Modeling of t-channel Single Top Production at the LHC

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based on 2005.12936 with Ed. Berger
and 2007.15527 with Mei Seng Gao, Shu Run Yuan

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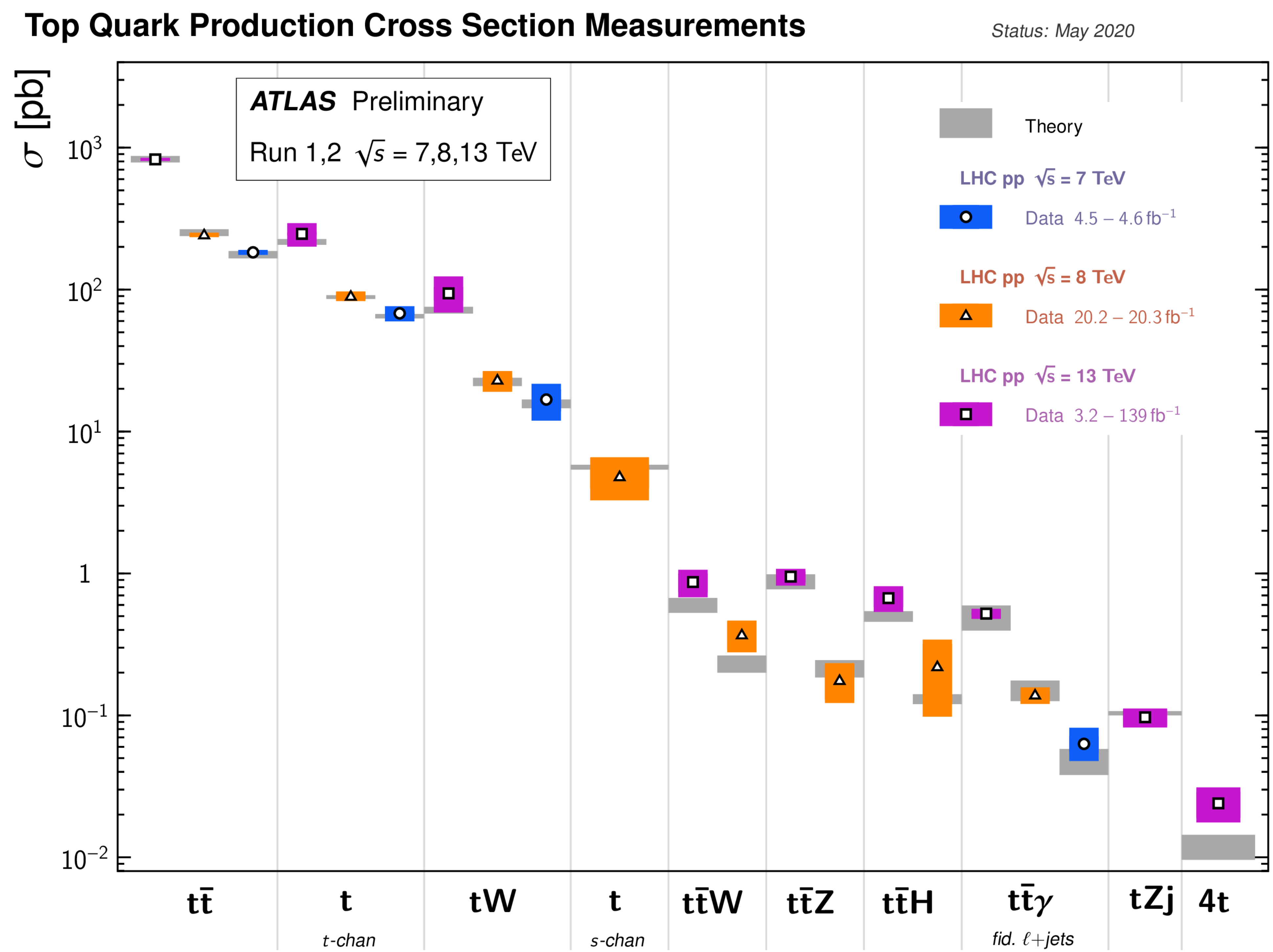
Top Priority

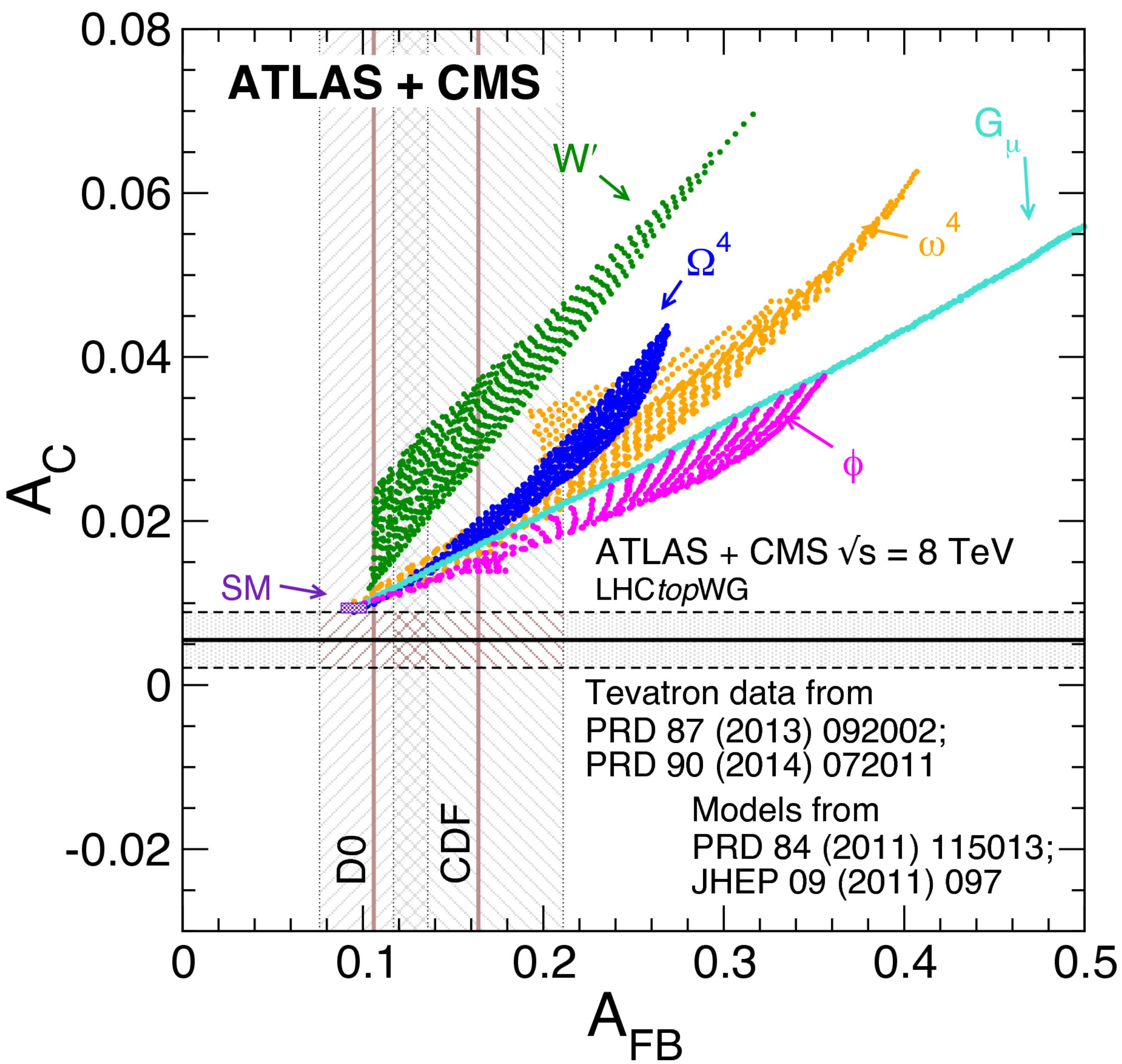
- Top quark plays an unique role in phenomenology studies of both electroweak and QCD sectors of the SM due to its large mass and short lifetime



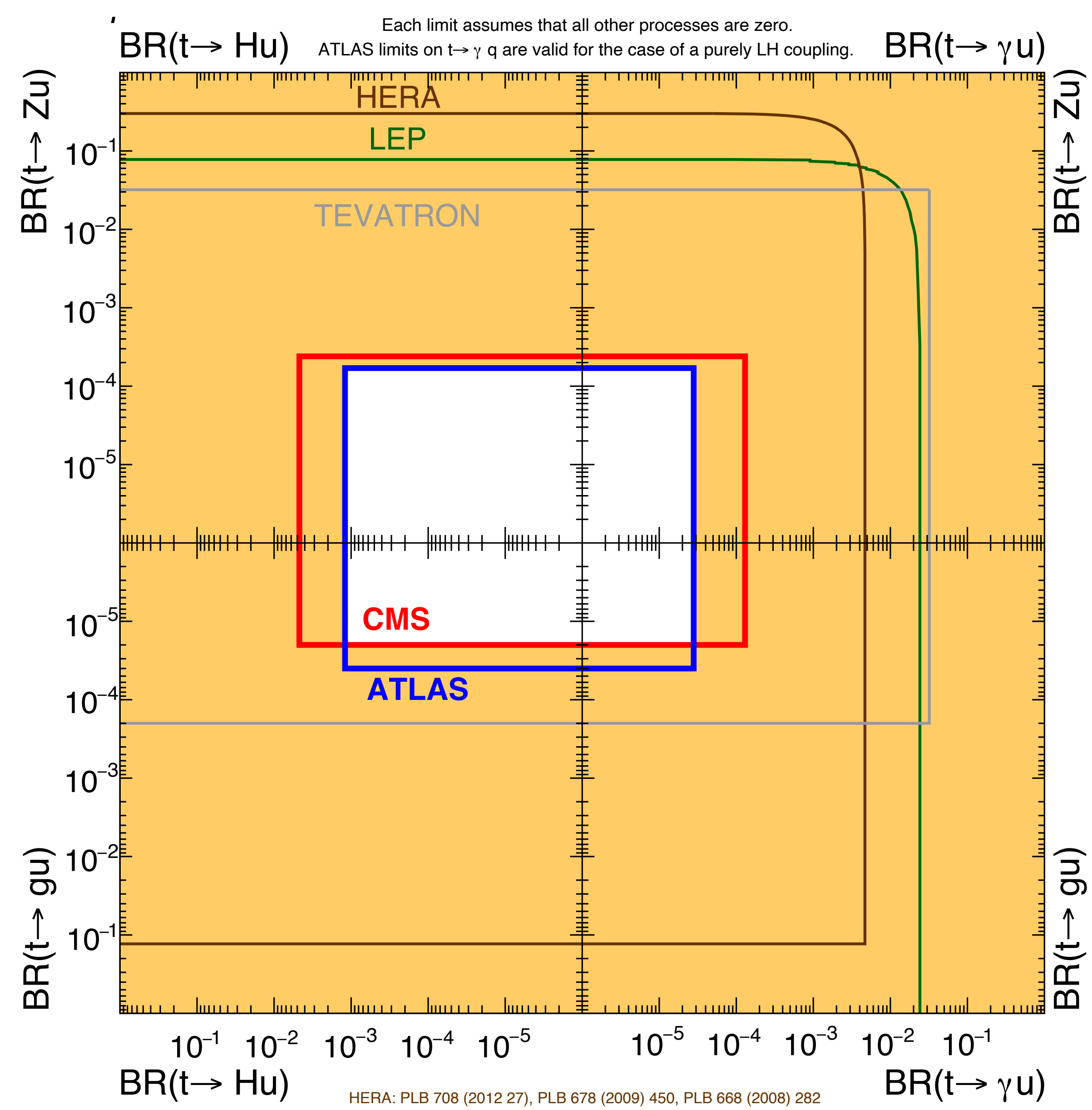
Probe of BSM physics

- Many well motivated extensions of the SM can modify production and decays of the top quark that can be tested at the (HL-)LHC for its high energy and great precision

