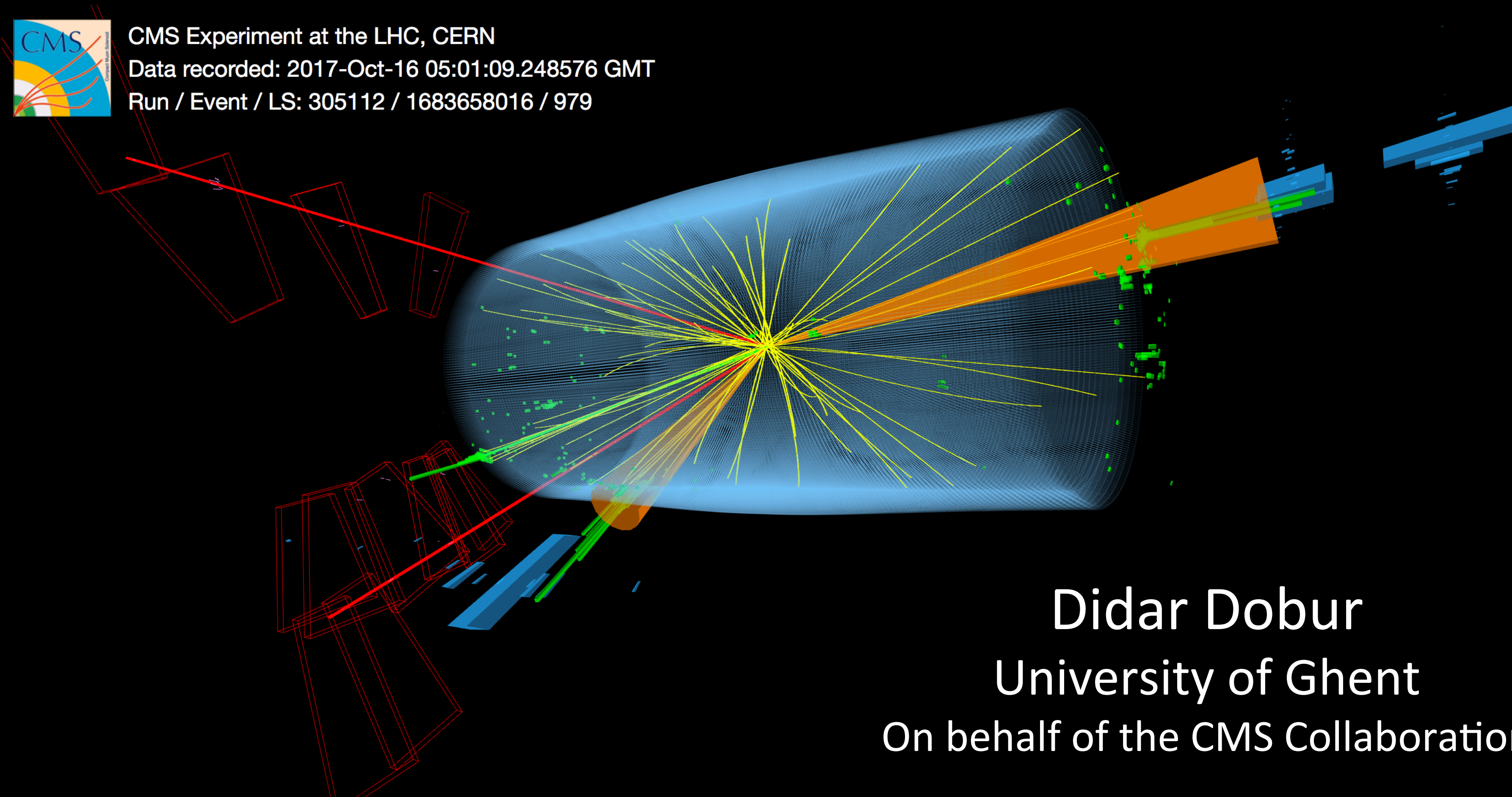
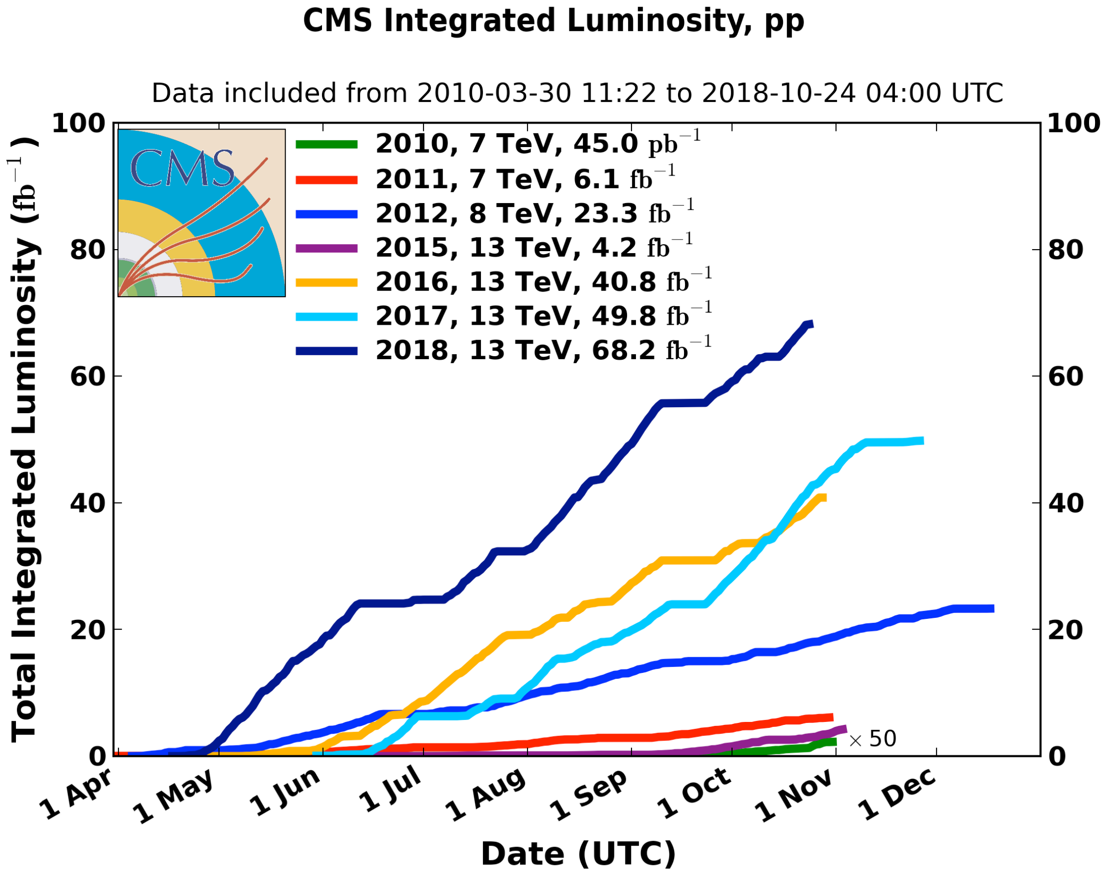
Observation of single top quark production in association with a Z boson at CMS



Didar Dobur
University of Ghent
On behalf of the CMS Collaboration

Turkish-Iranian conference on LHC physics, Istanbul, 2019

CMS pp collision data so far

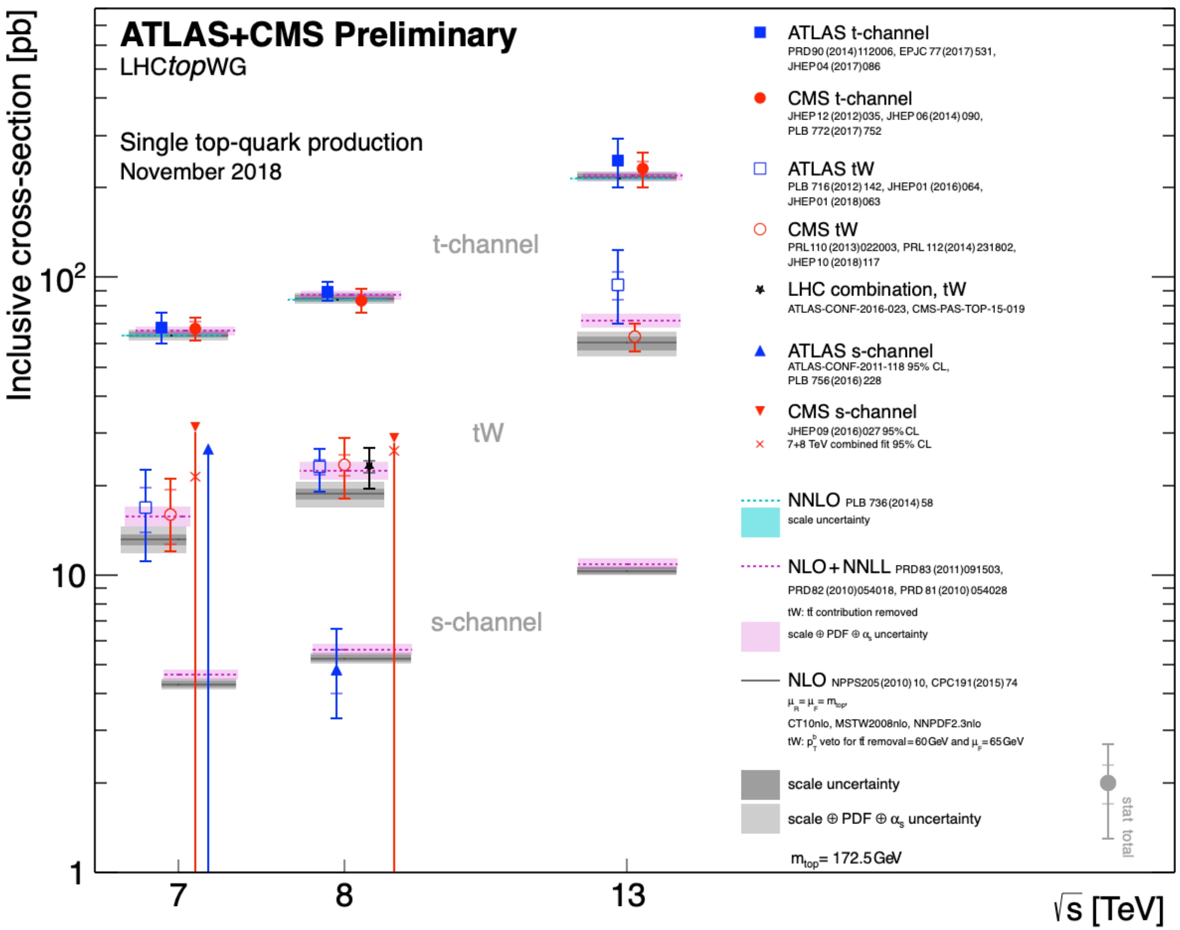


163 fb^{-1} delivered integrated luminosity @ 13 TeV !

