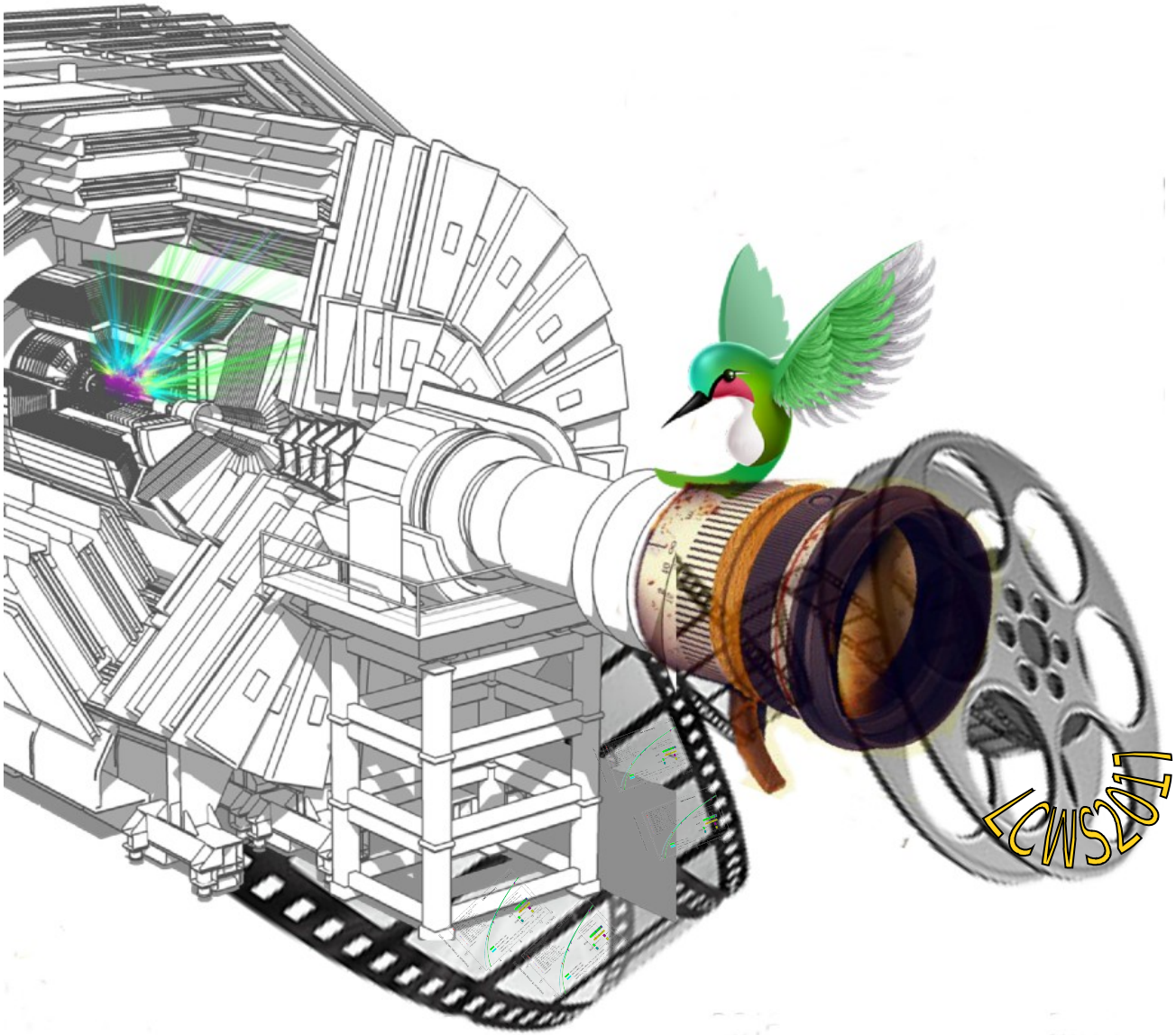
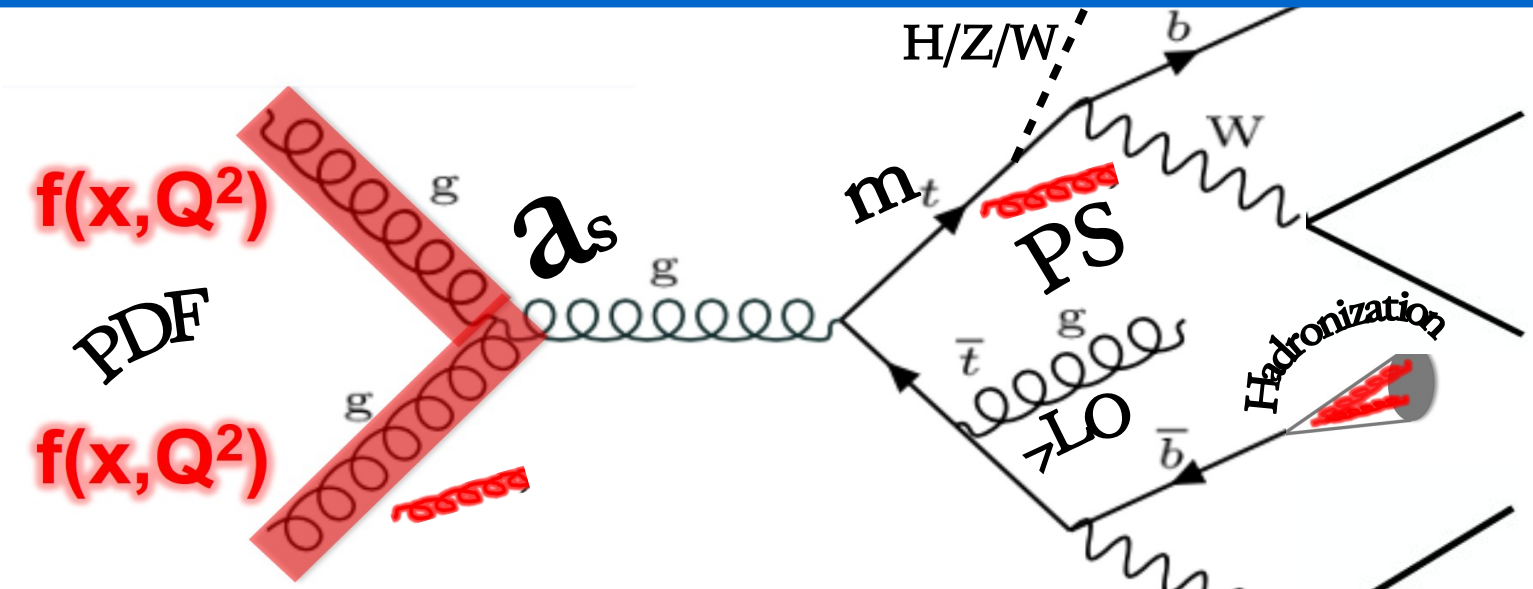


UCL
Université catholique de Louvain

Results on TOP physics from CMS

GK Krintiras on behalf of CMS Collaboration

The dominant top quark production @ LHC; ggF(usion)

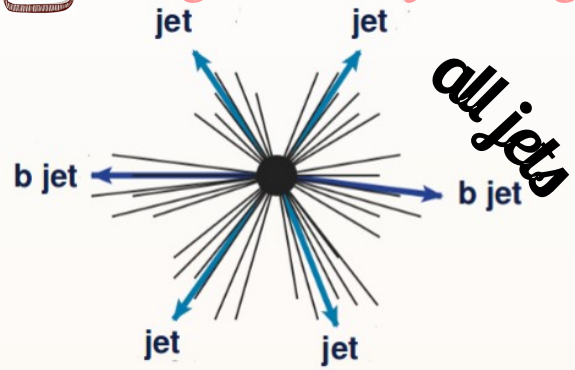


Present talk: Exp. overview on cross sections

↳ For TOP properties: see T. Kuhl talk

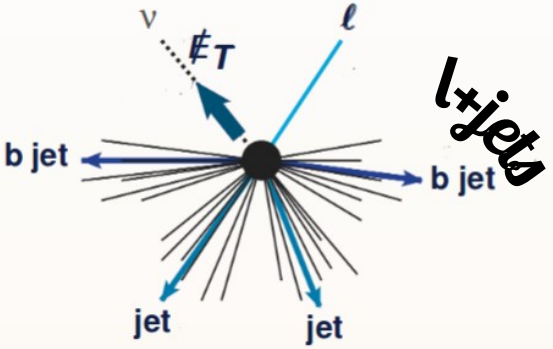
The highest BR

Large multi-jet bkg.



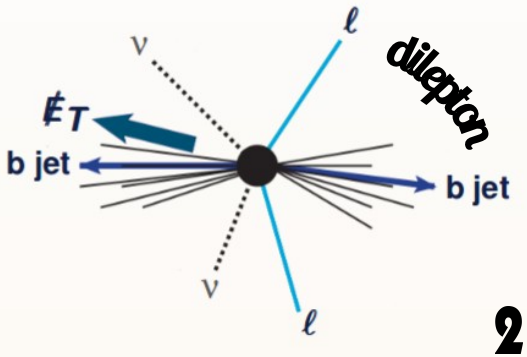
High BR, good S/B

W+jets bkg.

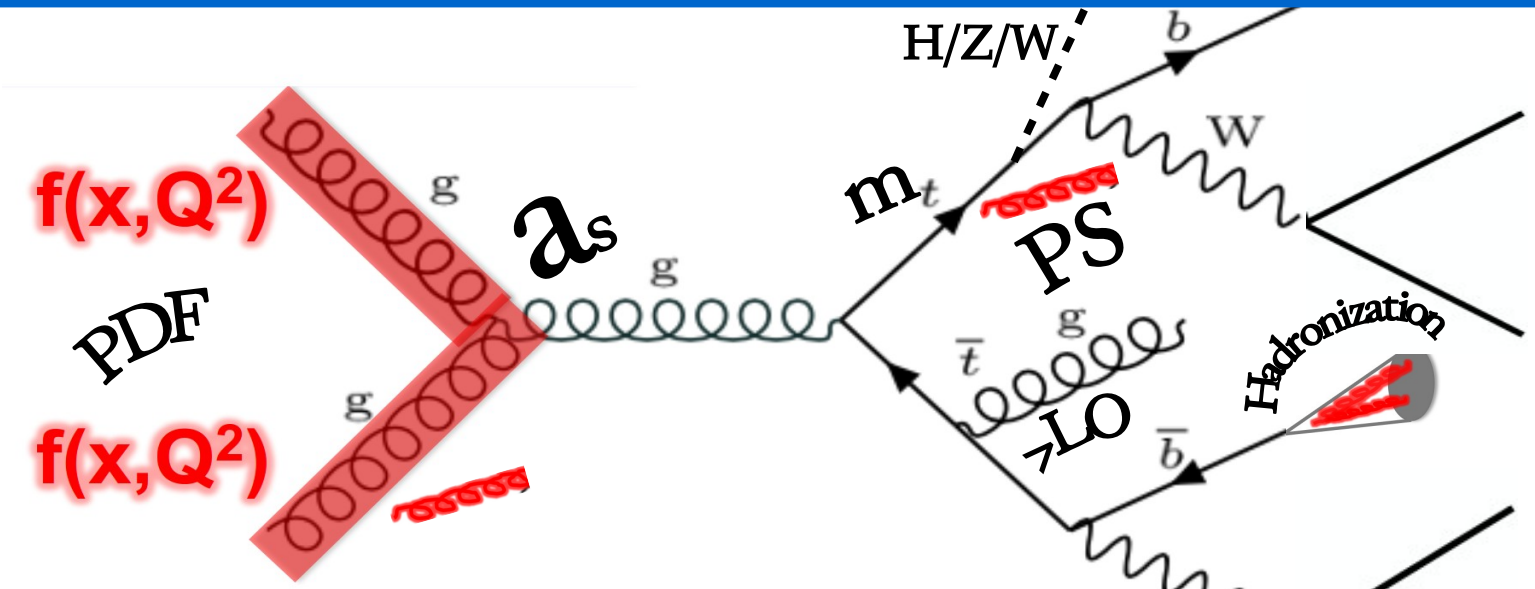


Excellent S/B

The lowest BR

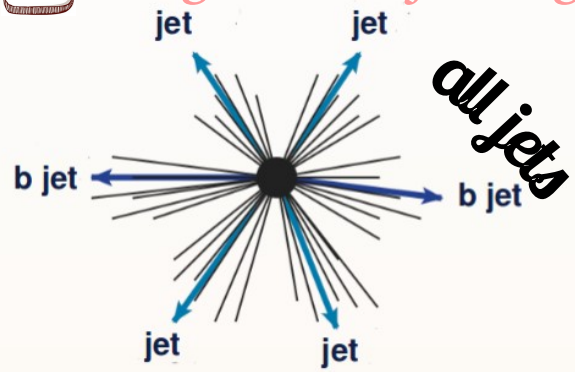


The dominant top quark production @ LHC; ggF(usion)



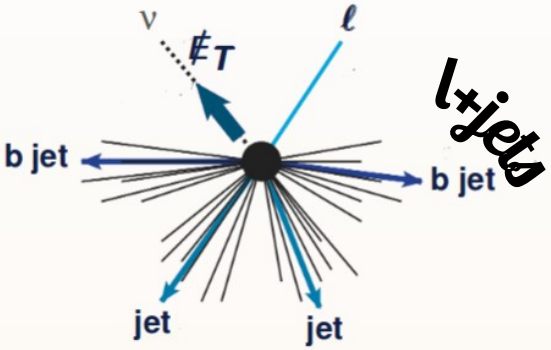
The highest BR

Large multi-jet bkg.



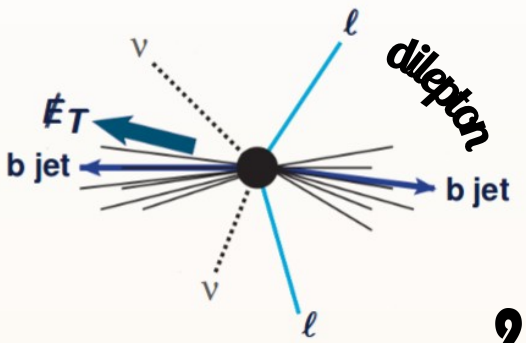
High BR, good S/B

W+jets bkg.



Excellent S/B

The lowest BR



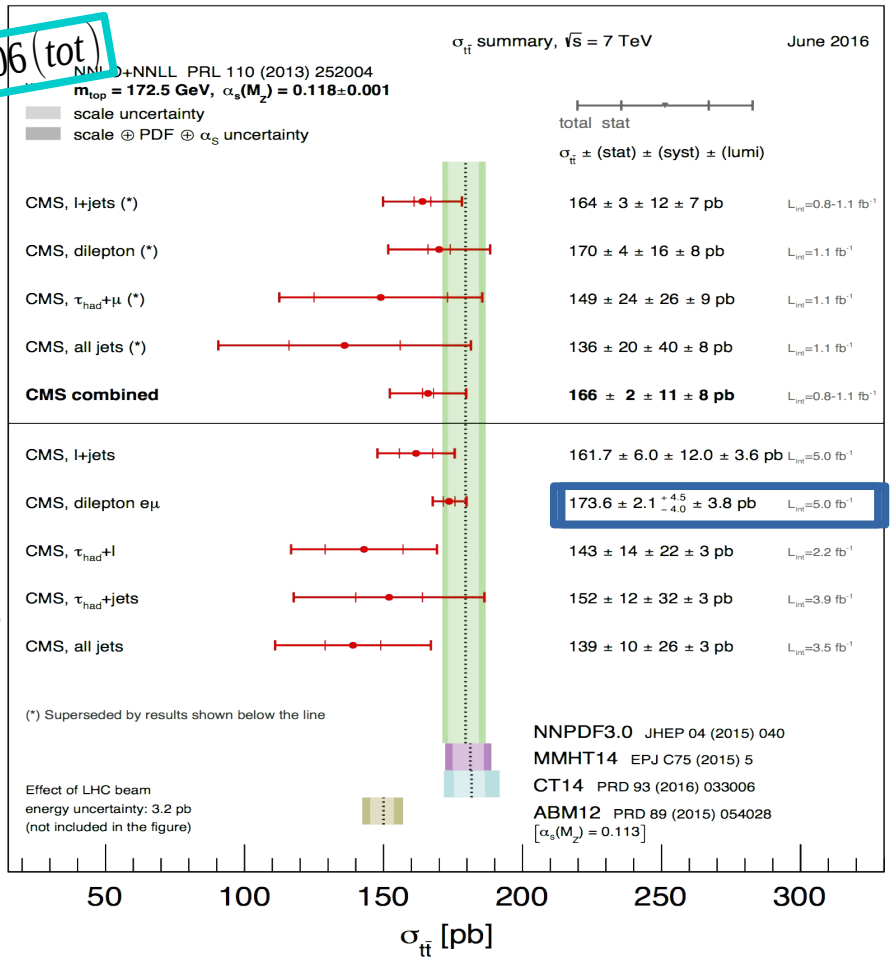
Pinning down uncertainties to NNLO+NNLL precision !

Run1

- from the very first measurement @ 7 TeV with **33%** tot. unc.
- to the Run1 legacy with **3.7%** tot. unc. in $e\mu$ due to
  - lepton identification (ID), DY contamination and lumi.
- to the **60% reduction** of JES impact in l+jets *in-situ*

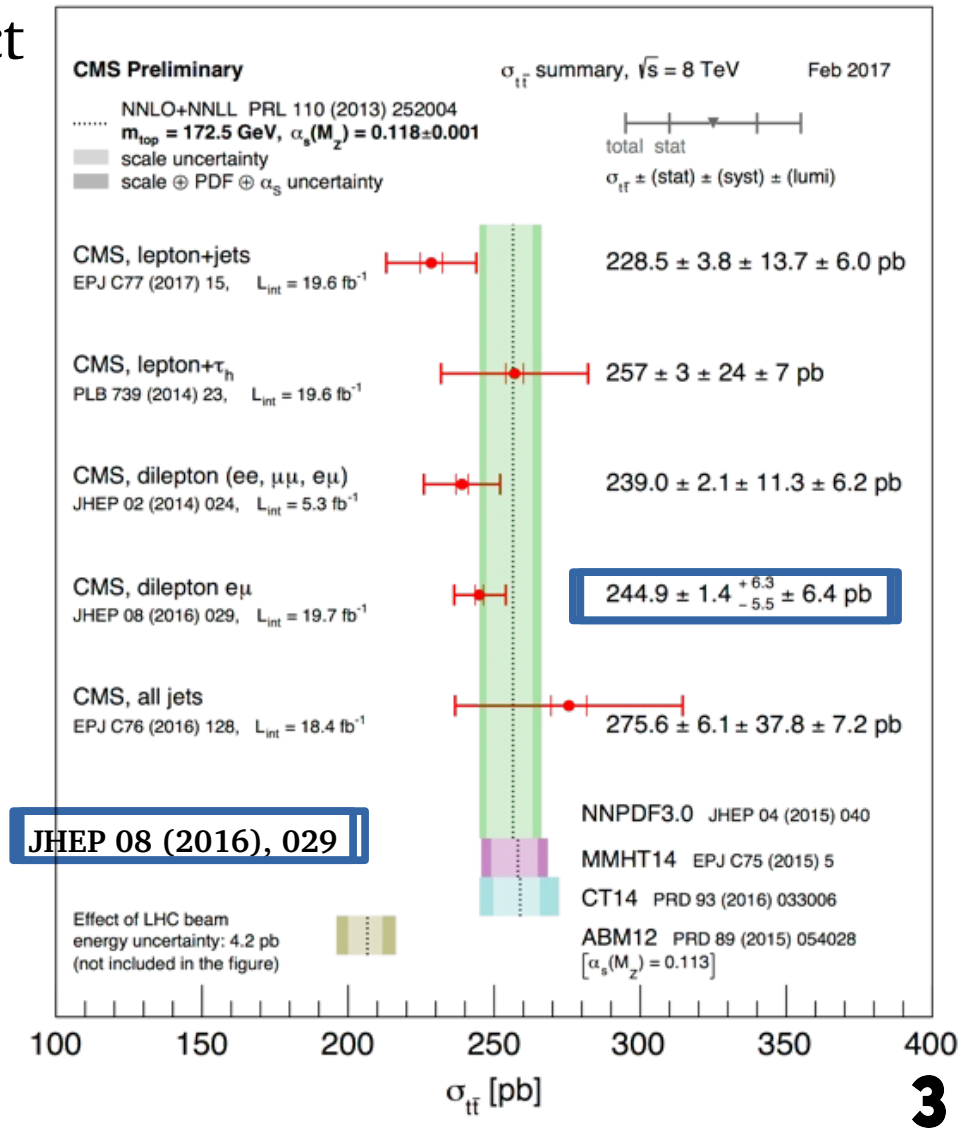
$R_{8/7} = 1.41 \pm 0.06\,(\text{tot})$

7 TeV



Consistent with QCD predictions

8 TeV

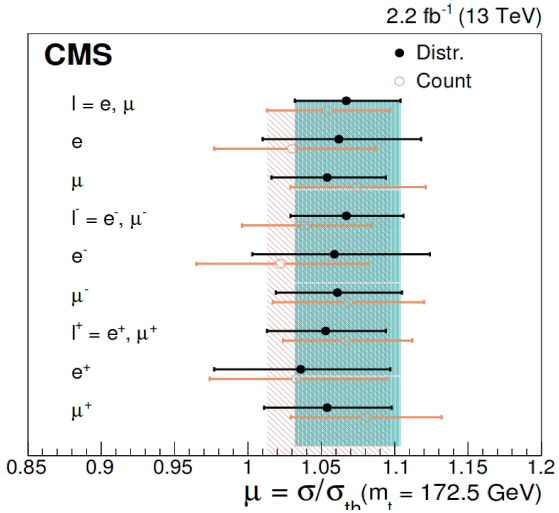


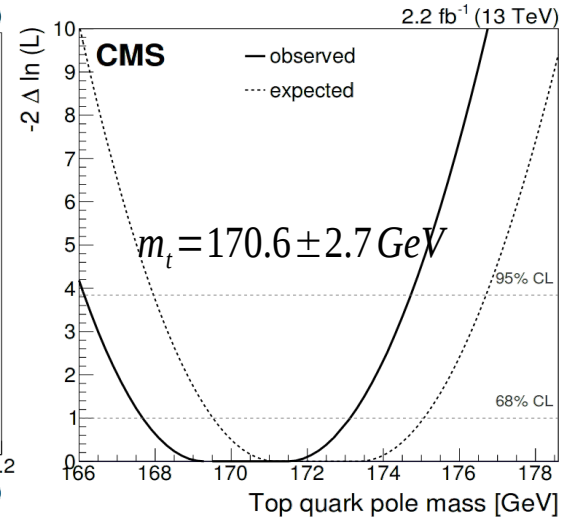
Continue the exercise with enchained (×4) *tt* production

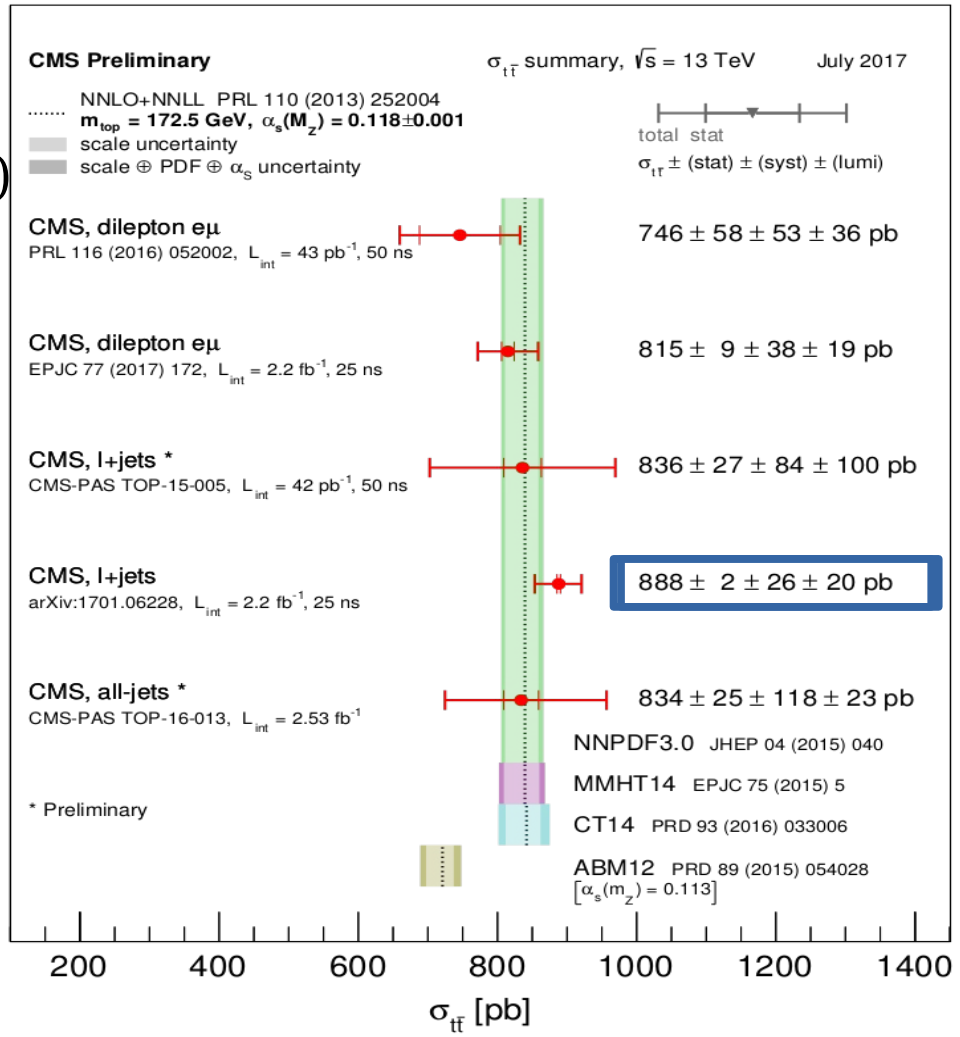
- already from the first 42pb-1 of eμ and *l*+jets data @ 13 TeV
  - **all** channels **updated** with the 2015 dataset, dominated by
  - lepton ID, JES and lumi. in eμ
  - *b*-tagging and JES in *all jets*
- reaching **3.9%** tot. unc. in *l*+jets
  - in-situ constraints of syst. with
  - lumi. being the dominant (& W+jets)
  - extraction of $m_t(pole)$