Charge vs. F-B asymmetry

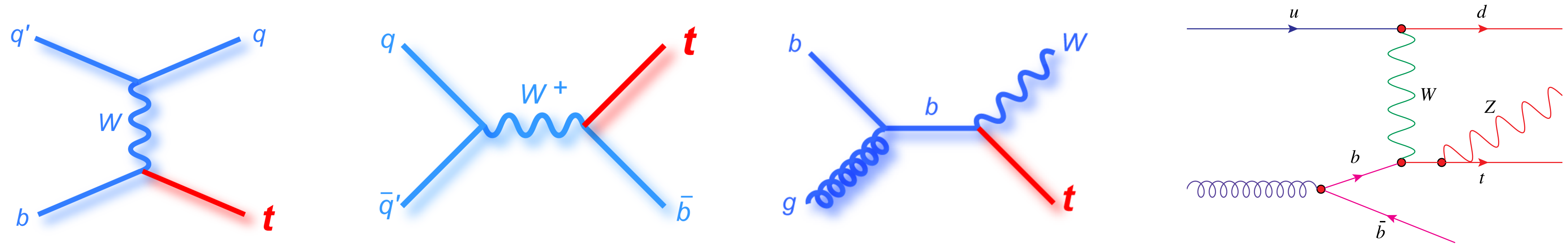


FCNC decays

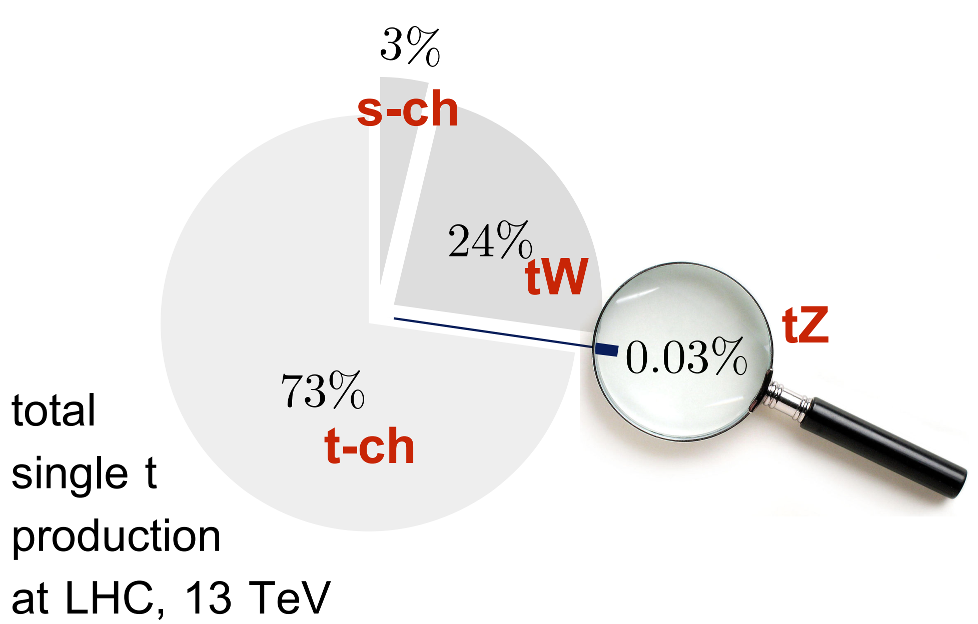


Single top-quark production

- Top quark can be produced singly at LHC via electroweak interactions, including t-channel, s-channel, and associated production



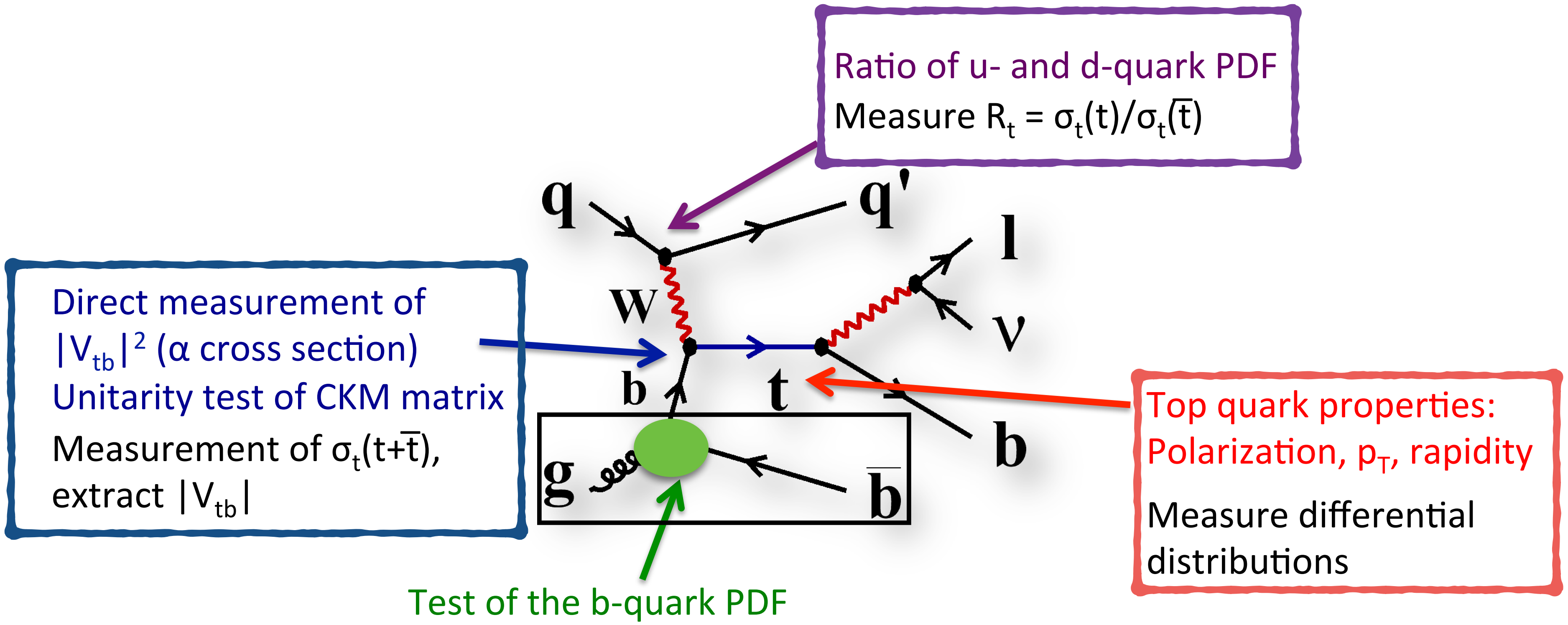
A total cross section of ~300 pb at 13 TeV

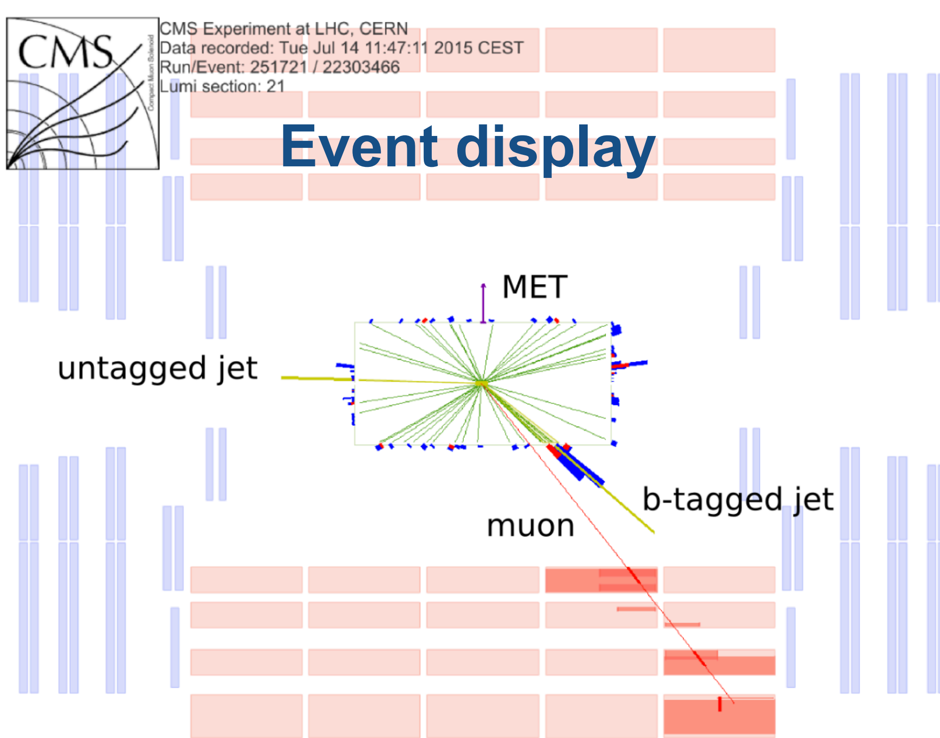


- probing EW coupling (Vtb)
- polarized top-quark production
- test of heavy-quark scheme
- constraining parton distributions
- sensitive to various new physics

t-channel production

- t-channel production mode enjoys special interest for its large cross section and several strong physics motivations



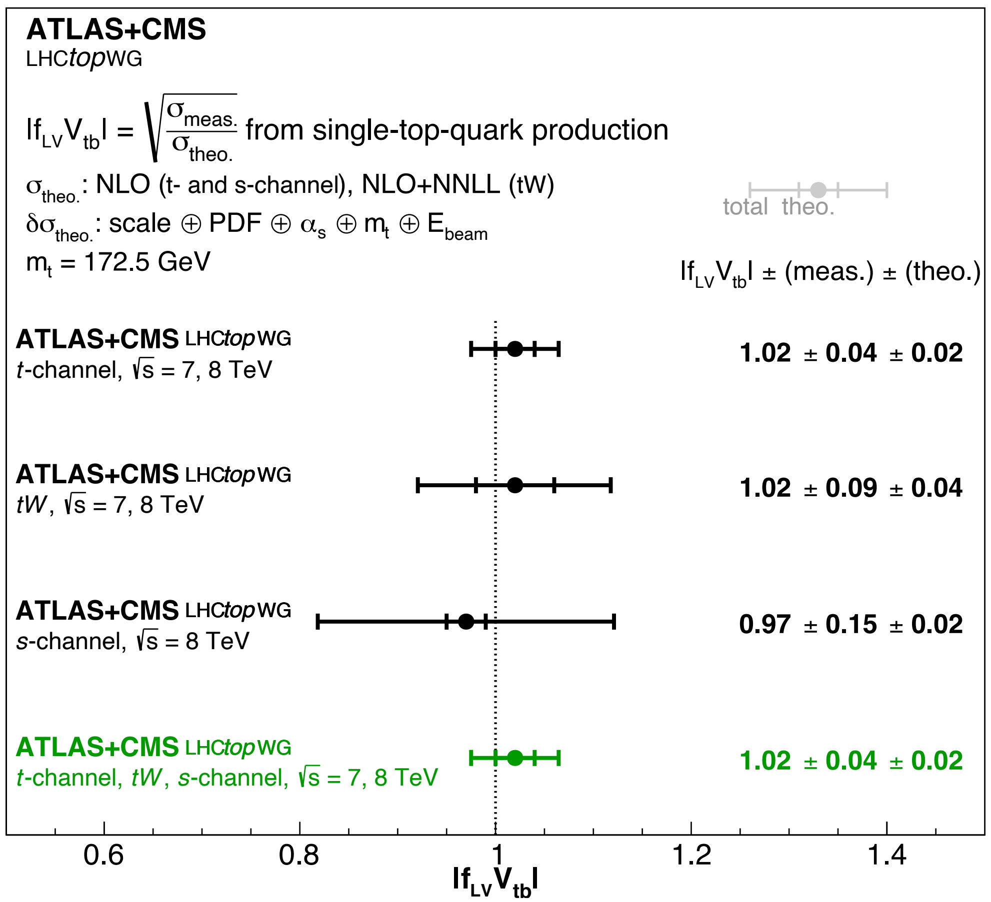


- only consider leptonic decays of top quark
- select the fiducial region with exactly "two jets" and "one-tagged", plus charged lepton
- untagged jet prefers in forward region