~140 fb^{-1} data physics

tZq measurement with 77 fb^{-1} & published in Phys. Rev. Lett. 122, 132003

Single top-quark production

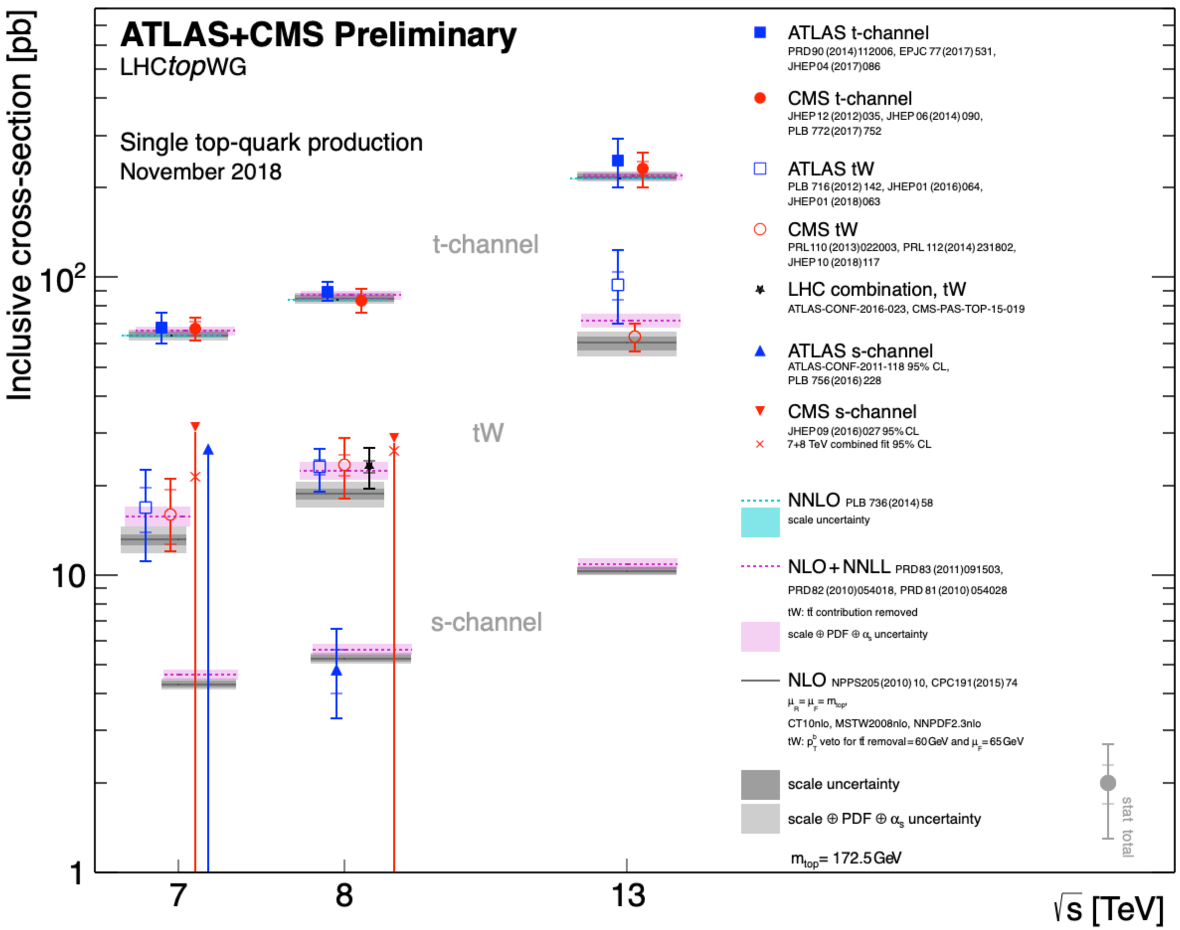


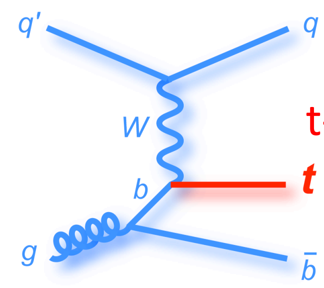
- Production via EWK interaction

  → smaller cross sections, large backgrounds

- Precise determination of |Vtb|, constrain PDFs, FCNC

Single top-quark production

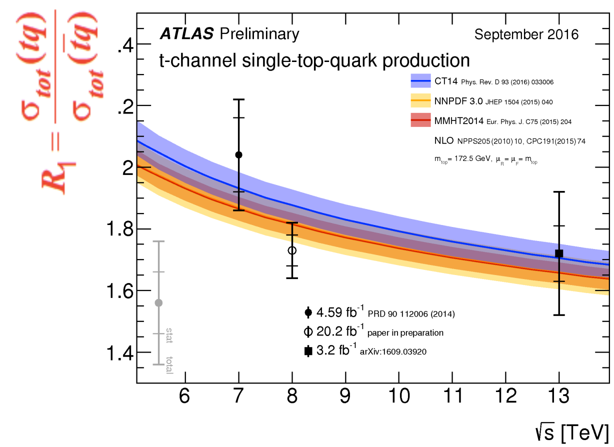




t-channnel

$\sigma(tq) = 136 \pm 1 \pm 22\text{pb}$

$\sigma(\bar{t}q) = 82 \pm 1 \pm 14\text{pb}$



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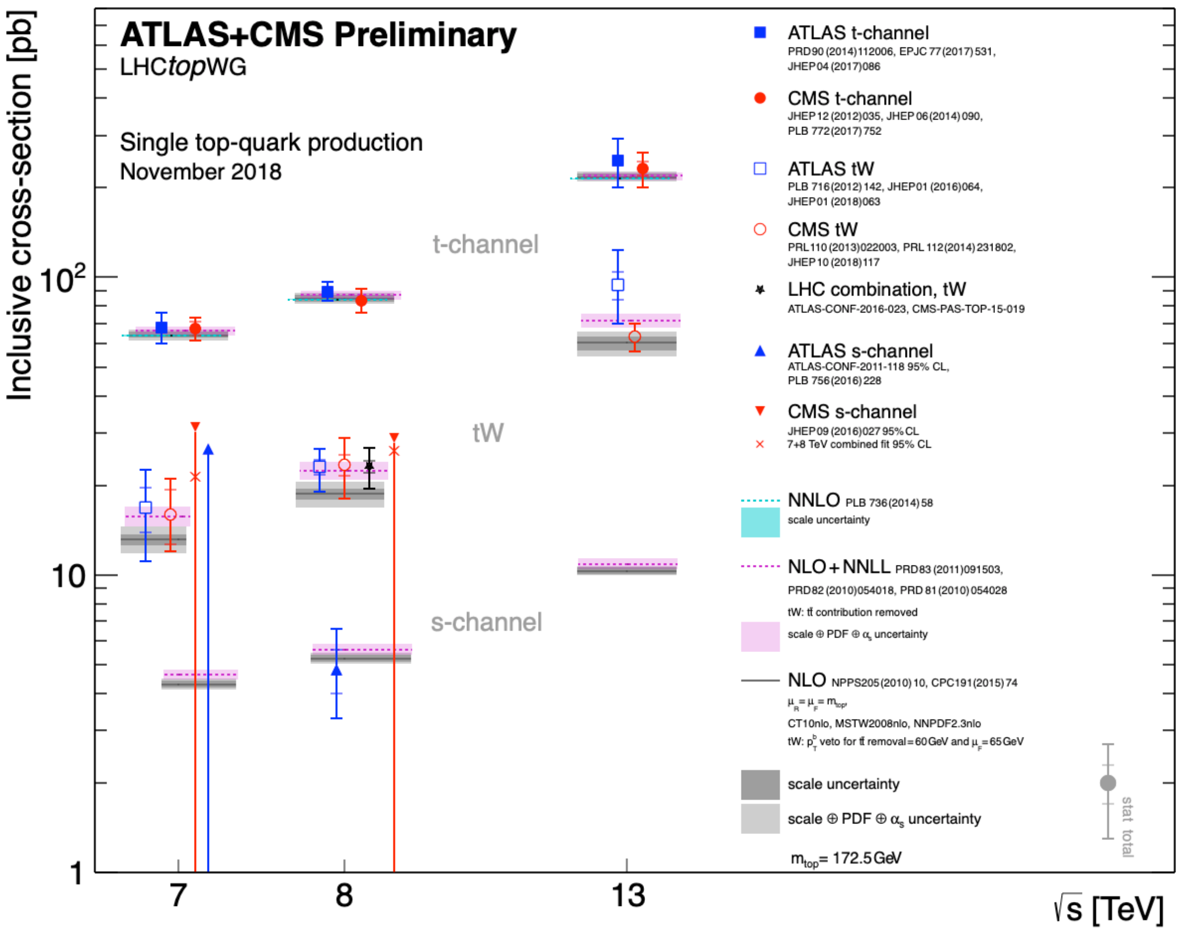

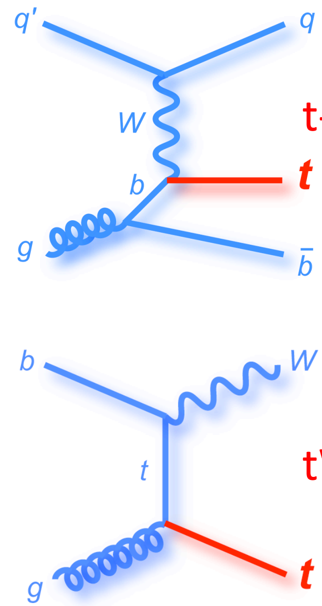

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tW-channel

$\sigma(tW) = 63 \pm 2 \pm 7\text{pb}$

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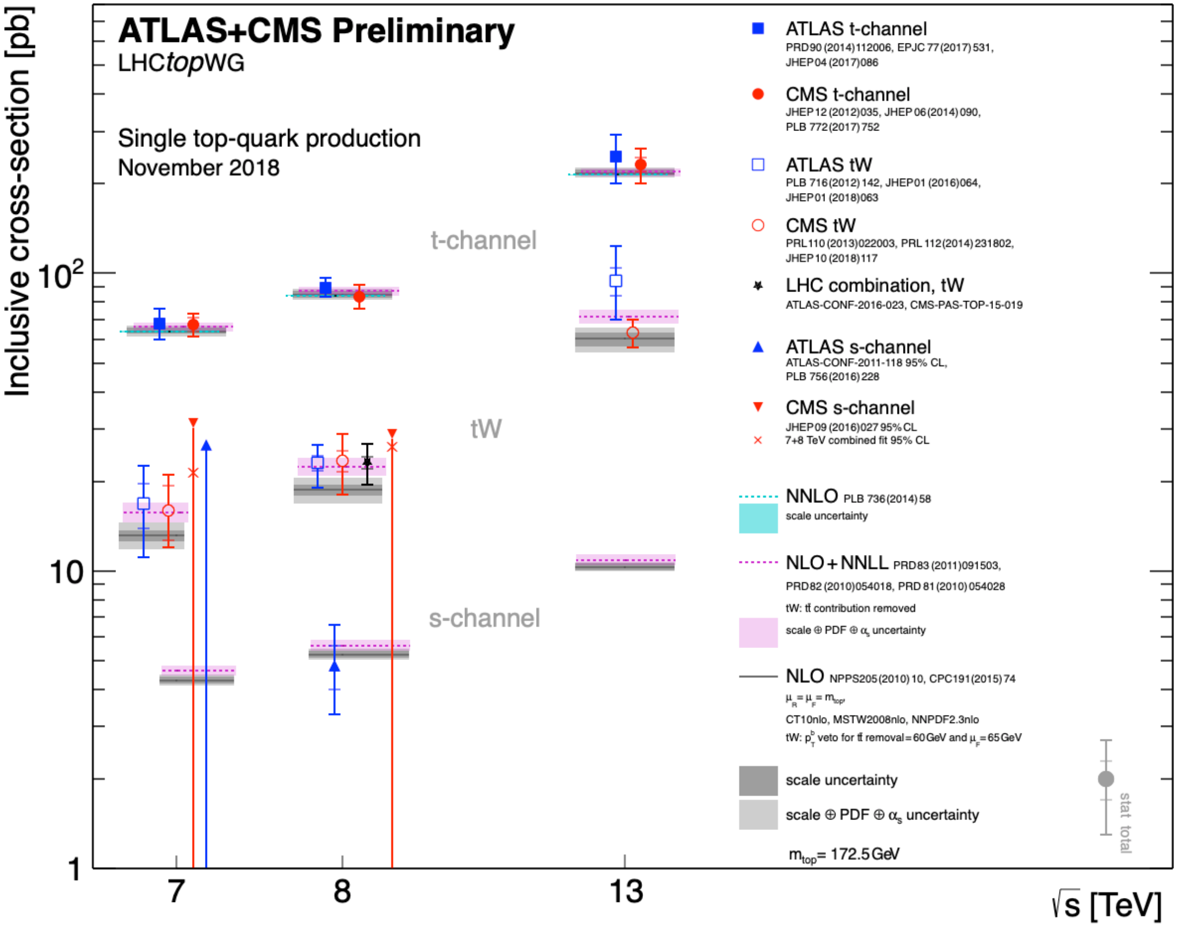
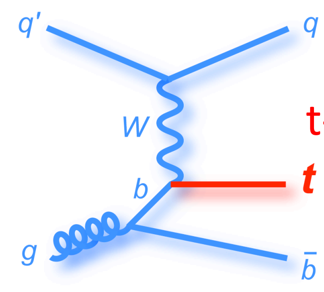
Single top-quark production





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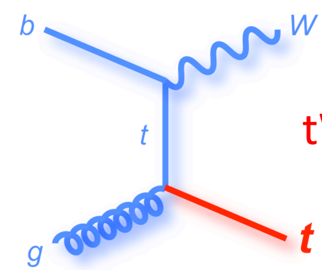
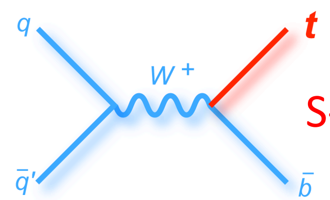


tW-channel

$\sigma(tW) = 63 \pm 2 \pm 7\text{pb}$



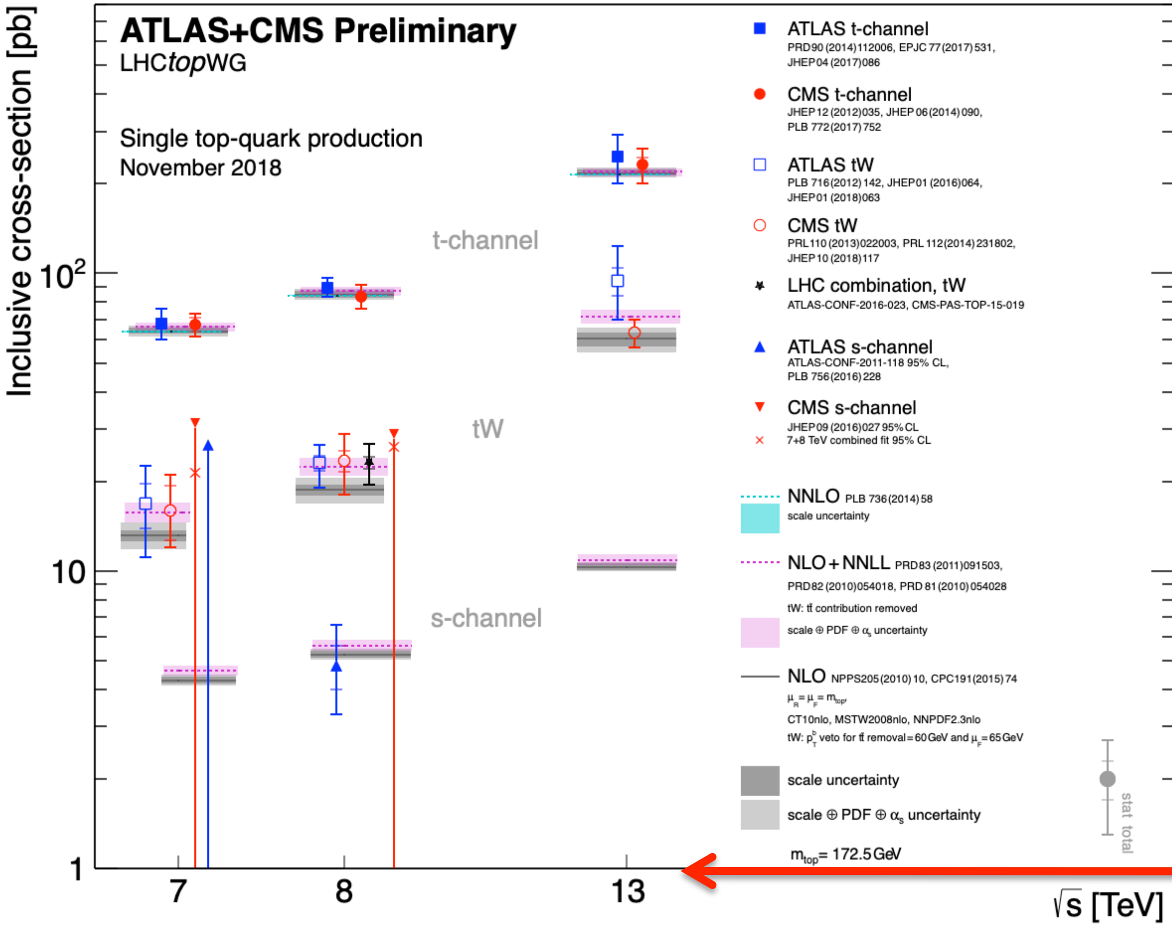
S-channel

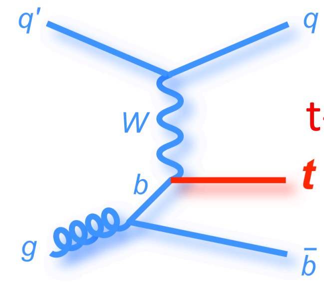
- Production via EWK interaction

  → smaller cross sections, large backgrounds

- Precise determination of |Vtb|, constrain PDFs, FCNC

Single top-quark production





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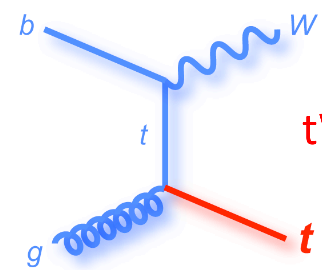

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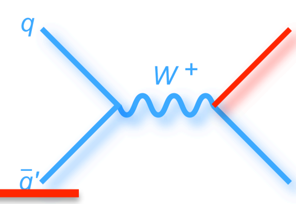
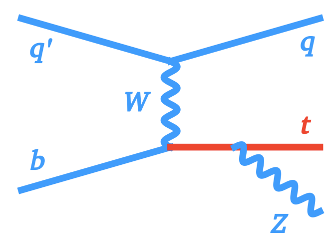


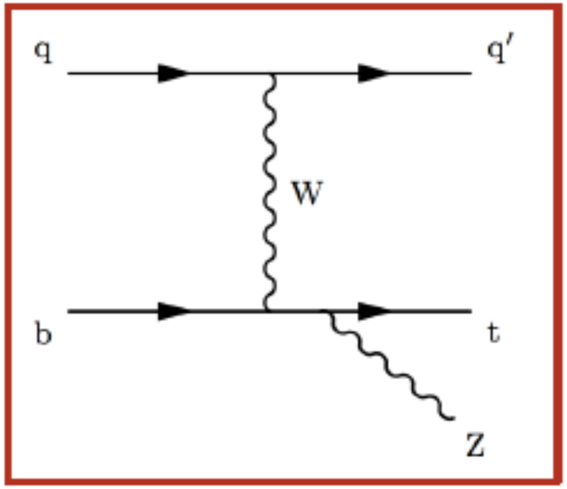
S-channel



tZq

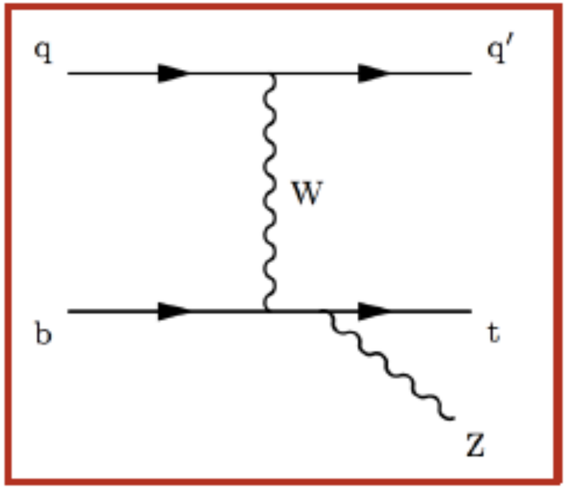
$\sigma(tZq) \sim 1\text{pb}$ **Rare!!!**

A rare process with interesting properties!



Top-Z coupling,
complementary to ttZ

A rare process with interesting properties!