Run2

JHEP 09 (2017), 051

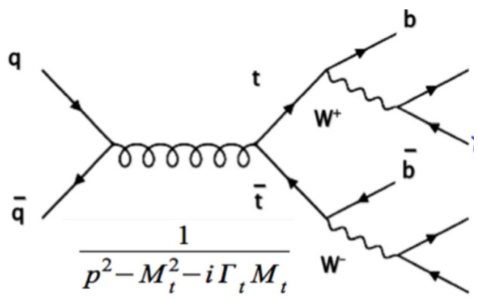




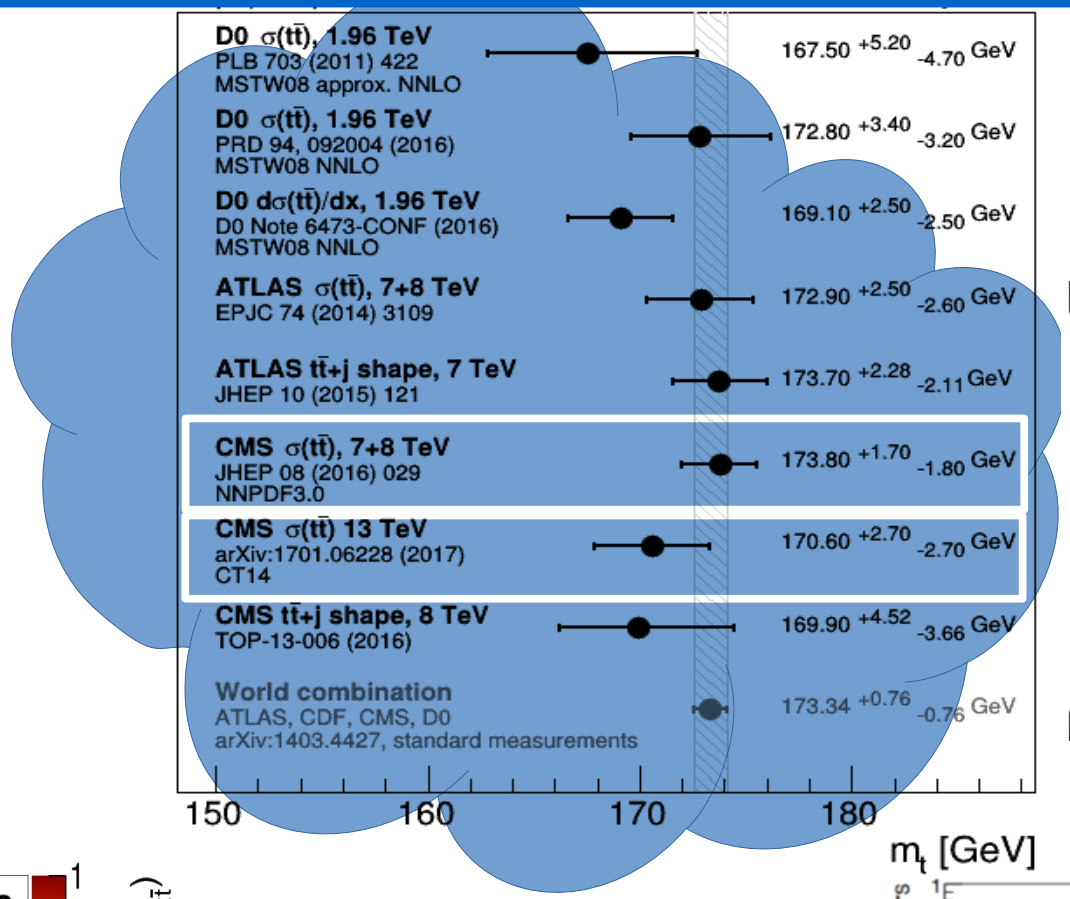


QM textbooks: mass and width defines a particle

Run1/2 & Beyond

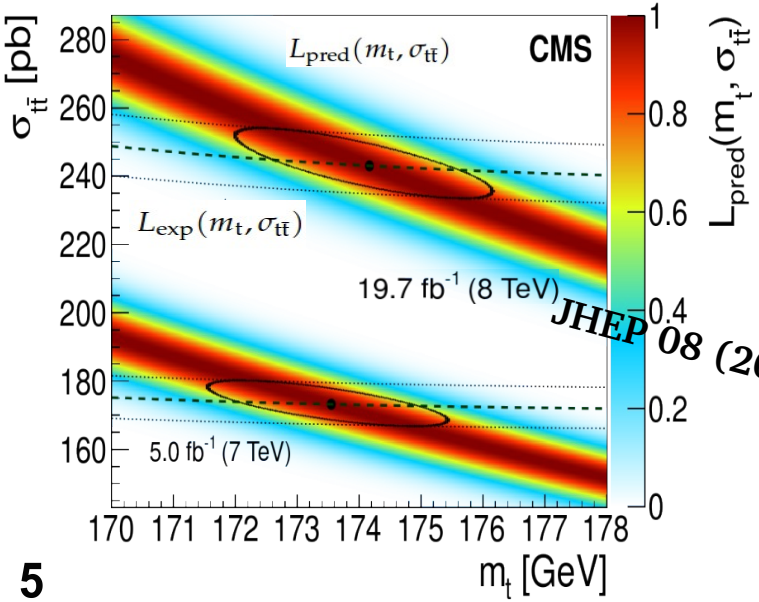


Pole mass:
***A* well defined parameter**
(not unique)



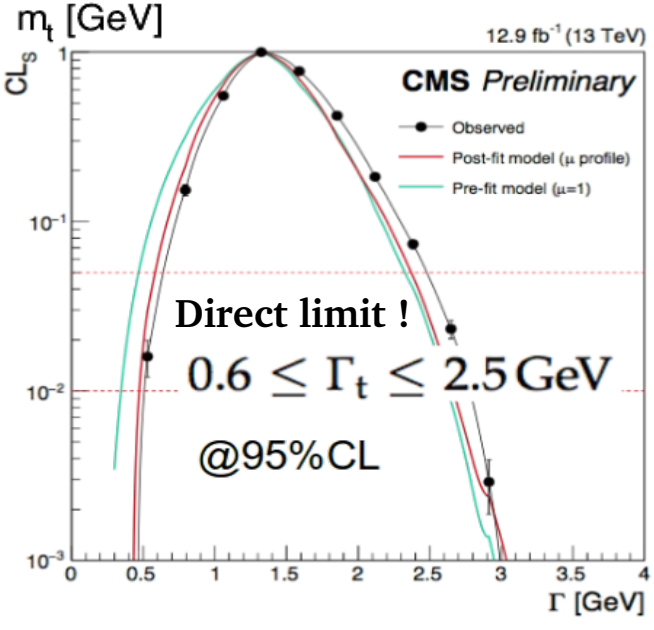
HL-LHC: 1% precision (FTR-16-006)

TOP-16-019



Maximize predicted*measured likelihoods

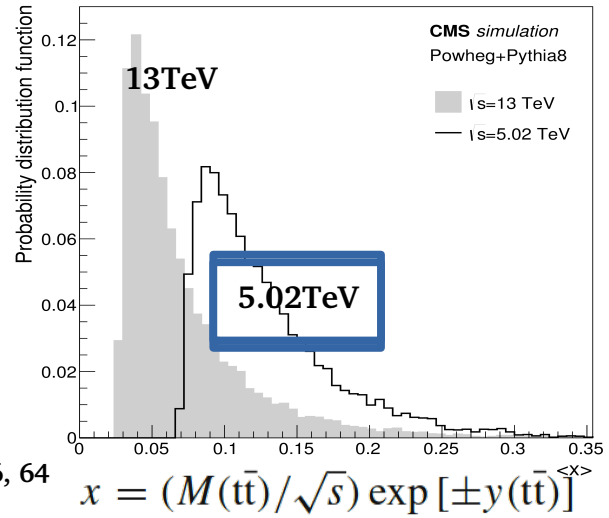
	m_t [GeV]
NNPDF3.0	$173.8^{+1.7}_{-1.8}$
MMHT2014	$174.1^{+1.8}_{-2.0}$
CT14	$174.3^{+2.1}_{-2.2}$



The only measurement at an interesting corner in √s evolution

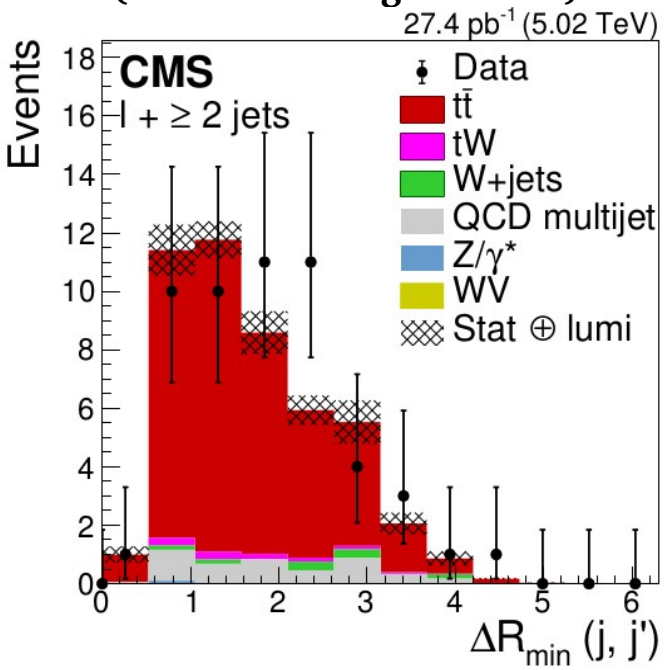
Run2

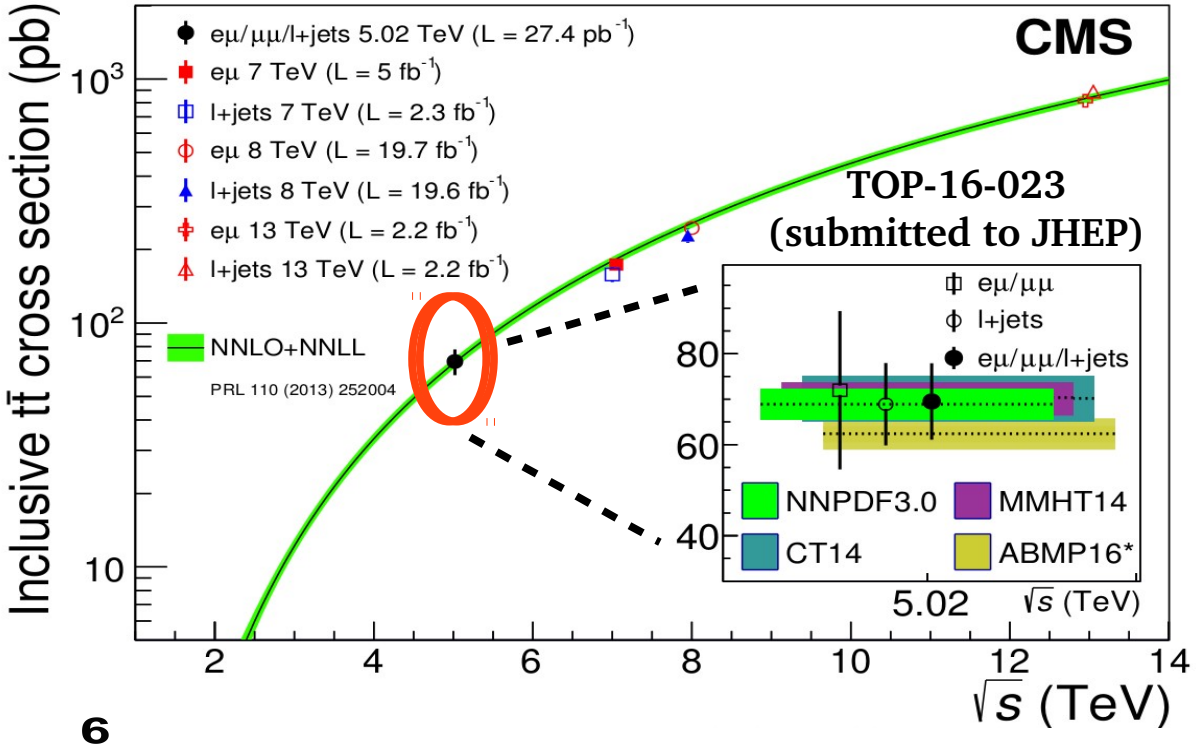
- achieved **only with** 6 low pileup fills resulting in a **12%** tot. unc.
  - in l+jets and eμ, $\mu\mu$ channels
  - stat. ≈ syst. unc. for the combined result
- potential to **constrain** poorly known high-x gluons
  - larger $\langle x \rangle$ of the incoming partons
- serve as a **reference** for tt in *hot* QCD



D. d'Enterria et al, Phys.Lett.B 746, 64

Angular distance of least separated jets (Discriminating variable)



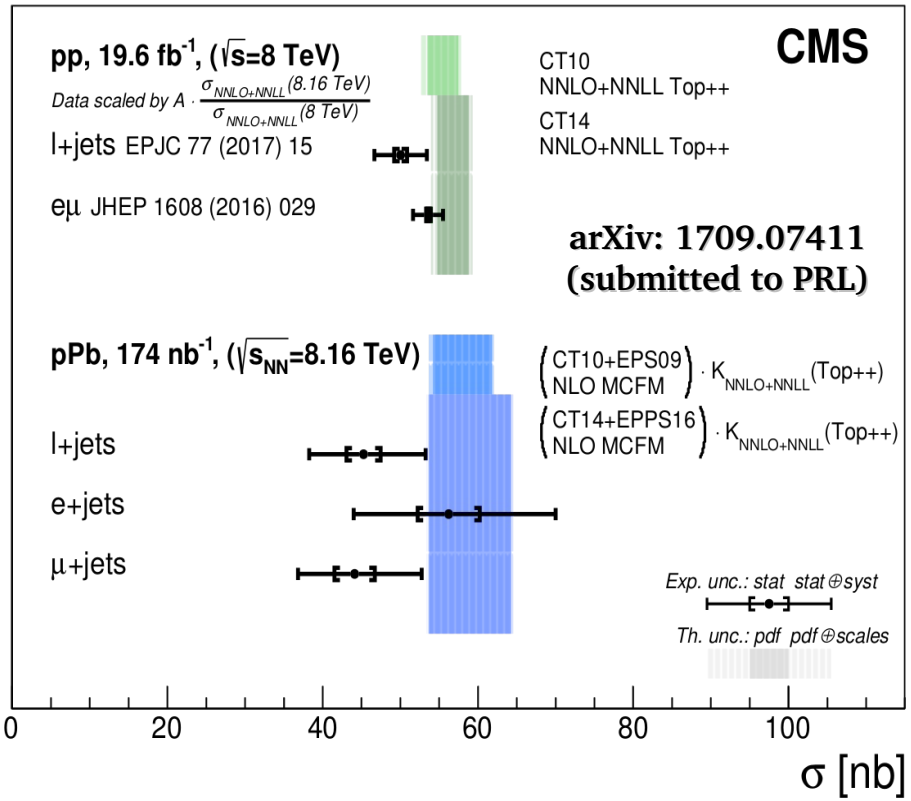


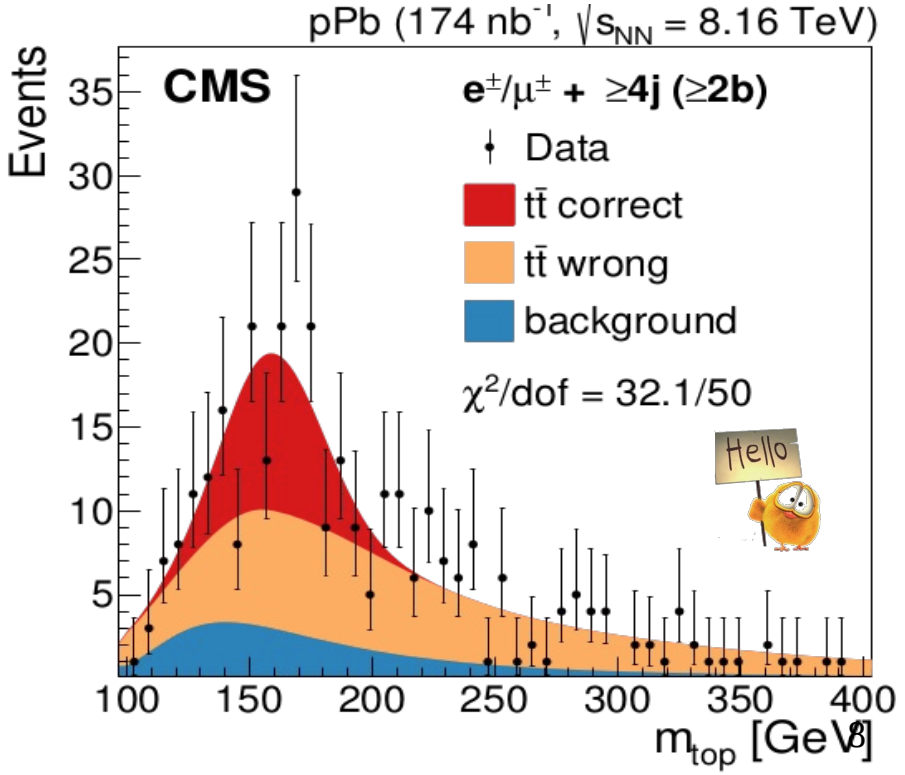
Up-to-date compilation: 4 $\sqrt{s_{NN}}$ & 2 systems @ LHC !

- First experimental **observation** of the top quark in nuclear collisions

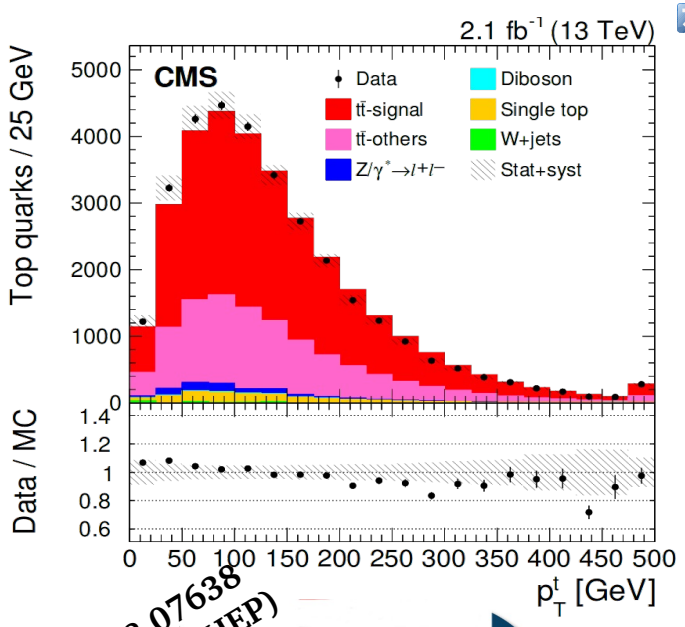
Run2

  - σ_{tt} measured in two independent decay channels i.e., μ,e+jets
    - $d\sigma_{tt} / \sigma_{tt}$ = **17%** in the l+jets
    - **consistent** with the scaled pp data as well as pQCD calculations
- **Minimally** rely on assumptions from MC simulation
  - paves the way for the study in AA collisions





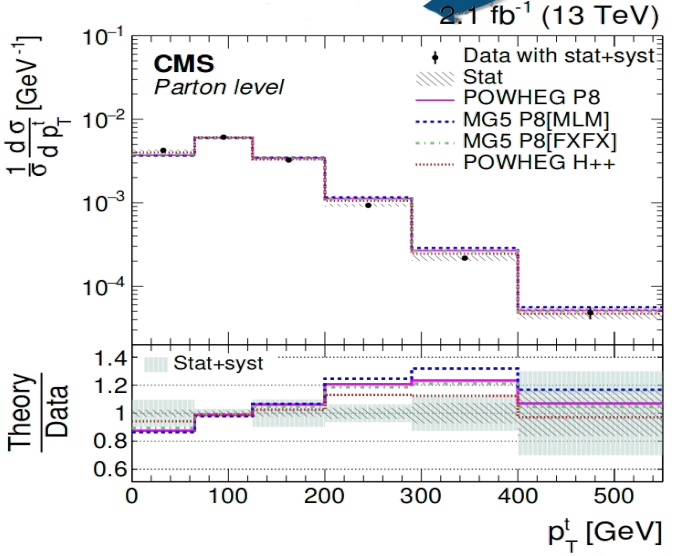
Increasing interest in (→ variety of) differential studies



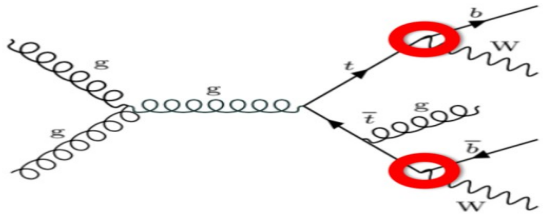
arXiv:1708.07638 (submitted to JHEP)

Δ^i_X = bin width for variable X

$$\frac{d\sigma}{dX_i} = \frac{\sum_j A_{ij}^{-1}\left[(N_{\mathrm{data,j}} - N_{\mathrm{BG,j}})\right]}{\Delta_{X_i} \cdot L}$$



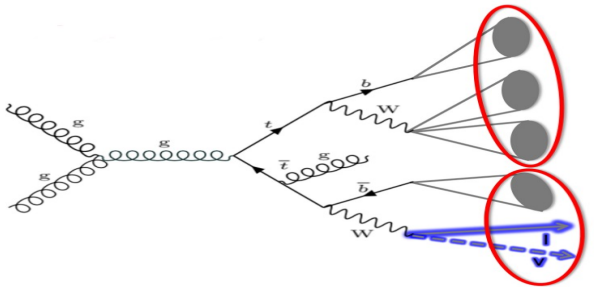
- Bin-wise cross section measurements
  - corrected for detector effects, acceptance & selection efficiency
  - regularize stat. fluctuations (limit bin migration effects)
  - finally get absolute or normalized values
    - normalization: mostly shape uncertainties contribute



Parton level:

Top quark after hadronization but before decay

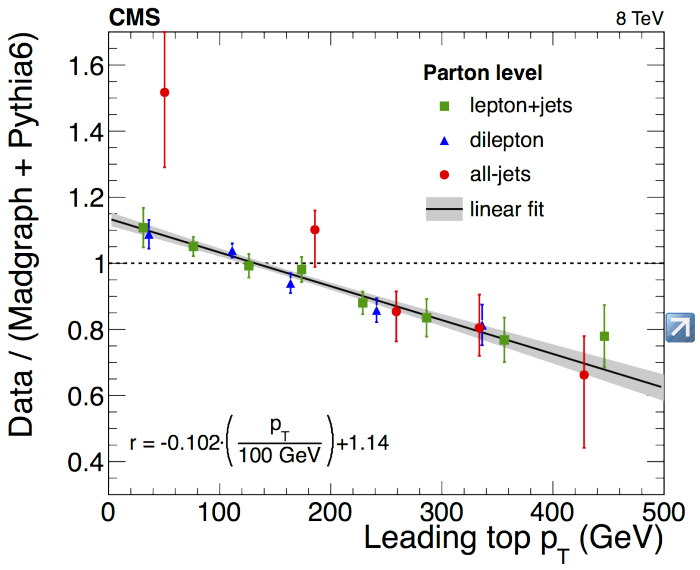
CMS-NOTE-2017-004



Particle level (i.e., well-defined objects in simulations):

Top quark *proxy* from decay products

All measurements reveal consistent patterns !



