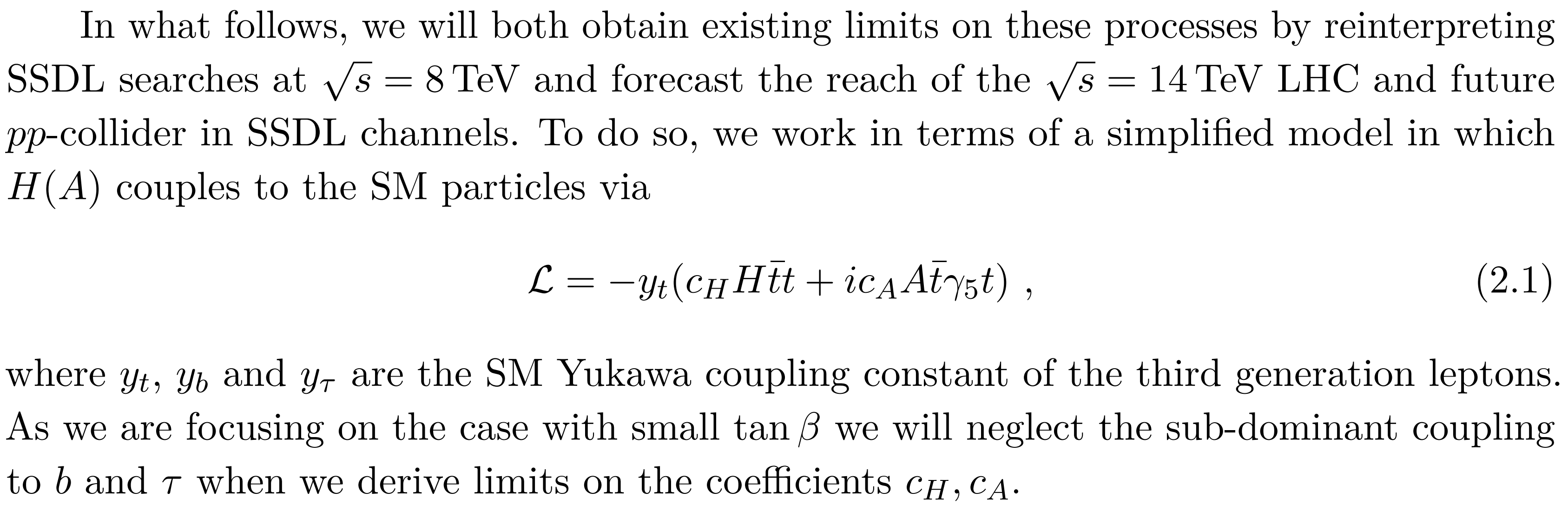


$$\begin{aligned} H^\pm &= \sin\beta\phi_1^\pm + \cos\beta\phi_2^\pm\,, \\ A &= \sin\beta\ \mathrm{Im}\phi_1^0 + \cos\beta\ \mathrm{Im}\phi_2^0\,, \\ H &= \cos\alpha(\mathrm{Re}\phi_1^0 - v_1) + \sin\alpha(\mathrm{Re}\phi_2^0 - v_2), \\ h &= -\sin\alpha(\mathrm{Re}\phi_1^0 - v_1) + \cos\alpha(\mathrm{Re}\phi_2^0 - v_2), \end{aligned}$$

$\cos(\beta-\alpha) \to 0$ is also called the alignment limit



production modes of the heavy Higgs bosons. In the alignment limit with small $\tan\beta$, the HW^+W^- and $b\bar{b}H(A)$ couplings are suppressed, so that the dominant contributions to $H(A)$ production arise from the $t\bar{t}H(A)$ vertex. This leads to a variety of production



In what follows, we will both obtain existing limits on these processes by reinterpreting SSDL searches at $\sqrt{s} = 8$ TeV and forecast the reach of the $\sqrt{s} = 14$ TeV LHC and future *pp*-collider in SSDL channels. To do so, we work in terms of a simplified model in which $H(A)$ couples to the SM particles via

$$\mathcal{L} = -y_t(c_H H\bar{t}t + ic_A A\bar{t}\gamma_5 t)\ , \qquad (2.1)$$

where y_t, y_b and y_τ are the SM Yukawa coupling constant of the third generation leptons. As we are focusing on the case with small $\tan\beta$ we will neglect the sub-dominant coupling to b and τ when we derive limits on the coefficients c_H, c_A.