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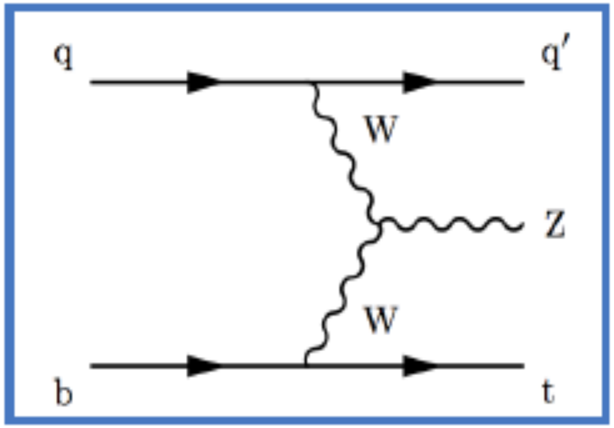

Sensitive to WWZ vertex

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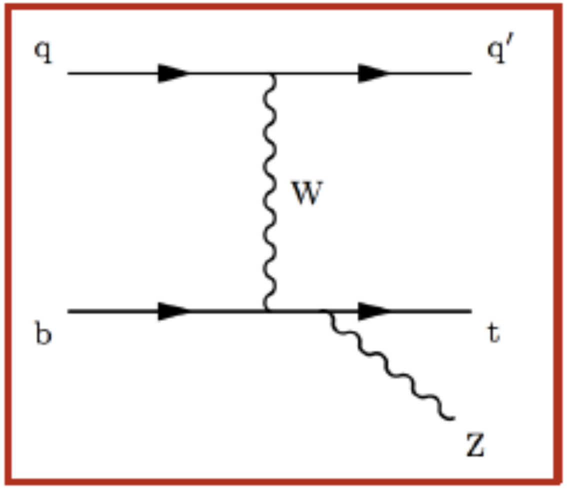

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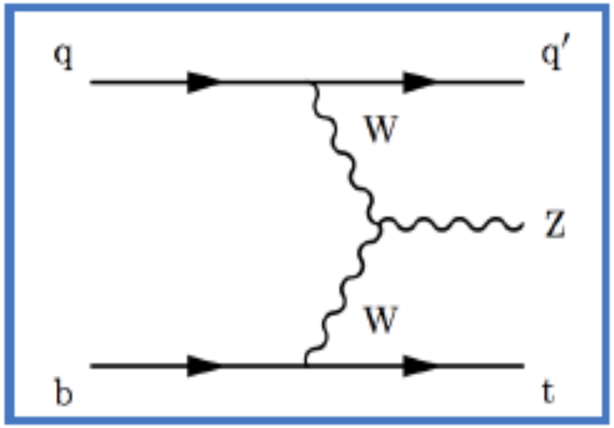

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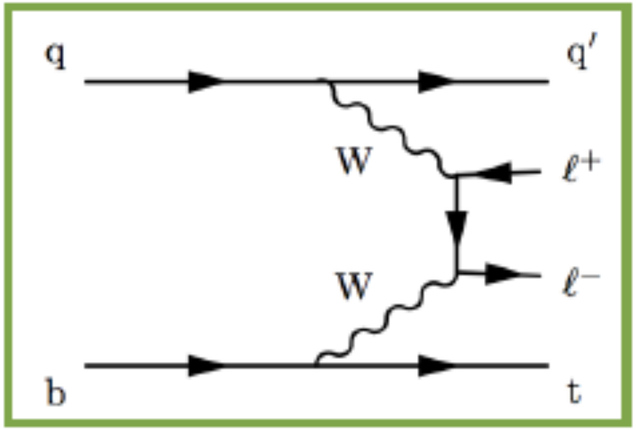
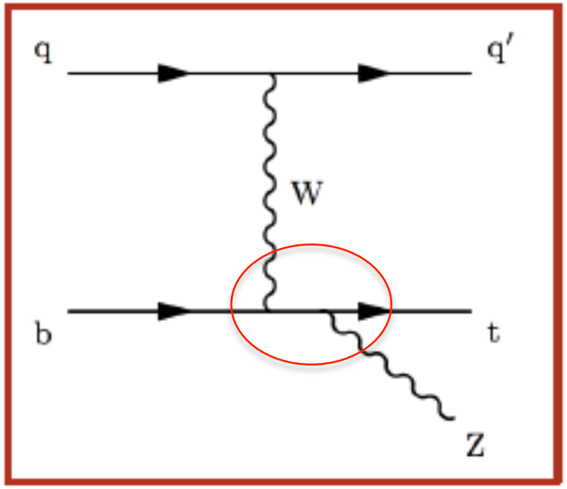
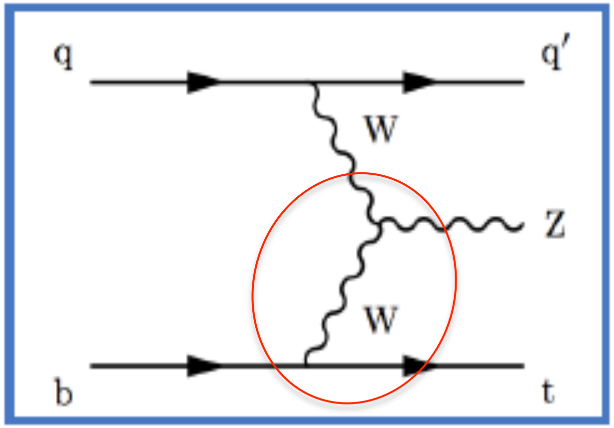
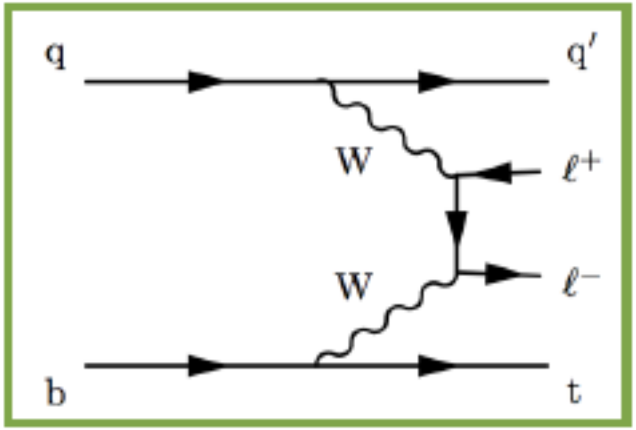


No on-shell Z

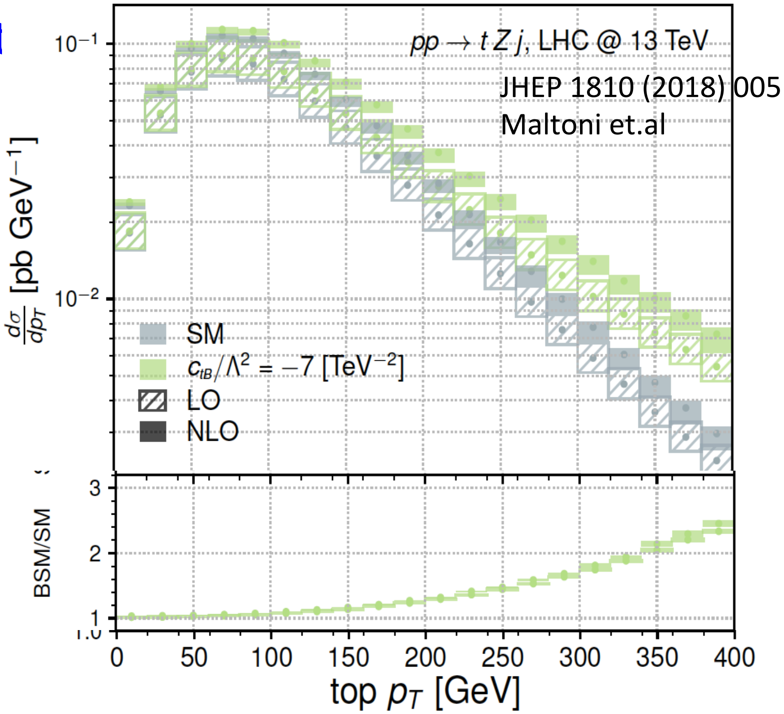






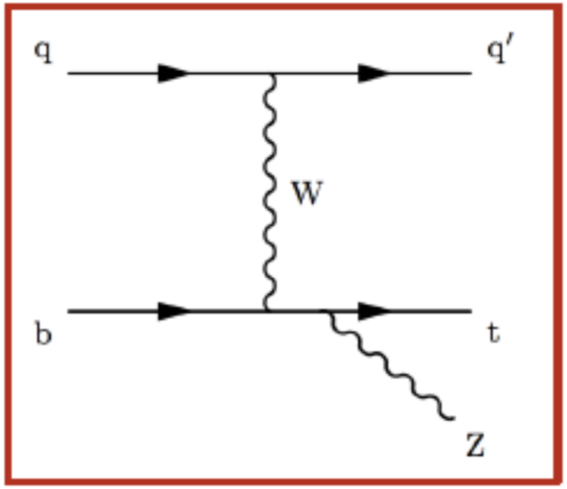
Top-Z coupling, complementary to ttZ

Sensitive to WWZ vert



- Unique sensitivity to some EFT operators due to Wb→tZ vertex
- FCNC

A rare process with interesting properties!



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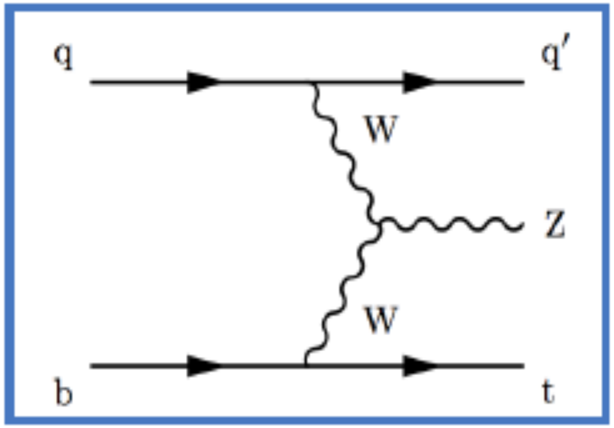

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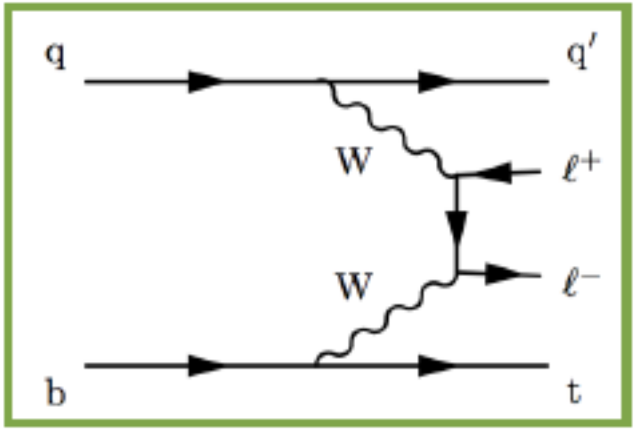
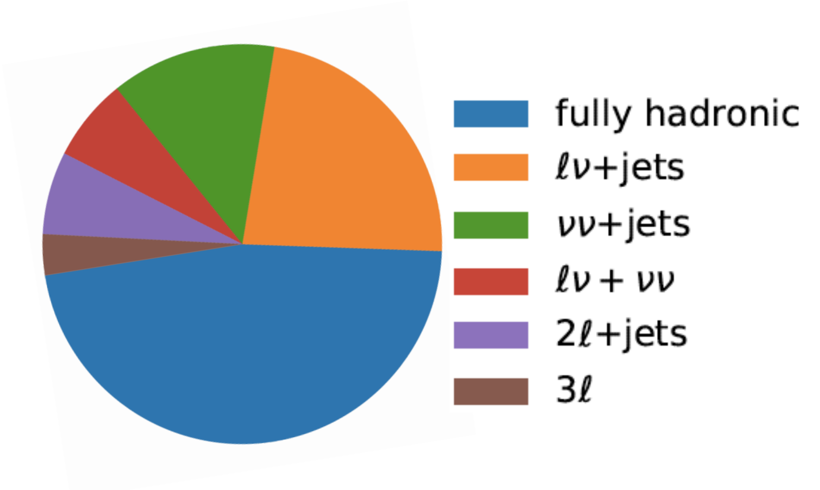


No on-shell Z

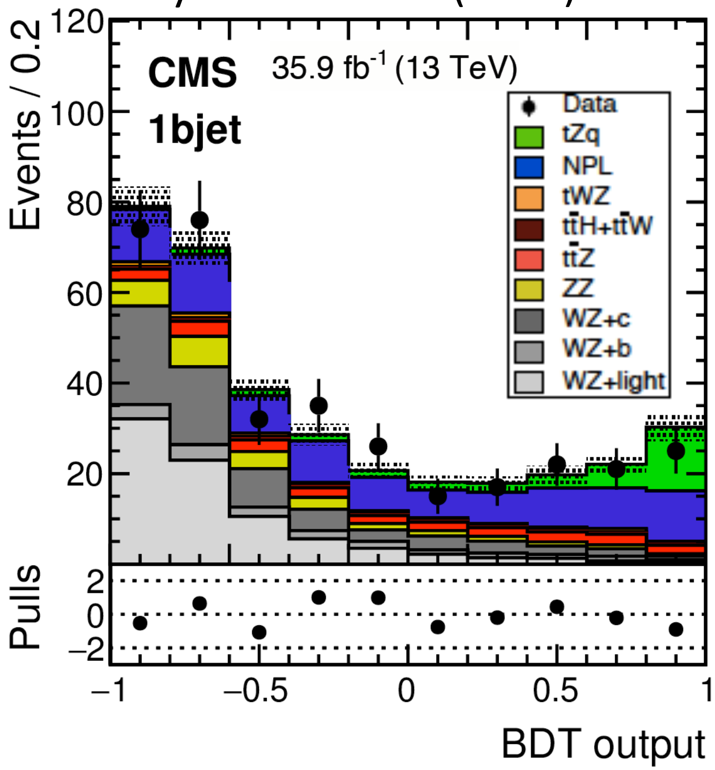
- $BR(tZq \to b\ell\nu\ell^{\pm}\ell^{\mp}q) \sim 3\%$, but experimentally easier
- Nonetheless challenging large SM bkg.



Previous results on tZq

CMS result with 2016 data

Phys. Lett. B 779 (2018) 358

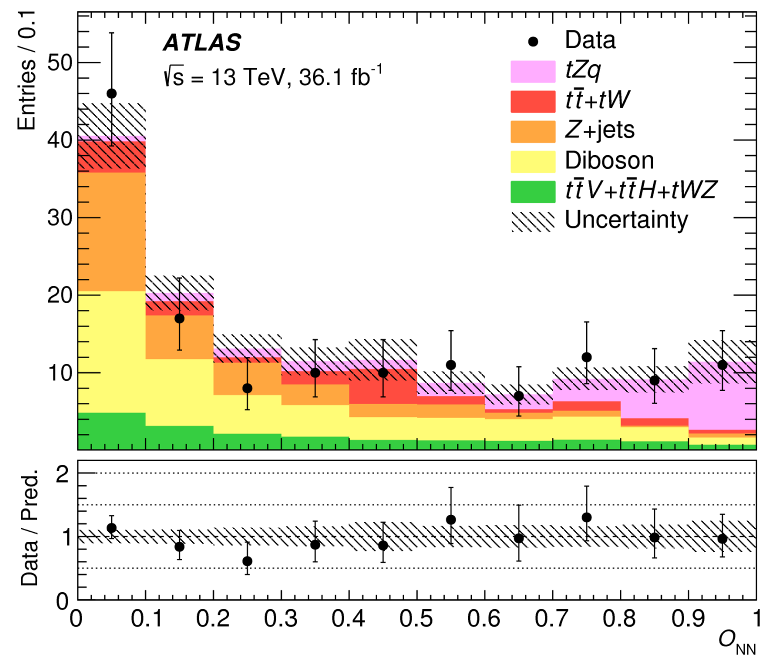


$$\mu = 1.31^{+0.35}_{-0.33}(\mathrm{stat})\ ^{+0.31}_{-0.25}(\mathrm{sys})$$

3.7 (3.1) σ Obs.(Exp.)