Comparisons with **all** channels to **LO/NLO+PS MCs** reveal

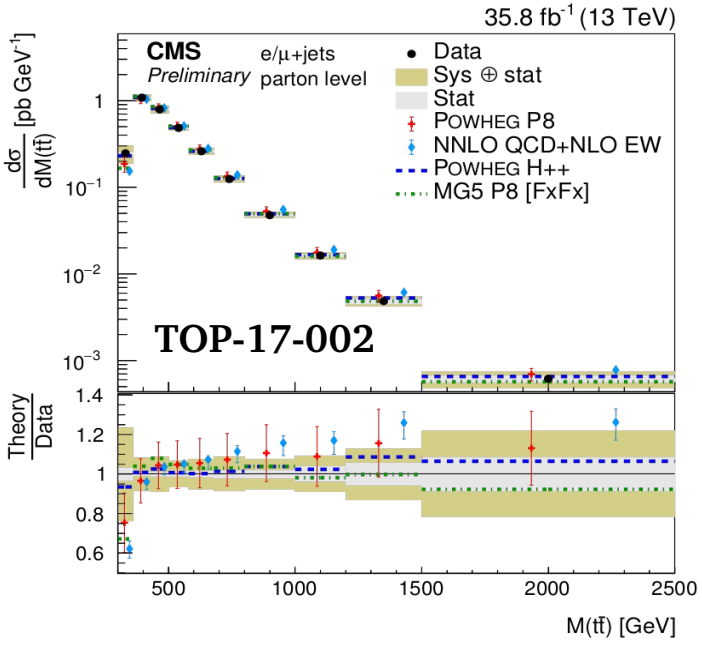
- overall good agreement, though spotted
- lepton p_T slightly softer and b-jet η less central in data
- top p_T softer and m_{tt} tails lower in data

Run1/2

Results in multiple **√s** and **final states**

- global event variables
- jet kinematics and multiplicities
- boosted regime and double-differential (2D)

Better agreement with NNLO QCD

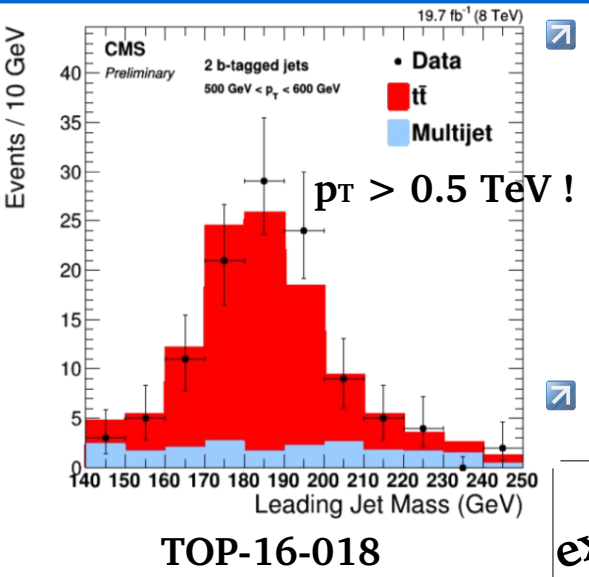


all = all jets
lj = 1+jets
ll = dilepton

	Full Phase Space			Fiducial Phase Space		
Objects	Parton level			Particle level		
	7	8	13	7	8	13
Top, $t\bar{t}$	(lj,ll)	(all,lj,ll)	(all,lj,ll)		(all,ll)	(all*,lj,ll)
Boosted top		(all,lj)	(all)		(all,lj)	(all*)
Final state (leptons, b-jets)			(ll)	(lj,ll)	(all,lj,ll)	(ll)
Global event (E_T^{miss}, H_T, …)	(lj)	(lj)				(lj)
$t\bar{t}$+jets				(lj,ll)	(lj,ll)	(lj,ll)
Single top (t-channel)						

* detector level

Boosted regime already complementary to resolved !



p_T > 0.5 TeV !

TOP-16-018

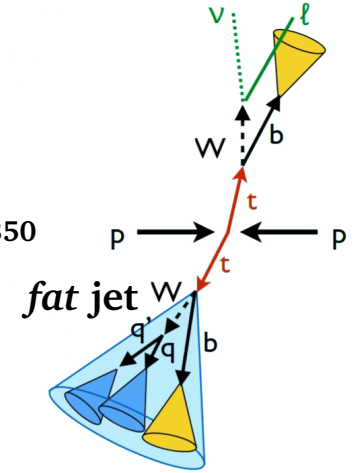
- top decay is reconstructed within a single-R (*fat*) jet of $R \geqslant 0.8$
  - **jet substructure** techniques that are evolving
  - in past: m_{inv} of subjets + CMS/HEP Top *tagger*
  - **in present**: soft Drop m_{inv} + τ_i + subjet b-tagging (+PUPPI)
- theoretical unc. dominate

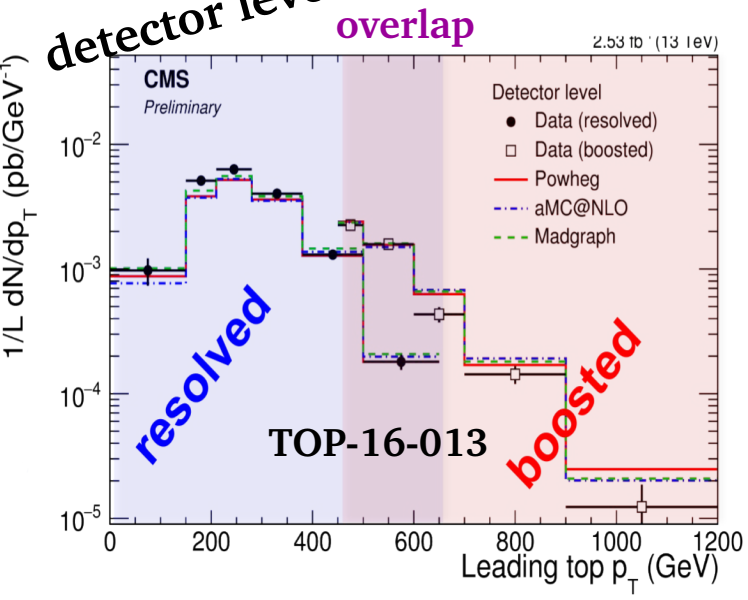
exp.

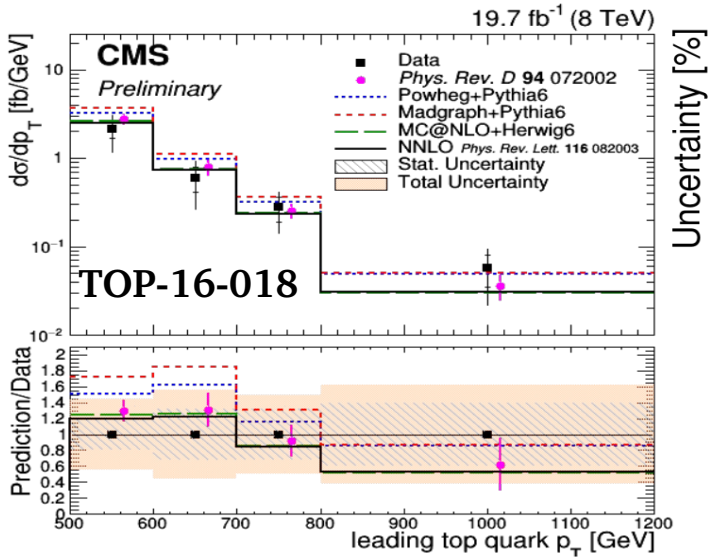
- *t-*/*b*-tagging efficiency
- JES and bkg. modeling
- **NNLO QCD** confirms observations

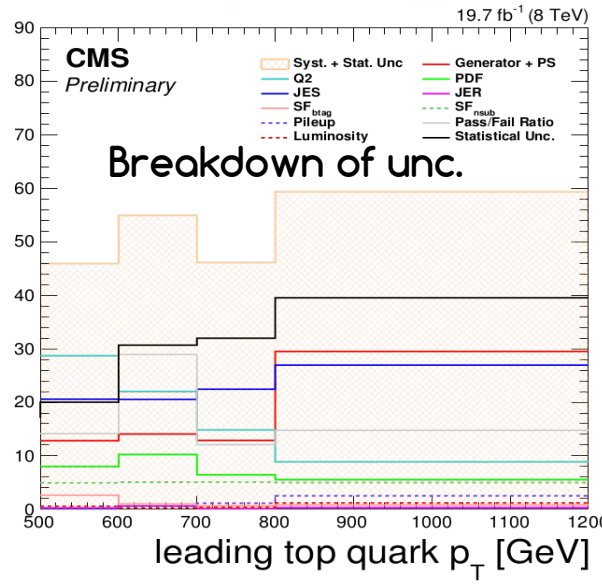
Run1/2

M.Czakon *et al*, arXiv:1606.03350



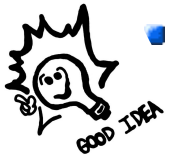




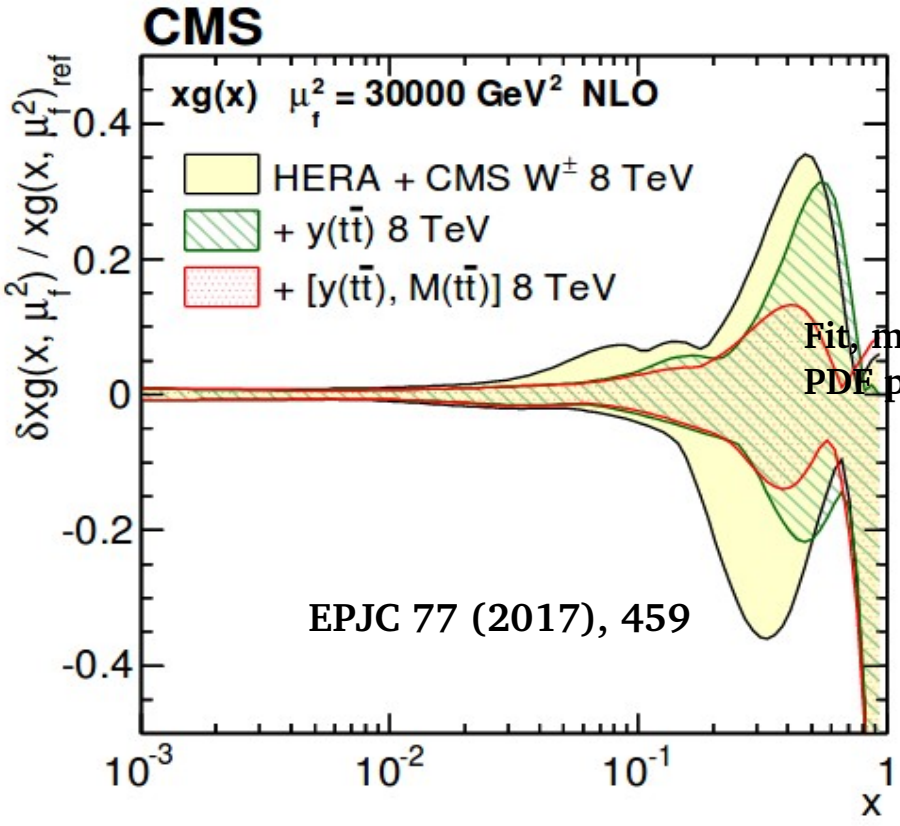


PDFs a crucial input for hadron hadron collisions

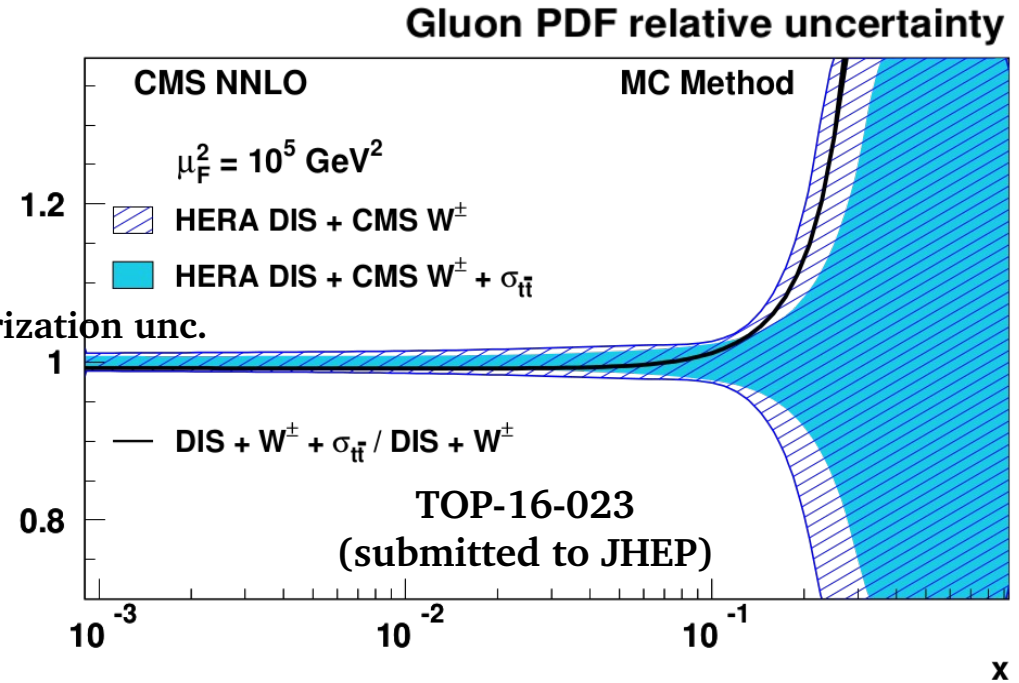
- *tt* production mainly through ggF → sensitivity to gluon PDF



  - bin *tt* events per two variables, e.g. m_{tt} vs y_{tt}, and make combinations sensitive to different aspects of *tt* production dynamics
    - **2D** distributions provide **stronger constraints** than 1D
- gluon PDF unc. reduced by a **factor 2** at $x \sim 0.3$ (largest impact)
  - Nominal samples: combined HERA inclusive DIS and $W^{\pm}$ charge asymmetry
  - utilized `xFitter` (former HERAFitter)



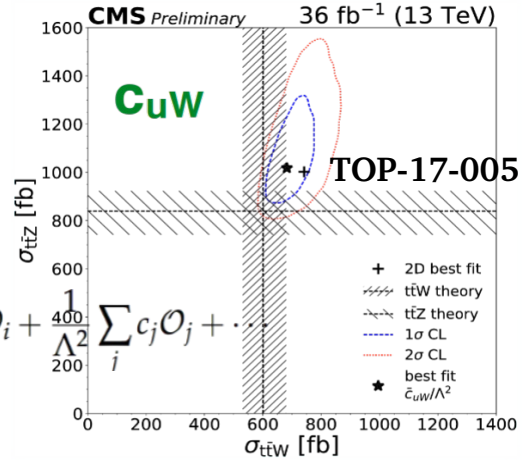
Fit, model & PDF parameterization unc.

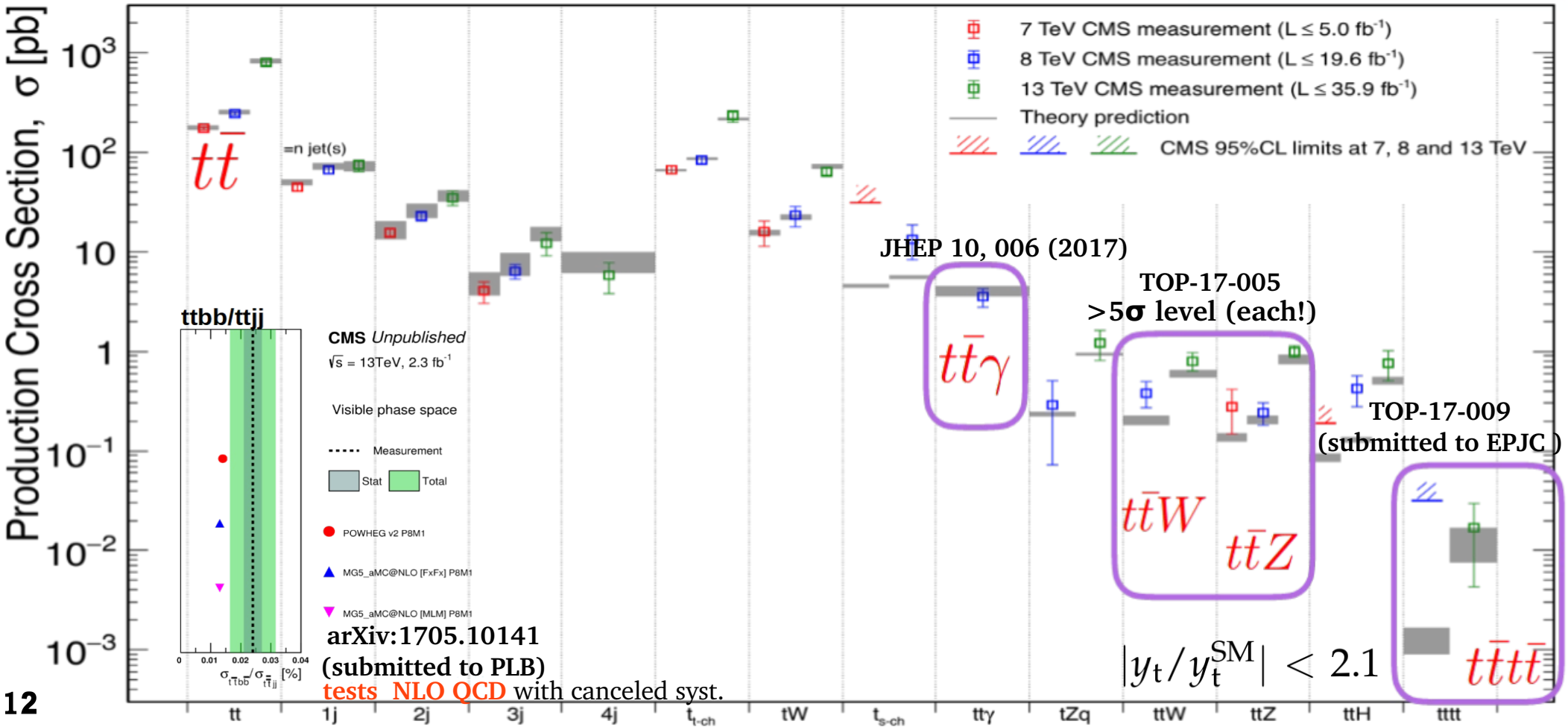


Testing the predictions for 5 orders of magnitude !

Run1/2

- **Direct** access to the EWK coupling of the top quark (tt+tt)
  - important **background** (ttV,γ,bb) for ttH measurements
- These final states can be **affected** by BSM Physics
  - interpretation in terms of e.g. EFT approach $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\sum_i c_i \mathcal{O}_i + \frac{1}{\Lambda^2}\sum_j c_j \mathcal{O}_j + \cdots$



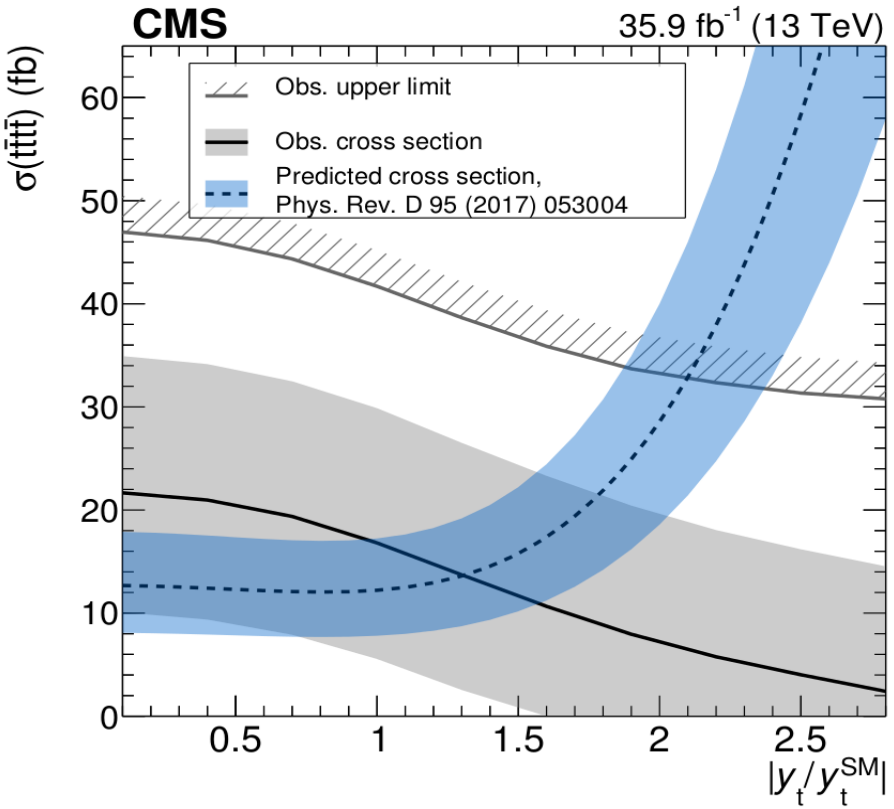


Accessing the Yukawa coupling of the top quark

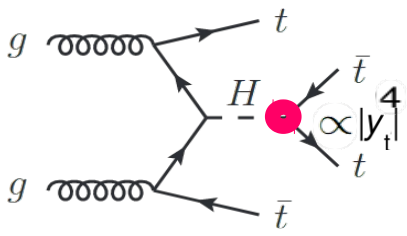
Run2

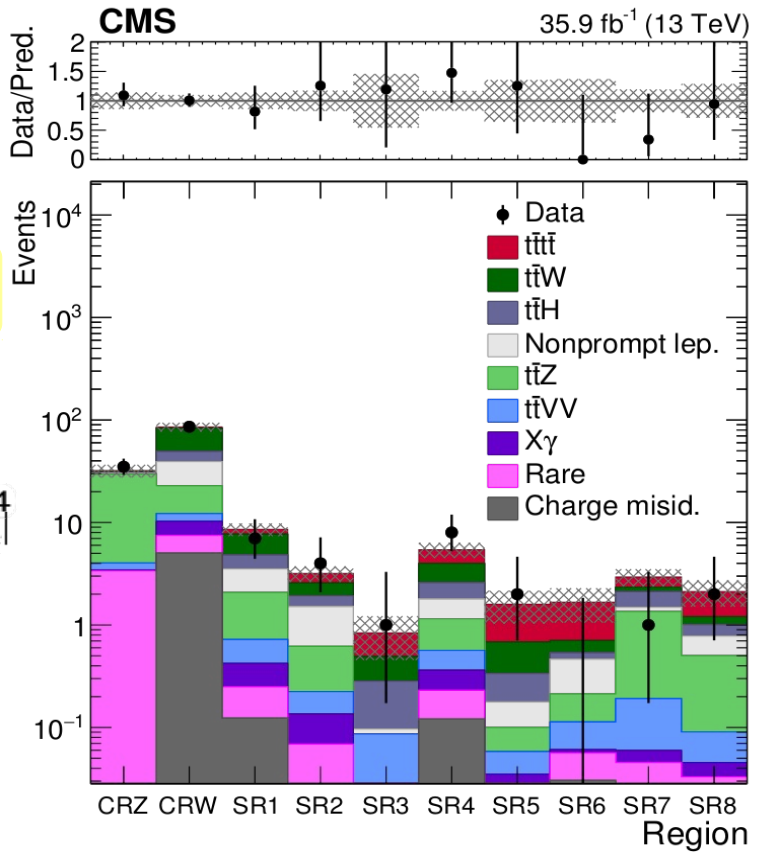
- $tt + tt$ production is rare
  - same-sign signature is similarly "rare"
- Categorize in N_j, N_b to obtain 8 signal regions (SR)
  - with 2 control regions (CR) for ttV
- Obs. (Exp.) significance: 1.6 (1.0)

N_{lep}	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

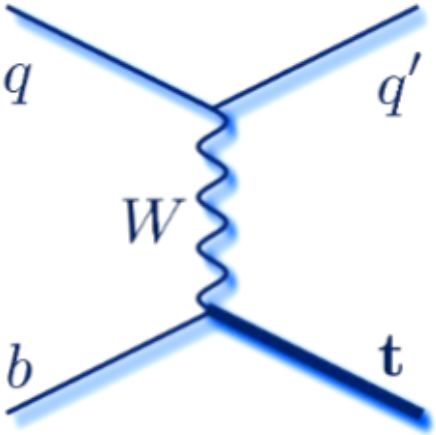


TOP-17-009
(submitted to EPJC)