Measurements on total/differential cross sections

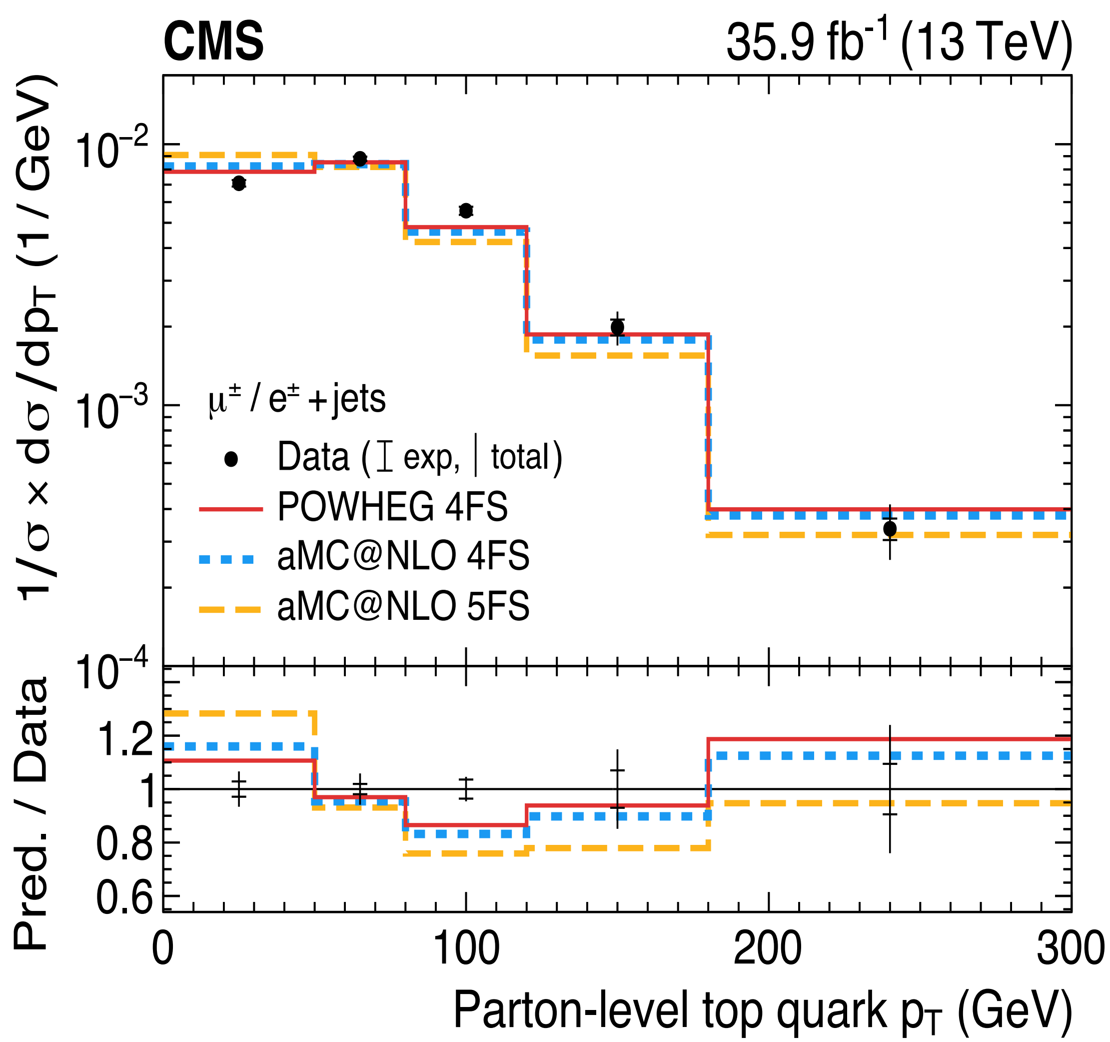
- Experimental precision of ~5-10% for total cross section and with a precision of ~5-20% at 13 TeV, unfolded back to parton level for easy comparison to theory

1902.07158



Run 1 combined measurement on cross sections/Vtb

1907.08330

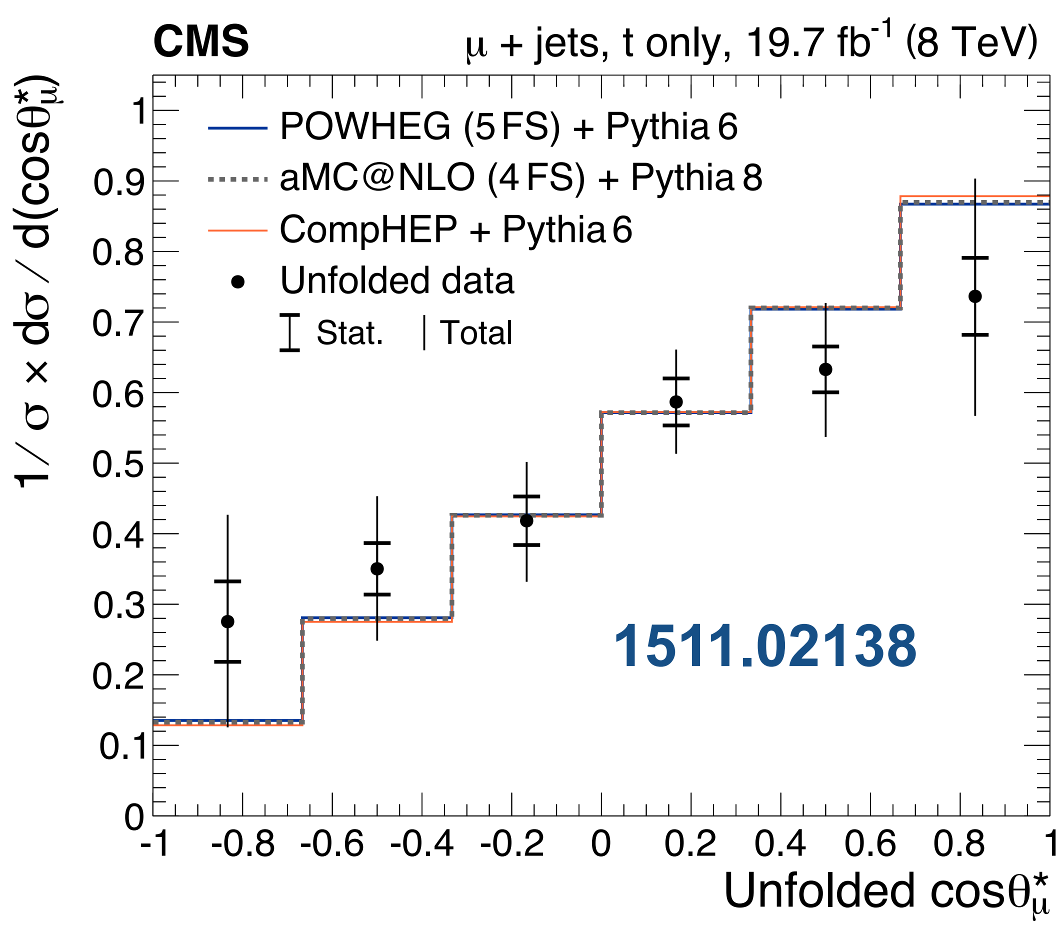


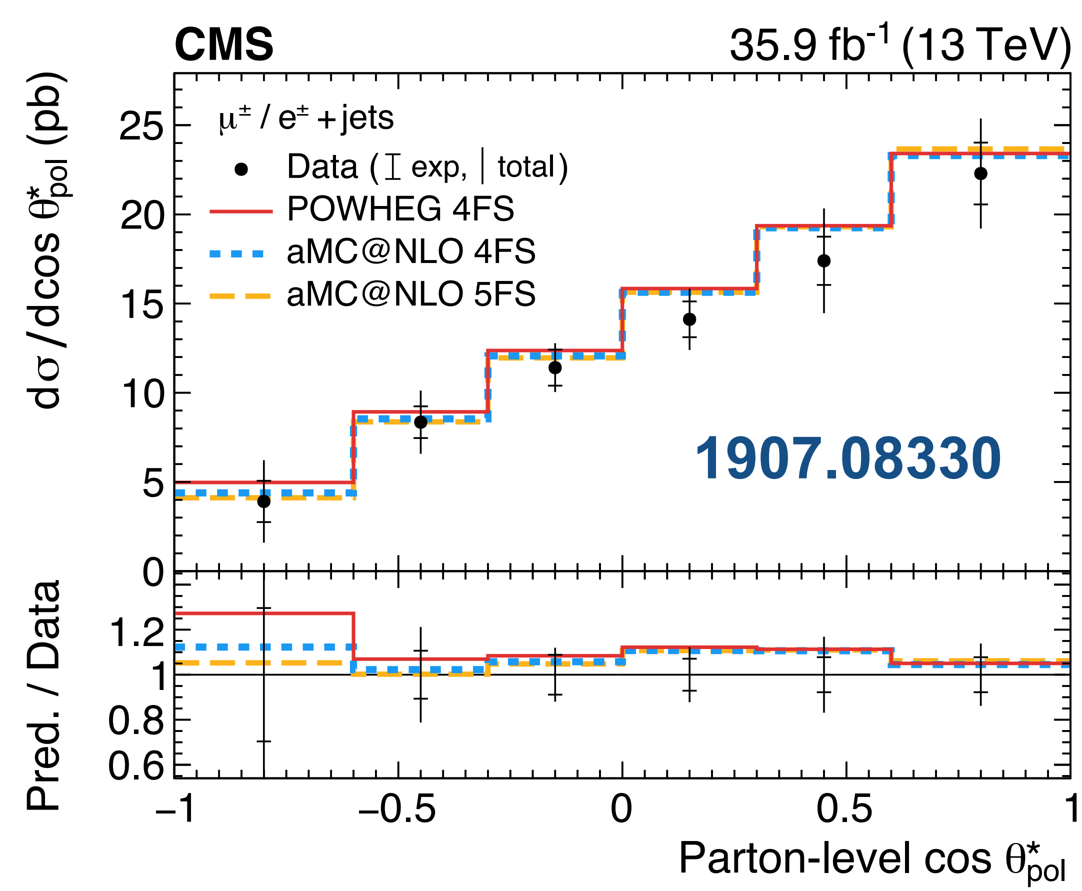
top quark transverse momentum

Measurements on top quark polarizations

- Polarization of the top quark can be extracted through polar angle distribution of charged lepton wrt. spin axis in top quark rest frame

$$\cos\theta^{\star}_{\mathrm{pol}} = \frac{\vec{p}^{\star}_{\mathrm{q}'} \cdot \vec{p}^{\star}_{\ell}}{|\vec{p}^{\star}_{\mathrm{q}'}||\vec{p}^{\star}_{\ell}|}, \qquad \frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^{\star}_{\mathrm{pol}}} = \frac{1}{2}\left(1 + 2A_{\ell}\cos\theta^{\star}_{\mathrm{pol}}\right), \quad A_{\ell} = \frac{1}{2}P\alpha_{\ell},$$