ATLAS result with 2016 data

Phys. Lett. B 780 (2018) 557



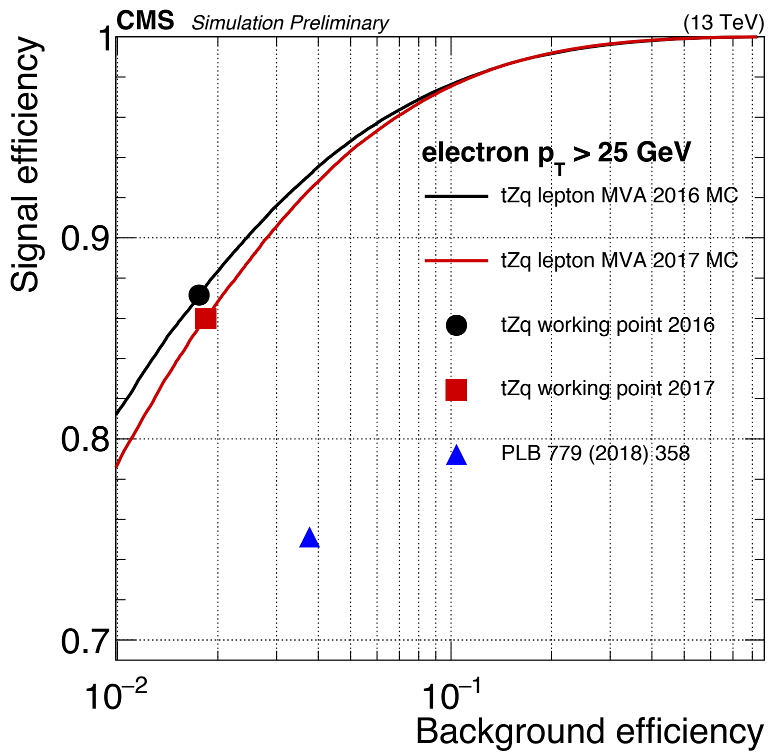
$$\mu = 0.75 \pm 0.21(\mathrm{stat}) \pm 0.17(\mathrm{sys})$$

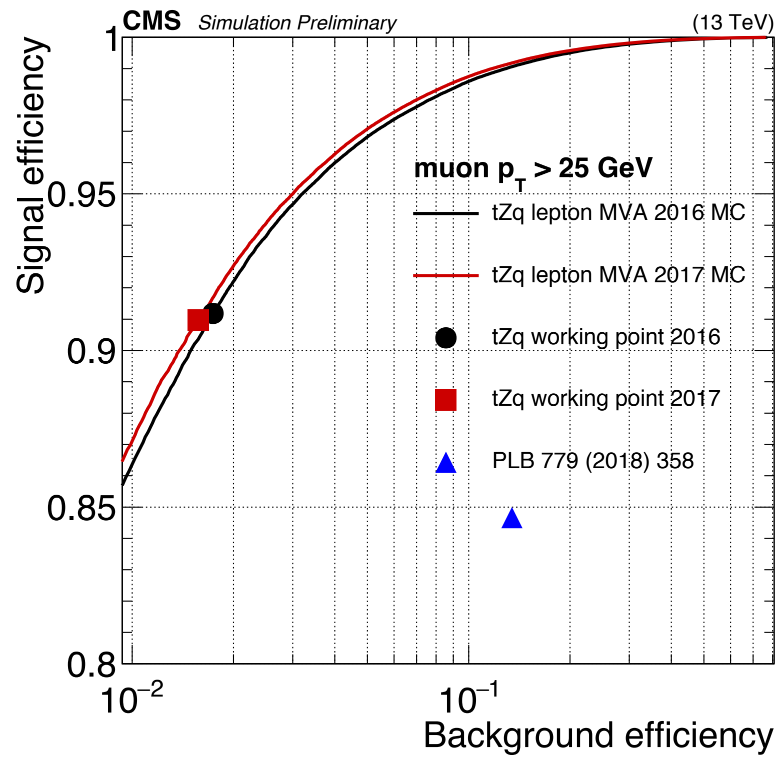
4.2 (5.4)σ Obs.(Exp.)

Both measurements with about 35% uncertainty

Lepton identification

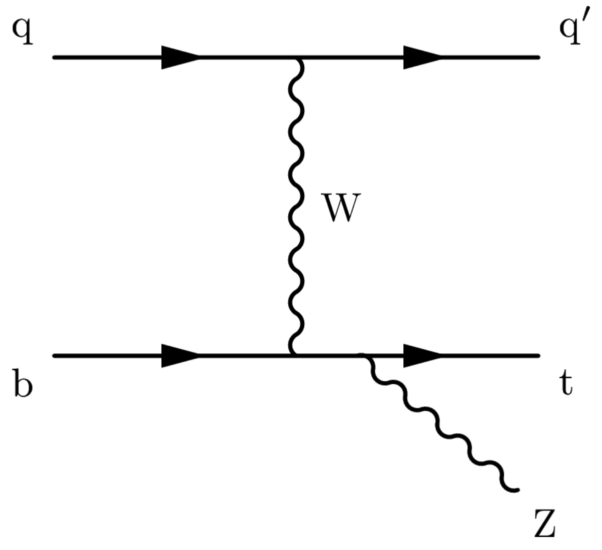
- Dedicated lepton selection using MVA for this analysis
- Crucial for reducing backgrounds from nonprompt leptons
- Input variables: jets closest to lepton, impact parameters, isolation, lepton p_T, η, +usual identification variables



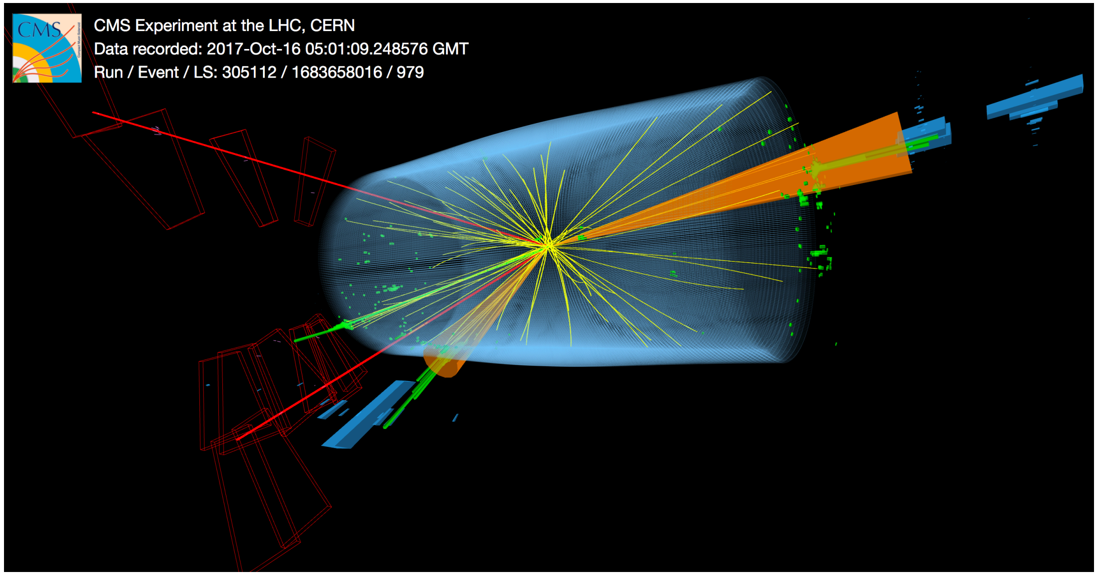


- ➔ 8-12% gain per signal lepton efficiency
- ➔ factor 2(8) reduction in nonprompt electron (muon) background

Event selection & strategy



- 3 leptons $eee, ee\mu, e\mu\mu, \mu\mu\mu$
- $p_T(\ell) > 10, 15, 25$ GeV
- Z candidate $|m_{\ell\ell} - m_Z| < 15$ GeV
- At least two jets with $p_T > 25(60)$ GeV



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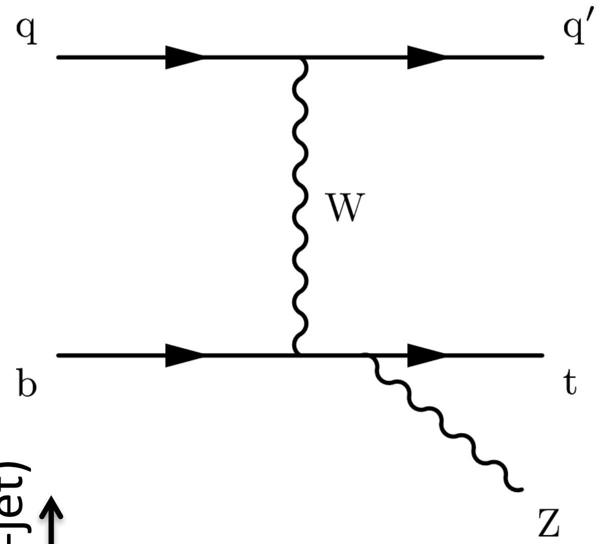

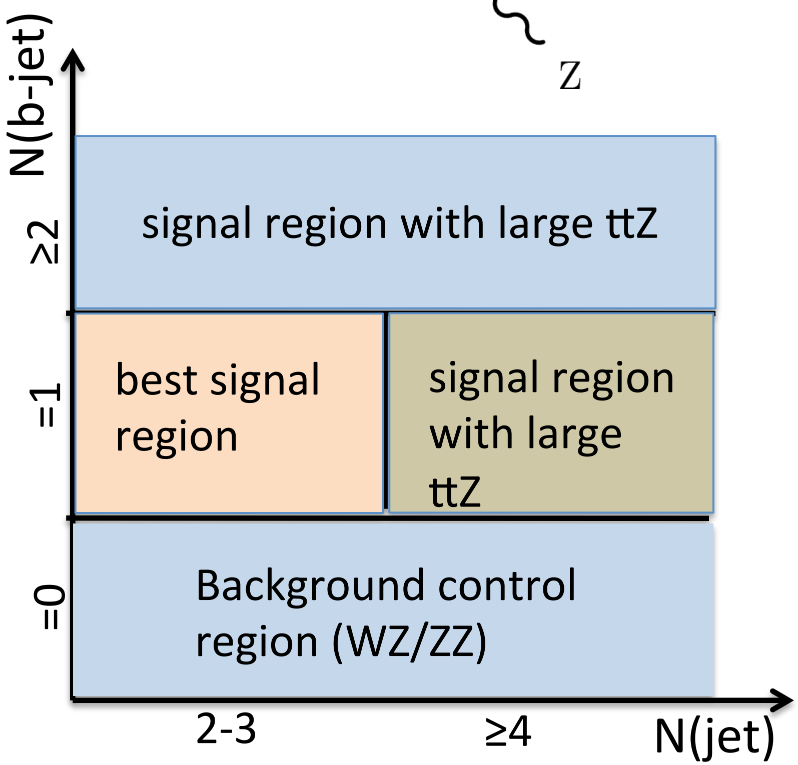

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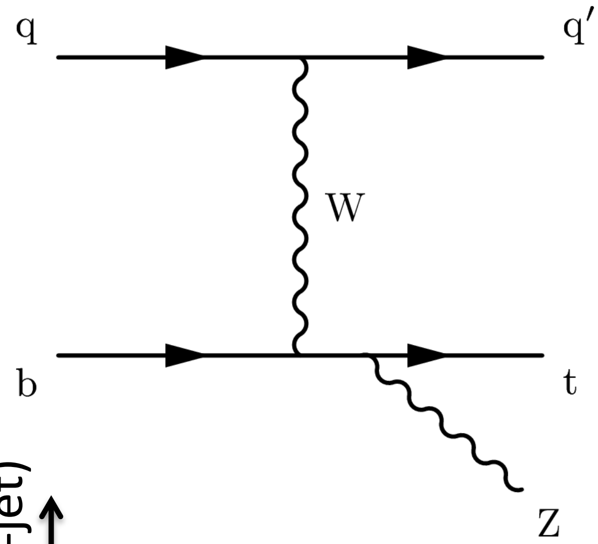

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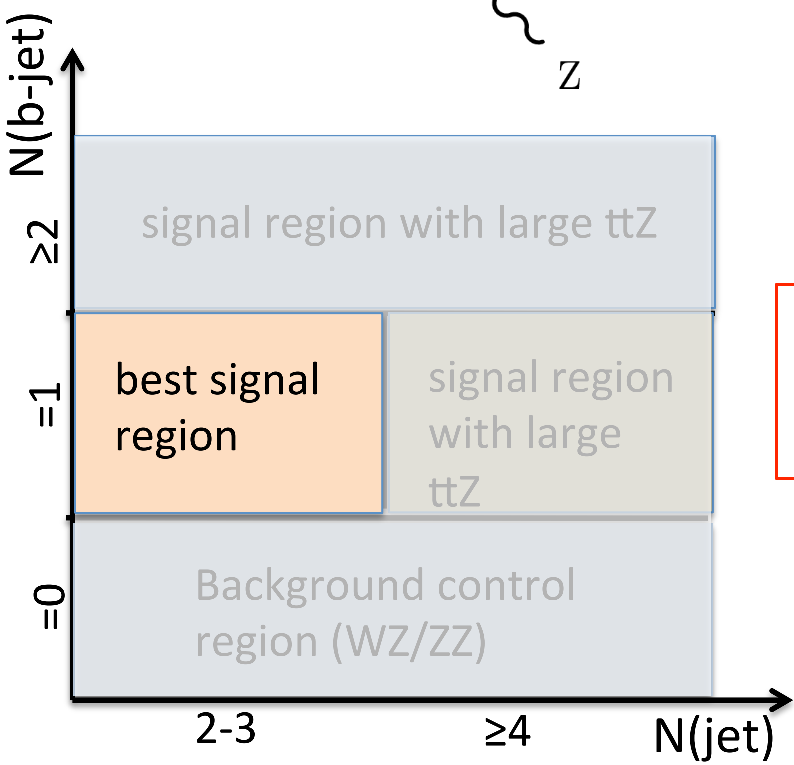
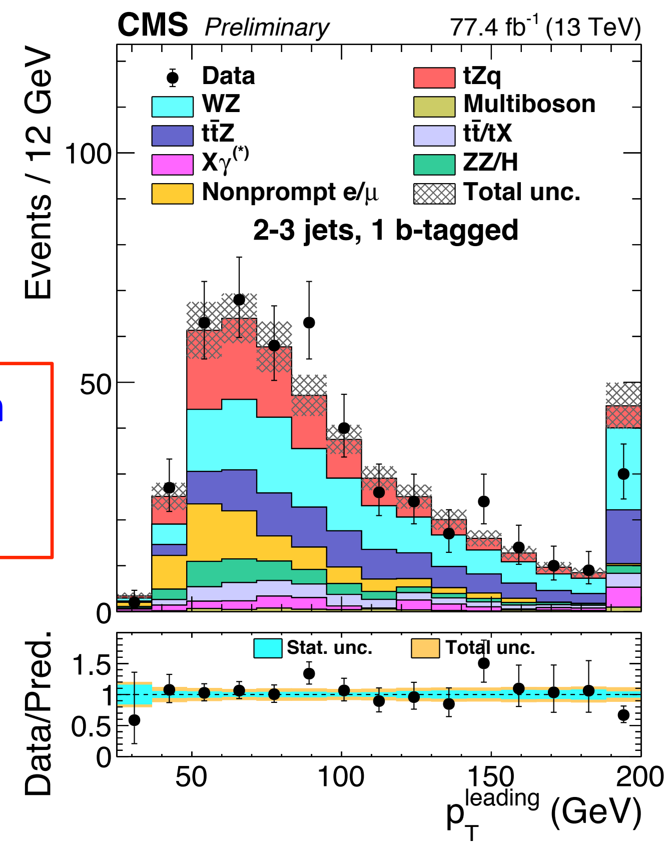