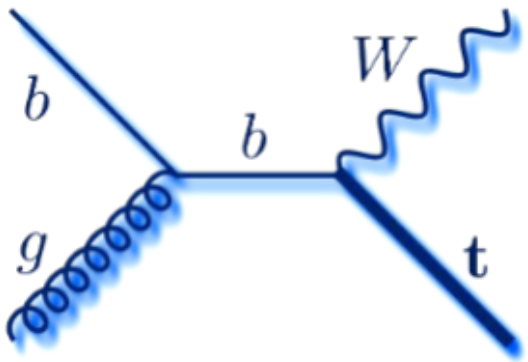




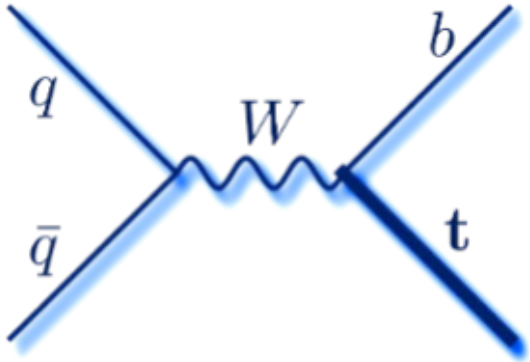
The sub-dominant top quark production @ LHC; EW



t-channel

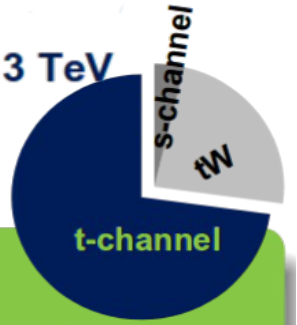


W associated producton (“tW”)



s-channel

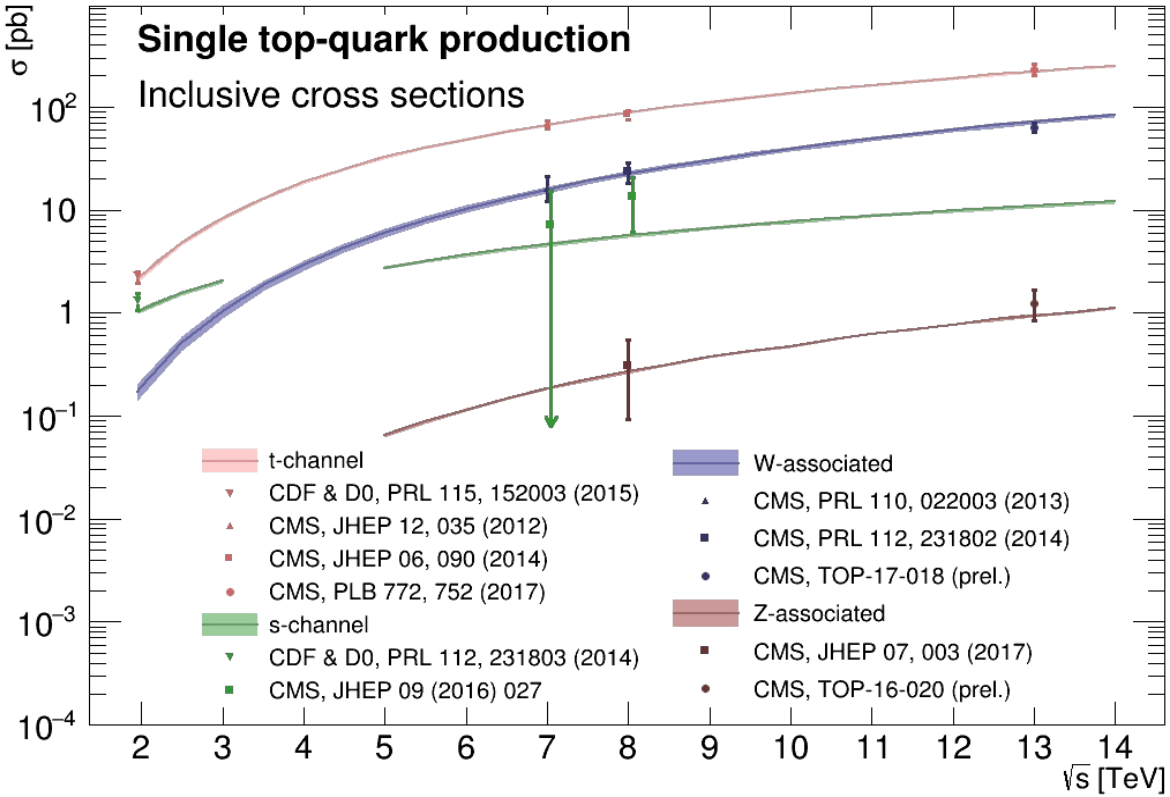
Distinct split no longer strictly valid at NLO → interfere with other processes



- ✓ Measurements of the single top production provide a **test of SM predictions**:
  - Production cross-section and direct determination of the quark mixing matrix element $|V_{tb}|$
    $\rightarrow$ Test of unitarity of the CKM matrix
  - Probe of the *b*-quark structure function
- ✓ Powerful **probe for physics beyond the SM (BSM)** related to EWSB:
  - Resonances (W',$H+$,B'), vector-like quarks, anomalous couplings.
- ✓ Significant **background** in search for Higgs and several expected BSM processes

Inclusive & differential results in multiple channels and √s !

Run1/2

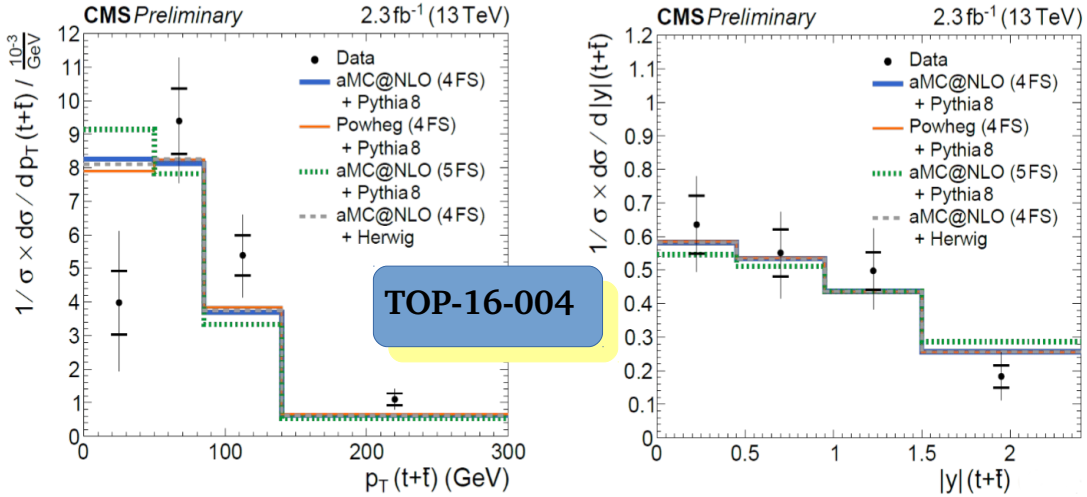


Neural Network → $|V_{tb}| = 1.05 \pm 0.07$

Boosted Decision Trees (BTDs) → 10% unc.

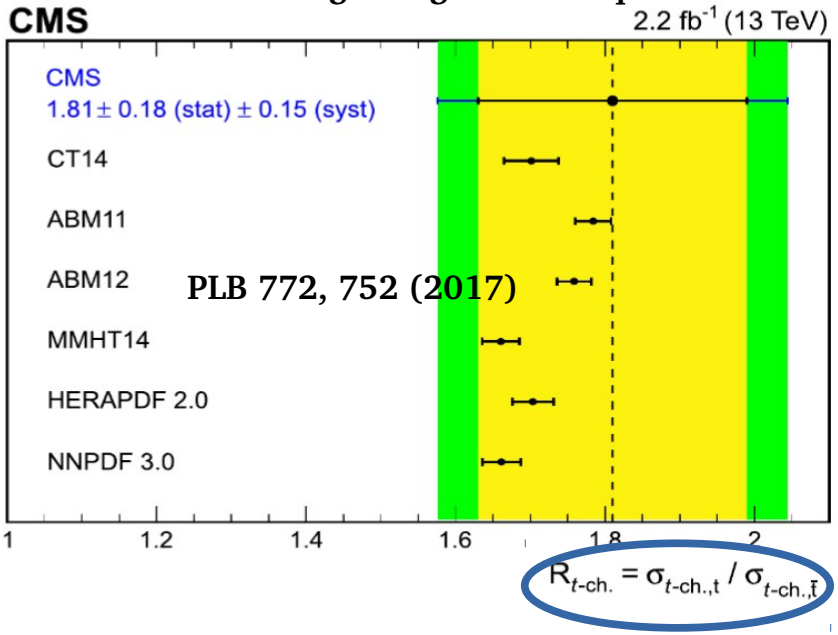
BDTs obs.(exp) $2.5\sigma(1.1\sigma)$

Matrix Element + BDTs → obs.(exp) $3.7\sigma(3.1\sigma)$



TOP-16-004

Start "grazing" valence quark PDFs

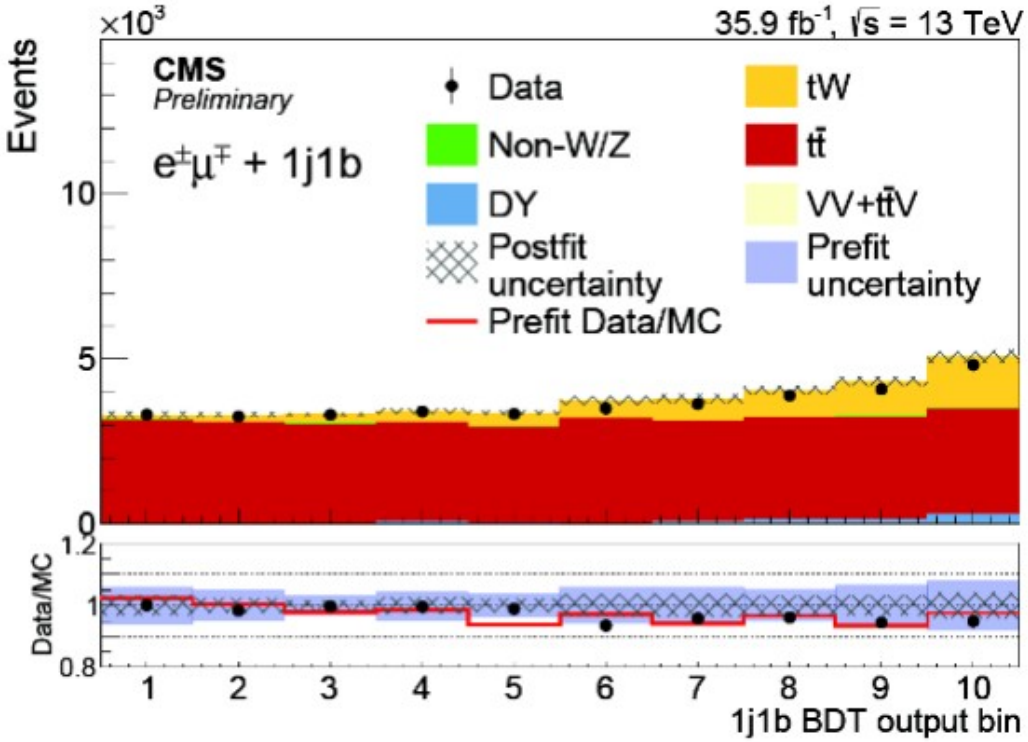


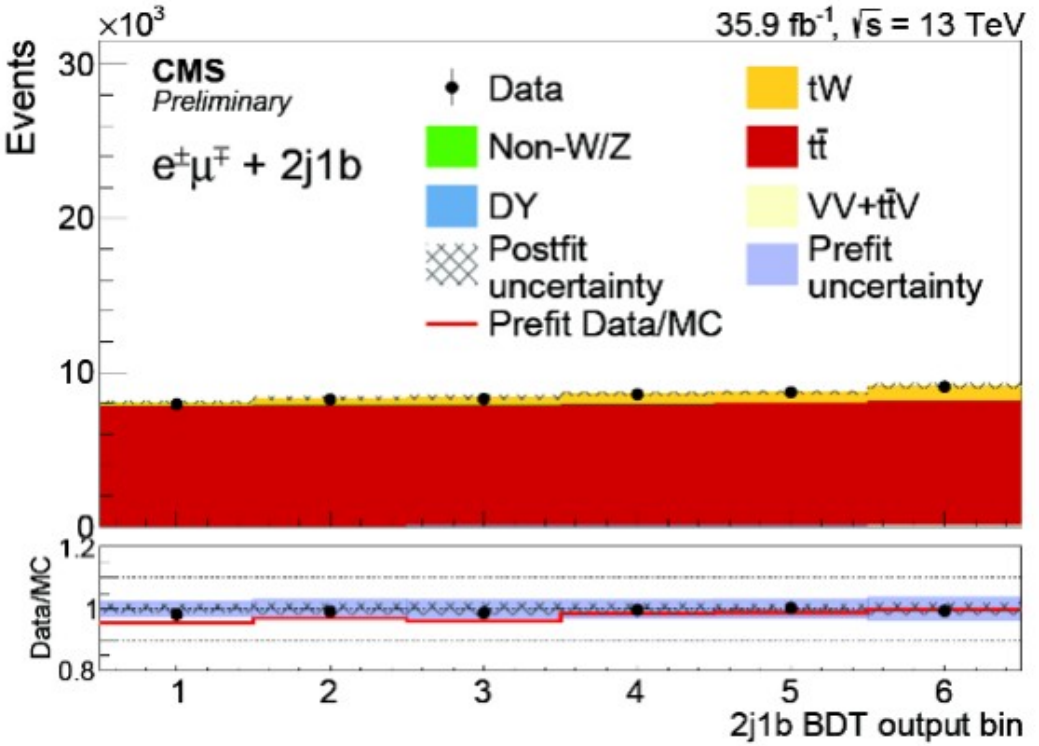
Thanks to MVA techniques, dominant channels already syst. limited !

tW cross section at 13 TeV using the entire 2016 dataset !

- signal strength (exp./obs.) measured through ML fit to BDT
  - in 1j1b, 2j1b & 2j2b (p_T of subleasing jet) event categories

Run2





- uncertainties
  - experimental (profiled): statistics (2.8%), pileup (3.3%), jet energy scale (3.2%), electron/muon efficiencies (3.3%/3.1%) trigger efficiencies (2.7%), ...
  - theoretical: Q scale (2.7%), color reconnection (2.0%), ME/PS matching (1.8%), ...

TOP-17-018

result

$$\sigma_{\mathrm{tW}} = 63.1 \pm 3\%\ (\mathrm{stat.}) \pm 9\%\ (\mathrm{syst}) \pm 3\%\ (\mathrm{lumi})\ \mathrm{pb}$$

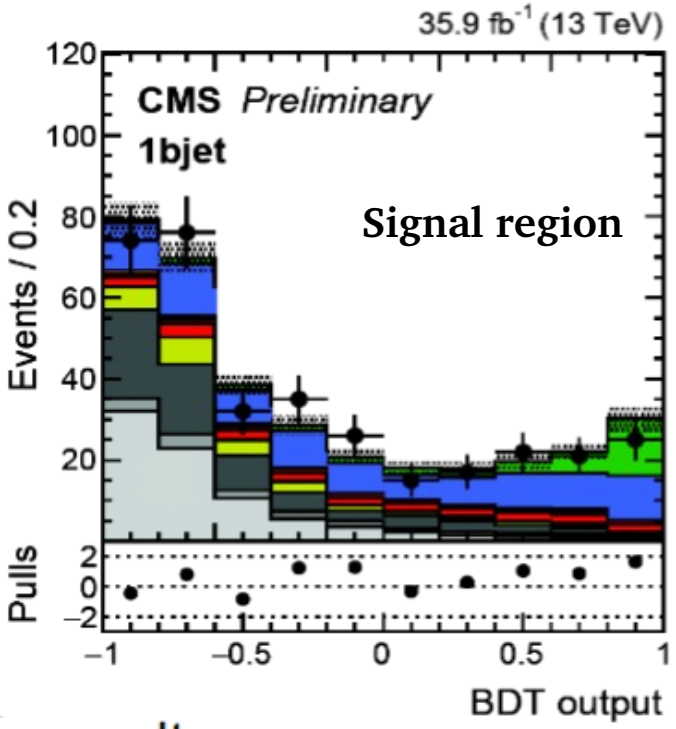
$$\sigma_{\mathrm{tW}} = 63.1 \pm 6.6\ \mathrm{pb}$$

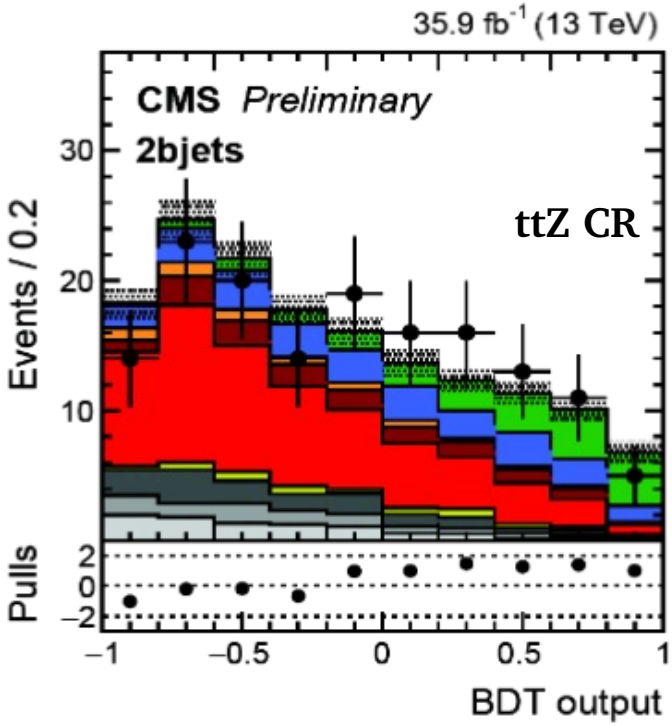
$$\left[\sigma_{\mathrm{tW}}^{\mathrm{SM}} = 72 \pm 2\ (\mathrm{scale}) \pm 3\ (\mathrm{PDF})\ \mathrm{pb}\right]$$

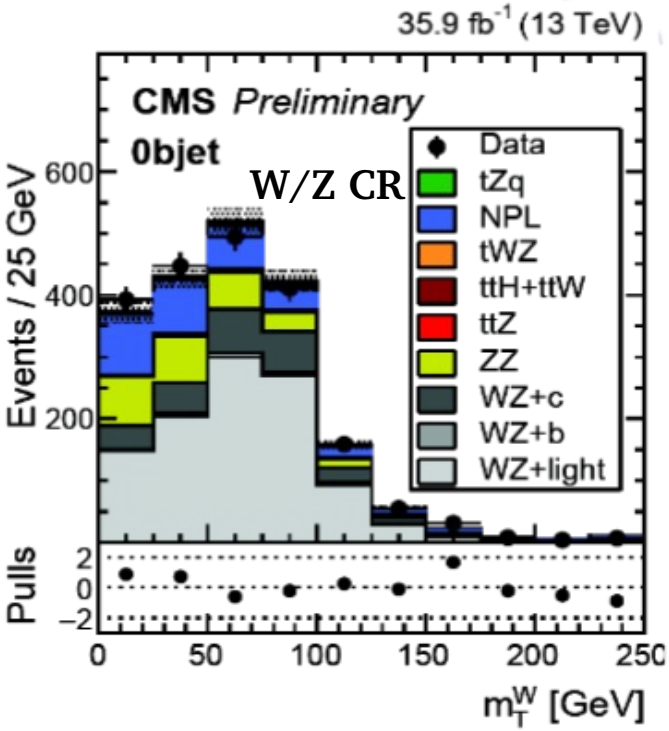
Evidence of the associated production with a Z boson !

Run2

- ML fit observables: (0,1,≥2 b) × (eee, eeμ, eμμ, μμμ)







- result
  - signal strength

$$\mu = 1.31^{+0.35}_{-0.33}\,(\text{stat})^{+0.31}_{-0.25}\,(\text{syst})$$ → dominated by statistical uncertainties

  - cross section

$$\sigma(\text{t}\ell^+\ell^-\text{q}) = 123^{+33}_{-31}\,(\text{stat})^{+29}_{-23}\,(\text{syst})\ \text{fb}$$ $$\left[\sigma^{\text{SM}}_{\text{tZq}} = 94 \pm 2\,(\text{scale}) \pm 3\,(\text{PDF})\ \text{fb}\right]$$

$(m_{\ell\ell} > 50\ \text{GeV})$

TOP-16-020

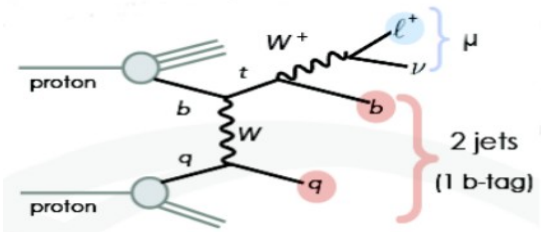
- significance

  3.7σ observed (3.1σ expected)

Measuring the top mass with single top events !

Run2

- Template method based on m$\ell\nu b$
  - a proxy for the reco. top mass
- Measurement syst. dominated
  - JES, bkg. and calibration to gen. top mass



Main systematics

source	GeV
JES	0.68
bkgd	0.39
fit calibration	0.39

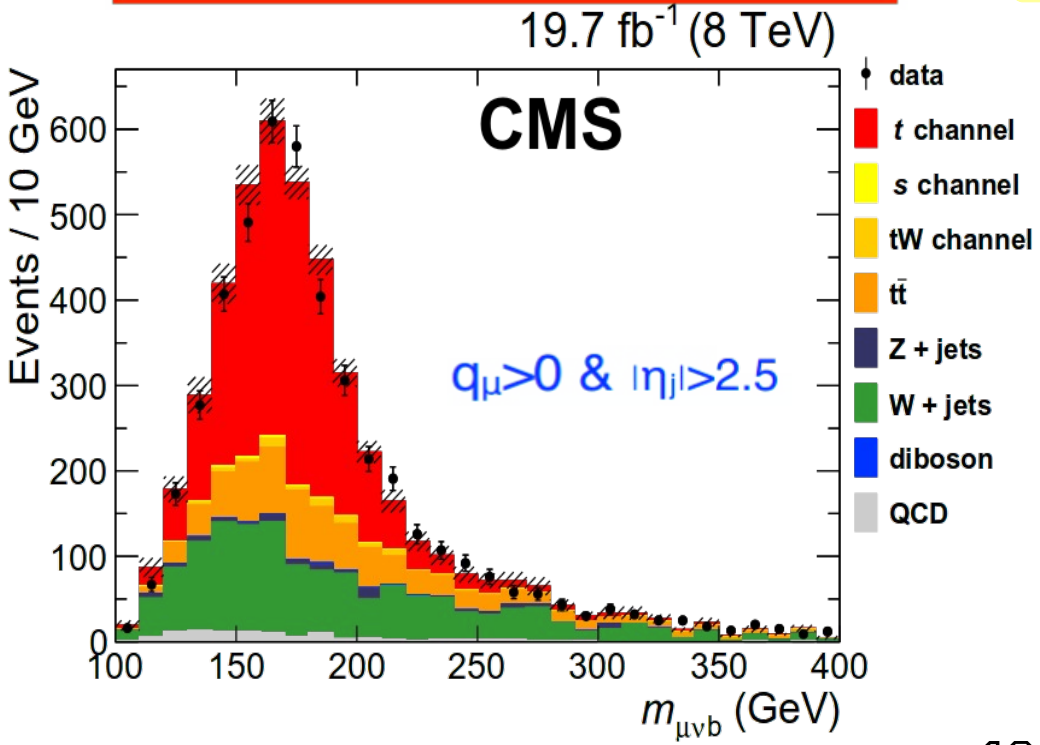
Fit

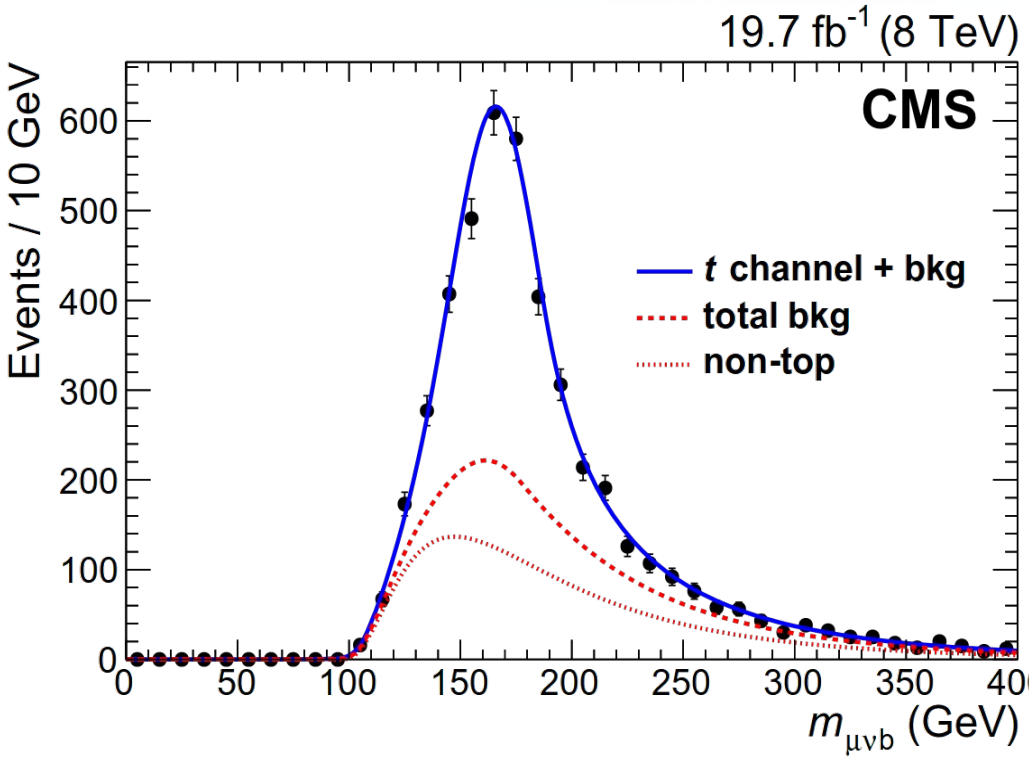
M_t=172.95±0.77(stat)+0.97−0.93(syst) GeV