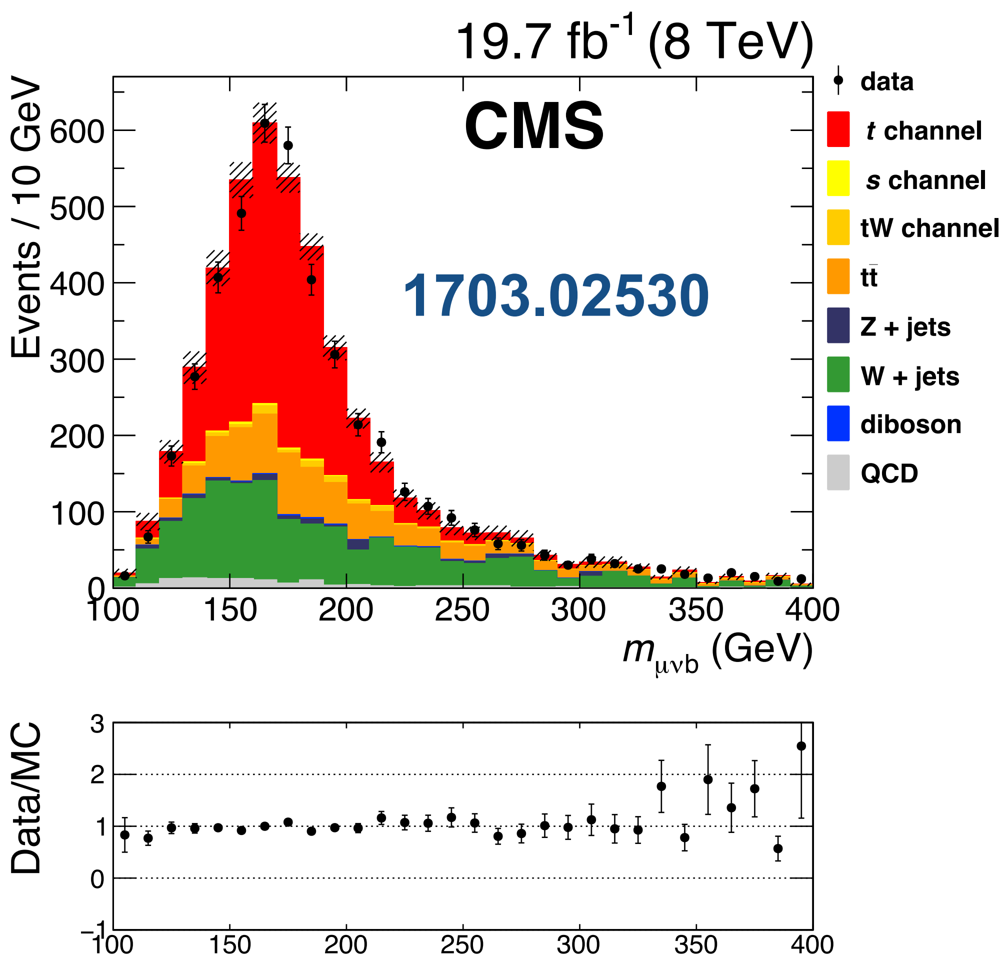
$A_{\mu}(\mathrm{t}+\bar{\mathrm{t}}) = 0.26 \pm 0.03\,(\mathrm{stat}) \pm 0.10\,(\mathrm{syst})$

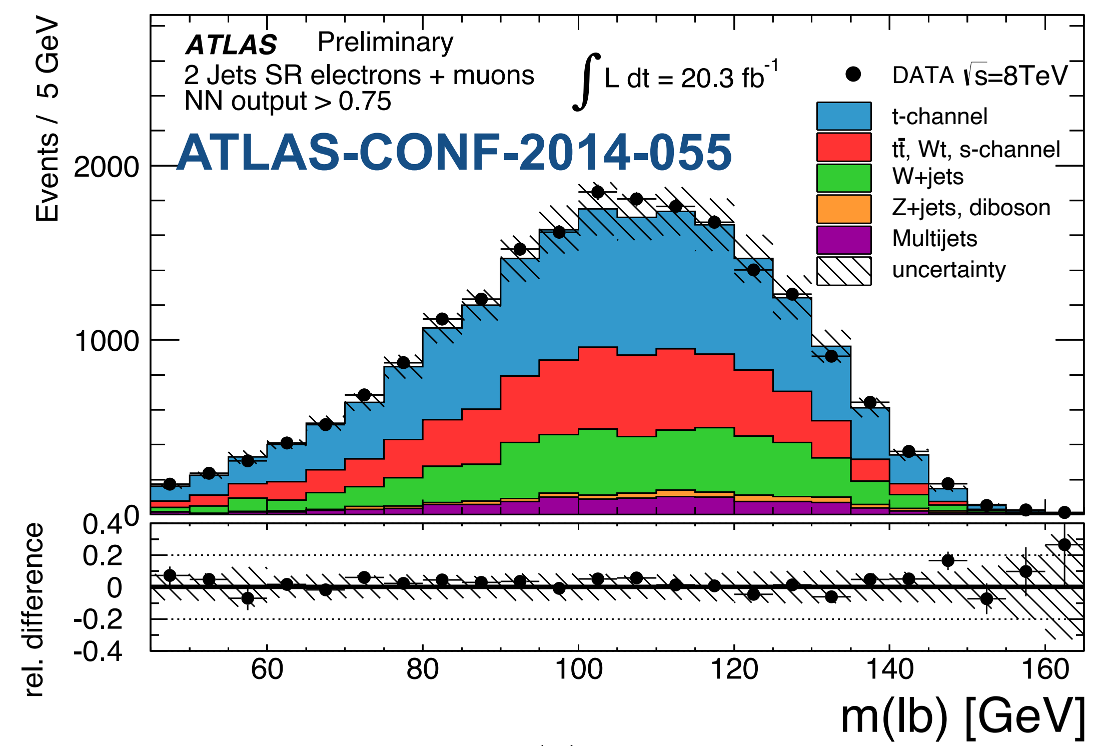
$A_{\mu+\mathrm{e}} = 0.439 \pm 0.032\,(\mathrm{exp}) \pm 0.053\,(\mathrm{theo})$

SM value of 0.436, found using POWHEG at NLO

Measurements on top quark mass

- Single-top quark production offers an opportunity to measure top quark mass that could be largely independent with those from pair production in theory and experimental uncertainties





full invariant mass

visible invariant mass

$172.95 \pm 0.77\,(\text{stat})^{+0.97}_{-0.93}\,(\text{syst})\,\text{GeV}$

$172.2 \pm 0.7(\text{stat.}) \pm 2.0(\text{syst.})\ \text{GeV}$

Modeling of t-channel single top production

- Surprisingly uncertainties due to theoretical modeling of the signal are far dominant in the final experimental results, e.g., for the total cross sections and thus Vtb

1902.07158, ATLAS+CMS, 8TeV

$\sigma_{t\text{-chan.}}, \sqrt{s} = 8$ TeV		
Combined cross-section	87.7 pb	
Uncertainty category	Uncertainty	
	[%]	[pb]
Data statistical	1.3	1.1
Simulation statistical	0.6	0.5
Integrated luminosity	1.7	1.5
Theory modelling	5.3	4.7
Background normalisation	1.2	1.1
Jets	2.6	2.3
Detector modelling	1.8	1.6
Total syst. unc. (excl. lumi.)	6.3	5.5
Total syst. unc. (incl. lumi.)	6.5	5.7
Total uncertainty	6.7	5.8

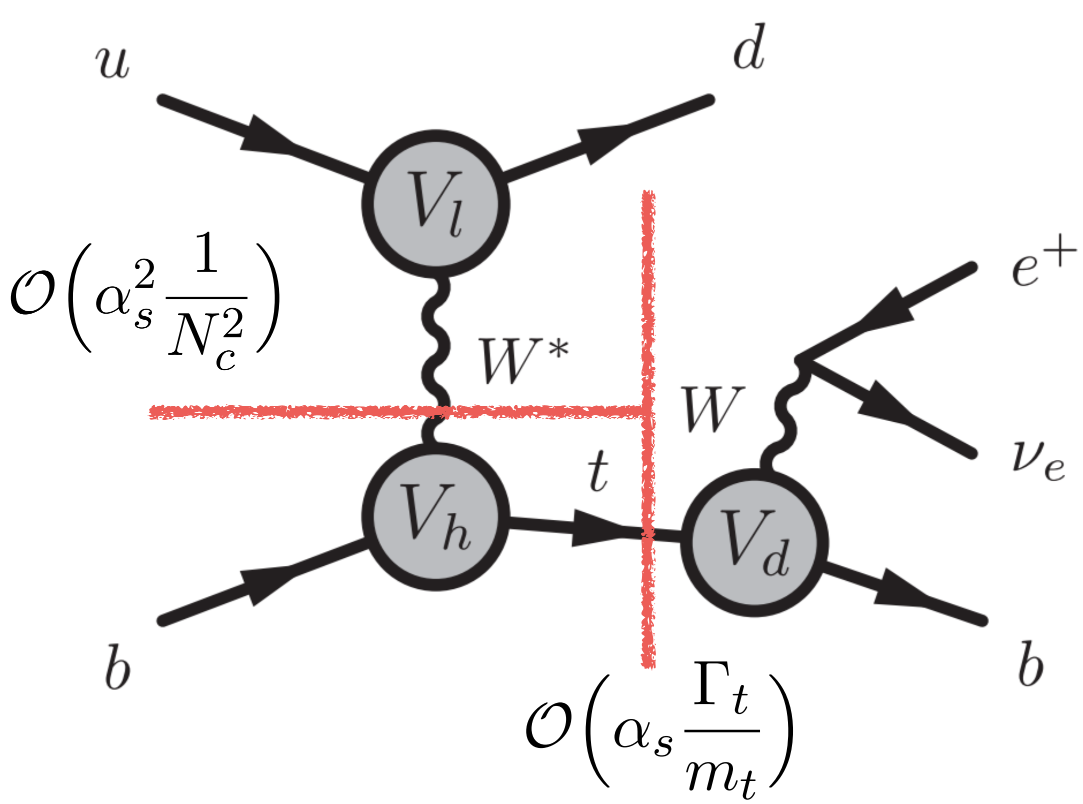
1812.10514, CMS 13 TeV, 36 fb-1

	$\Delta R_{t\text{-ch}}/R_{t\text{-ch}}$	$\Delta\sigma/\sigma(\mathrm{t})$	$\Delta\sigma/\sigma(\bar{\mathrm{t}})$
Nonprofiled uncertainties			
μ_R/μ_F scale t channel	1.5	6.1	5.0
ME-PS scale matching t channel	0.5	7.1	7.8
PS scale t channel	0.9	10.1	9.6
PDF t channel	3.0	3.1	5.8
Luminosity	—	2.5	2.5
Profiled uncertainties			
JES	0.9	1.5	1.8
JER	0.2	< 0.1	0.2
Unclustered energy	< 0.1	0.1	0.2
b tagging	0.1	1.1	1.2
Muon and electron efficiencies	0.2	0.8	0.6
Pileup	0.1	0.9	1.0
QCD bkg. normalization	< 0.1	0.1	0.1
MC sample size	2.5	2.2	3.2
$\mathrm{t\bar{t}}$ bkg. model and normalization	0.2	0.6	0.6
Top quark p_T	< 0.1	< 0.1	< 0.1
tW bkg. normalization	0.1	0.5	0.6
W/Z+jets bkg. normalization	0.3	0.6	0.9
μ_R/μ_F scale $\mathrm{t\bar{t}}$, tW, W/Z+jets	0.1	0.2	0.3
PDF $\mathrm{t\bar{t}}$, W/Z+jets	< 0.1	0.2	0.2

$$\begin{aligned}\sigma_{t\text{-ch},\mathrm{t}+\bar{\mathrm{t}}} &= 207 \pm 2\,(\text{stat}) \pm 6\,(\text{prof}) \pm 29\,(\text{sig-mod}) \pm 5\,(\text{lumi})\,\text{pb} \\ &= 207 \pm 2\,(\text{stat}) \pm 31\,(\text{syst})\,\text{pb} \\ &= 207 \pm 31\,\text{pb},\end{aligned}$$