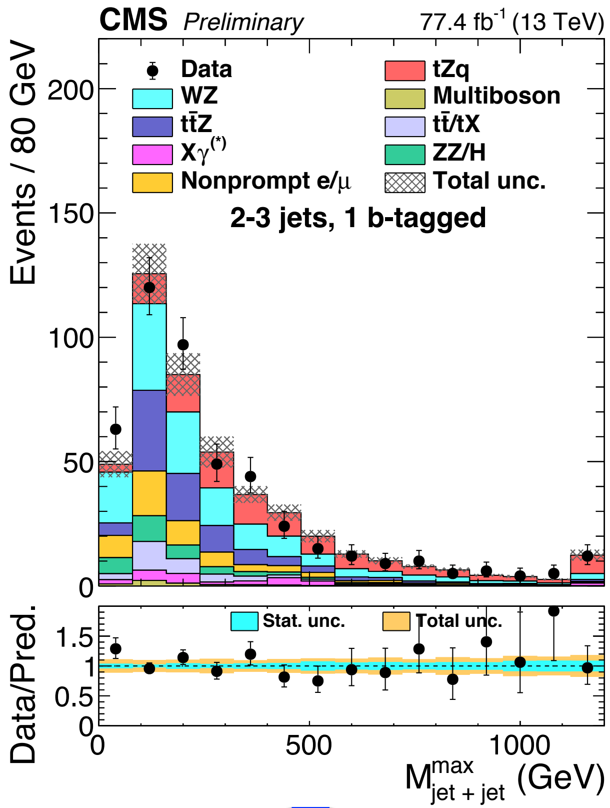
Train BDT in each signal category



Signal and Background separation

$N_{jets} = 2,3 \quad N_{bjets} = 1$

Most sensitive kinematic variables:



Maximum di-jet invariant mass

Signal and Background separation

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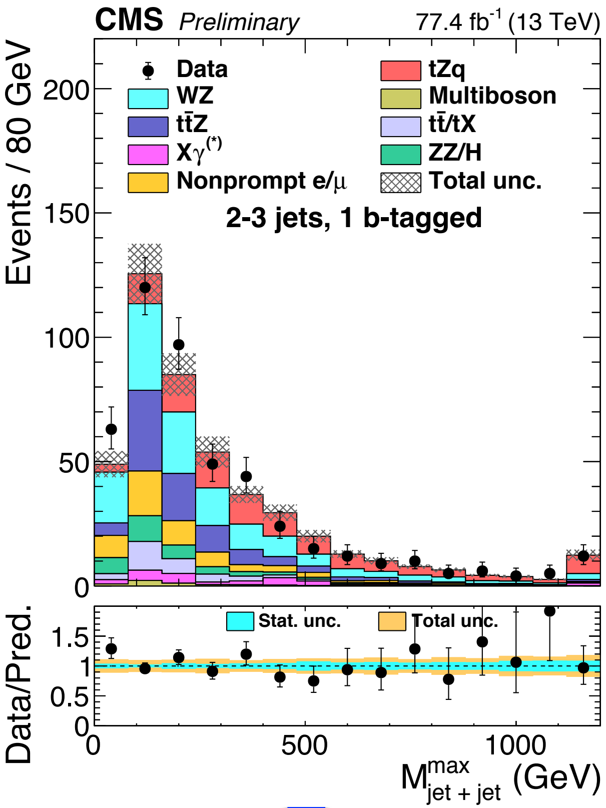

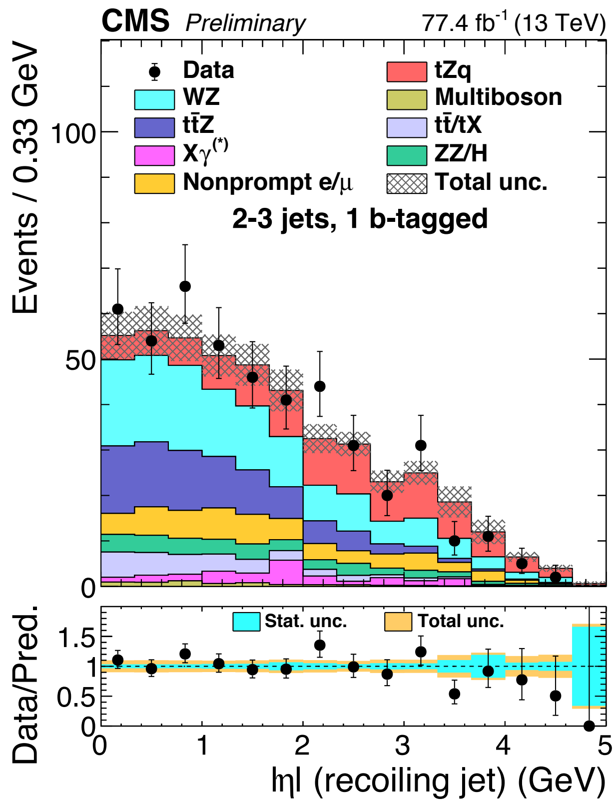

Maximum di-jet invariant mass

η of the jet recoiling top

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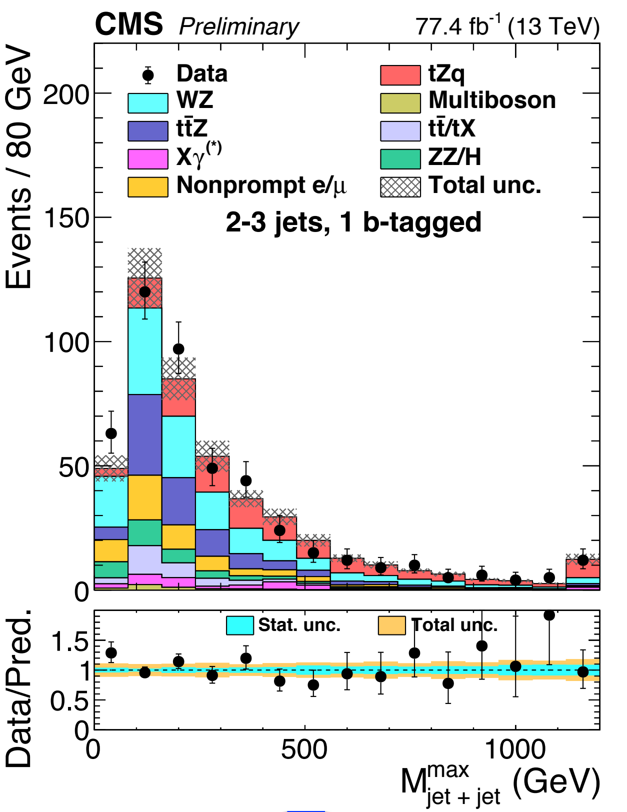
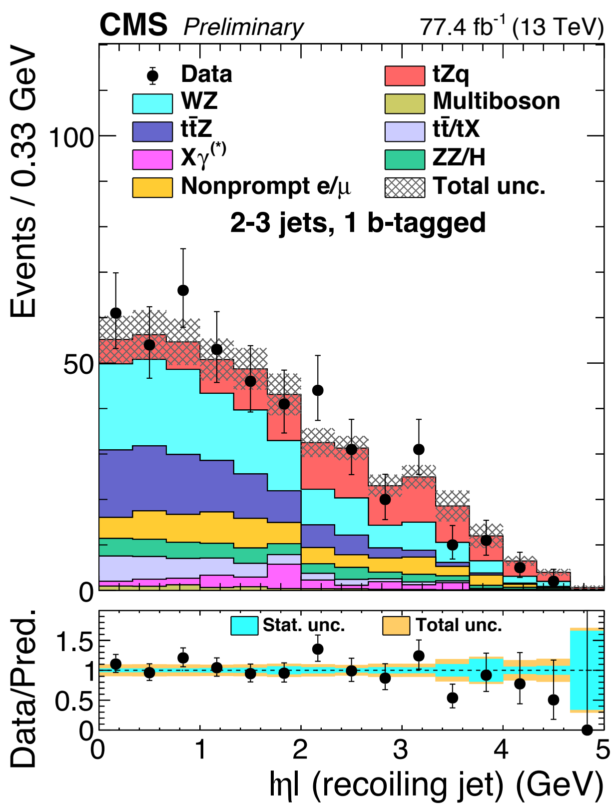
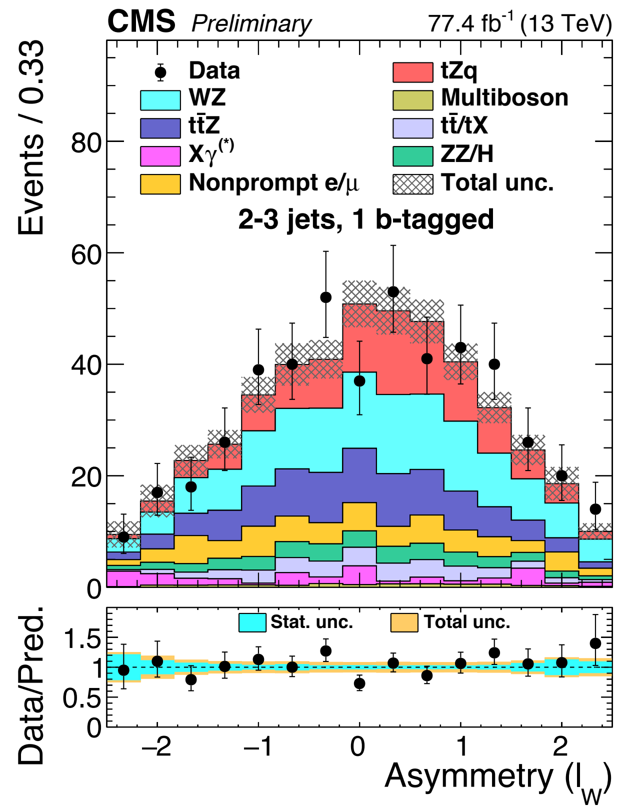
Most sensitive kinematic variables:







Maximum di-jet invariant mass

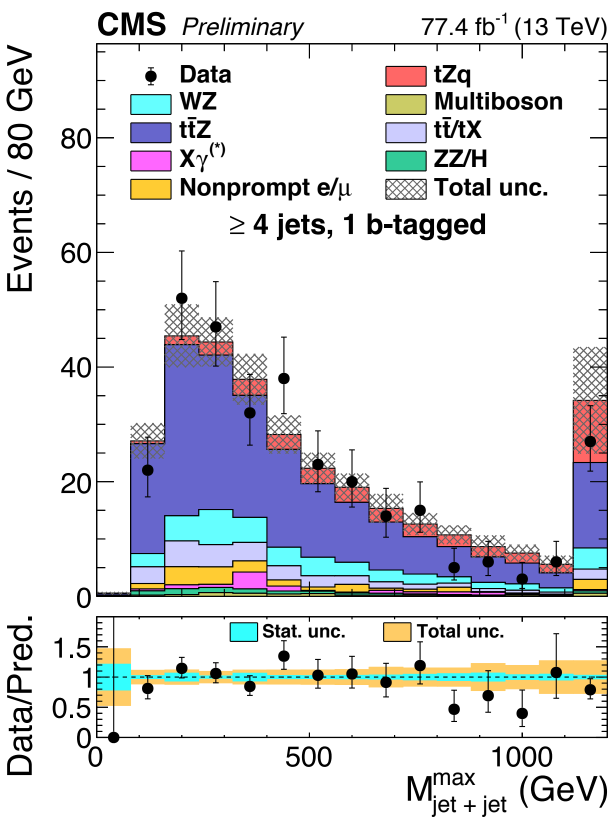
η of the jet recoiling top

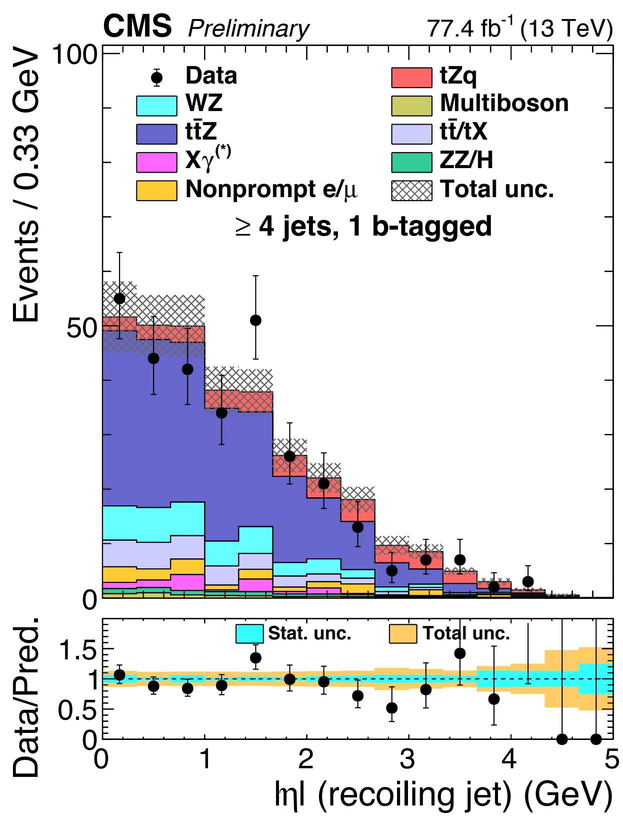
$|\eta| \times \text{charge}(\ell_W)$

Main backgrounds: WZ, ttZ and nonprompt lepton

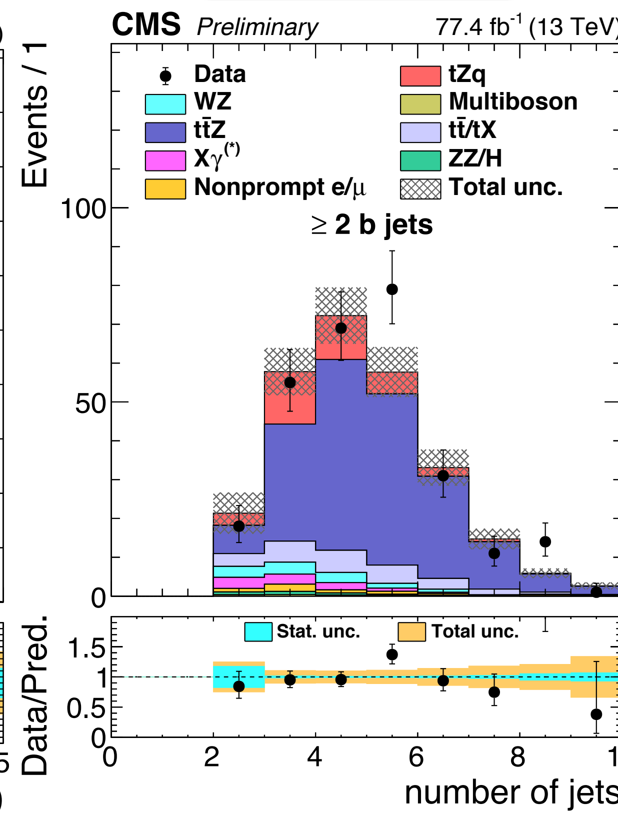
Signal and Background separation

$N_{jets} \geq 4 \quad N_{bjets} = 1$



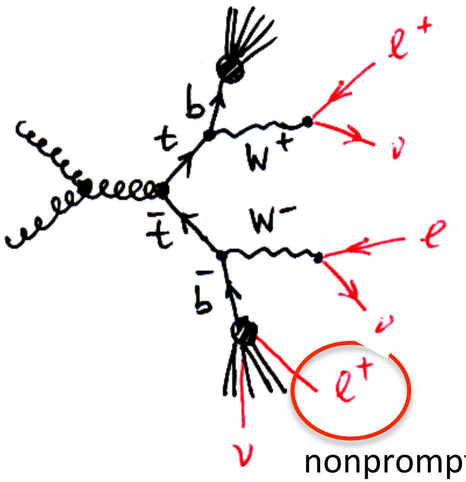


$N_{jets} \geq 4$



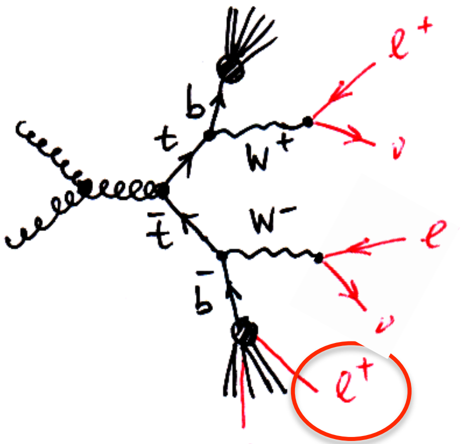
Main background: ttZ with some contribution from ttX and WZ