M_t=172.95±1.24 GeV (±0.72%)

EPJC 77 (2017), 354

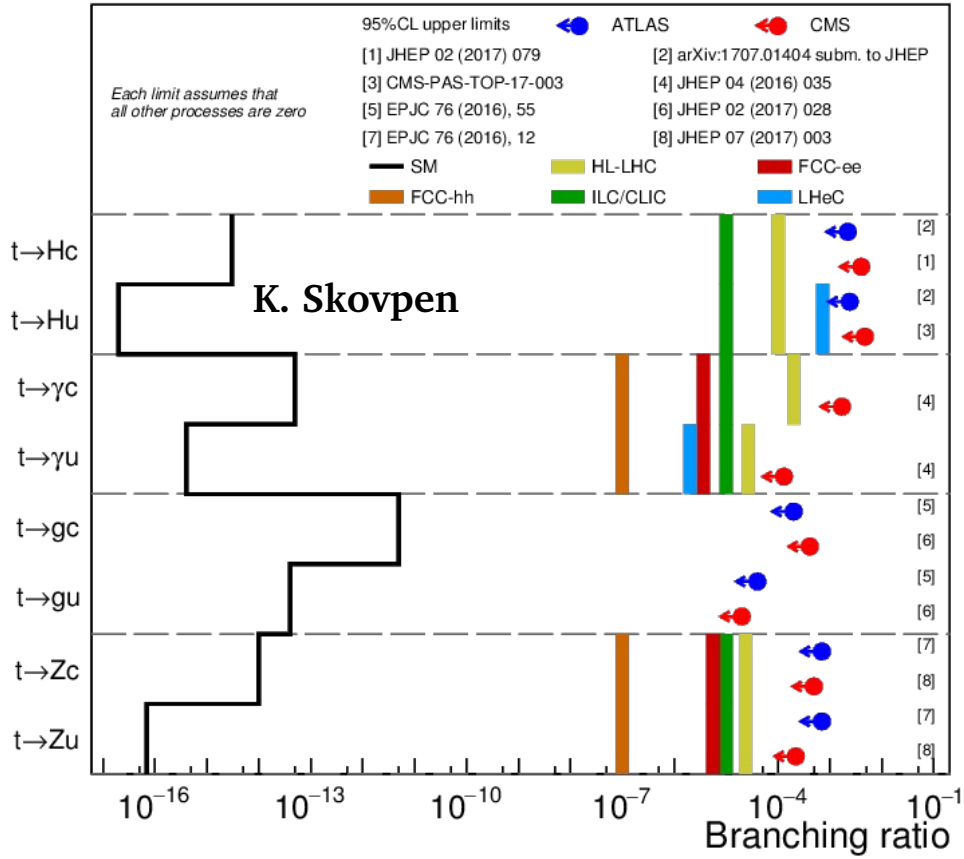
Gaussian core (μ,σ)+ tails:
- t: Crystal Ball
- tt: Crystal Ball
- non-t: Novosibirsk





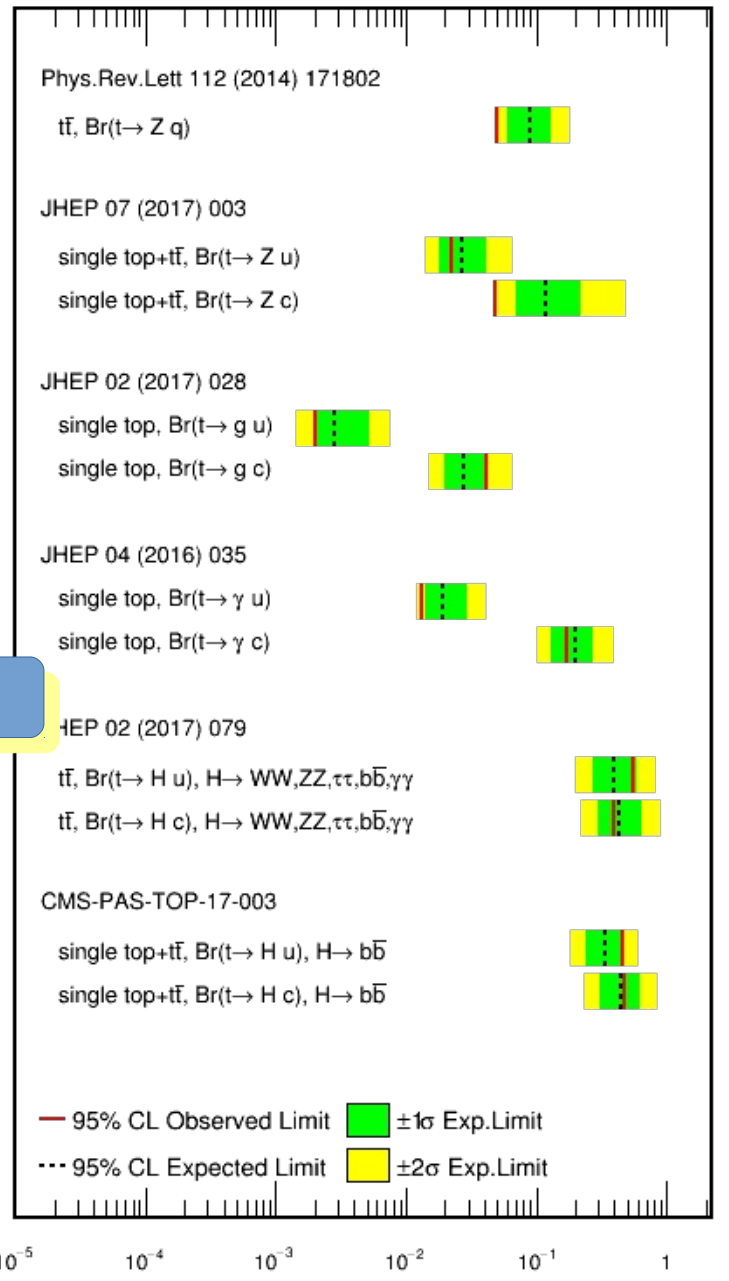
Flavour Changing Neutral Currents with top quarks

Run1/2 & Beyond

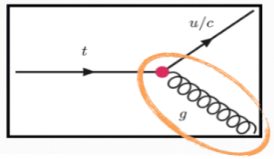


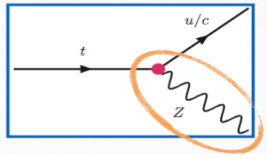
Future

Present



Top + gluon

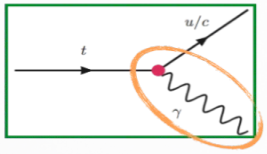


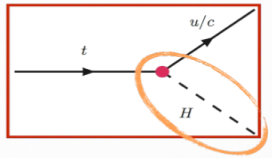


Top + Z

$$\mathcal{L} = \sum_{q=u,c} [\sqrt{2} g_s \frac{\kappa_{gqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} T_a (f_{Gq}^L P_L + f_{Gq}^R P_R) q G_{\mu\nu}^a +$$
$$+ \frac{g}{\sqrt{2} c_W} \frac{\kappa_{zqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} (f_{Zq}^L P_L + f_{Zq}^R P_R) q Z_{\mu\nu} + \frac{g}{4 c_W} \zeta_{zqt} \bar{t} \gamma^\mu (f_{Zq}^L P_L + f_{Zq}^R P_R) q Z_\mu -$$
$$- e \frac{\kappa_{\gamma qt}}{\Lambda} \bar{t} \sigma^{\mu\nu} (f_{\gamma q}^L P_L + f_{\gamma q}^R P_R) q A_{\mu\nu} +$$
$$+ \frac{g}{\sqrt{2}} \kappa_{Hqt} (f_{Hq}^L P_L + f_{Hq}^R P_R) q H] + h.c.$$

Top + gamma



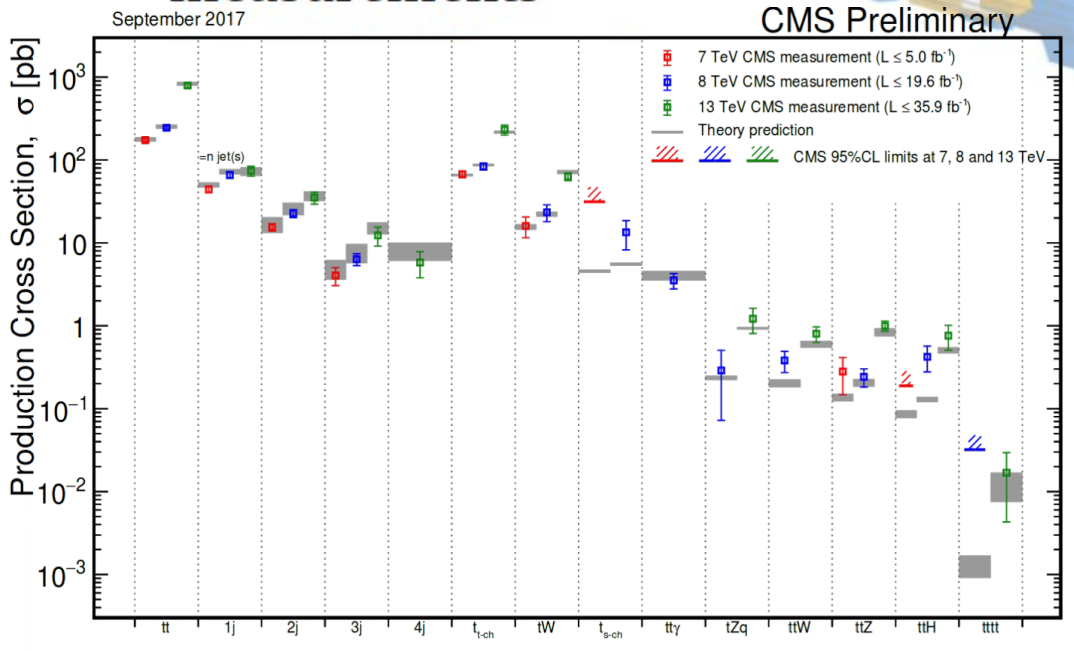


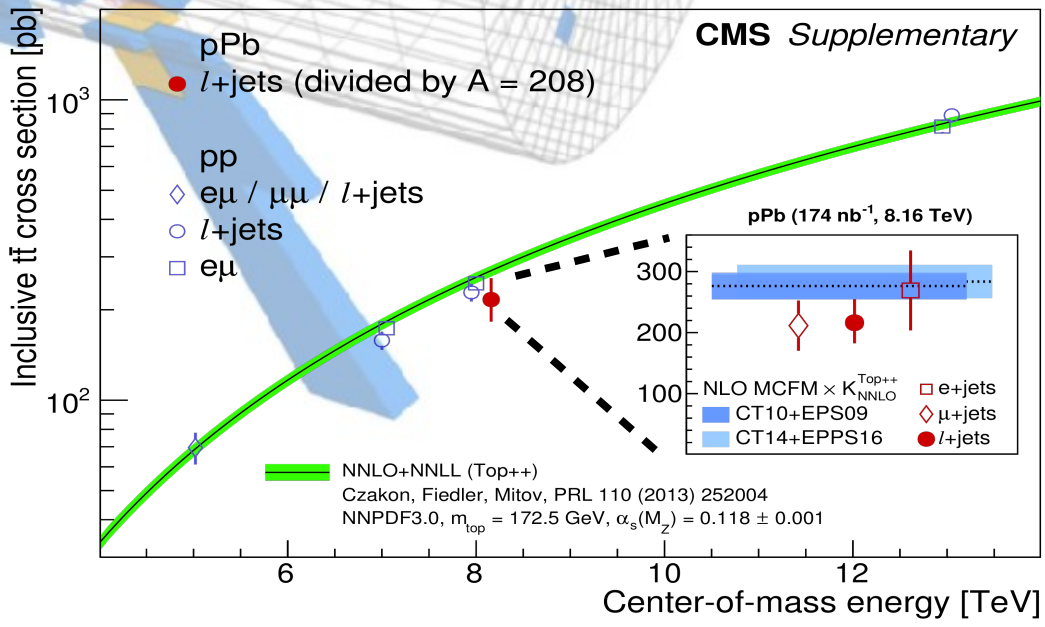
Top + Higgs

All CMS TOP Results

$\sqrt{\quad}$ +single top

- CMS has a **broad** program in *tt* cross section measurements
  - theory predictions with unprecedented precision follow results
    - at **4** different energies (+ **2** collision systems)
    - in **all** *tt* decay modes
  - Differential analyses → **multiple interfaces** to compare with theory
  - Input to **constrain background**,e.g. in top-Higgs coupling measurements
  - Top up with 2016: **minimize sensitivity** to statistics, extending differential measurements





slides

Hitting the systematics wall

We can safely forget about beam calibration, but we can still legitimately freak out about *luminosity* calibration!

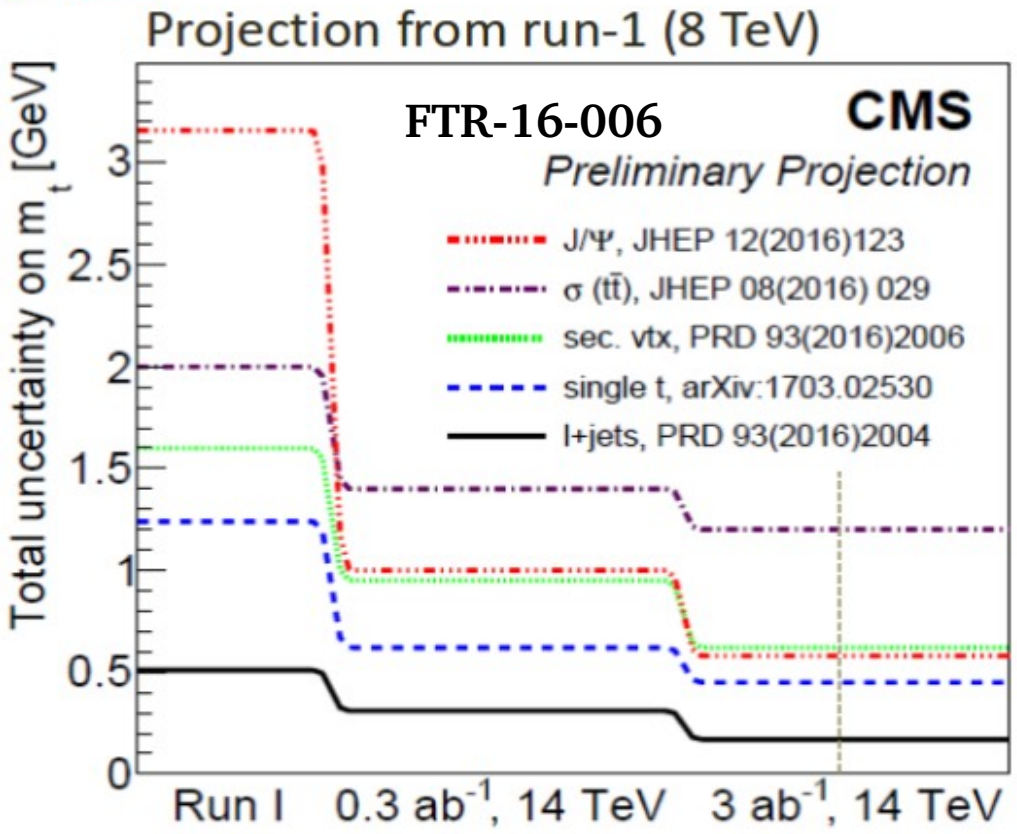
$\sqrt{s}$ (TeV)	$\int L$ (fb^{-1})	Measurement	Stat.	tt model	Det.	Bkg	Lumi	**Total**
13	3.2	ATLAS dilepton	0.9	3.0	1.1	0.9	2.3	**4.2**
13	2.2	CMS dilepton	1.0	2.4	3.6	1.5	2.3	**5.3**
13	2.2	CMS l+jets	0.2	1.7	2.3	1.9	2.3	**3.8**
8	20.2	ATLAS dilepton	0.7	1.7	1.2	0.9	2.1	**3.2**
8	19.7	CMS dilepton	0.6	1.3	2.2	1.5	2.6	**3.7**
8	20.2	ATLAS l+jets	0.3	4.1	2.3	1.3	1.9	**5.7**
8	19.6	CMS l+jets	1.6	5.4	2.5	0.2	2.6	**6.7**

- If you break the systematics down, luminosity is the largest individual source of uncertainty
- Very tough to go below $\Delta L/L$ ~2%
  (LHCb goes down to ~1%, but they can use beam imaging)
- Asymptotically, we may actually monitor lumi calibration with tt

A. Giammanco (TOP2017)

Precision of Top Mass

K. Hoepfner (ICNFP2017)



Many channels contribute:

1) ttbar -> lepton + jets reference analysis
2) Single t
3) J/psi

} Profits from TK extension

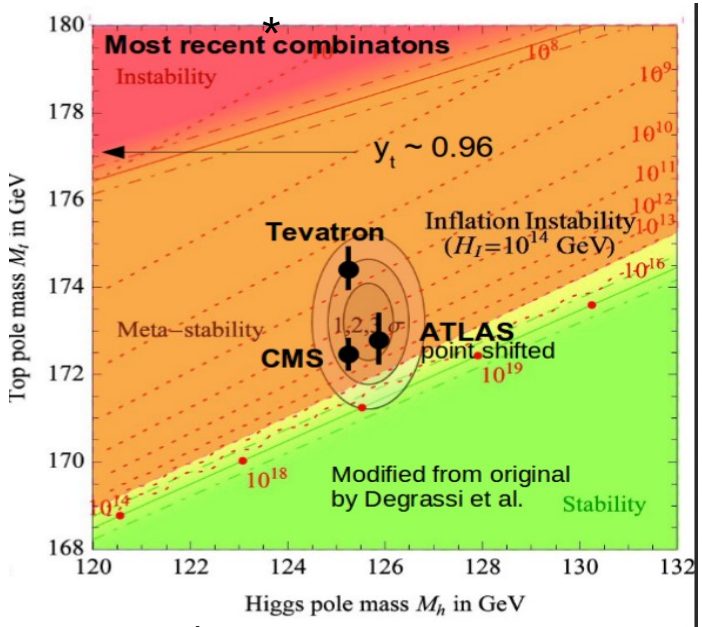
Avoid jet reco (and hence JES) or rely solely on leptons

4) Secondary vtx

HL beneficial for low stats channels (single top, J/psi). Can do without systematics from JES which limits present resolution.

Why should we care about top mass?

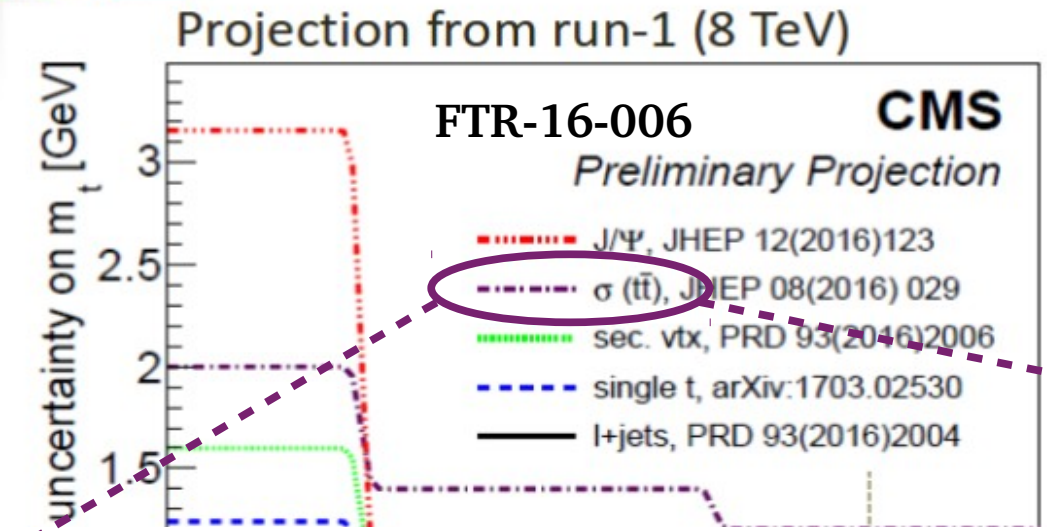
You care if the universe is stable? Wikipedia will tell you that m_{top} is a decisive factor. HL-LHC will provide needed precision (or built a new accelerator).



*March 17

Precision of Top Mass

K. Hoepfner (ICNFP2017)



Many channels contribute:

1) ttbar -> lepton + jets reference analysis
2) Single t
3) J/psi

Profits from TK extension

Avoid jet reco (and hence JES) or rely solely on leptons

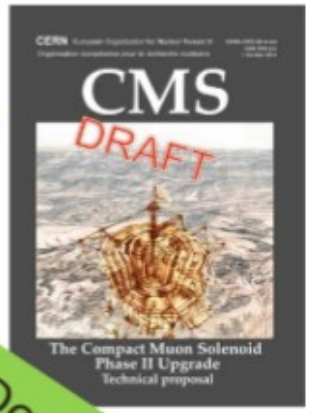
4) Secondary vtx

Source	Value			
	7 & 8 TeV, 25 fb^{-1}	13 TeV, 2.3 fb^{-1}	14 TeV, 0.3 ab^{-1}	14 TeV, 3 ab^{-1}
Predicted $\sigma_{t\bar{t}}$				
PDF and $\alpha_S(m_Z)$ at ME	$\pm 0.5\%$	$\pm 0.4\%$	$\pm 0.3\%$	$\pm 0.2\%$
Ren. and fact. scales	$\pm 0.6\%$	$\pm 0.4\%$	$\pm 0.4\%$	$\pm 0.4\%$
Measured $\sigma_{t\bar{t}}$				
Uncertainty	$\pm 0.8\%$	$\pm 1.3\%$	$\pm 0.6\%$	$\pm 0.4\%$
Slope	$\pm 0.3\%$	$< 0.1\%$	$< 0.1\%$	$< 0.1\%$
Other uncertainties				
LHC beam energy	$\pm 0.3\%$	$\pm 0.5\%$	$< 0.1\%$	$< 0.1\%$
$m_t^{MC} = m_t^{pole}$	$\pm 0.3\%$	$< 0.1\%$	$< 0.1\%$	$< 0.1\%$
Total uncertainty m_t [%]	± 1.1	± 1.5	± 0.8	± 0.7
Total uncertainty m_t	± 2 GeV	± 2.7 GeV	± 1.4 GeV	± 1.2 GeV

It is taking shape...

K. Hoepfner
(ICNFP2017)

First document for all CMS upgrade = technical proposal
CERN-LHCC-2015-10
approved by CERN and FA.



Done

Scope document discussing different (de)scoping scenarios.

Detector scenarios:

- Phase-1 detector, PU=50, 300/fb
- Phase-1 aged (except pixels) PU=140, 1000/fb
- Phase-2 detector PU=140, 3000/fb

Now going into technical details of detector design & construction, gain in performance & physics.

- Tracker TDR-17-001 (finished)
- Muon TDR-17-003
- ECAL Barrel TDR-17-002
- Timing layer, interim document (TDR Oct 2018)

For Nov 2017 LHCC meeting.