State of art calculation

- We will address two questions with the state of art calculations at NNLO in QCD in a 5-flavor scheme, for t-channel production with leptonic decays



- double deep inelastic scattering (DIS) approximation
- narrow width approximation (NWA)

[Berger, JG, Yuan, Zhu, 2016]

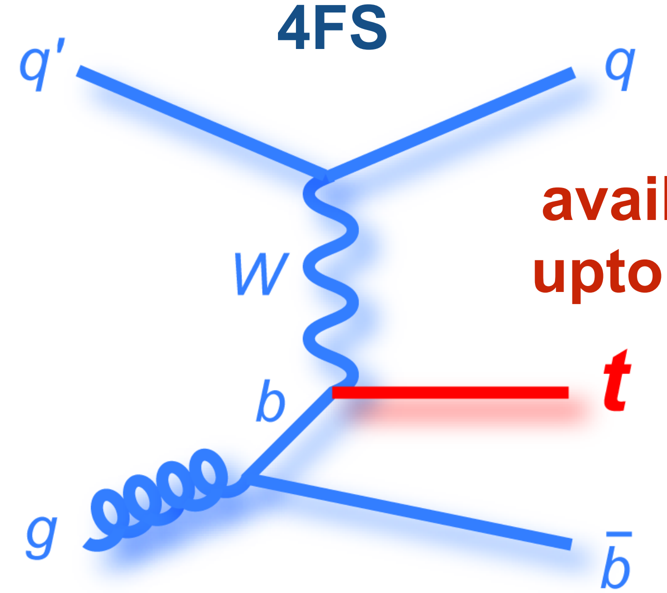
[Berger, JG, Zhu, 2017]

- What are the true theoretical uncertainties in modeling of the t-channel production, especially related to heavy-quark schemes?
- Is it possible to extract top-quark mass without relying directly on kinematics of the b-jet?

Heavy-quark schemes

- The production can be calculated either in a factorization scheme based on 4 flavor of quarks in the initial state **(4FS)** or also treats the bottom quark as a massless parton in initial hadrons **(5FS)**

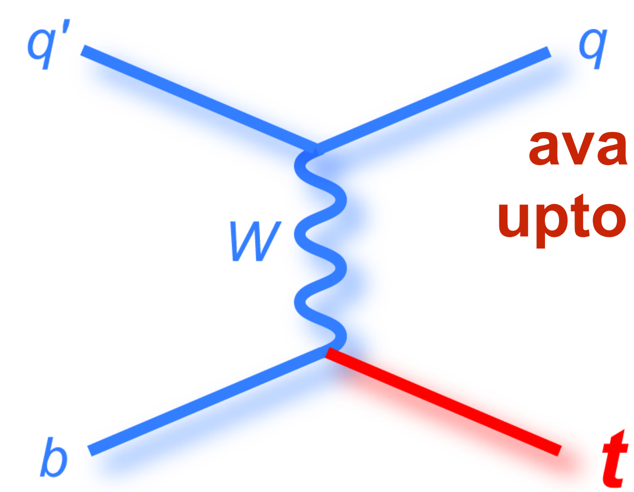
4FS



available upto NLO

exact mb dependence at fixe orders

5FS



available upto NNLO

resummation of large logarithms of mb

4FS@LO vs 5FS@NLO

$$\boxed{\sigma^{\mathrm{LO}}_{4\mathrm{F}} = \alpha_s(\mu)[a_1 \ln(m_t^2/m_b^2) + c_1 + d_1(m_b^2/m_t^2)]}$$

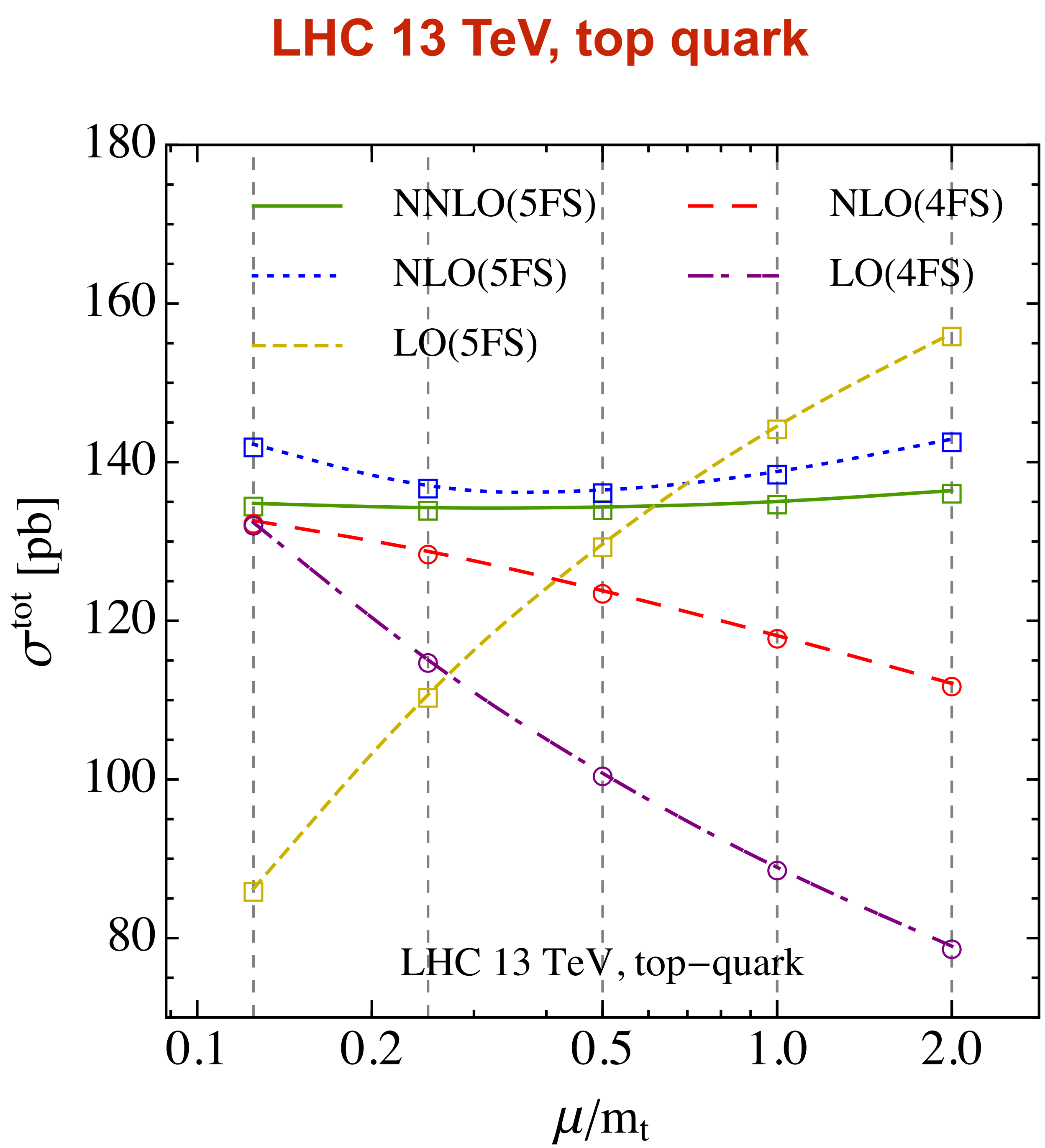
$$\begin{aligned}\sigma^{\mathrm{NLO}}_{5\mathrm{F}} &= \alpha_s(\mu)[a_1 \ln(m_t^2/m_b^2) + c_1] \\ &+ \alpha_s^2(\mu)[a_2 \ln^2(\mu^2/m_b^2) + a_3 \ln(\mu^2/m_b^2)] \\ &+ \text{higher} \quad \text{orders,}\end{aligned}$$

What are agreements of the two schemes?

Which scheme is better for LHC study?

Total inclusive cross sections

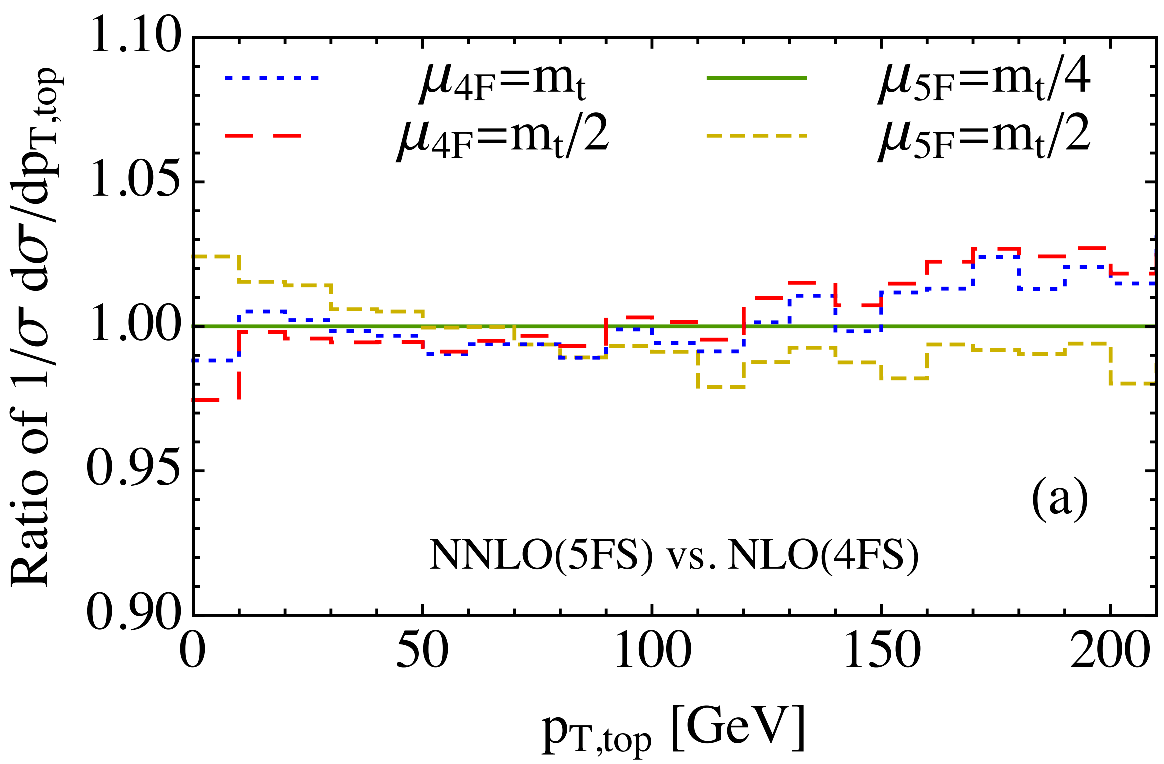
- Shown below are predictions on total cross section as a function of QCD scales at various orders and in both 4FS and 5FS