Nonprompt lepton background



- Mainly from $t\bar{t}$ and DY:
  - Typically two prompt lepton + nonprompt
  - Use events with at least 1 ℓ fails “tight” selection but passes the “loose” selection → “Tight-to-Loose” (TL)
  - Need to evaluate TL probability (*f*)

Nonprompt lepton background



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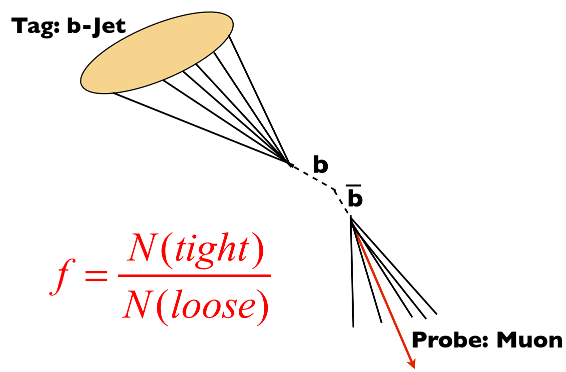
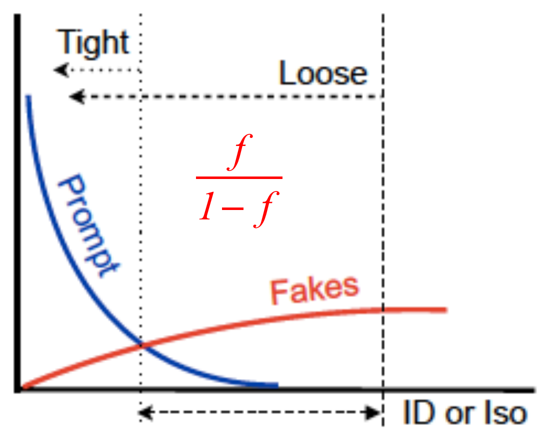
Measure in QCD di-jet events



$$f = \frac{N(tight)}{N(loose)}$$

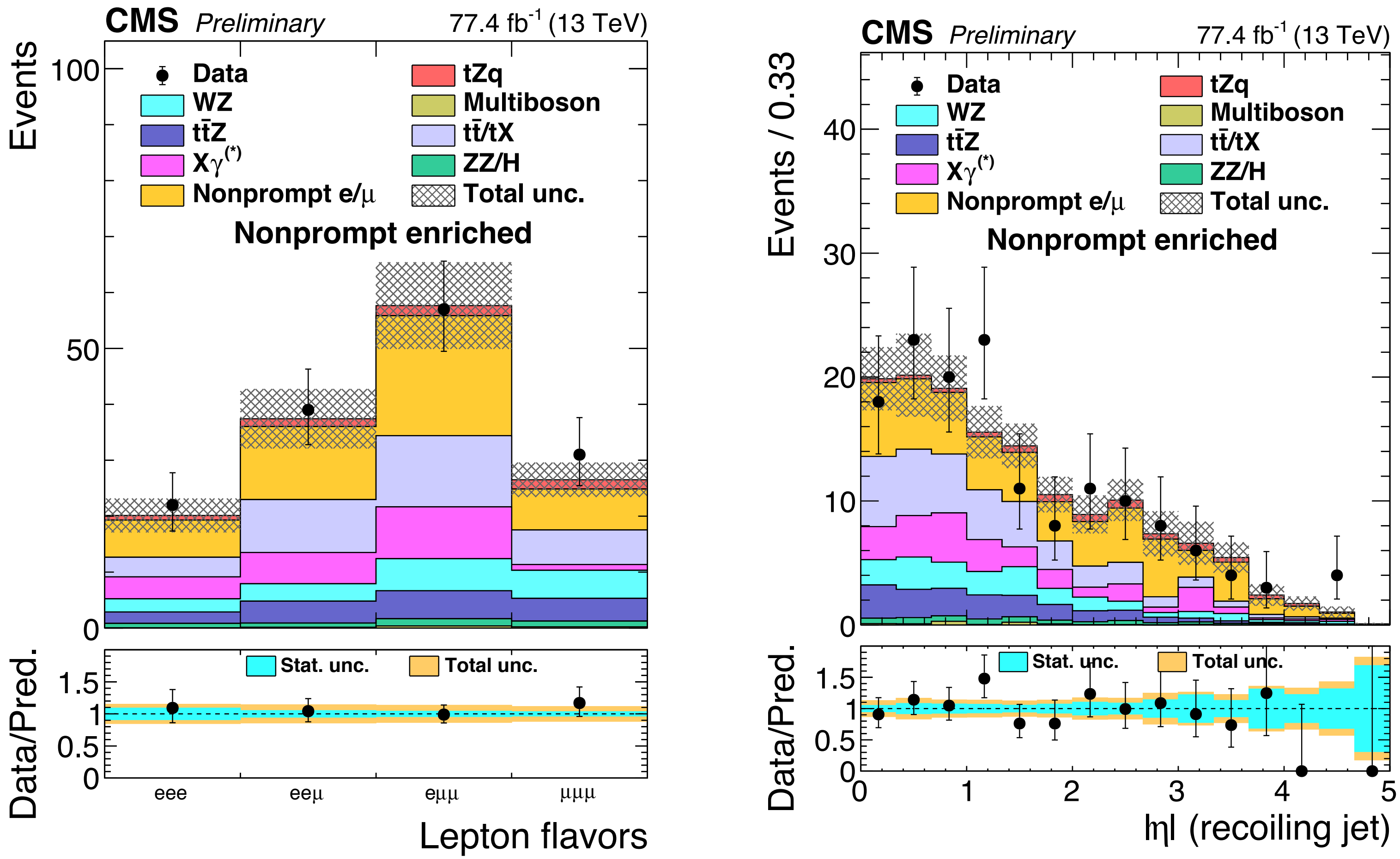
Apply in the signal region



- Problem: f is dependent on mother parton p_T
- p_T of the closest jet as a proxy $f(p_T, \eta)$

Nonprompt lepton bkg. validation

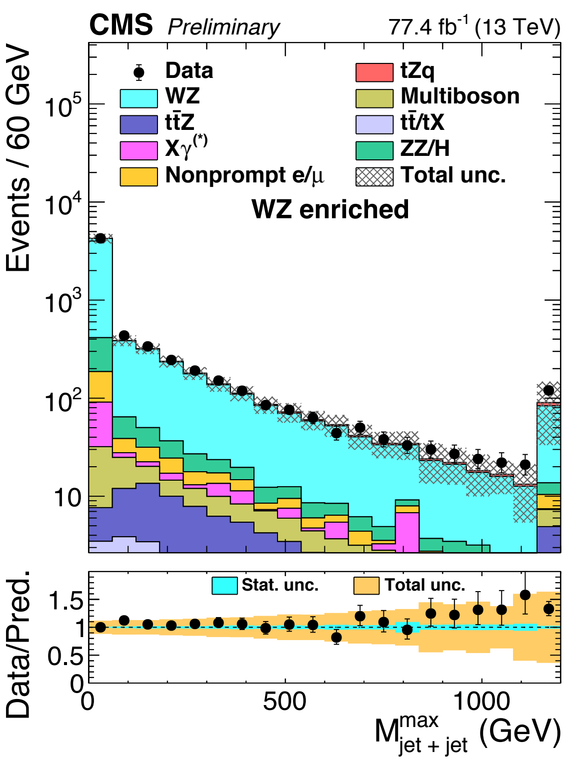
No OSSF pair or $m(\ell\ell)$ outside Z mass window

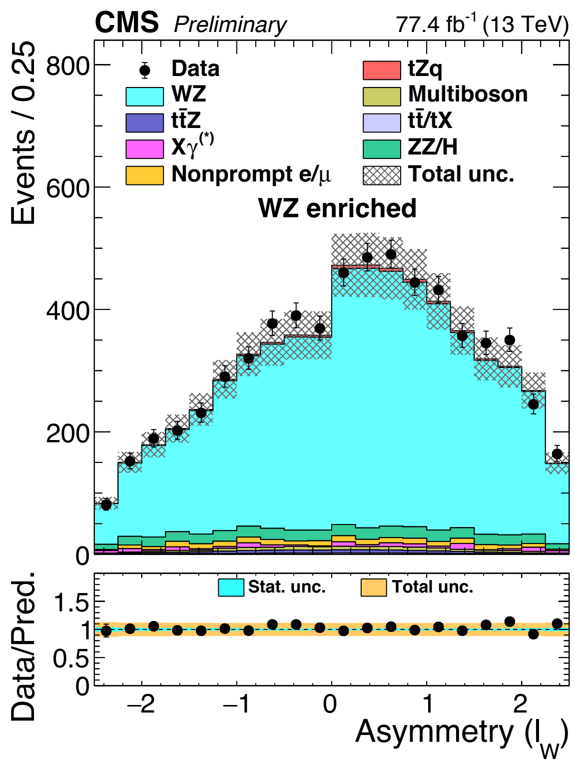


- Low statistics -> powerful lepton selection
- 30% systematic uncertainty + stat uncertainty in the control region

WZ/ZZ control regions

3ℓ, with a Z candidate, $N_{bjet} = 0, E_T^{miss} > 50$ GeV

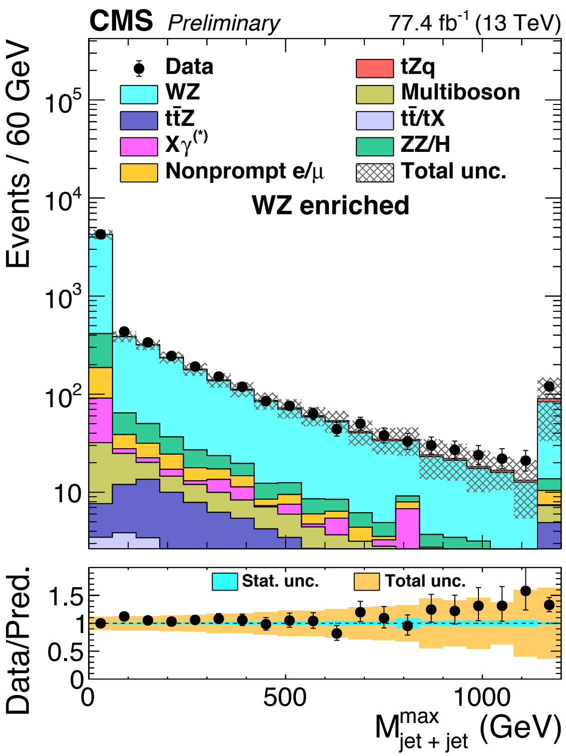


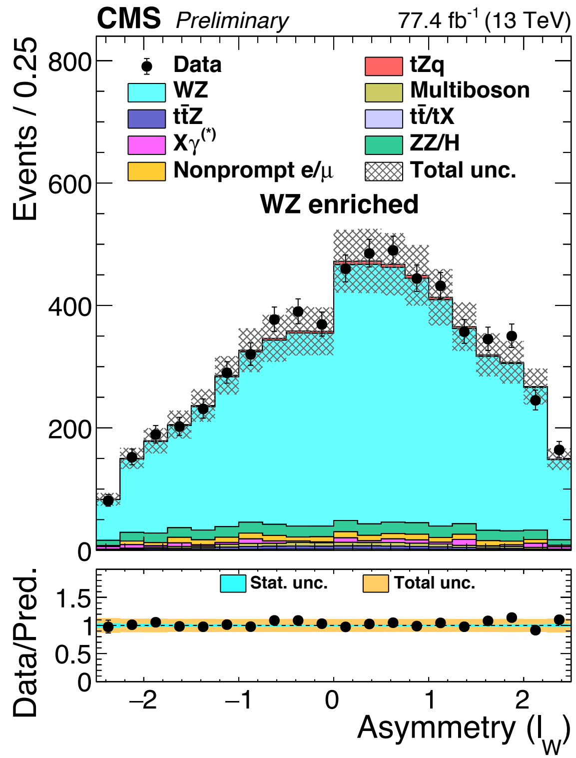


- Good agreement for both normalization & shape of BDT input variables
- 10% normalization uncertainty & 8% for extrapolating to N_{bjet}>0

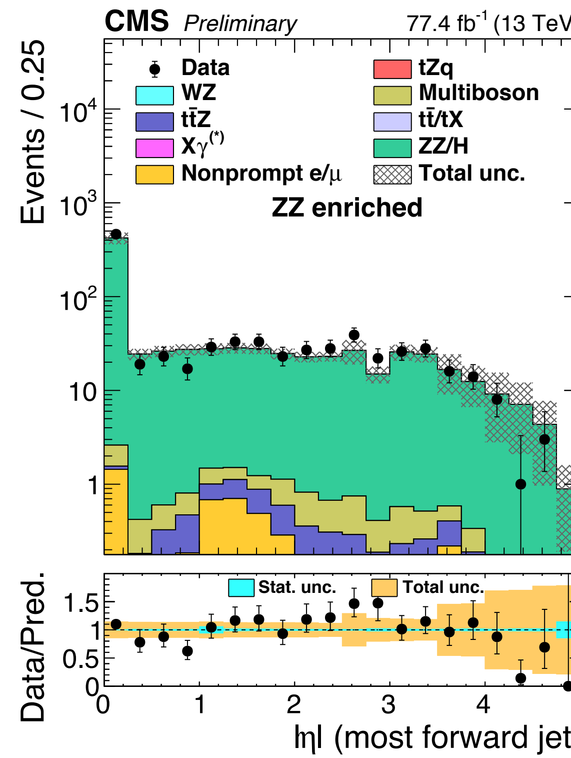
WZ/ZZ control regions

3ℓ, with a Z candidate, $N_{bjet} = 0, E_T^{miss} > 50$ GeV





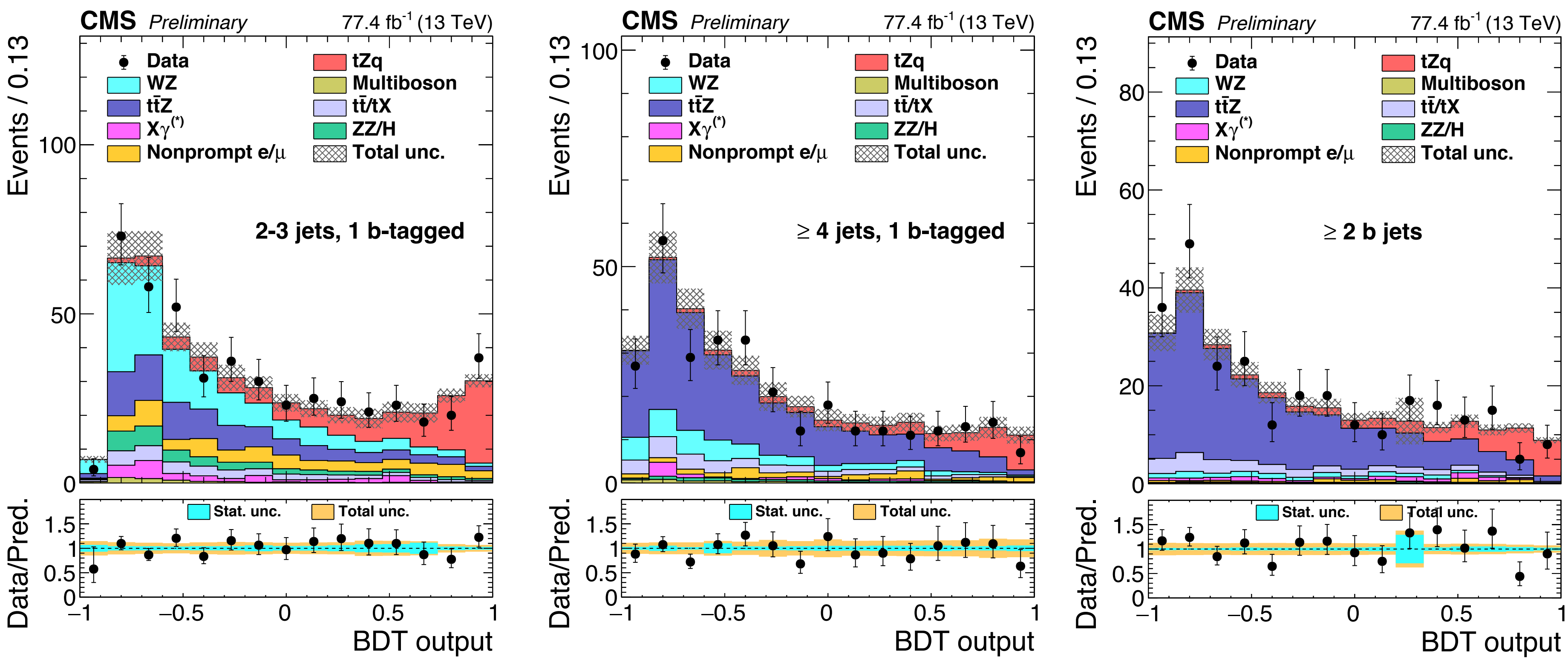
4ℓ, two Z candidates



- Good agreement for both normalization & shape of BDT input variables
- 10% normalization uncertainty & 8% for extrapolating to N_{bjet}>0

- Other small backgrounds (ttW, ttH, tWZ, multiboson taken from simulation with theoretical and experimental uncertainties

tZq results (1)



- Binned maximum-likelihood fit to all three distributions & WZ and ZZ control regions
- Nuisance parameters for normalization and shape uncertainties
- Good agreement between prediction and observed data

tZq results (2)

$$\mu = 1.36^{+0.22}_{-0.20}(\text{stat})\ {}^{+0.14}_{-0.12}(\text{sys})$$ 2016 data

$$\mu = 1.03^{+0.18}_{-0.17}(\text{stat})\ {}^{+0.14}_{-0.12}(\text{sys})$$ 2017 data

$$\mu = 1.18^{+0.14}_{-0.13}(\text{stat})\ {}^{+0.11}_{-0.10}(\text{sys})$$

observed(expected) significance 8.2(7.7)σ

Asymptotic CLs approach

First observation of tZq process !