- Endcap calorimeter TDR-17-007 (later LHCC meeting)

Approve all Phase-2 documents and validate the overall Phase-2 funding plan for endorsement at Apr. 2018 RRB. (tbc)

Top quark mass extraction: mass schemes

M. Vos
(TOP2015)

The scheme makes a difference:
For a top quark pole mass of 173 GeV,
the $\overline{\text{MS}}$ mass at the top mass ~167 GeV

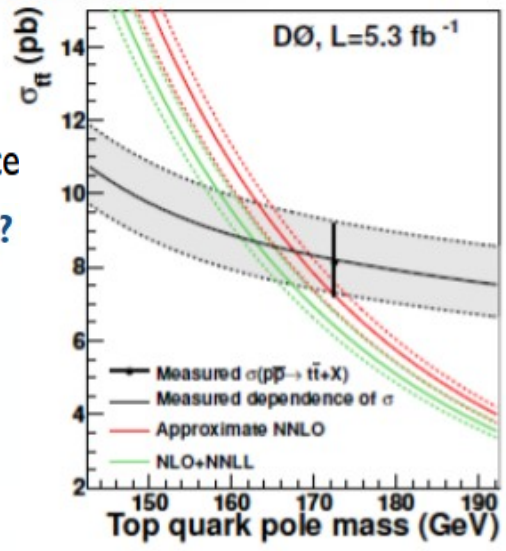
We need the mass as input to calculations:
Pole mass → ultimately limited by $O(\Lambda_{QCD})$ ambiguity?
Running mass → hopes of faster convergence?

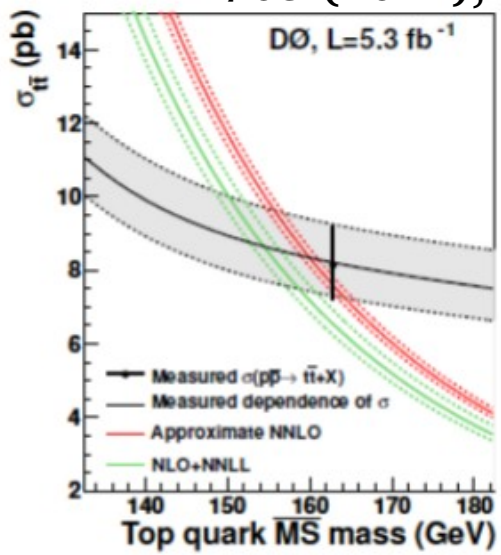
Tentatively, for O(1 GeV):
whichever can be extracted most precisely
Ultimately, for O(100 MeV):
$\overline{\text{MS}}$ mass?

Conversion between schemes can be made very precise
Marquard et al., PRL 114 (2015)

- Top mass extraction at fixed order scheme
  - benefits from loose selections ⇒ flat acceptance
- How far do we need go experimentally?
  - assuming current $\delta\sigma_{th}^{NNLO} \approx 5.5\%$
    PRL110 (2013) 252004
  - may reach $\delta m_t^{pole} \approx 0.5\%$ if $\delta\sigma_{exp} \approx 2\%$

PLB 703 (2011), 422





CMS

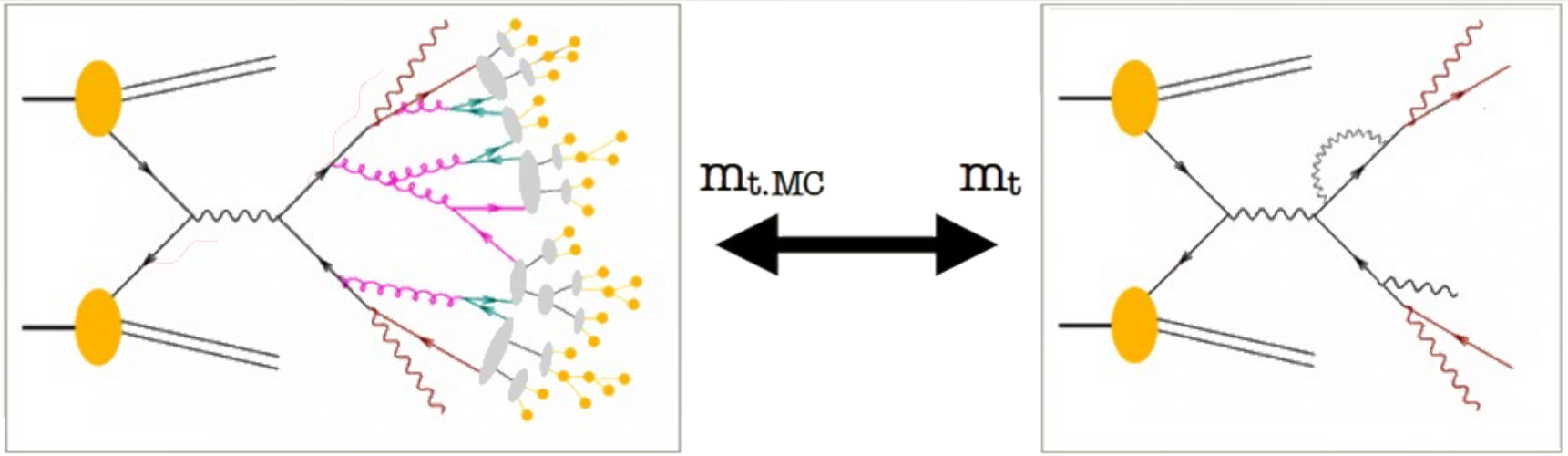
$m_t^{pole} = 173.8^{+1.7}_{-1.8}$ (GeV) Δm/m=1%

$m_t^{pole} = 167.5^{+5.2}_{-4.7}$ GeV

$m_t^{\overline{MS}} = 160.0^{+4.8}_{-4.2}$ GeV

Relation between MC simulations and an accurate definition of the quark mass ? (in a given renormalization scheme)

J. Kieseler
(DIS17)



- Direct top-quark mass measurements
  - Using final states from MC simulation (models)
  - Measure MC parameter $\mathbf{m_{t,}(MC)}$ (in principle depends on generator)

$m_{t,MC}$=172.44±0.49 GeV

CMS Collaboration
PRD 93 (2016) 072004

Hoang, Steward, NPPS 185 (2008)
Butenschoen et al., PRL 117 (2016) 232001

- Exact interpretation of $m_{t,MC}$ in terms of well-defined m_t
  - Uncertainty ≈1 GeV (pp), studies to reduce uncertainty ongoing

Buckley et al, Phys. Rept. 504 (2011)

  - For measurements: often assumed $m_{t,pole} - m_{t,MC} \approx 1$ GeV

Mitigate dependence on MC mass then & improve interpretation !

J. Kieseler (DIS17)

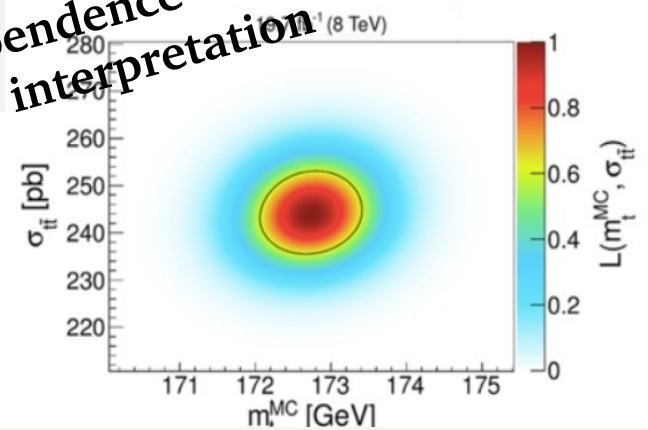
Well-defined m_t:

- Without assuming any relation to m_t(MC)
- Higher precision than accounting for slope (CMS/ATLAS/Tevatron)
- Consistently lower for ABM
- About 1 GeV difference between directly measured and converted pole mass
  → sizeable corrections beyond NNLO

	$\alpha_S(M_Z)$	$\bar{m}_t$ [GeV]	m_t^p [GeV]	$m_t^{p,c}$ [GeV]
ABM12	0.113	$158.4\pm^{1.2}_{1.9}$	$166.6\pm^{1.6}_{1.9}$	$168.0\pm^{1.3}_{2.1}$
NNPDF3.0	0.118	$165.2\pm^{1.1}_{1.7}$	$174.0\pm^{1.4}_{1.7}$	$175.1\pm^{1.2}_{1.9}$
MMHT2014	0.118	$165.4\pm^{1.1}_{1.9}$	$174.3\pm^{1.4}_{1.8}$	$175.3\pm^{1.3}_{2.1}$
CT14	0.118	$165.5\pm^{1.5}_{2.0}$	$174.4\pm^{1.8}_{2.0}$	$175.4\pm^{1.7}_{2.2}$

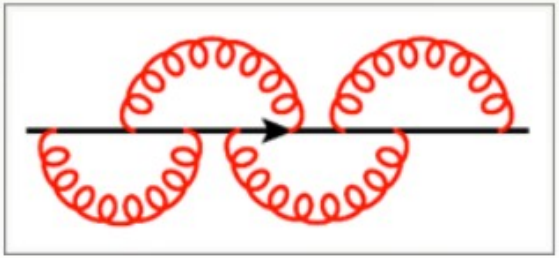
JK,KL,SM, PRL 116 (2016) 162001

Absorb MC mass dependence → Improved physics interpretation



- Conversion between $\overline{\text{MS}}$ and pole mass known up to 4-loop QCD
  - Indicates the size of higher-order corrections to $m_{t,\text{pole}}$ beyond NNLO (2-loop): about 250 MeV

Marquard et al., PRL 114 (2015) 142002



$$m_t^{\text{pole}}(k) = m_t^{\overline{\text{MS}}}(\mu)\left[1+\sum_{n=1}^{k} c_n \left(\frac{\mu}{m_t^{\overline{\text{MS}}}(\mu)}\right)\alpha_S^n(\mu)\right]$$

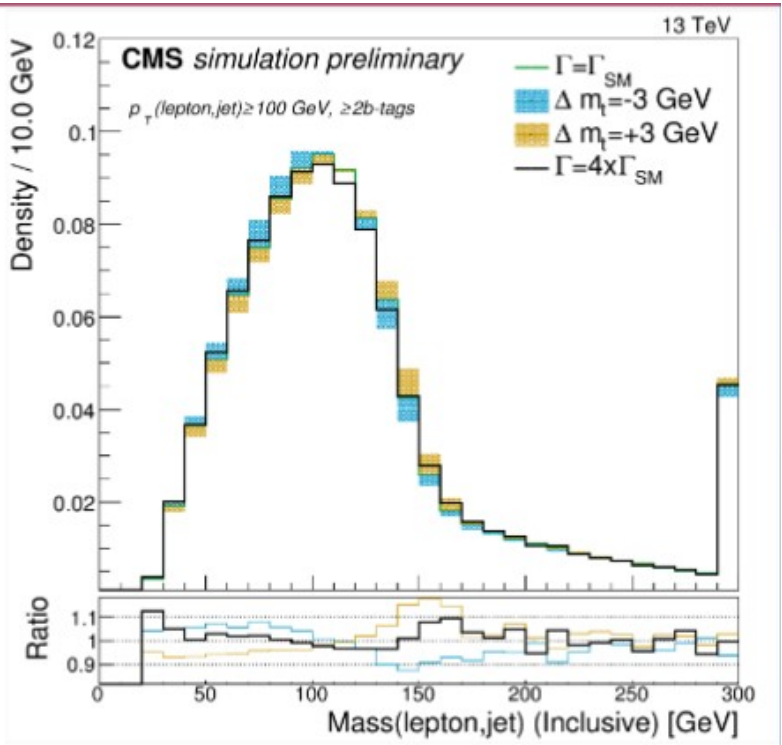
Top Width

E. Palencia
(EPS17)

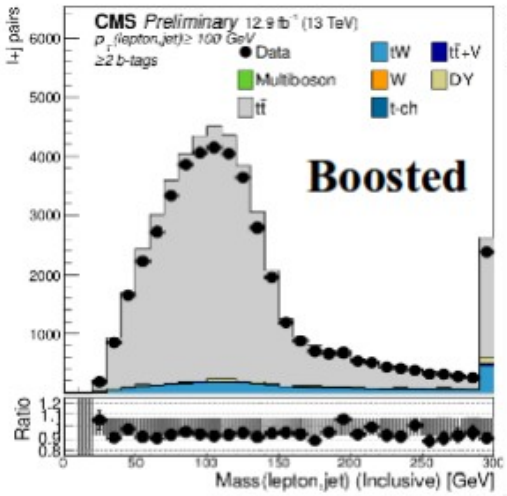
- Less tested of the top quark properties!
- Dilepton channel

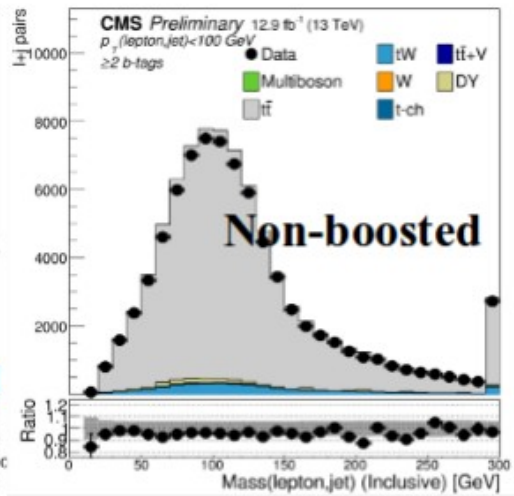
CMS-PAS-TOP-16-019

- Reconstructed mass of the decay products (lepton and b) is used as observable to probe variations in Γ_t
- Observable compared to the simulated expectations for different Γ_t scenarios using a likelihood technique



- MC modeling main systematic uncertainty

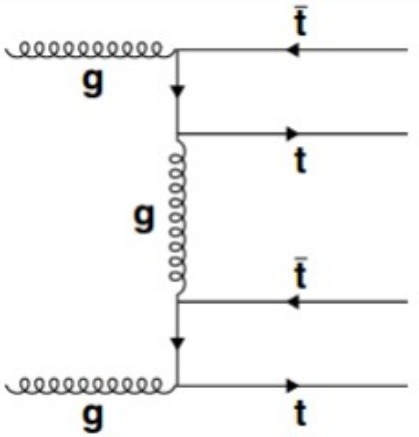




- For a SM-like top quark hypothesis:
  - Observed limit: $0.6 \leq \Gamma_t \leq 2.5$ GeV, expected limit: $0.6 \leq \Gamma_t \leq 2.4$ GeV
  - Γ_t (NLO) = 1.35 GeV
- Indirect measurement Phys. Lett. B 736 (2014) 33
  - $\Gamma_t = 1.36 \pm 0.02$ (stat) +0.14-0.11 (syst)

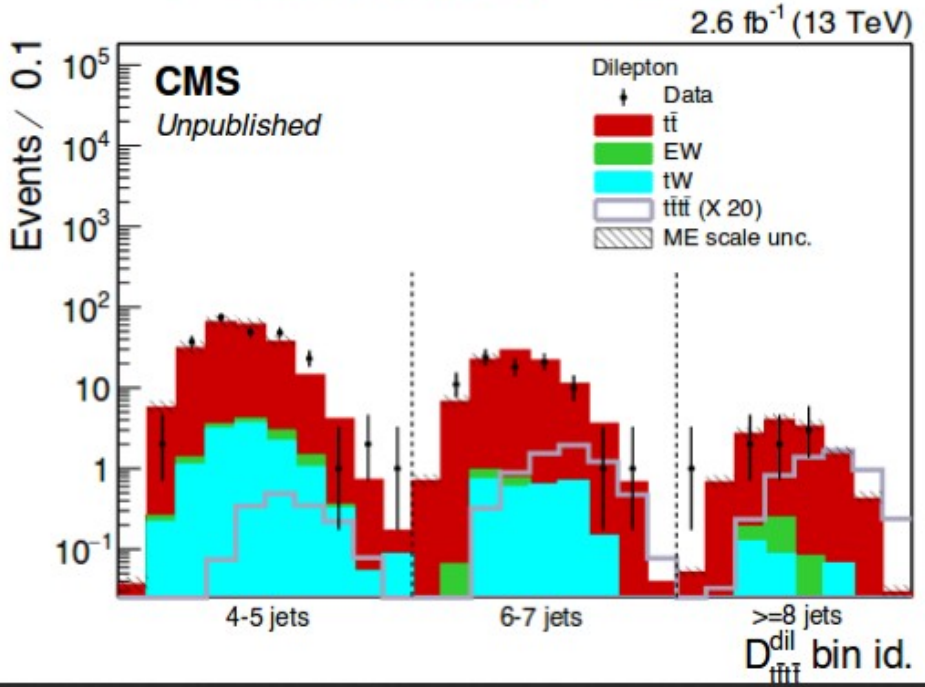
PLB 772 (2017), 336

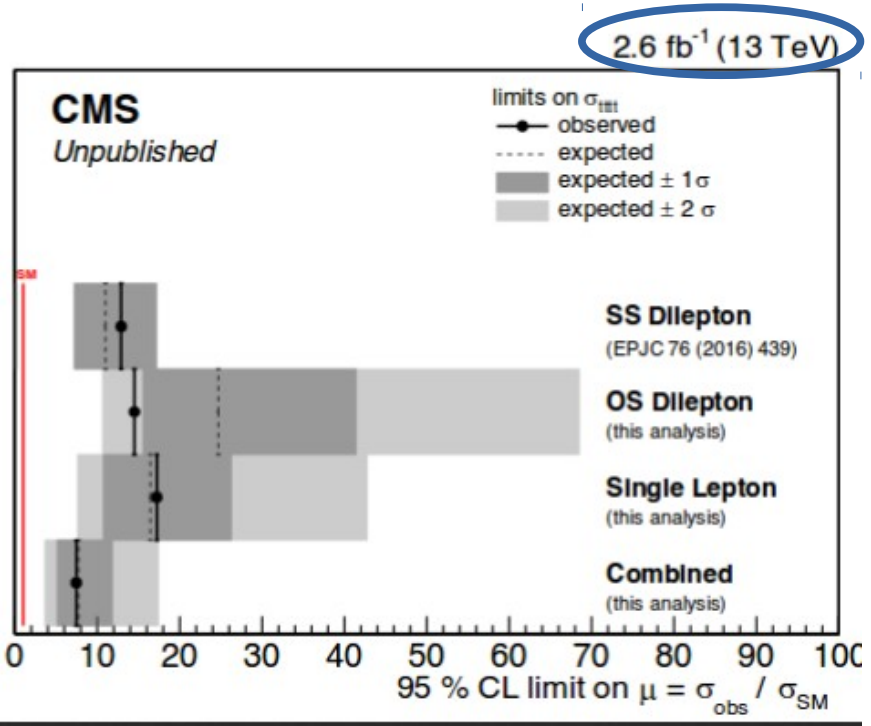
Four tops



- Very low SM prediction ($9.2^{+2.9}_{-2.4}$ fb), potentially enhanced by a number of BSM models
- Single lepton and opposite-sign dilepton + jets
- BDT combines global event and jet properties:
  - First BDT ranks 3-jet combinations consistent with all-hadronic top quark decays based on invariant masses and b-tag information
  - Second BDT uses 1st BDT ranking plus global event kinematic variables
- $\sigma < 94$ fb(95%CL) $= 10.2\times$SM
- Combined with same-sign dilepton channel:
- $\sigma < 69$ fb(95%CL) $= 7.4\times$SM

L. Lista (ICNFP2017)

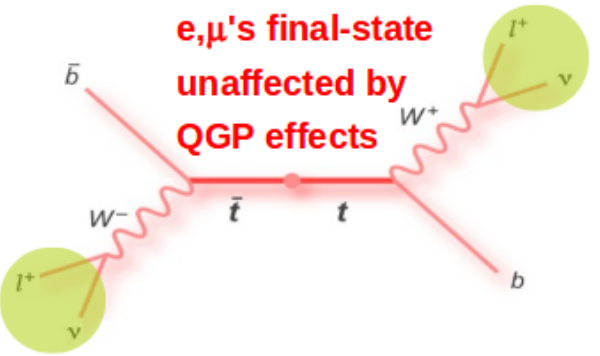




Top-quark dileptons measurement

D. d'Enterria *et al*, PL.B 746 (2016), 64

- Experimental setup:
  - LHC (ATLAS/CMS): $|\eta_{lepton}|,|\eta_{\text{b-jet}}| < 2.5$
  - FCC ("CMS+LHCb"): $|\eta_{lepton}|,|\eta_{\text{b-jet}}| < 5.0$



- Analysis cuts (typical ones in p-p at LHC, l=e,μ):

D. d' Enterria (Hard Probes 16)

t-tbar: $p_T(l),p_T(\text{b-jet}) > 20,30$ GeV; $R_{\text{isol}}(\text{b-jet},l) = 0.3$

$|\eta(l)|,|\eta(\text{b-jet})| < 2.5$ (LHC), 5.0 (FCC)

MET > 40 GeV; $m_{ll} > 20$ GeV; $|m_{ll}-m_Z| > 15$ GeV

Single-t: Same cuts as for t-tbar
(only W+t, backgrounds are much worst for s-,t-channel)

- Branching ratios, acceptance & efficiency losses:

t-tbar: BR~5%, Acc×Eff ~ 40% (LHC), 50% (FCC)

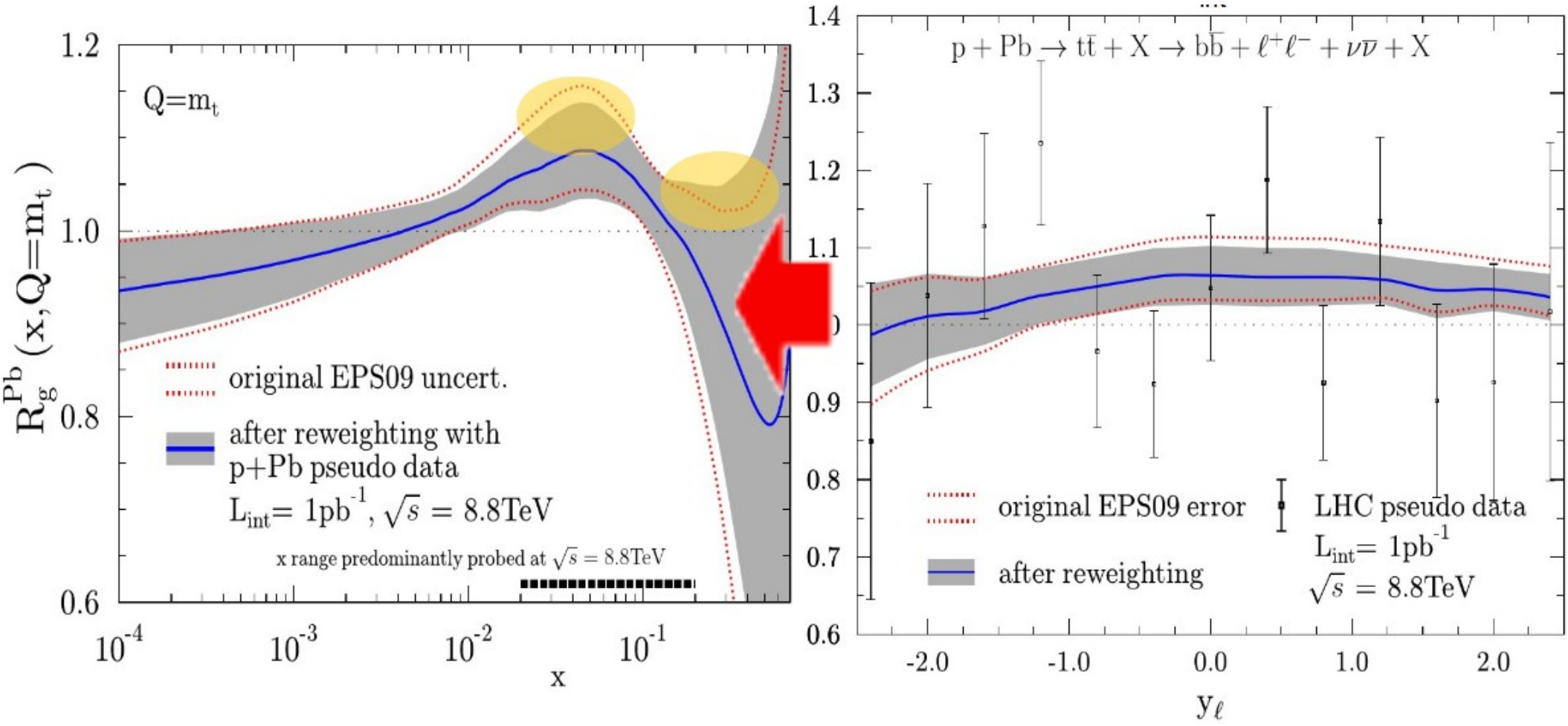
Single-top: BR~22%, Acc×Eff ~ 21% (LHC), 30% (FCC)

- Backgrounds (W,Z+j): Controllable for t-tbar (much worst for single-t)

Top quark is a novel probe of bound gluon PDF

- A toy study demonstrating the constraining power in
  - **middle**-x (anti-shadowing) and **high**-x (EMC) regions
  - complementary to dijet measurements