- resummation leads to fast convergence and stability against scale choice at higher orders in 5FS, less than 2%
- preferable scale of mt/4 or mt/2 in 5FS
- predictions of the two schemes do approach each other at high orders
- the collinear logarithms beyond 4FS@NLO are still significant

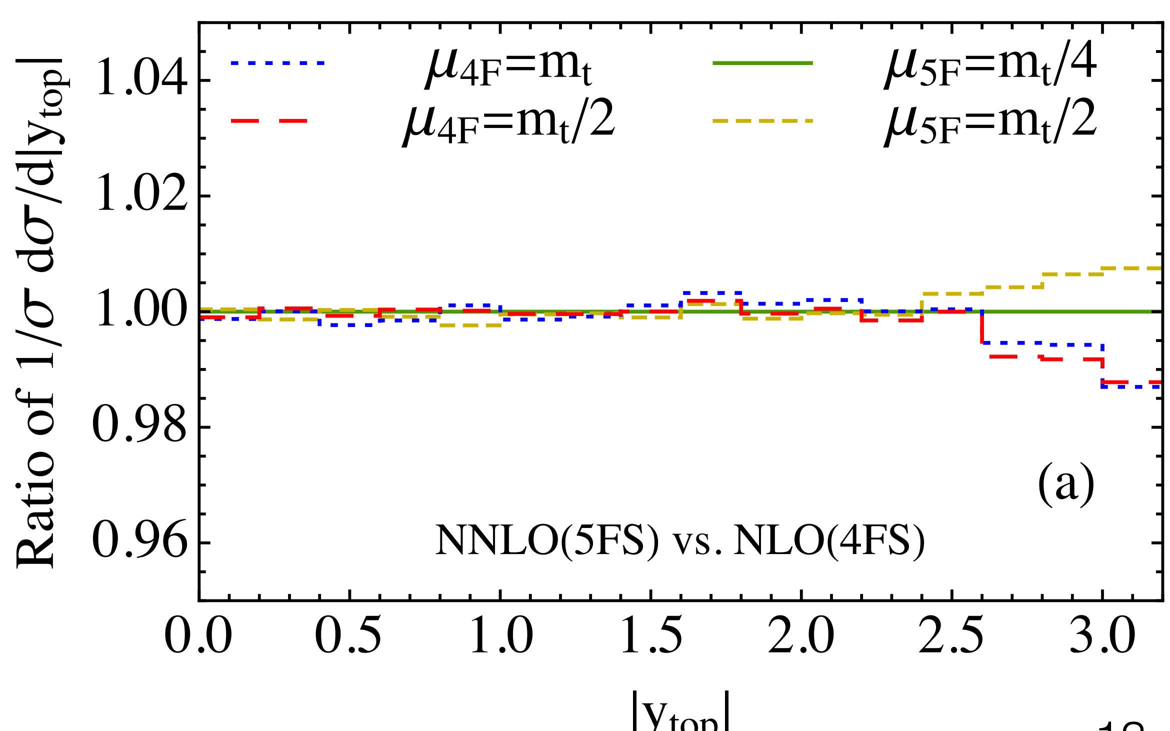
Top quark distributions

- A direct comparison of the two schemes at the highest order available , i.e. 5FS@NNLO and 4FS@NLO, **on normalized distributions**



transverse momentum of top quark

- excellent agreement at a few percent level in bulk region of cross sections

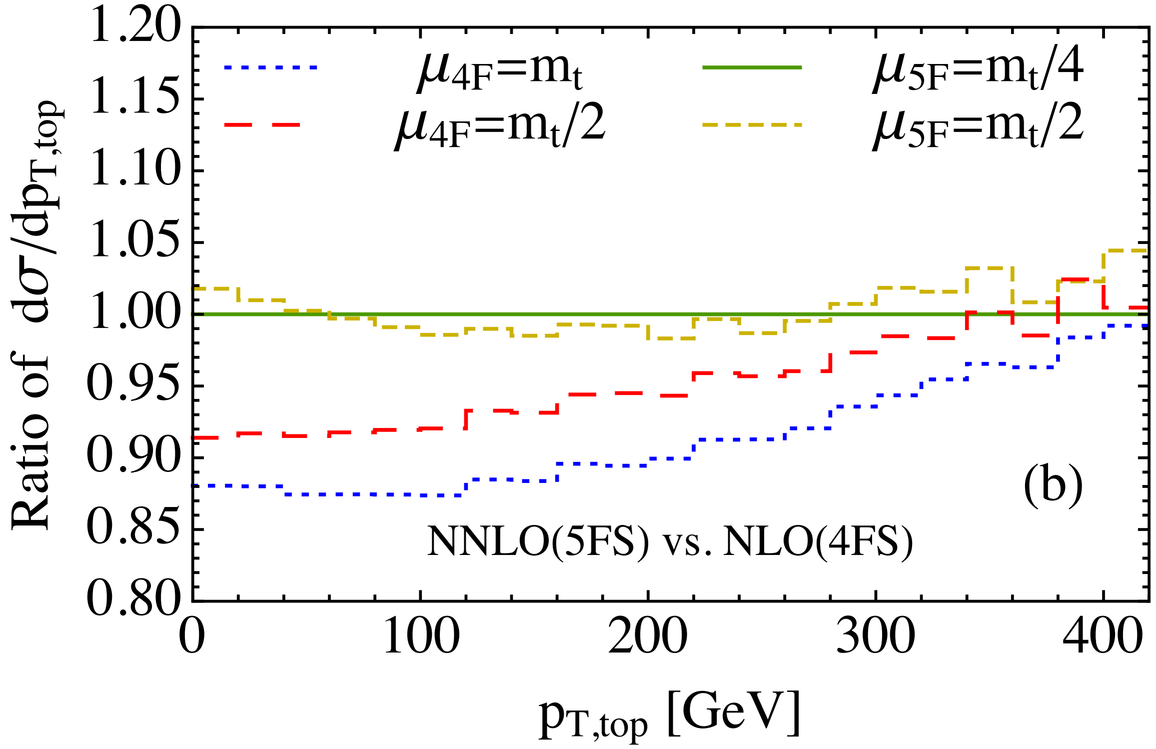


rapidity of top quark

- even better agreement, differ by a few permille for rapidity up to 2.4

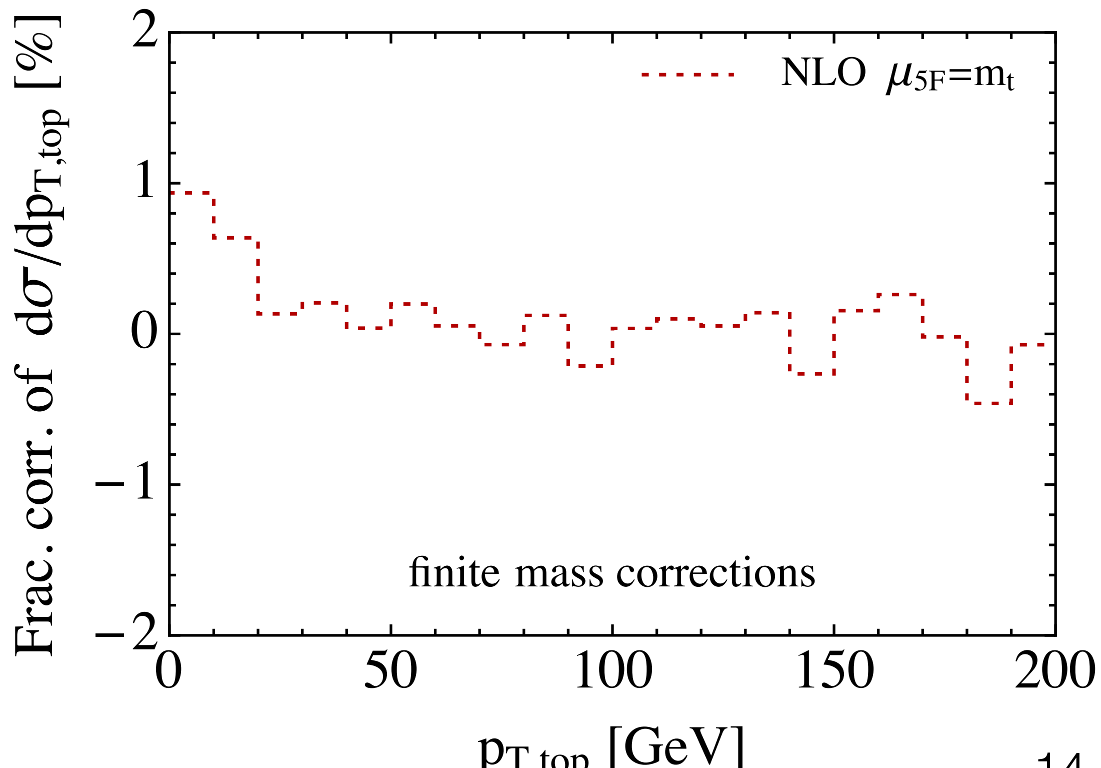
Top quark distributions

- A direct comparison of the two schemes at the highest order available , i.e. 5FS@NNLO and 4FS@NLO, **on absolute distributions**



absolute distribution with extended pT range

- 4FS and 5FS converge in tail region; 4FS is off exactly in region sensitive to resummation

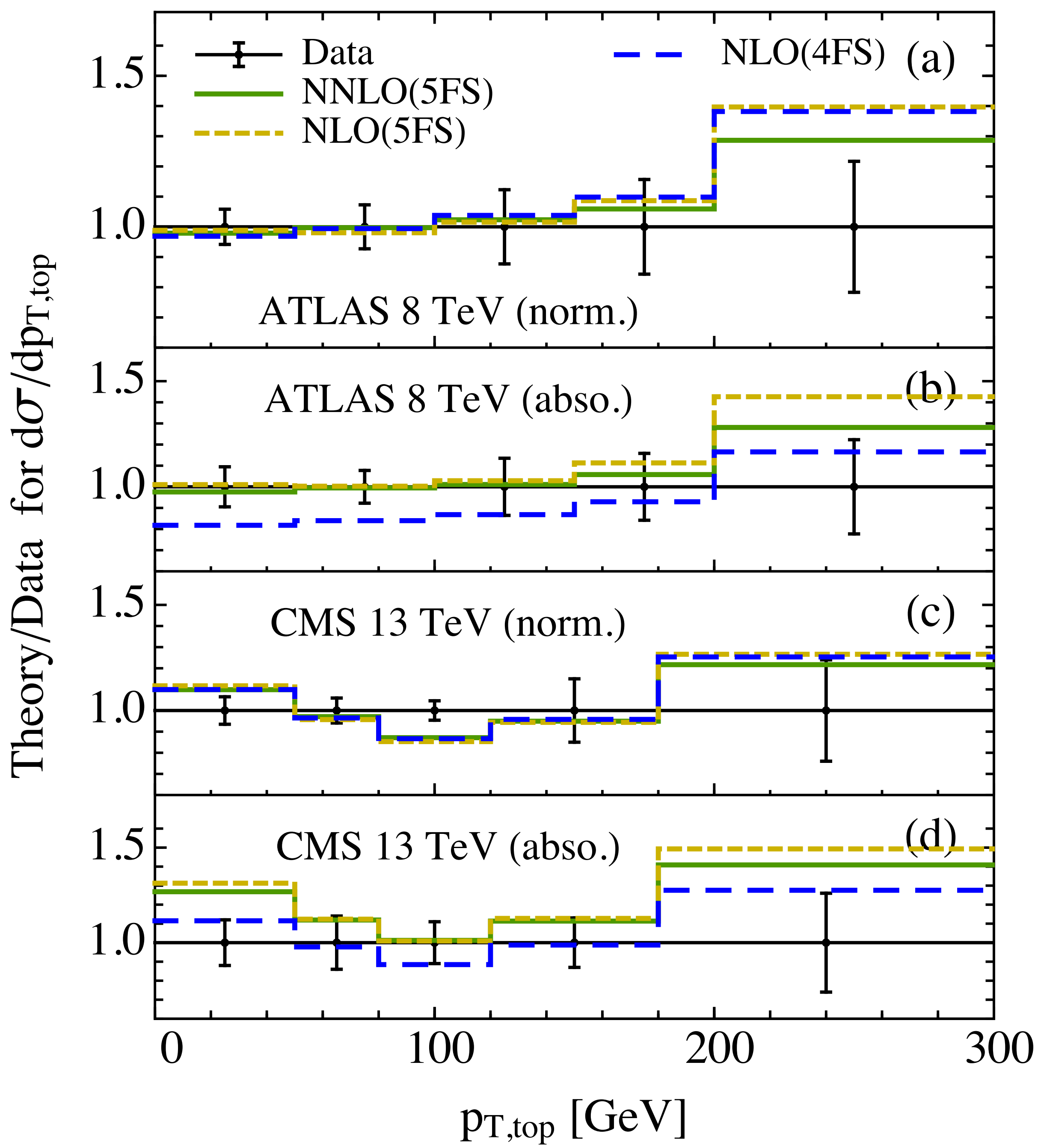


impact of power corrections of bottom mass, SACOT@NLO

- increase the total cross section by 0.1%, distribution at most 1% wrt. 5FS

Predictions vs LHC measurements

- Select two measurements from ATLAS at 8 TeV and CMS at 13 TeV, comparing to predictions of both 5FS and 4FS with their nominal scale choices, for **transverse momentum of top quark**