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Asymptotic CLs approach

First observation of tZq process !

Measured cross section	NLO SM prediction (Phys. Lett. B 779 (2018) 358)
$\sigma(tZq \to t\ell^+\ell^- q) = 111 \pm 13(stat)\ ^{+11}_{-9}(syst)\ \text{fb}$	$94.2 \pm 3.1\ \text{fb}$

15% precision

tZq results (3)

Measured cross section

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

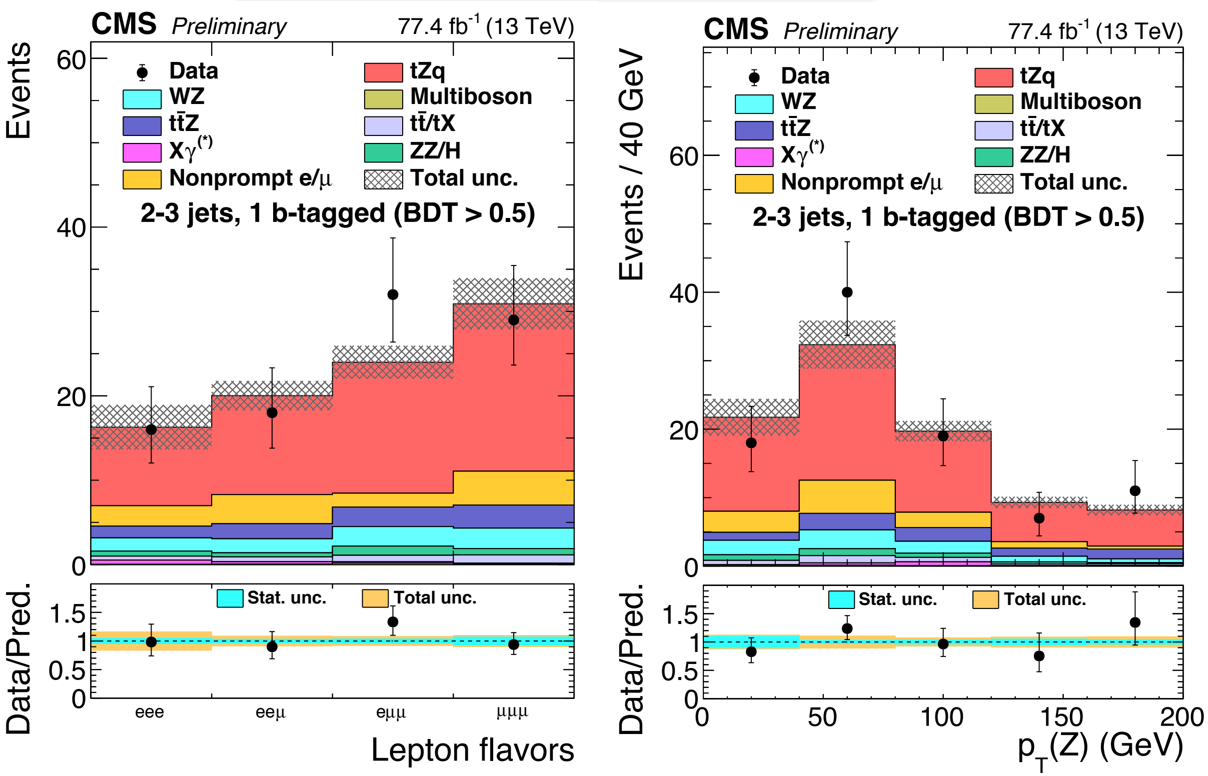
15% precision

Source	impact (±%)
Nonprompt bkg.	4.1
Lepton selection	3.2
Jet Energy Scale 2016(2017)	0.9(3.1)
Parton Shower Mod.	2
QCD Scale choice (tZq)	2
Pile Up	1.9
QCD Scale choice (ttZ)	1.4

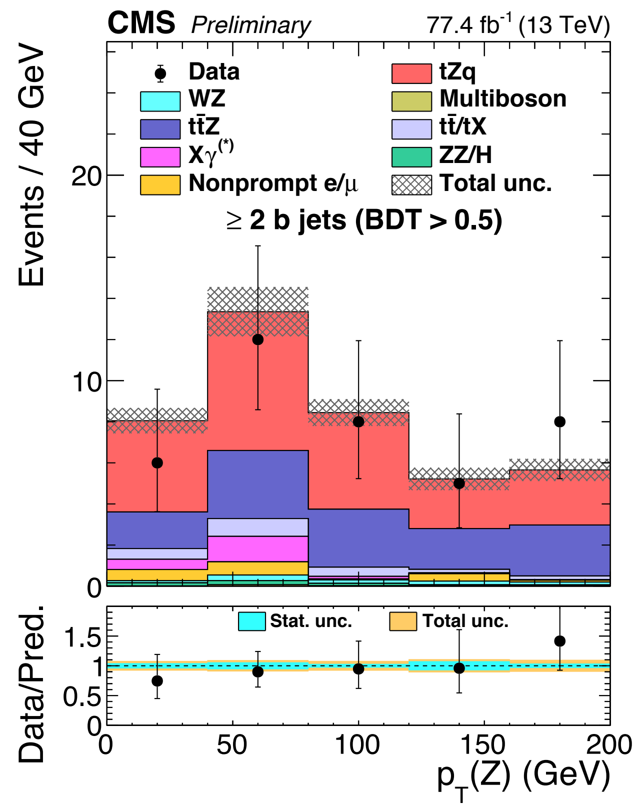
- Several improvements in the analysis paid off
- In particular nonprompt lepton background reduction
- Still statistical uncertainties dominate

tZq results (4)

$N_{jets} = 2{,}3 \quad N_{bjets} = 1, \; BDT > 0.5$



$N_{bjets} \geq 2 \;\; BDT > 0.5$



- Next step is to measure differential cross sections and explore constraining new physics via EFT

Summary & outlook

- First observation of the tZq production with significance well above 5σ

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

15% precision

- In agreement with the SM prediction

Summary & outlook

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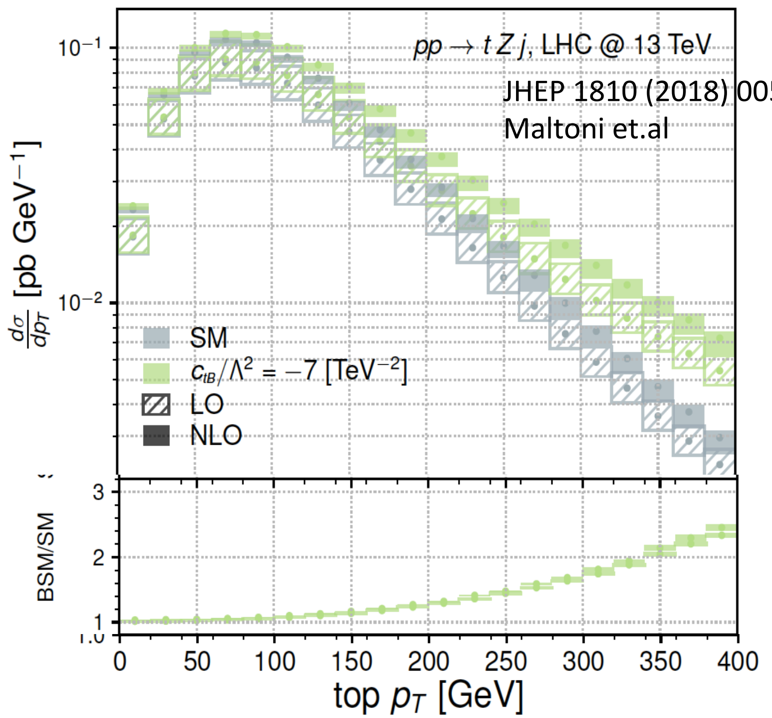
Next:

- Full Run II data will reduce the stat uncertainty by~40%
- Important to reduce dominant systematic uncertainties

- Differential measurements are important to probe new physics eg. via EFT



Summary & outlook

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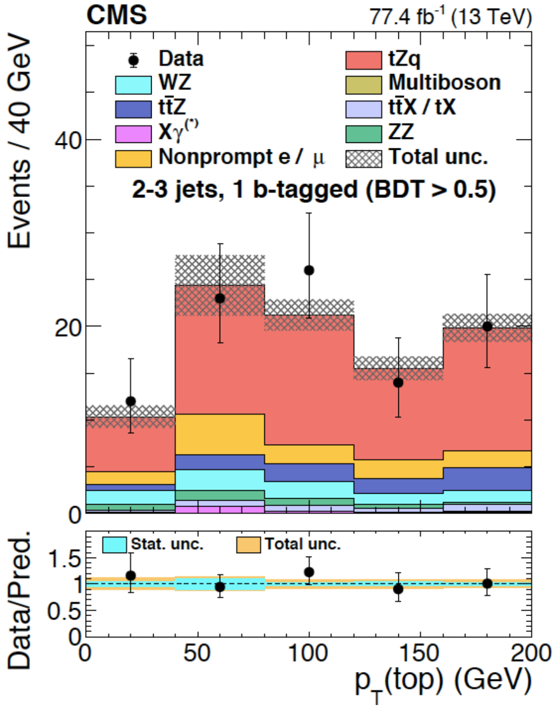
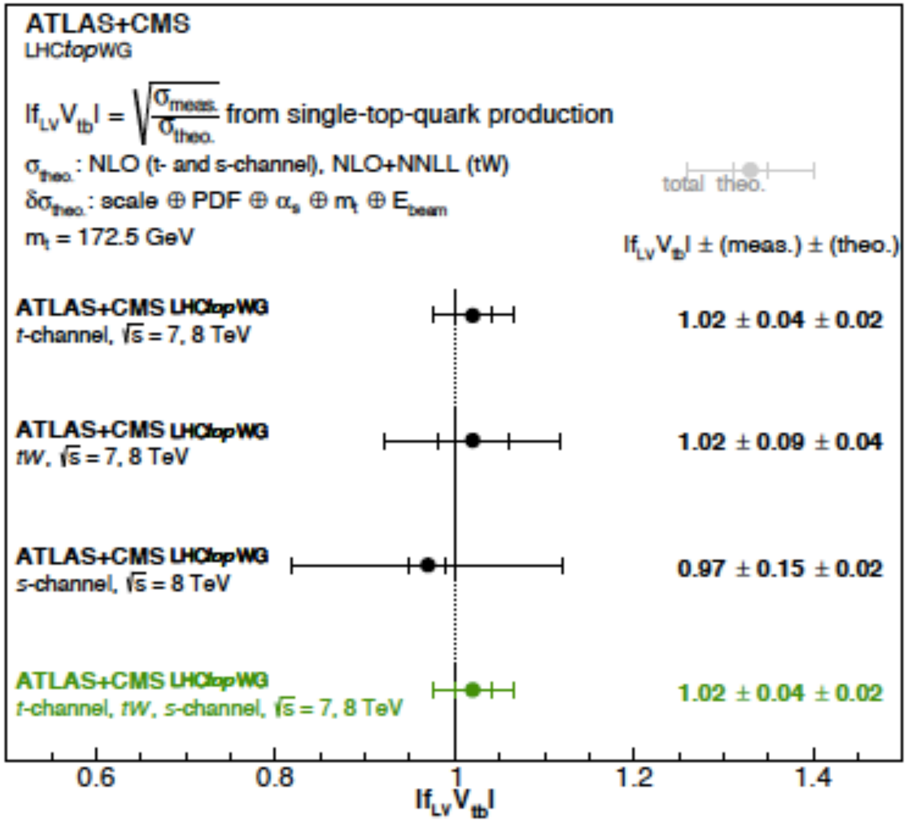
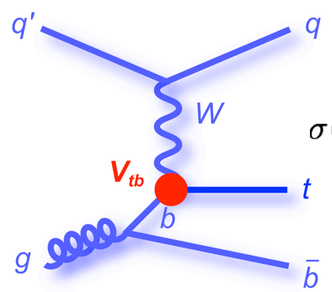


Backup

Vtb extraction





V_{tq} enter in production and decay vertices

$$\sigma(\mathrm{tj}+\bar{\mathrm{t}}\mathrm{j}) = \sum_{q=b,d,s} \alpha_{tq} \cdot |V_{tq}|^2 \cdot \mathcal{B}(t \to Wq)$$

Deviations from the SM are parameterized with f_{LV}

$$|f_{LV} \cdot V_{tb}| = \sqrt{\frac{\sigma_{measured}}{\sigma_{predicted}}}$$

Best measurement is obtained from 7 & 8 TeV combination with ~4% uncertainty

- Expect to improve with luminosity
- limited by theory (~3% at NNLO)