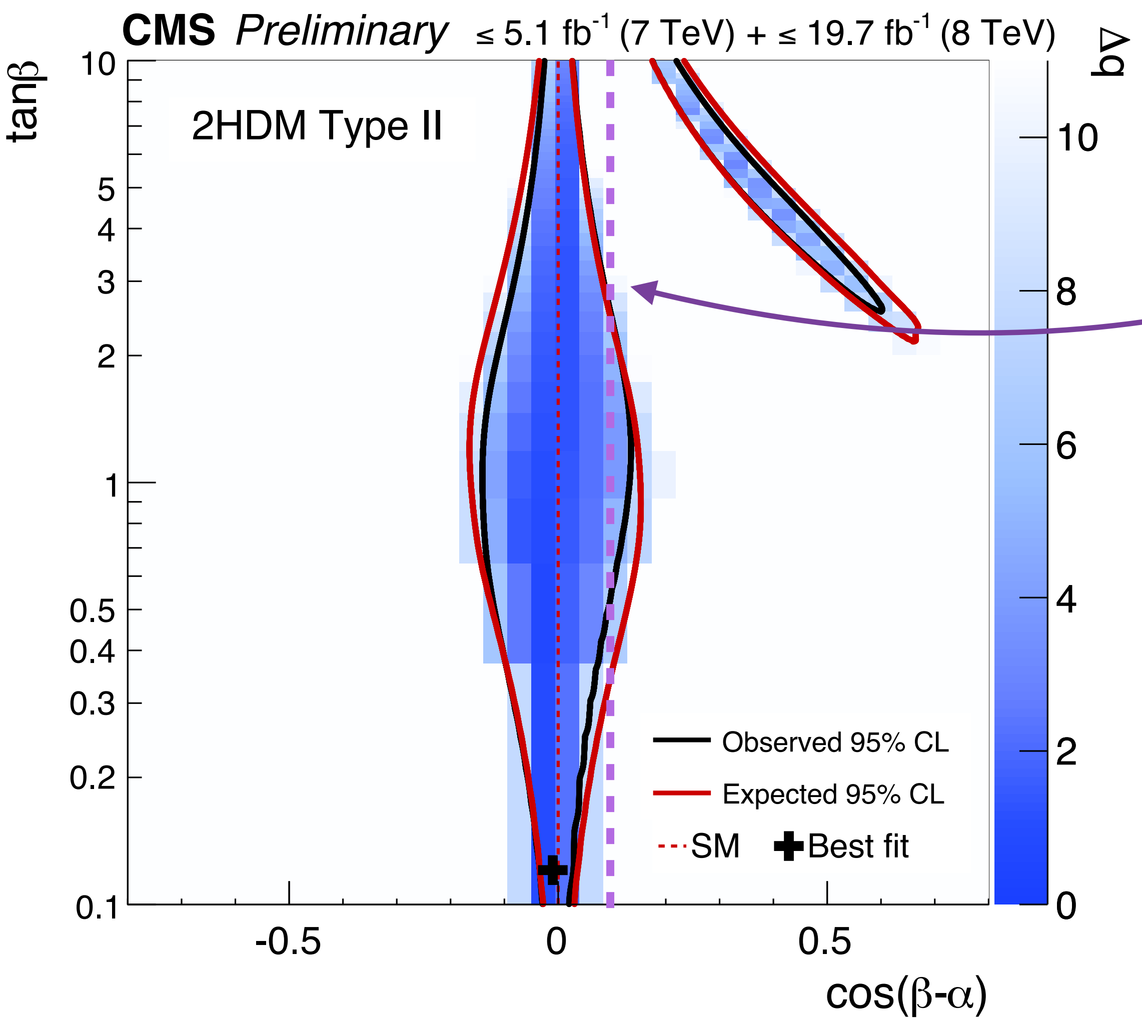
HIG-16-007 results on Type II 2HDM

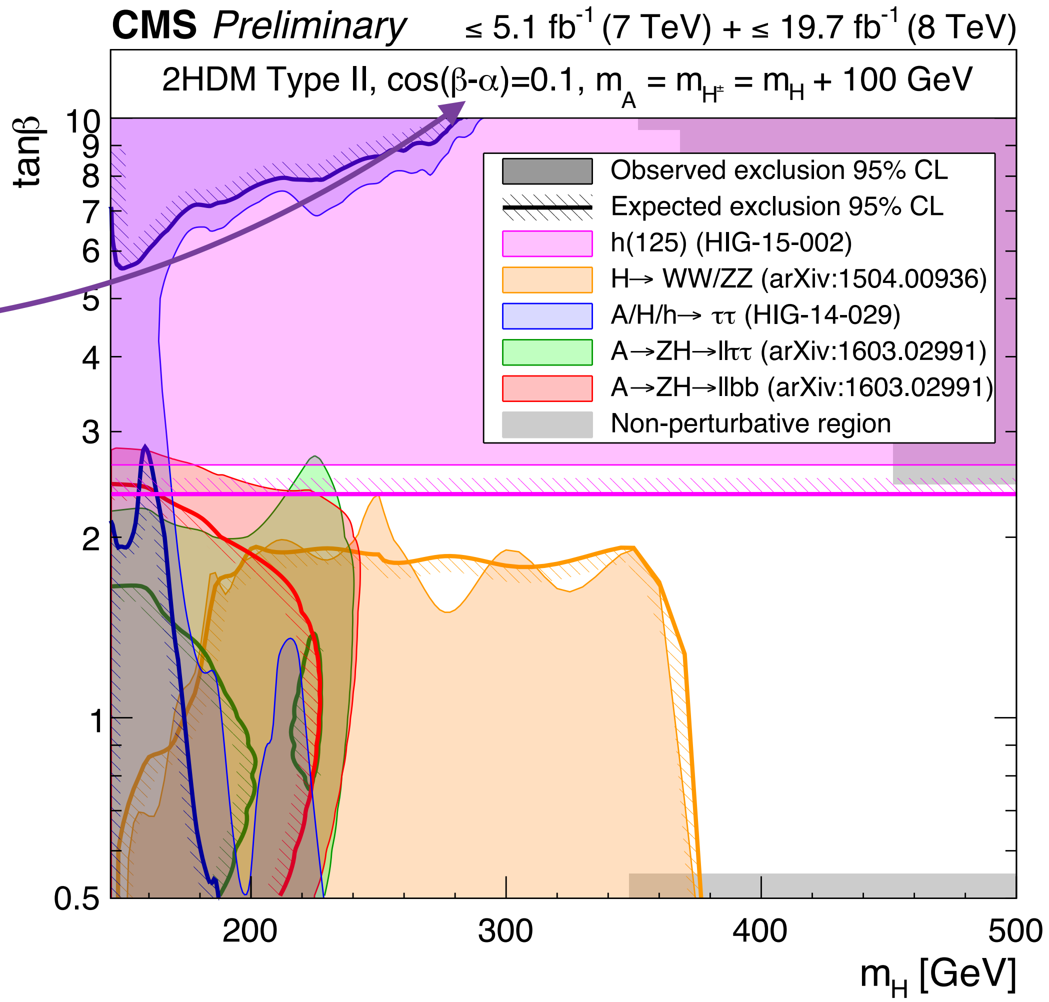
Current constraints on tanβ and cos(β-α) from SM Higgs measurements

- cos(β-α) close to 0
- tanβ free for cos(β-α)=0

Current limits on tanβ and mA/H from SM and BSM Higgs

- low-tanβ high-mass uncovered
  - H/A->tt in this region
- high-tanβ exclusion due to choice of cos(β-α)