- very good agreement with ATLAS data for 5FS@NNLO
- 4FS@NLO is off on normalization comparing to ATLAS data
- none of predictions describes CMS data particularly well
- interestingly CMS data agrees better with 4FS@NLO on normalization **[not the case for measurement on total inclusive cross sections]**

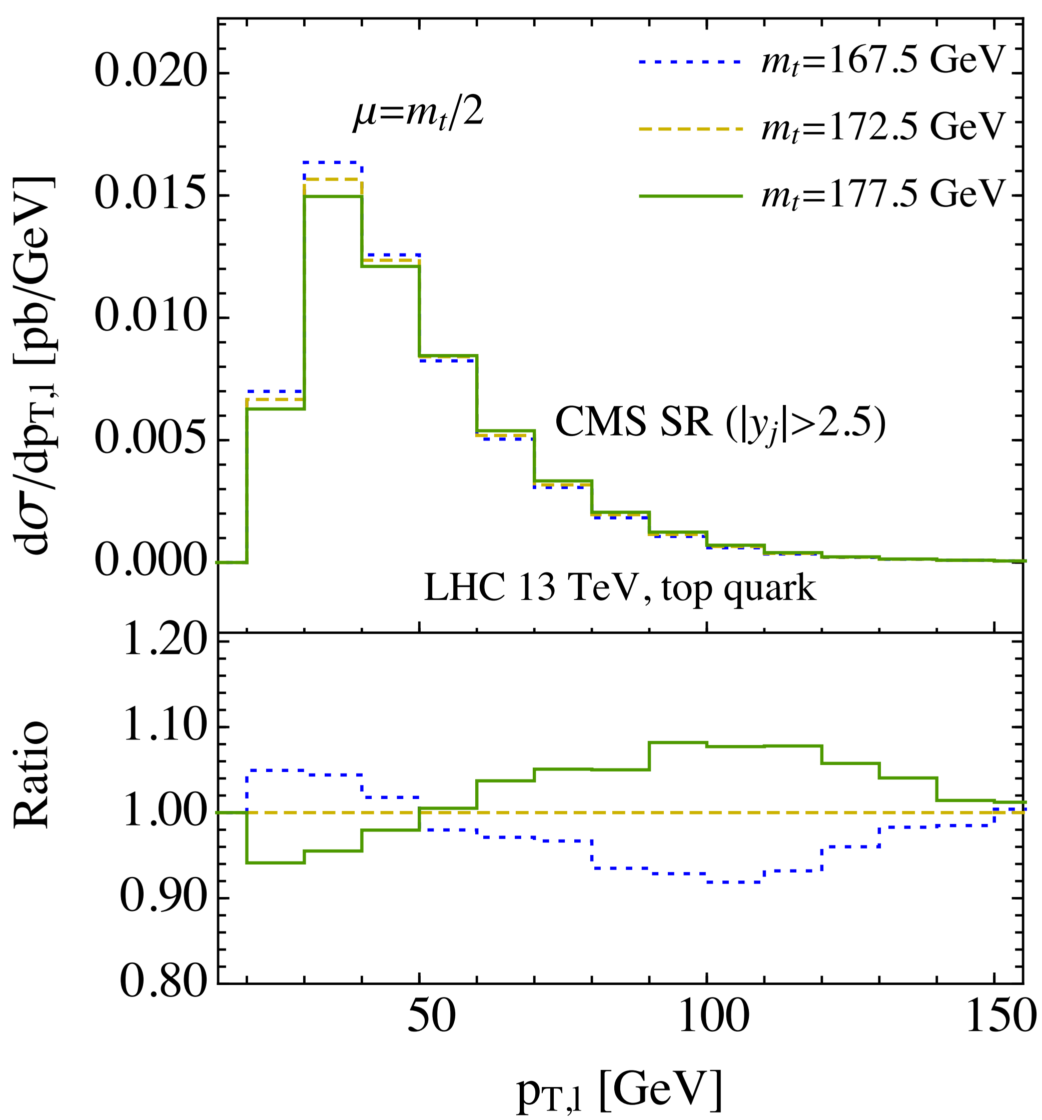
Extraction of top quark mass

- Mass of the top quark can be extracted from transverse momentum of the charged lepton without explicit dependence on hadronic activities

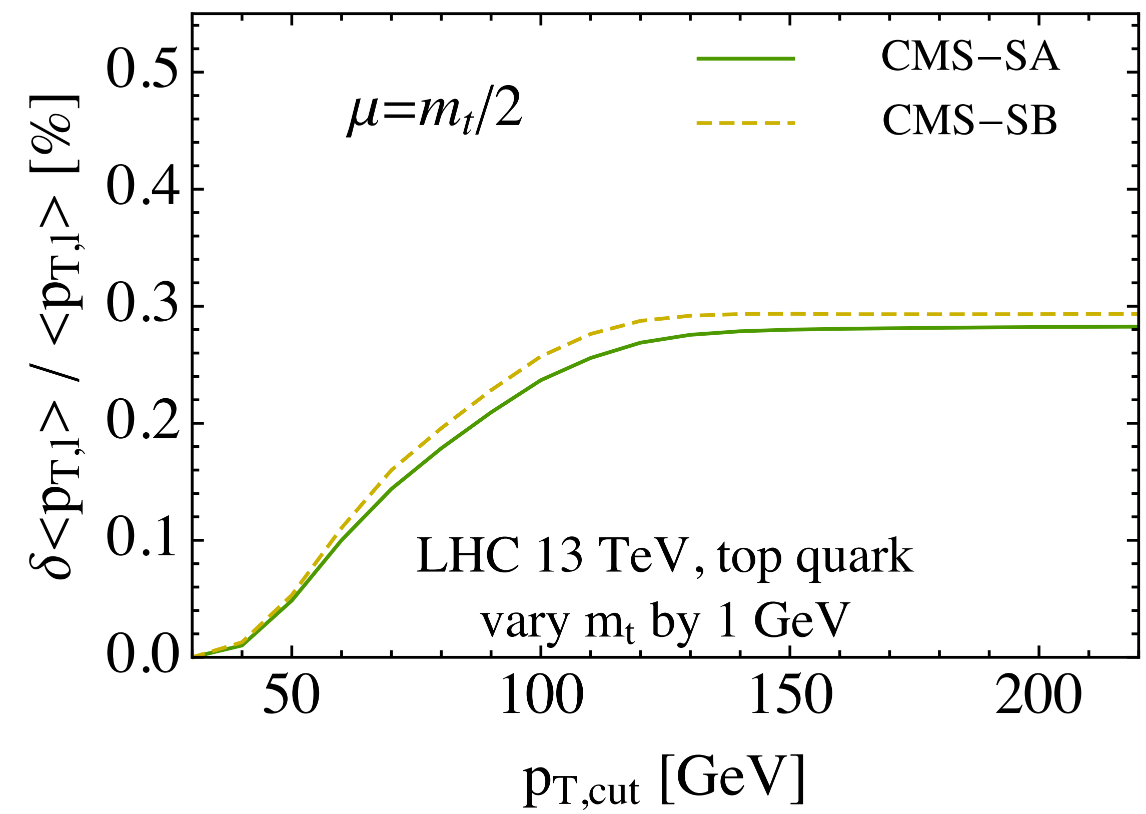
$\langle P_{T,l} \rangle$ for top quark at rest

$$\langle p_{T,l} \rangle \equiv \frac{\int p_{T,l} d\Gamma}{\int d\Gamma} = \frac{\pi}{16} \frac{1 + 2\bar{y} + 3\bar{y}^2}{1 + 2\bar{y}} m_t$$

$P_{T,l}$ in t-channel production



relative change of $\langle P_{T,l} \rangle$ when varying m_t by 1 GeV



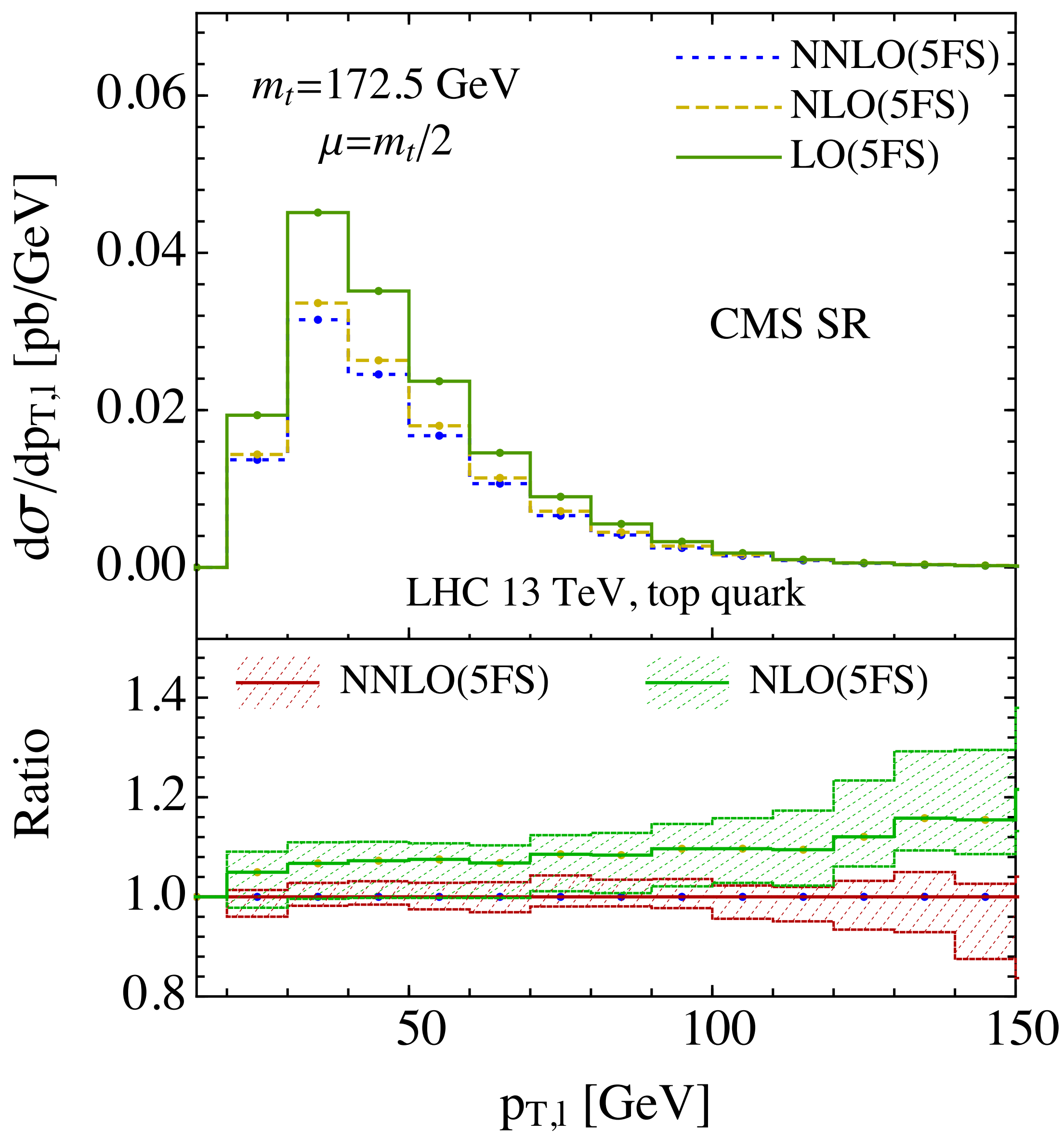
- optimal observable: **$\langle P_{T,l} \rangle$** within a region of $P_{T,l}$ < 100 GeV and with $|y_j|$>2.5