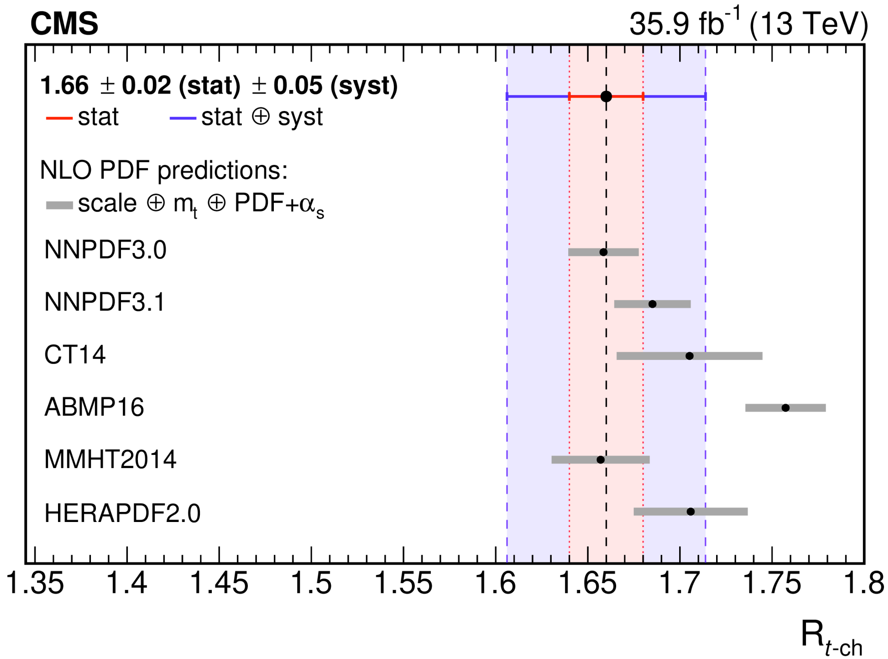
Single-top t-channel production

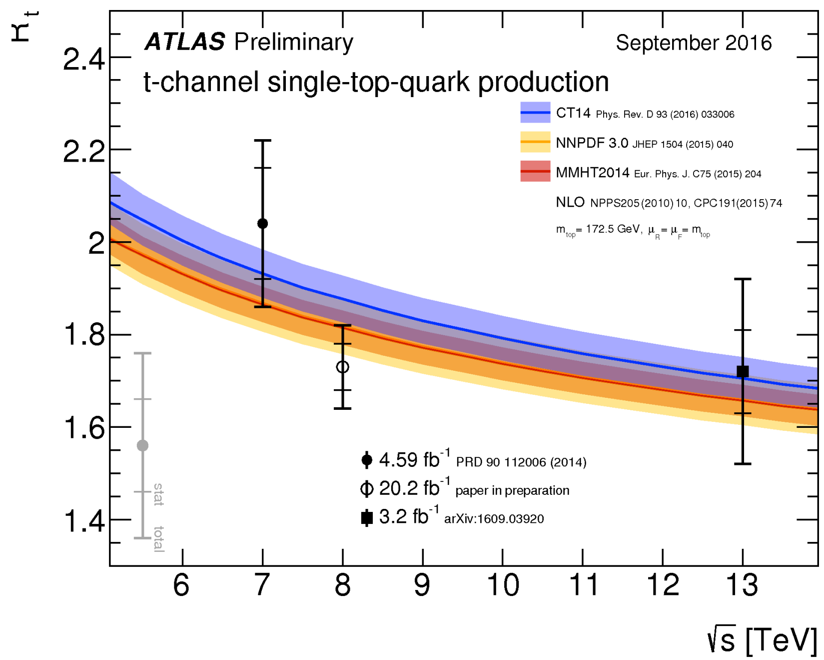
$$R_1 = \frac{\sigma_{tot}(tq)}{\sigma_{tot}(\bar{t}q)} = 1.66 \ \pm 0.02\ (\text{stat}) \ \pm\ 0.05\ (\text{syst})$$

- At higher $\sqrt{s}$, R_1 approaches 1

As "sea quarks" become important

arXiv:1812.10514



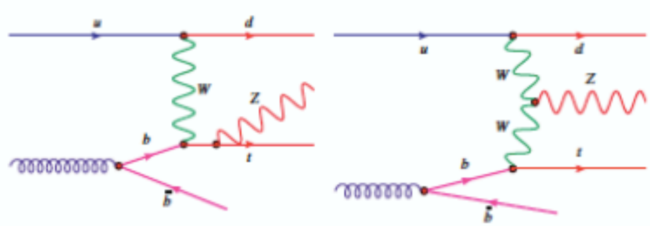


Lidia Dell'Asta
TOPWG November 2017

Signal samples & theory cross section

ATLAS

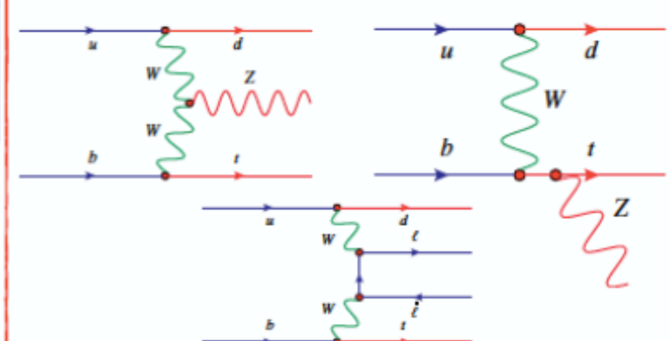
- Signal MC: LO rescaled to NLO.
- Theory cross section:
  - Z boson is forced to be on shell,
  - no cuts are applied,
  - 4-flavour scheme.
- $\sigma_{NLO}(tZq)$ = 800 fb
  - ±6/7% scale



- Tau leptonic decays included.
- Different scale choice between ATLAS and CMS.
- Theory paper https://arxiv.org/abs/1302.3856
  - $\sigma_{NLO}(tZq)$ ~ 820 fb.

CMS

- Signal MC: NLO.
- Theory cross section:
  - Z boson can be off shell/γ* is also included,
  - m_{ll} > 30 GeV,
  - 5-flavour scheme (4FS for MC generation).
  - $\sigma_{NLO}(tllq)$ = 94 fb
    - ±2% scale
    - ±2.5% PDF



tZq systematics

uncertainty source	impact (%)
Experimental	
lepton selection	3.2
trigger efficiency 2016 (2017)	1.0 (1.1)
jet energy scale 2016 (2017)	0.9 (3.1)
b-tagging efficiency 2016 (2017)	0.7 (1.2)
nonprompt normalization	4.1
$t\bar{t}Z$ normalization	1.0
luminosity 2016 (2017)	1.2 (1.3)
pileup	1.9
other experimental	1.3
Theoretical	
final-state radiation	2.0
tZq QCD scale	2.0
$t\bar{t}Z$ QCD scale	1.4

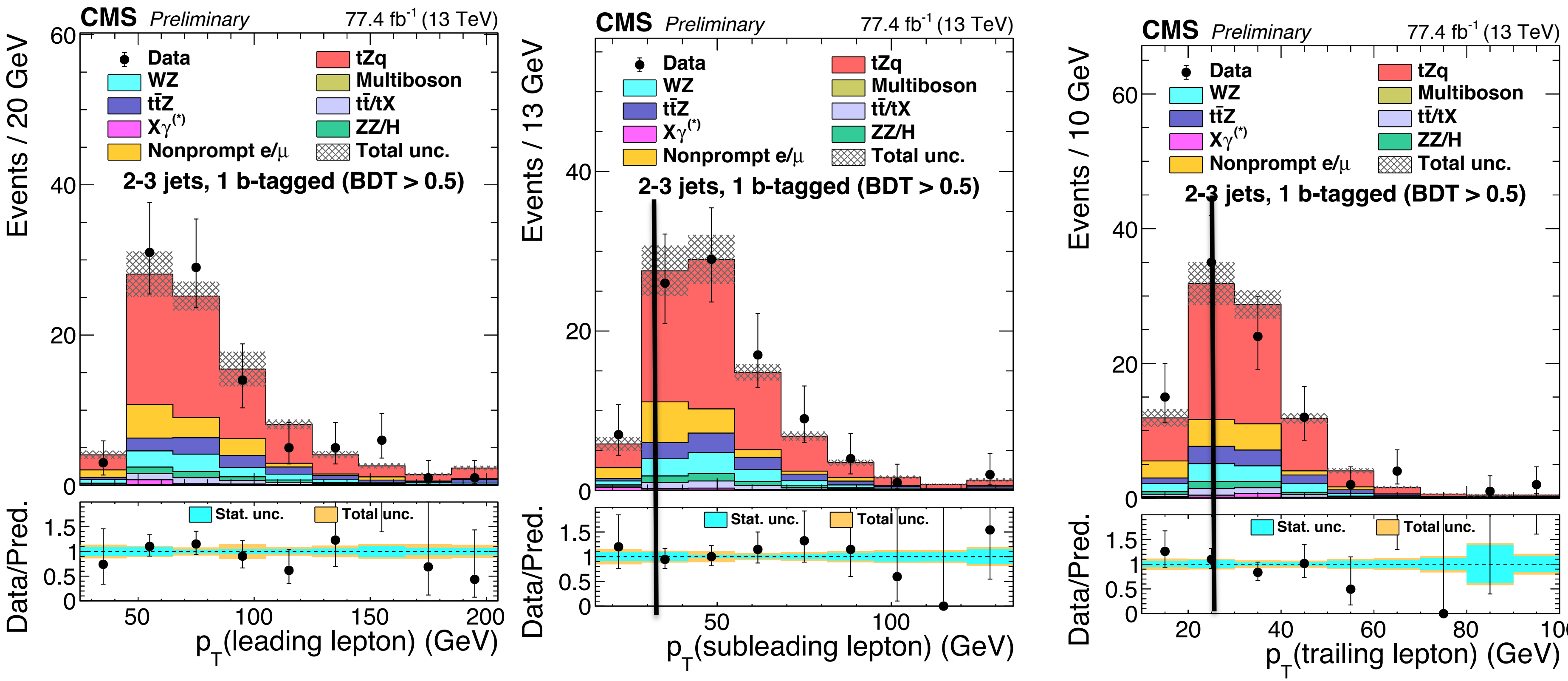
BDT discriminator

Signal& Background discriminating variables

- Maximum di-jet invariant mass
- η of the jet recoiling top
- $|\eta| \times \mathrm{charge}(\ell_W)$
- highest btag discriminator
- $\max \Delta\phi(\ell\ell)$
- $\min \Delta R(\mathrm{jet}, \ell_W)$
- $\max p_T(\mathrm{jet,jet})$
- $\mathrm{m}(\ell\ell\ell)$, m_T, H_T, N_{jets}, …

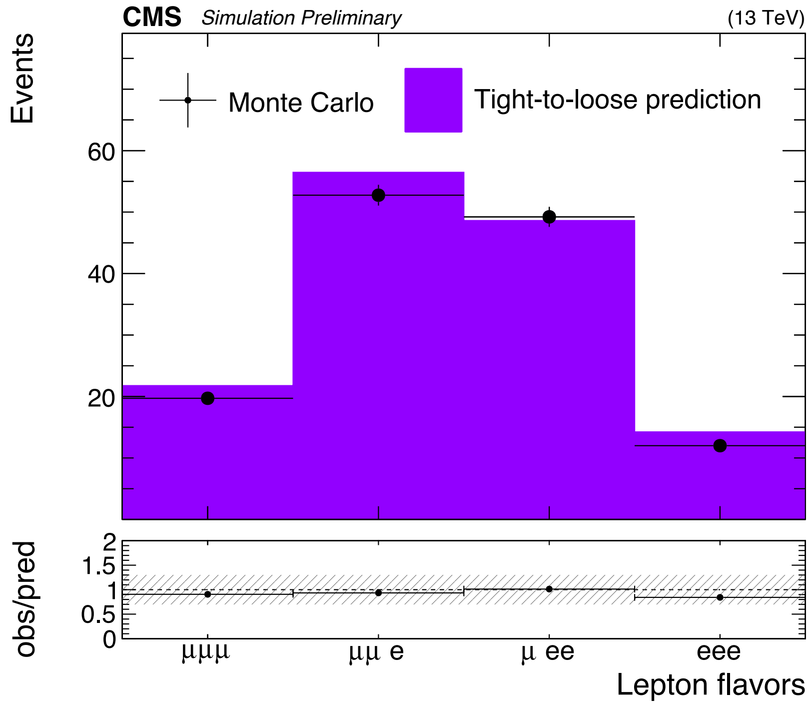
- 6 BDTs in total: 3 for each category and separate for 2016/2017 data
- Training against the sum of all backgrounds
- Good discrimination power in all categories

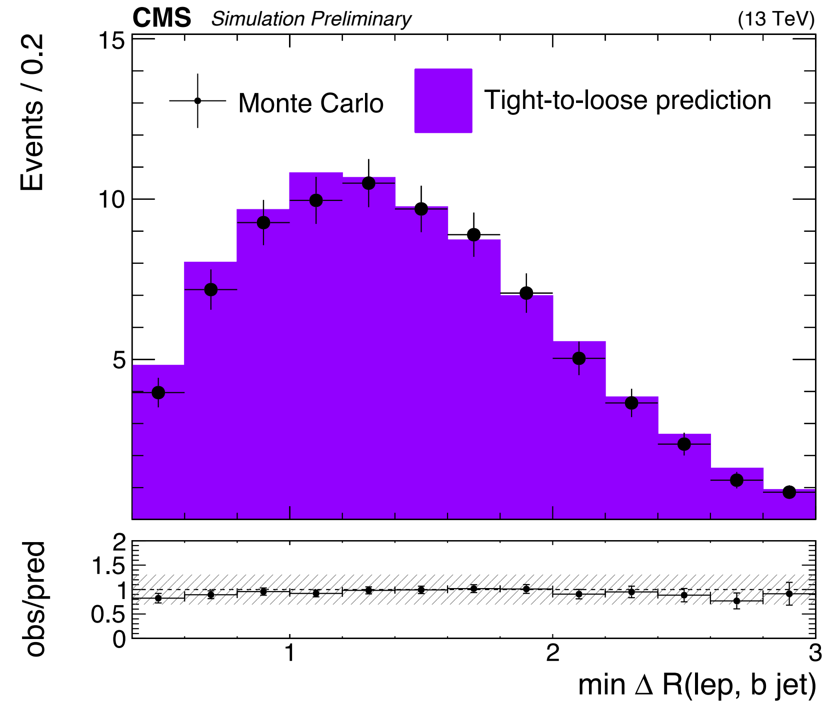
p_T spectrum of leptons in tZq



Nonprompt lepton bkg. validation

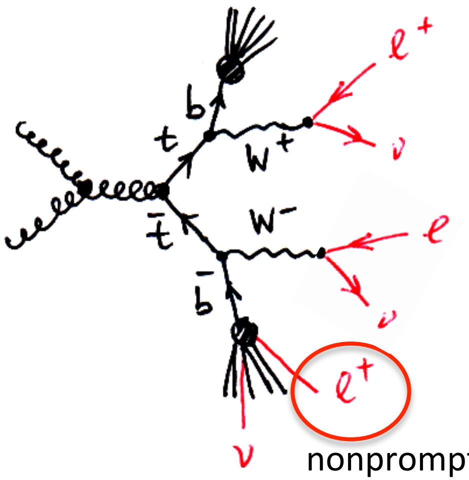
MC closure test:



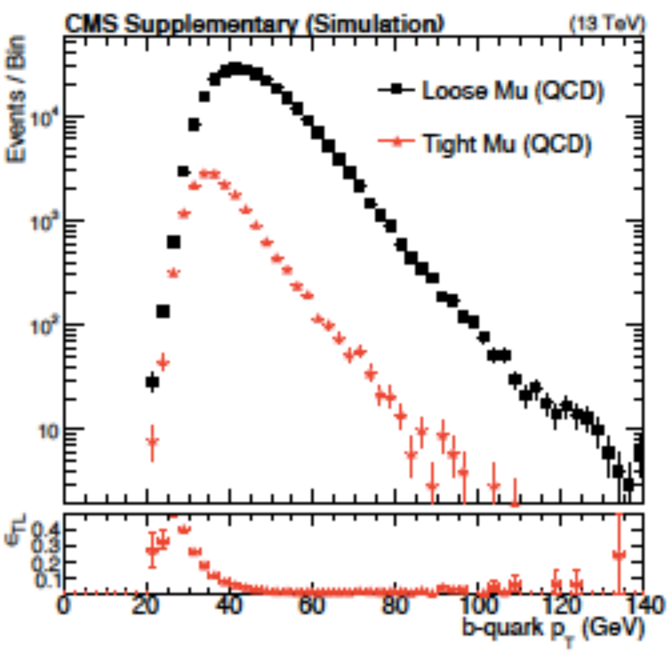


- Measure TL-ratio in QCD apply in ttBar/DY
- Check all BDT input variable
- Good closure

Nonprompt lepton background



- Mainly from $t\bar{t}$ and DY:
  - Typically two prompt lepton + nonprompt
  - Use events with at least 1 ℓ fails "tight" selection but passes the "loose" selection → "Tight-to-Loose" (TL)
  - Need to evaluate TL probability (*f*)



- Problem: f is dependent on the mother parton p_T
- Parametrise f versus modified lepton pT

$$f(p_T^{\text{mod}},\eta)$$