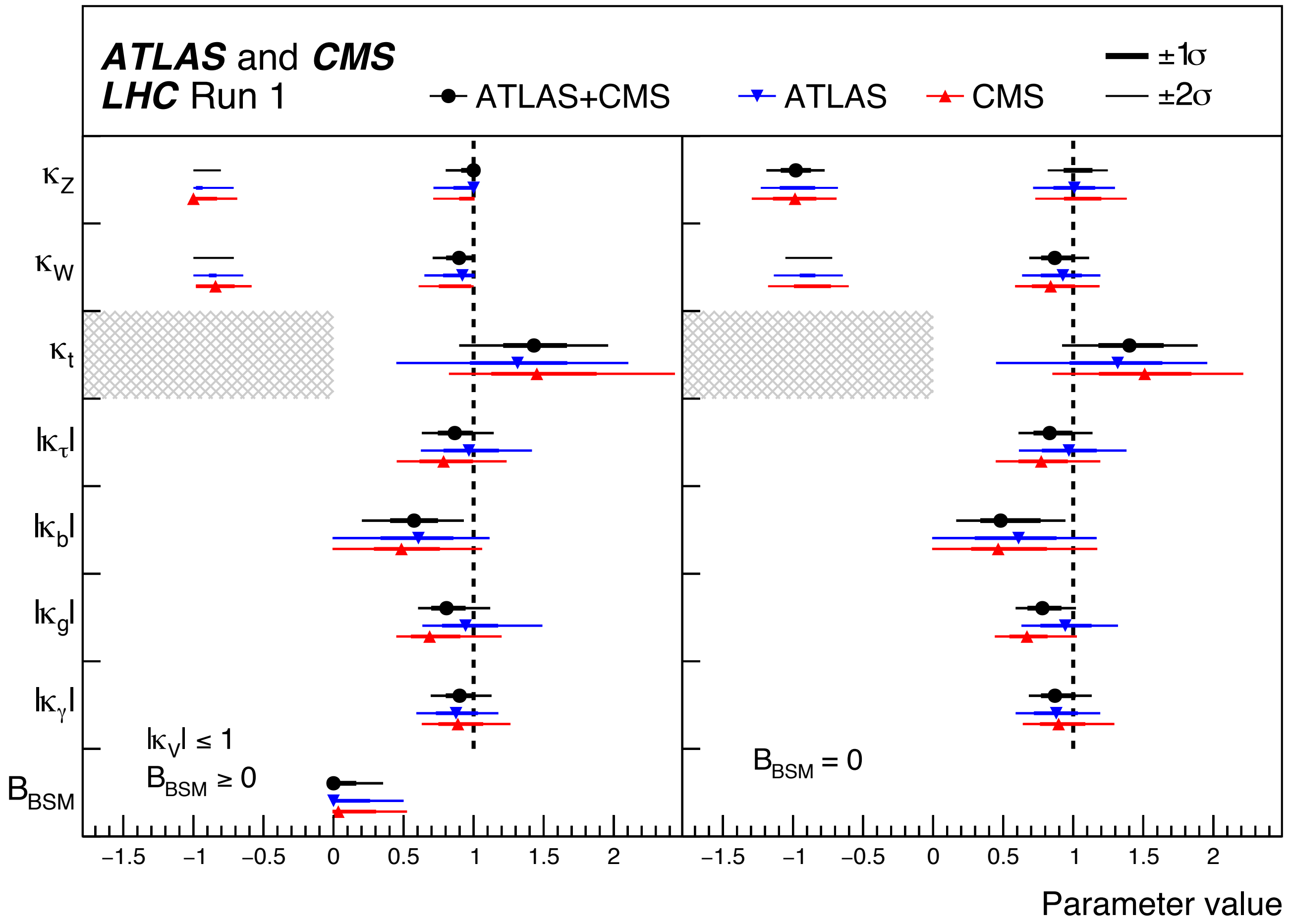


Higgs Combination

arXiv:1606.02266

Table 4: Higgs boson production cross sections σ_i, partial decay widths Γ^f, and total decay width (in the absence c BSM decays) parameterised as a function of the κ coupling modifiers as discussed in the text, including higher-orde QCD and EW corrections to the inclusive cross sections and decay partial widths. The coefficients in the expressio for Γ_H do not sum exactly to unity because some contributions that are negligible or not relevant to the analyse presented in this paper are not shown.

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(gg\mathrm{F})$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t\kappa_b$
$\sigma(\mathrm{VBF})$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z\kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb \to tHW)$	–	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t\kappa_W$
$\sigma(qq/qb \to tHq)$	–	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t\kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width ($\mathrm{B_{BSM}} = 0$)				
Γ_H	✓	–	κ_H^2	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 +$ $0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$



Changes in the values of the couplings will result in a variation of the Higgs boson width. A new modifier, κ_H, defined as $\kappa_H^2 = \sum_j \mathrm{B}_{\mathrm{SM}}^j \kappa_j^2$ and assumed to be positive without loss of generality, is introduced to characterise this variation. In the case where the SM decays of the Higgs boson are the only ones allowed, the relation $\kappa_H^2 = \Gamma_H/\Gamma_H^{\mathrm{SM}}$ holds. If instead deviations from the SM are introduced in the decays, the width Γ_H can be expressed as:

$$\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{\mathrm{SM}}}{1 - \mathrm{B_{BSM}}}, \tag{6}$$

where $\mathrm{B_{BSM}}$ indicates the total branching fraction into BSM decays. Such BSM decays can be of three types: decays into BSM particles that are invisible to the detector because they do not appreciably interact with ordinary matter, decays into BSM particles that are not detected because they produce event topologies that are not searched for, or modifications of the decay branching fractions into SM particles in the case of channels that are not directly measured, such as $H \to cc$. Although direct and indirect experimental constraints on the Higgs boson width exist, they are either model dependent or are not stringent enough to constrain the present fits, and are therefore not included in the combinations. Since Γ_H is not experimentally constrained in a model-independent manner with sufficient precision, only ratios of coupling strengths can be measured in the most generic parameterisation considered in the κ-framework.