Theory predictions for signal

- NNLO predictions in 5FS shows a theoretical uncertainty on the average P_T of lepton of 0.1~0.3%; uncertainties from other sources are well under control

$P_{T,l}$ in t-channel production

NNLO vs. NLO with scale variations



predictions on <$P_{T,l}$> at fixed orders

$\langle p_{T,l}\rangle$ [GeV]	CMS-SB < 100 GeV	CMS-SB < 200 GeV
LO	$47.38^{+0.01}_{-0.02}(47.38)$	$48.73^{+0.05}_{-0.04}(48.73)$
NLO	$47.49^{+0.13}_{-0.09}(47.84)$	$49.66^{+0.36}_{-0.27}(50.02)$
NNLO	$47.35^{+0.14}_{-0.03}(47.75)$	$49.25^{+0.17}_{-0.12}(49.67)$

with NLO+parton showering and hadronization

$\langle p_{T,l}\rangle$ [GeV]	CMS-SB < 100 GeV	CMS-SB < 200 GeV
PYTHIA8	47.41(47.48)	49.29(49.25)
PYTHIA6	47.43(47.23)	49.34(49.08)
HERWIG7	47.15(46.91)	48.89(48.73)
NNLO	47.35	49.25

Background estimation

- Uncertainties from modeling of SM backgrounds, e.g. from top-quark pair or W+jets production, are another major theoretical error in the proposed measurement of top quark mass

$\langle P_{T,l} \rangle$ and fiducial cross sections

[GeV]/[pb]		CMS-SB	
		< 100 GeV	< 200 GeV
$t\bar{t}$	$\langle p_{T,l} \rangle$	51.9	59.1
	σ_{fid}	0.40	0.44
$tW^-(\bar{t}W^+)$	$\langle p_{T,l} \rangle$	52.5	61.1
	σ_{fid}	0.019	0.021
s-channel t	$\langle p_{T,l} \rangle$	47.2	49.4
	σ_{fid}	0.007	0.007
s-channel $\bar{t}$	$\langle p_{T,l} \rangle$	47.4	49.1
	σ_{fid}	0.004	0.004
QCD W^+JJ	$\langle p_{T,l} \rangle$	51.0	58.8
	σ_{fid}	0.157	0.174
QCD W^-JJ	$\langle p_{T,l} \rangle$	52.9	62.8
	σ_{fid}	0.107	0.117
t-channel t	$\langle p_{T,l} \rangle$	47.35	49.25
	σ_{fid}	0.493	0.506
t-channel $\bar{t}$	$\langle p_{T,l} \rangle$	47.70	49.54
	σ_{fid}	0.250	0.257

- can utilize charge symmetry/asymmetry to remove impact of most backgrounds almost completely

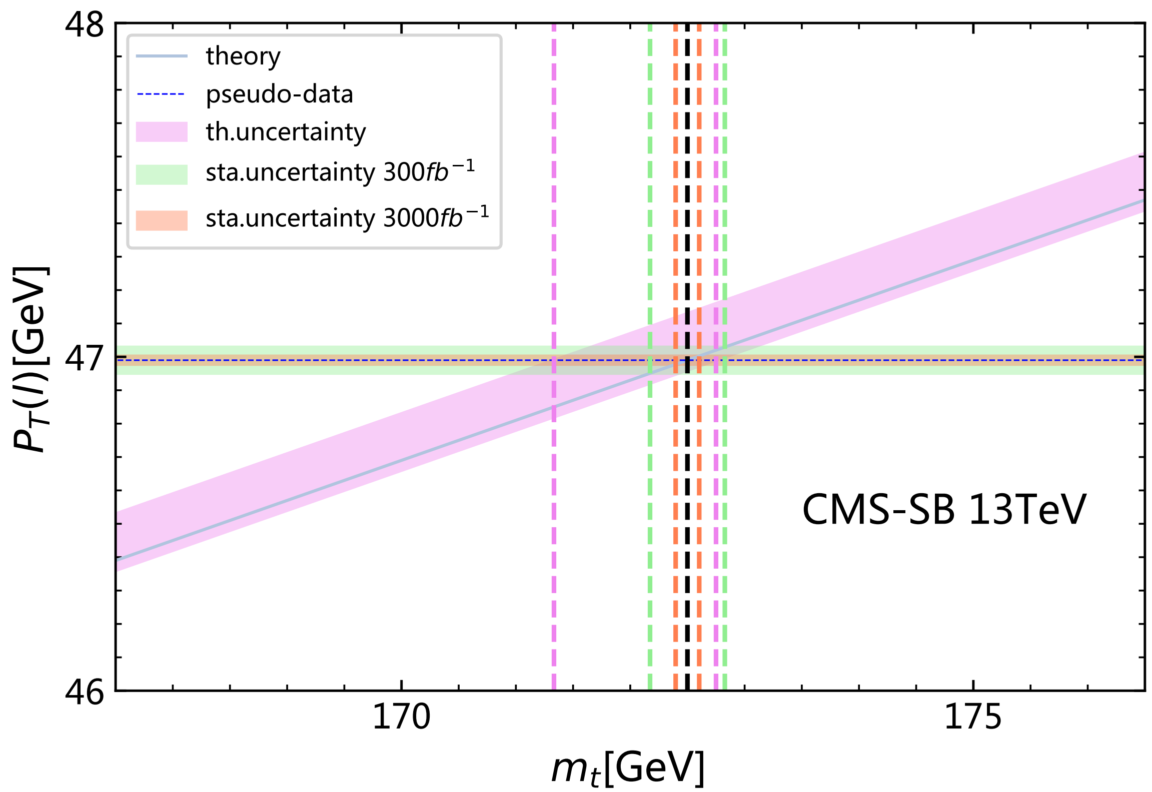
$$\langle p_T \rangle_{obs} \equiv \frac{\int p_{T,l}[d\sigma^{l^+} - d\sigma^{l^-}]}{\sigma^{l^+} - \sigma^{l^-}} = \langle p_T \rangle_S + \frac{r}{1+r}[\langle p_T \rangle_B - \langle p_T \rangle_S]$$

- remaining theoretical uncertainty from BKs are dominated by predictions on normalization and $\langle P_{T,l} \rangle$ of W+jets production

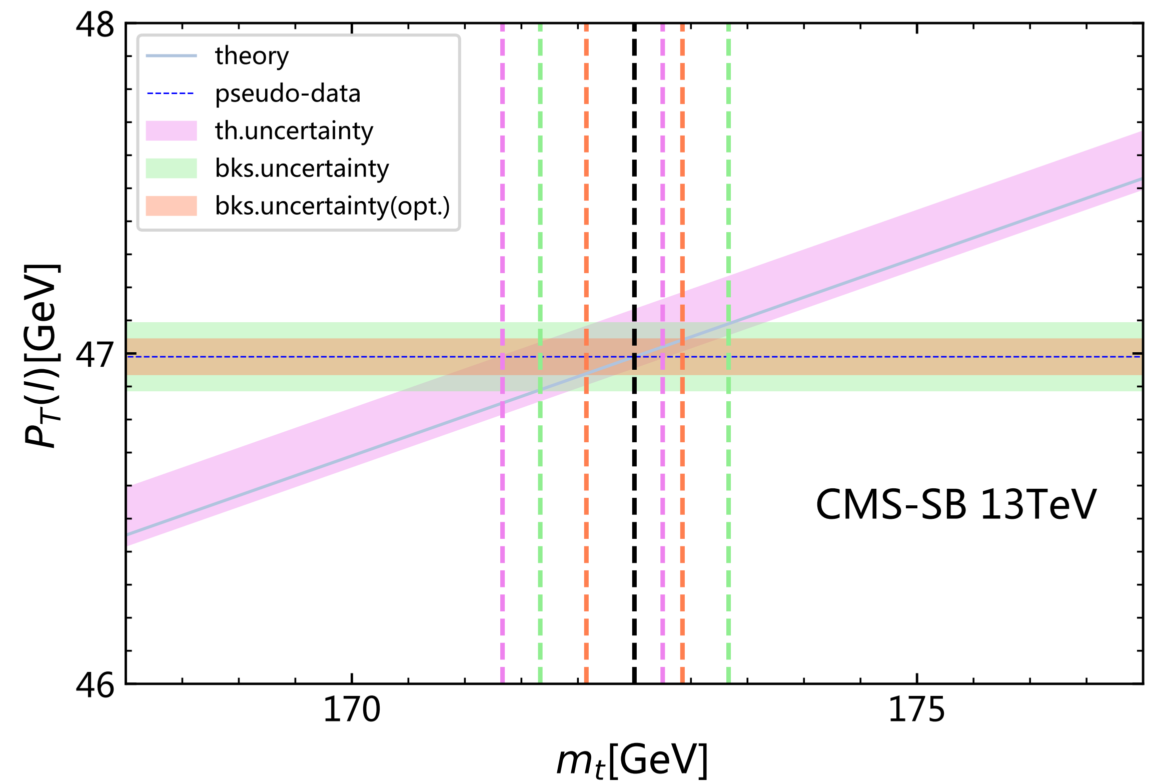
Projections for (HL-)LHC

- Projections for (HL-)LHC are found to be very promising with a total uncertainty on extracted top-quark mass of about 1 GeV, from theory modeling on both signal and background processes

sta. unc. vs theo. unc. (signal)



theo. unc. (BKs) vs theo. unc. (signal)



- statistical uncertainties (300/3000 fb^{-1}) are much smaller than theoretical ones from modeling of the signal (t-channel) process with the latter ~1 GeV

- theoretical uncertainty due to modeling of background processes are comparable, ~0.8 GeV

Summary and outlook

- The predictions in the 5FS show strong stability for both normalization and distributions, and are superior to those of the 4FS at comparable orders

- The NNLO predictions in 5FS shows perturbative uncertainty of a few percents; large modeling uncertainty in experimental measurements possibly deserves a careful examination

- More works on matching 5FS@NNLO to parton showering would be desirable to further test stability of predictions from 5FS

- Extraction of top quark mass with our precision calculation and using leptonic observables are proposed and shows promising sensitivities

Thank you for your attention!