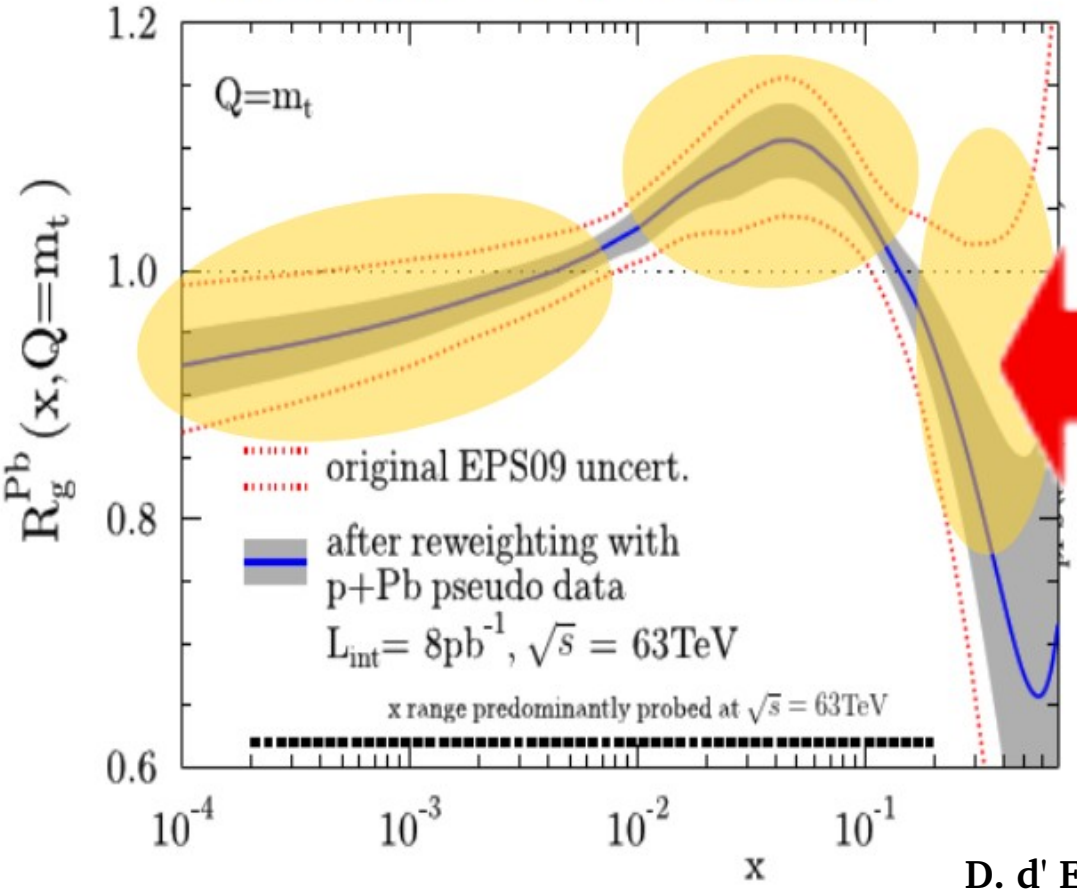
D. d'Enterria *et al*, PL.B 746 (2016), 64



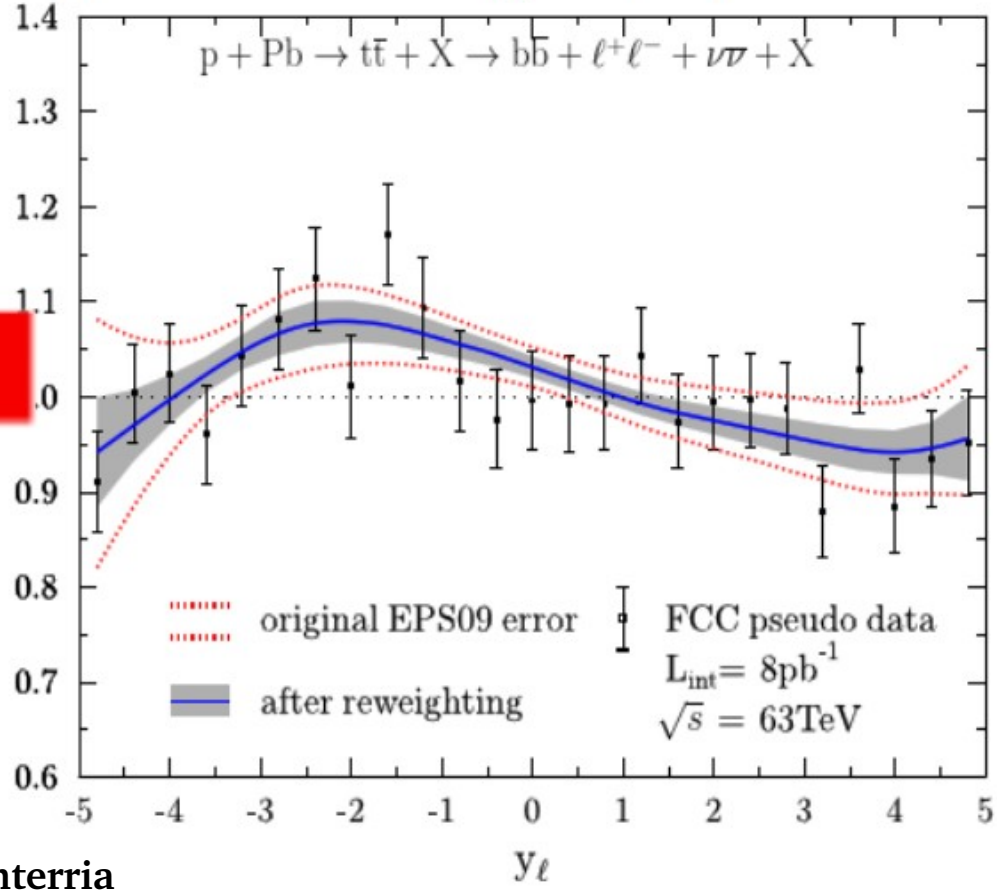
nPDF effects more prominent differentially !

pPb→ttbar+X (63 TeV): Gluon density constraints

- Improved gluon density via Hessian PDF reweighting



- Isolated lepton y-distrib. after cuts: (Pseudodata for L_{int}= 8 pb^{-1})



D. d' Enterria
(Hard Probes 16)

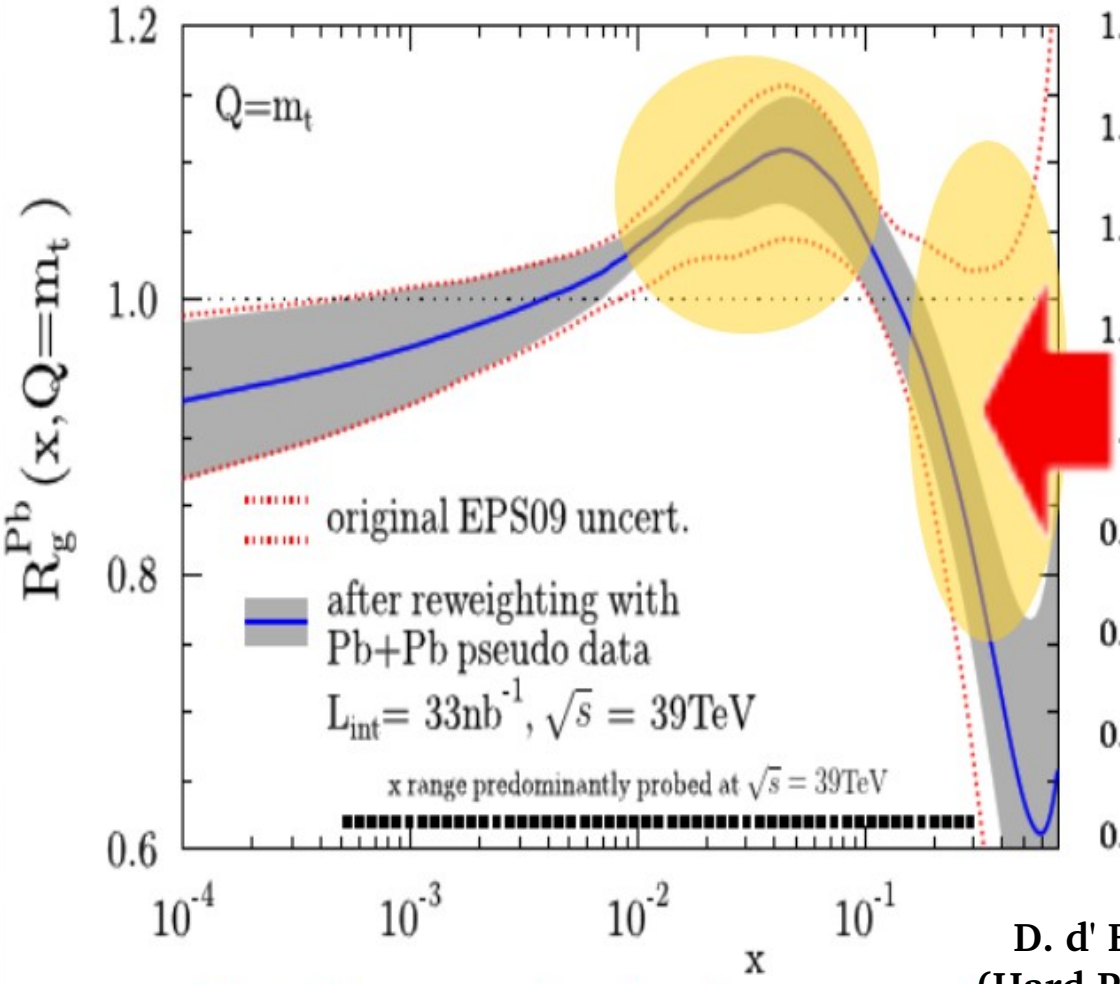
- Significant reduction in uncertainties at low-x ($x<10^{-2}$), antishadowing ($x\sim0.05$) and EMC ($x\sim0.5$) regions

(stat. to dominate over syst. uncertainties)

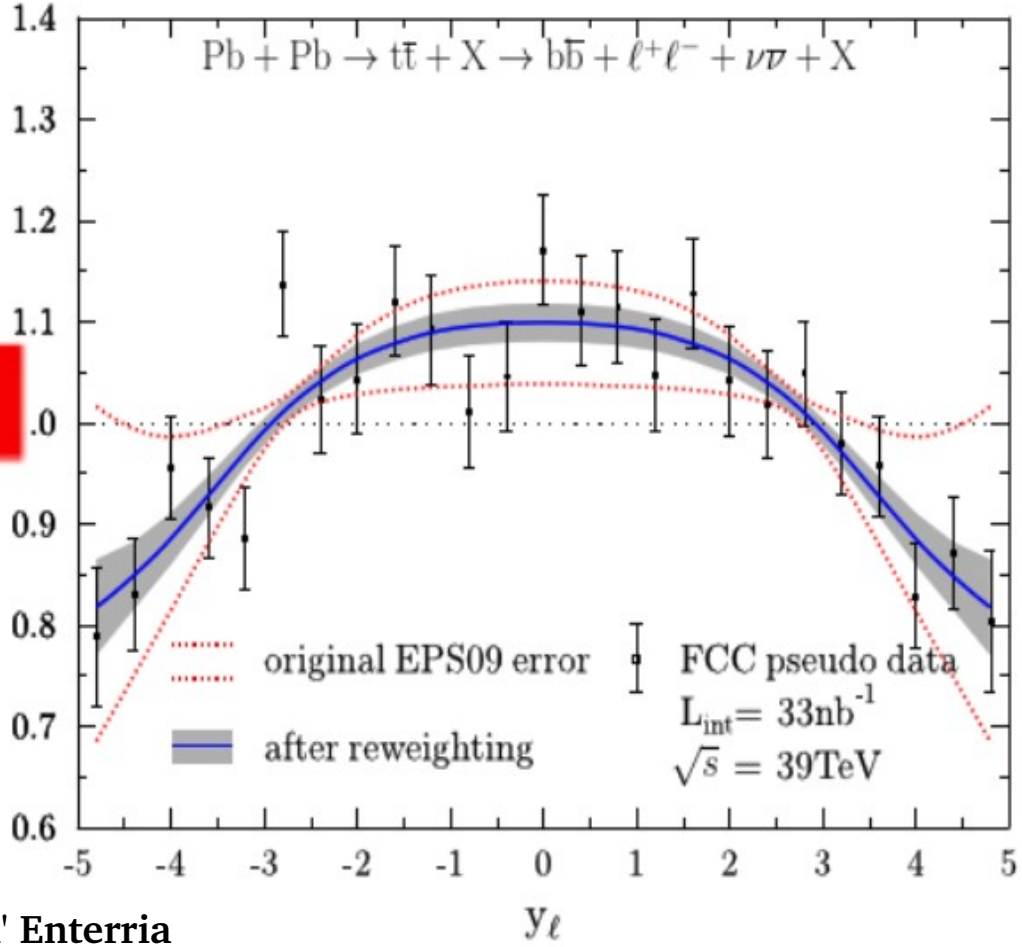
- nPDF effects (lepton): ±10%
  Strong constraining power

PbPb→ttbar+X (39 TeV): Gluon density constraints

- Improved gluon density via Hessian PDF reweighting



- Isolated lepton y-distrib. after cuts: (Pseudodata for L_{int} = 33 nb^{-1})



D. d' Enterria
(Hard Probes 16)

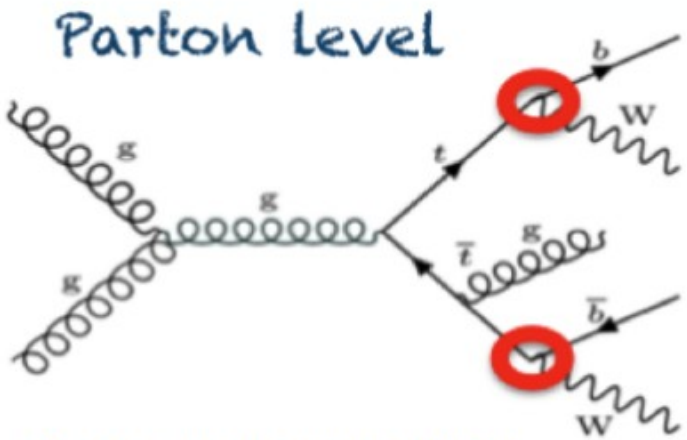
- Significant reduction in uncertainties at antishadowing (x~0.05) and EMC region (x~0.5) regions

(stat. dominate over syst. uncertainties)

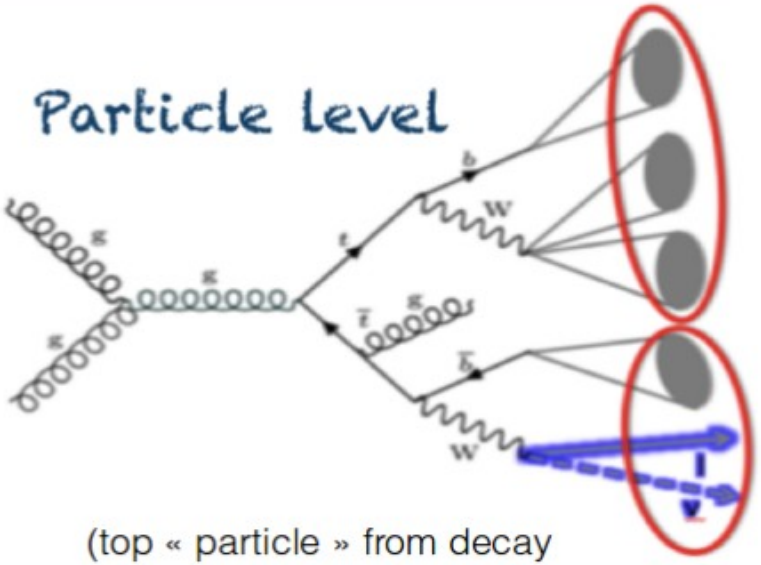
- nPDF effects (lepton): ±(10-20)%
  Strong constraining power

Improving uncertainties: Object Definitions for Top Particle

CMS-NOTE-2017-004

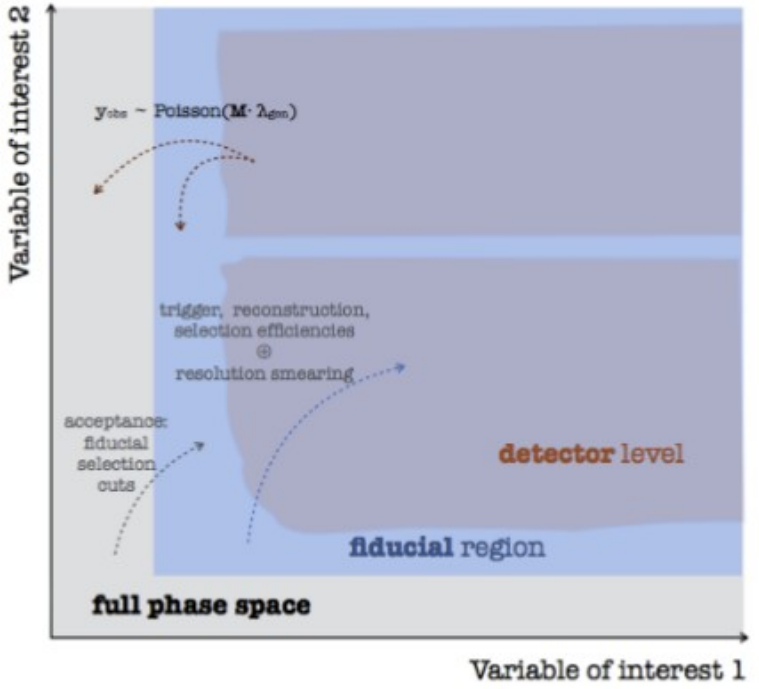


(before decay after radiation)



(top « particle » from decay products after hadronization)

- Fundamental aspect of performing current and future measurements of top quark differential production cross sections: Use well-defined objects in simulations —> Construct tops only from observed final-state = particle level top.
  - Parton level top ill-defined - more so at NLO
    - finite width of the top quark for off-shell production and interference with the backgrounds.



E. Yazgan
(TOP2017)

Factorized Parton Shower/Hadronization Uncertainties

Source	Handle	Weights	Variation	Note/Reference
Shower scales	ISR scale (SpaceShower:renormMultFac)	No	0.5-2.0	FSR variations can be scaled down by $\sqrt{2}$ from LEP
	FSR scale (TimeShower:renormMultFac)	No	0.5-2.0	
ME-PS Matching	hdamp	No	hdamp=1.58m_t +0.66-0.59 m_t	see TOP-16-021
Soft QCD	UE parameters	No	CUETP8M2T4 up/down	See TOP-16-021 MPI & CR strength doesn't affect resonance decays
Color reconnection (odd clusters)	MPI based, QCD-inspired, gluon move	No	different models	CR affecting resonance decays
Fragmentation	momentum transfer from the b-quark to the B hadron: $x_b=p_T(B)/p_T(b\text{-jet})$	Yes	Vary Bower-Lund parameter within uncertainties from LEP/SLD fits	see TOP-16-022 (re-weight x_b)
Flavor response/ hadronization	Pythia vs Herwig	No	Vary the JES independently per flavour for light, g, c, b.	
Decay tables	B semi-leptonic BR	Yes	vary semileptonic BR +0.77%/-0.45%	re-weight the fraction of semi-leptonic b jets by the PDG values (scale Λ_b to match PDG)

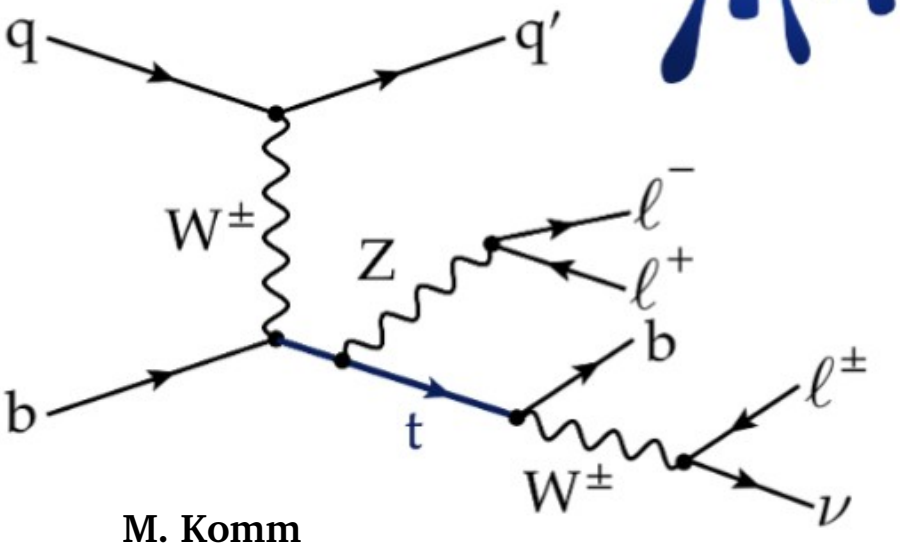
E. Yazgan (TOP2017)

Search for single top + Z

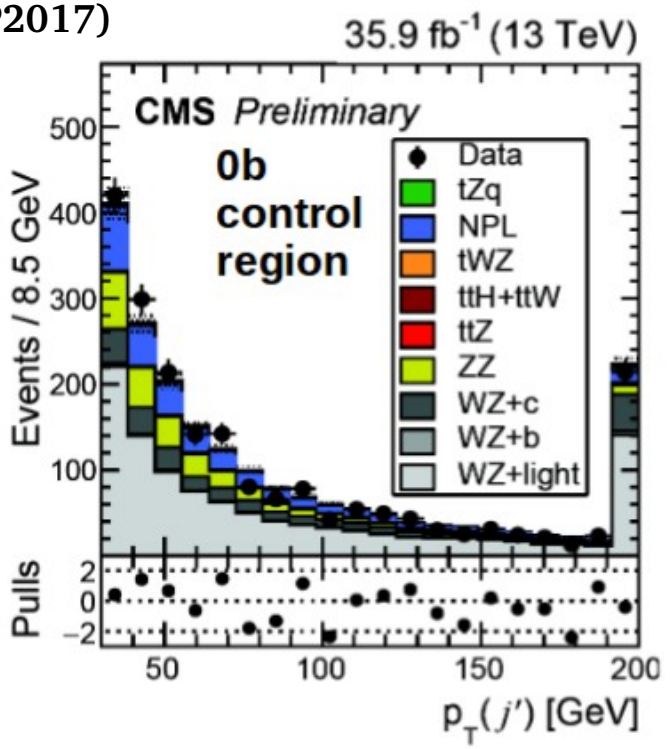
→ CMS-PAS-TOP-16-020

NEW

- event selection
  - 3 isolated muons or electron
    w/ 1 opposite sign & same flavor pair
    $p_{\mathrm{T}} > 25\ \mathrm{GeV},\ |\eta_{\mathrm{e}}| < 2.5$ or $|\eta_{\mu}| < 2.4$
  - Z mass window of 15 GeV
  - veto additional leptons to reject ttZ, ttH, ZZ
  - anti-k_{T} jets $(R = 0.4)$
    $p_{\mathrm{T}} > 30\ \mathrm{GeV},\ |\eta| < 4.5$
  - b-tagging: MVA based on secondary vertices
    $\epsilon_b \approx 83\%,\ \epsilon_{fake} \approx 10\%$
- data from 2016: $36\ \mathrm{fb}^{-1}$ at 13 TeV
- analysis strategy
  - shape of non-prompt lepton background estimated from data by inverting isolation
  - estimate signal yield through fit to
    - BDT in 2–3 jets with 1 b-tag (signal region)
    - BDT in $\geq$2 jets with $\geq$2 b-tags ($\mathrm{t\bar{t}Z}$ control region)
    - transverse W boson mass in $\geq$1 jet with 0 b-tags (W/Z+jets & non-prompt lepton control region)



M. Komm (TOP2017)



Search for single top + Z

→ CMS-PAS-TOP-16-020

NEW

- matrix element method
  - calculate weight per event based on matrix element for $\mathrm{tZq}, \mathrm{t\bar{t}Z}, \mathrm{WZ}$+jets

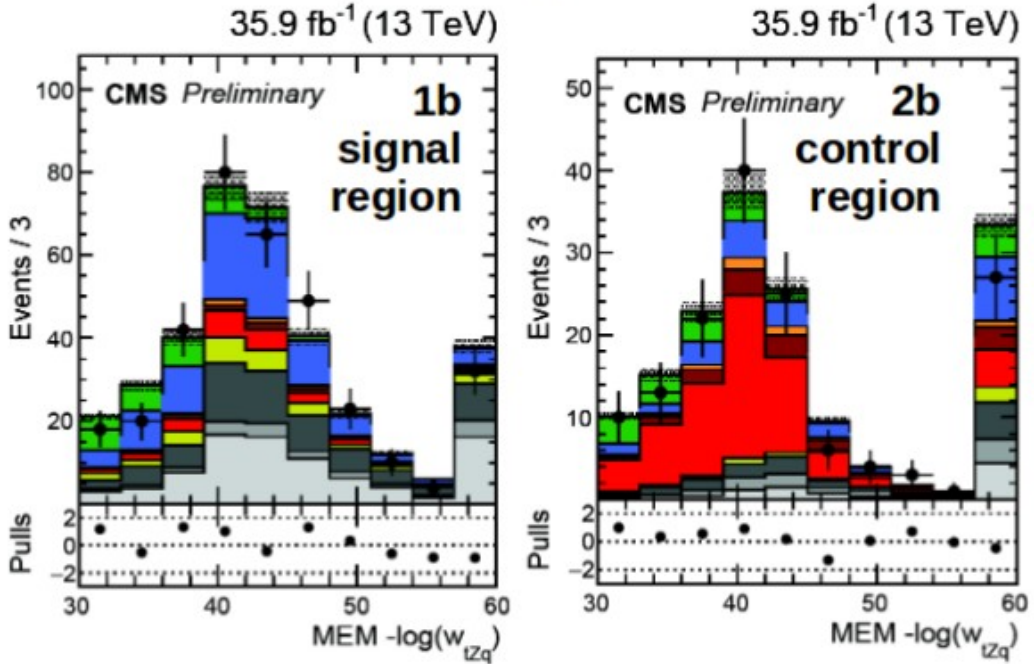
normalization — enforce conservation of momentum — PDF — ME from MadGraph

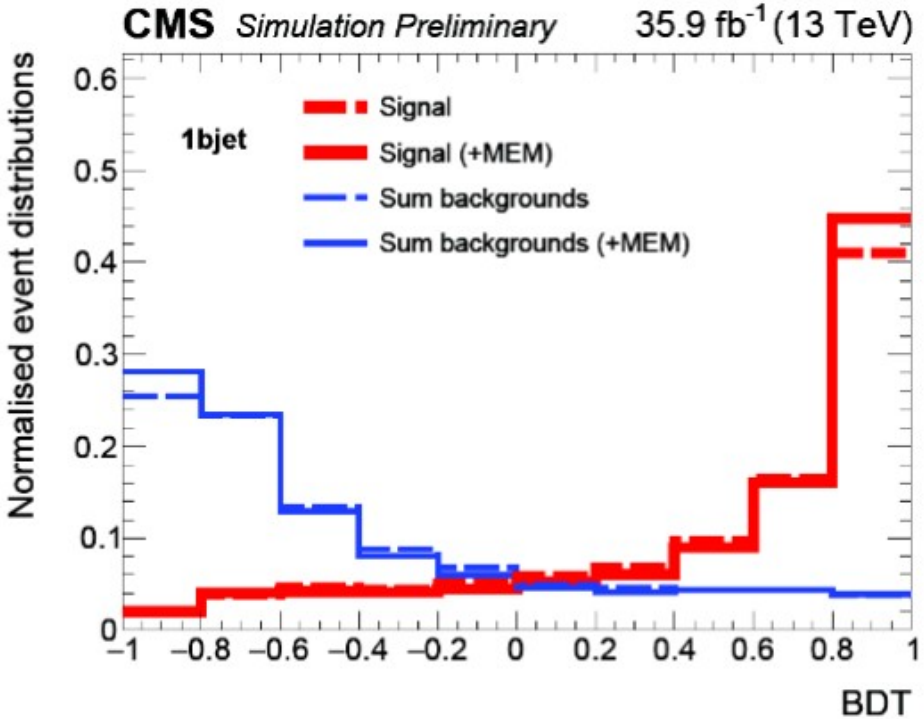
$$w_{i,\alpha}(\Phi') = \frac{1}{\sigma_\alpha} \int \mathrm{d}\Phi_\alpha \cdot \delta^4\left(p_1^\mu + p_2^\mu - \sum_{k\geq 2} p_k^\mu\right) \cdot \frac{f(x_1,\mu_F) f(x_2,\mu_F)}{x_1 x_2 s} \cdot \left|\mathcal{M}_\alpha(p_k^\mu)\right|^2 \cdot W(\Phi'|\Phi_\alpha)$$

phase space integral — flux — transfer functions for jets & MET

M. Komm (TOP2017)

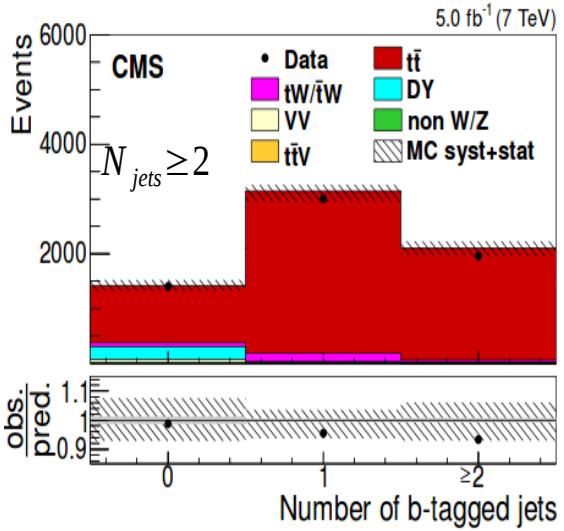
- combine with BDT → powerful discriminant

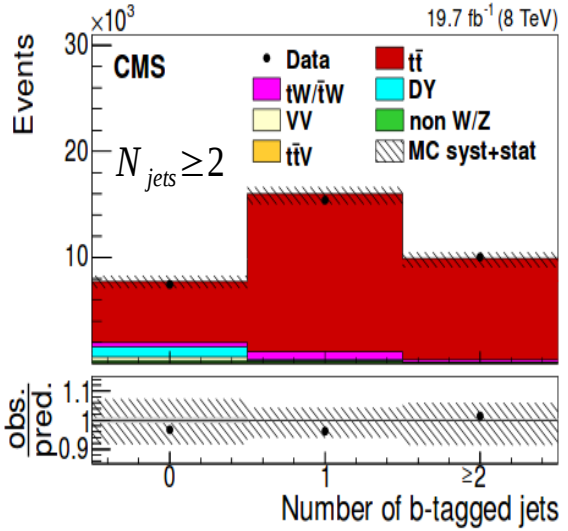




- Inclusive measurement with Run1 (5fb-1 + 19.7fb-1) data
  - Utilizing the eμ channel **JHEP 08 (2016), 029**
    - template fit in several bins of (b-) jet multiplicity
    - extract visible cross section
    - correct to parton level
  - theory likelihood includes
    - NNLO + NNLL scale variations + a_s
    - PDF uncertainties from one PDF set at a time
    - +-1 GeV shift for MC and pole mass relation
    - 1.7-1.8% uncertainty for beam energy unc.

Source	Uncertainty [%] 7 TeV	8 TeV
Trigger	1.3	1.2
Lepton ID/isolation	1.5	1.5
Lepton energy scale	0.2	0.1
Jet energy scale	0.8	0.9
Jet energy resolution	0.1	0.1
$tW/\bar{t}W$	1.0	0.6
DY	1.4	1.3
$t\bar{t}$ bkg.	0.1	0.1
$t\bar{t}V$	0.1	0.1
Diboson	0.2	0.6
W+jets/QCD	0.1	0.2
b-tag	0.5	0.5
Mistag	0.2	0.1
Pileup	0.3	0.3
μ_R, μ_F scales	0.3	0.6
ME/PS matching	0.1	0.1
MadGraph vs powheg	0.4	0.5
Hadronisation (JES)	0.7	0.7
Top quark p_T modelling	0.3	0.4
Colour reconnection	0.1	0.2
Underlying event	0.1	0.1
PDF	0.2	0.3
Integrated luminosity	2.2	2.6
Statistical	1.2	0.6

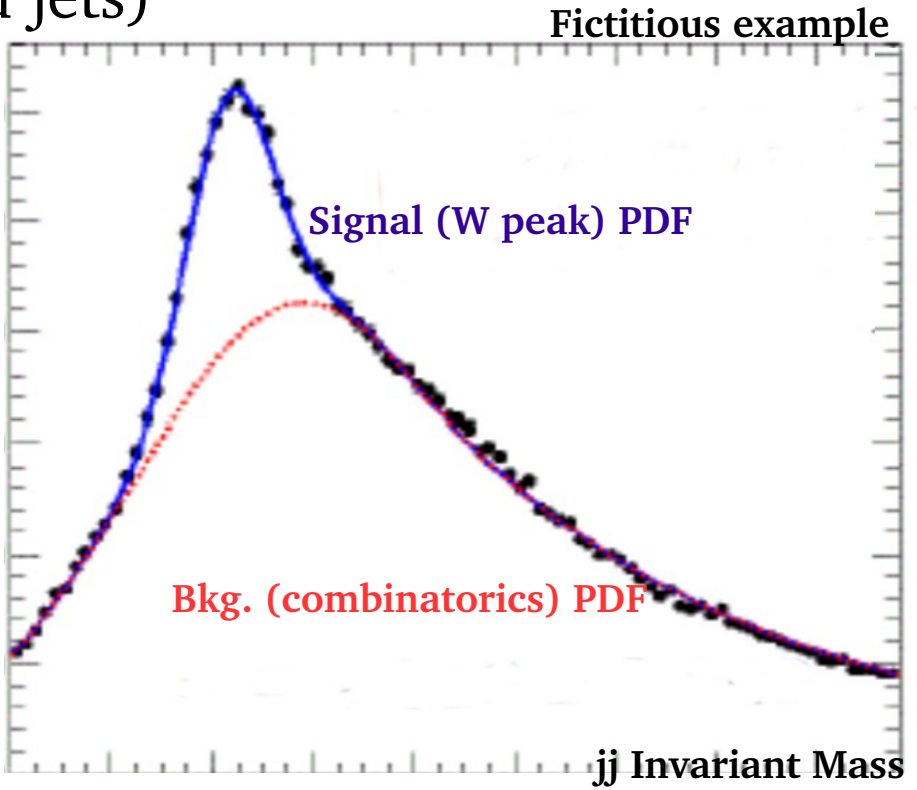




$$\sigma_{tot} = \frac{\sigma_{vis}}{A_{e\mu}}$$

Source	Uncertainty [%] 7 TeV	8 TeV
Total (visible)	$^{+3.6}_{-3.4}$	$^{+3.7}_{-3.4}$
Q^2 scale (extrapol.)	$^{+0.1}_{-0.4}$	$^{+0.2}_{-0.1}$
ME/PS matching (extrapol.)	$^{+0.1}_{-0.1}$	$^{+0.3}_{-0.3}$
Top quark p_T (extrapol.)	$^{+0.5}_{-0.3}$	$^{+0.6}_{-0.3}$
PDF (extrapol.)	$^{+0.1}_{-0.1}$	$^{+0.1}_{-0.1}$
Total	$^{+3.6}_{-3.5}$	$^{+3.7}_{-3.5}$

- JES calibrated using a CR (+ 2 b-tagged jets)
  - global correction factor a
    - a = fitted W mass in data / MC
    - a = 1.011+-0.004
    - 1.5% impact of JES on a
    - a applied to jet pT for all MC before the nominal selection



EPJC 77 (2017), 15

Source	μ+jets	e+jets	Correlation
Absolute scale	±0.33	±0.40	0.0
Global jet scale factor	±0.59	±0.39	0.0
Radiation modeling	±0.46	±0.41	1.0
Relative p_T extrapolation	±0.67	±0.57	1.0
Parton flavour mixture	±1.84	±1.79	1.0
b jet fragmentation	±0.50	±0.46	1.0
B jet semileptonic decay fraction	±0.11	±0.16	1.0
High-p_T extrapolation	±0.18	±0.23	1.0
High-p_T single-jet response	±0.21	±0.27	1.0
Pileup random-cone simulation	±0.35	±0.31	1.0
Time-dependent detector effects	±0.17	±0.24	1.0
Total JES	±2.23	±2.13	0.9

- most of the effects not explicitly dependent from the lepton flavour
  - absolute scale is the only one with a per-channel dedicated calibration
    - corr. coefficient from all JES contributions = 0.9

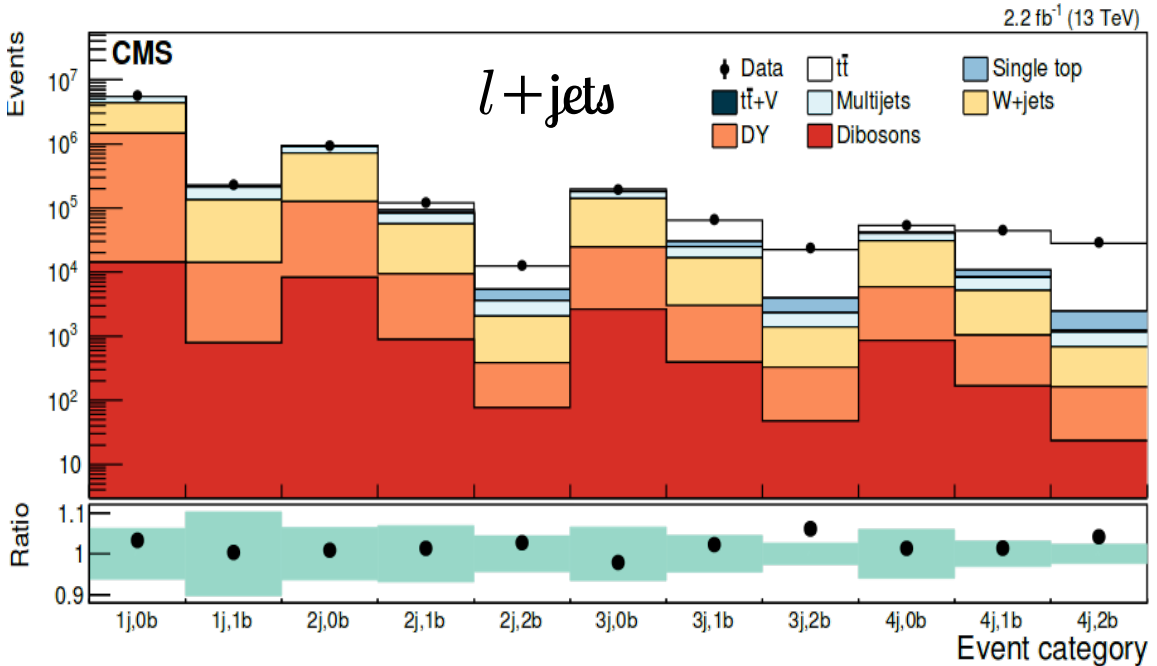
CMS-PAS-JME-14-003

- Low jet/btag categories to constrain backgrounds while high jet/btag to fit the signal
  - signal strengths μ from shape-based analysis; Ct&Cnt as a cross-check
    - W+jets using aMC@NLO and uncertainty mainly coming from QCD scale var.
    - QCD from non-isolated region; normalization and shape uncertainty **from MC**
  - μ re-interpreted to measure the top quark pole mass $\mu(m_t) = \frac{\sigma(m_t)}{\sigma_{th}} \cdot \frac{A}{A(m_t)}$
    - TOP++(v2.0) and NNPDF3.0 to build $L_{exp}(m_t, \sigma_{t\bar{t}})$
    - log-uniform PDF for QCD scale choice

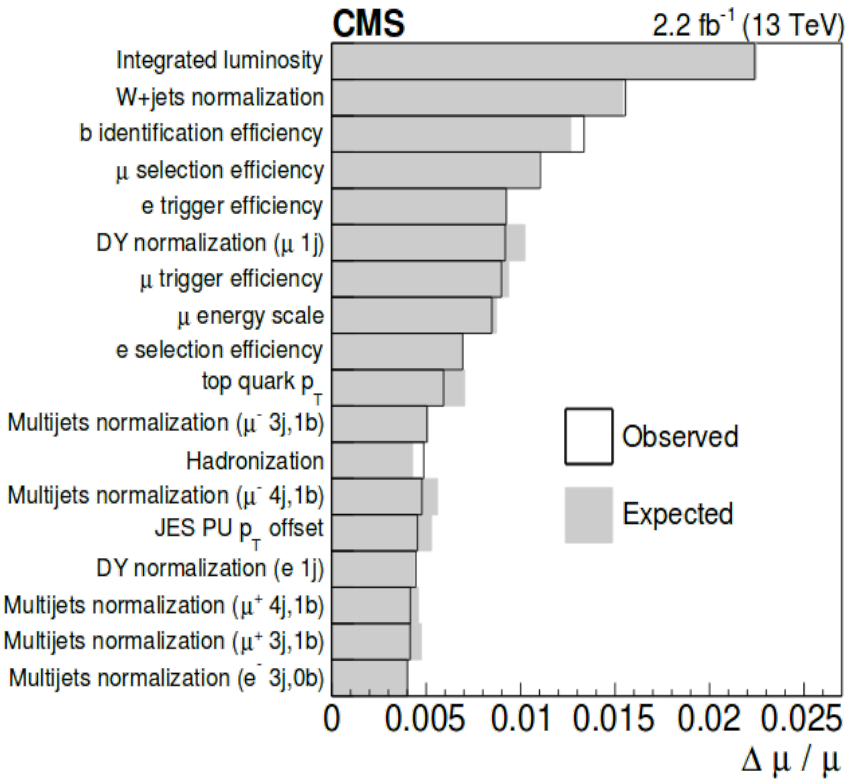
JHEP 09 (2017), 051

Source	Δm_t [GeV]
Uncertainties from the fit in the fiducial region	-2.2 /$+2.5$
Extrapolation to the full phase space	-0.7 /$+1.1$
Beam energy	-0.08 /$+0.12$
μ_R/μ_F and PDF+α_S	-0.9 /$+1.1$
Total	± 2.7

pole mass



cross section



- **TOP-16-023** is a **significant update** relative to the eμ only preliminary result (June 2016)
  - that establishes **CMS** as the only experiment measuring *tt* inclusively in **4** energies
  - inclusion of **four independent** channels i.e. eμ, μμ, μ+jets & e+jets
    - leading to a total combined unc. of **12%**, which is
    - a nice achievement given a pp dataset of only ~ 27.4±0.6 pb-1

TOP-16-023 (submitted to JHEP)

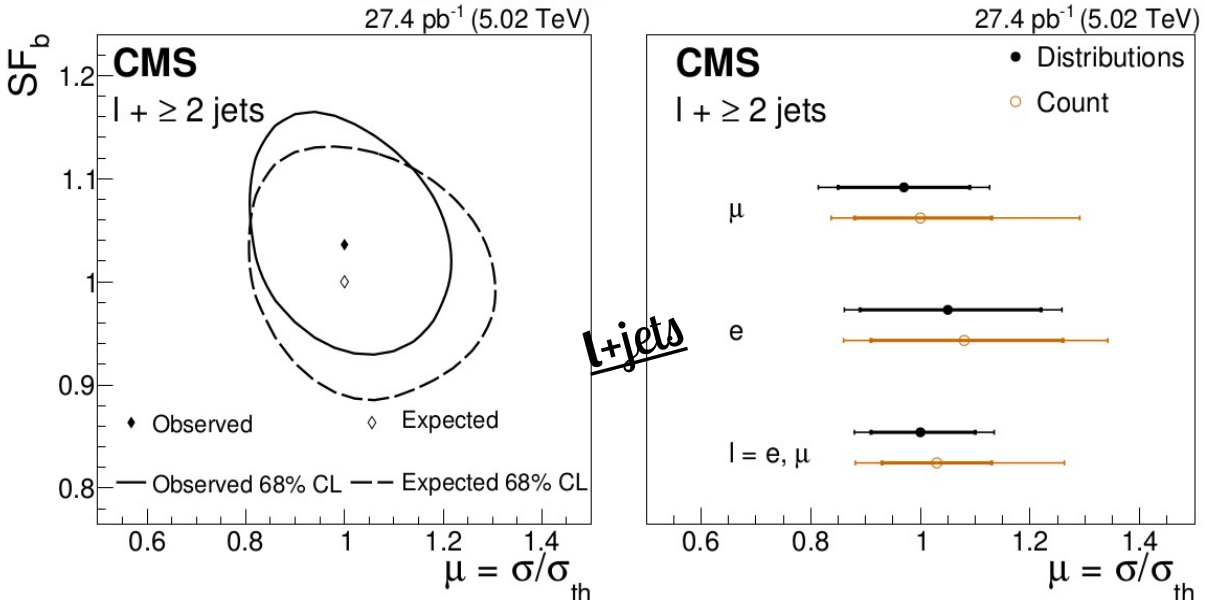
Competing !

Uncertainty	Δμ/μ Distr.	Count
Statistical uncertainty	0.095	0.100
Systematic uncertainty	0.085	0.160
Experimental uncertainties		
W+jets background	0.035	0.025
QCD multijet background	0.024	0.044
"Other backgrounds"	0.013	0.013
Jet energy scale	0.030	0.031
Jet energy resolution	0.006	0.023
b-tagging efficiency	0.034	0.045
Electron efficiencies	0.011	0.028
Muon efficiencies	0.017	0.022
Theory uncertainties		
Hadronization model of $t\bar{t}$ signal	0.028	0.069
μ_R/μ_F scale of $t\bar{t}$ signal (PS)	0.044	0.115
μ_R/μ_F scale of $t\bar{t}$ signal (ME)	<0.01	<0.01
Total	0.127	0.189

l+jets

All channels

$$\sigma_{tot}(pp \to t\bar{t}) = 69.5 \pm 6.1\,(stat) \pm 5.6\,(syst) \pm 1.6\,(lumi)\ pb$$



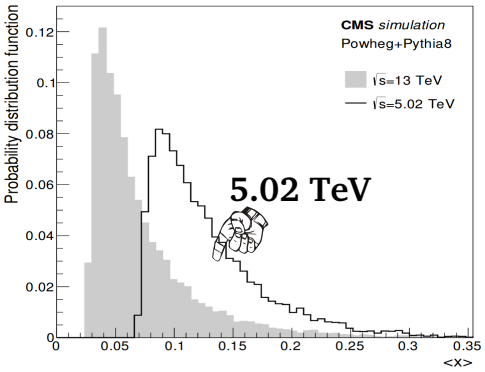
But, do we really probe high-$\langle x \rangle$ gluons ?

- **QCD analysis @ NNLO** with brand new xFitter **2.0.0** release
  - baseline data: HERA inclusive DIS [EPJ C75 (2015)580], CMS $W^{\pm}$[EPJ C76 (2016) 469]
  - theory predictions obtained from Hathor (NNLO) with top mass of 172.5 GeV

14-parameter fit

$$
\begin{aligned}
xg(x) &= A_g x^{B_g} \cdot (1-x)^{C_g} \cdot (1 + D_g x), && \text{gluons} \\
xu_v(x) &= A_{u_v} x^{B_{u_v}} \cdot (1-x)^{C_{u_v}} \cdot (1 + D_{u_v} x + E_{u_v} x^2), && \text{valence quarks} \\
xd_v(x) &= A_{d_v} x^{B_{d_v}} \cdot (1-x)^{C_{d_v}}, && \text{valence quarks} \\
x\overline{U}(x) &= A_{\overline{U}} x^{B_{\overline{U}}} \cdot (1-x)^{C_{\overline{U}}} \cdot (1 + E_{\overline{U}} x^2) && \text{sea quarks} \\
x\overline{D}(x) &= A_{\overline{D}} x^{B_{\overline{D}}} \cdot (1-x)^{C_{\overline{D}}}. && \text{sea quarks}
\end{aligned}
$$

$Q_0^2 = 1.9\ \text{GeV}^2$



All datasets are consistent
Good fit quality for the 5.02 TeV dataset

Data sets	Partial χ^2/n_{dp}
HERA1+2 neutral current, e^+p, $E_p = 920$ GeV	449/377
HERA1+2 neutral current, e^+p, $E_p = 820$ GeV	71/70
HERA1+2 neutral current, e^+p, $E_p = 575$ GeV	224/254
HERA1+2 neutral current, e^+p, $E_p = 460$ GeV	218/204
HERA1+2 neutral current, e^-p, $E_p = 920$ GeV	218/159
HERA1+2 charged current, e^+p, $E_p = 920$ GeV	43/39
HERA1+2 charged current, e^-p, $E_p = 920$ GeV	53/42
CMS $W^{\pm}$ muon charge asymmetry $\mathcal{A}(\eta_\mu)$, $\sqrt{s} = 8$ TeV	2.4/11
CMS inclusive $t\bar{t}$ 5.02 TeV, $e^{\pm}\mu^{\mp}$	1.03/1
CMS inclusive $t\bar{t}$ 5.02 TeV, $\mu^{\pm}\mu^{\mp}$	0.01/1
CMS inclusive $t\bar{t}$ 5.02 TeV, ℓ+jets	0.70/1
Correlated χ^2	100
Global χ^2/n_{dof}	1387/1145

arXiv:1706.08128 → JHEP

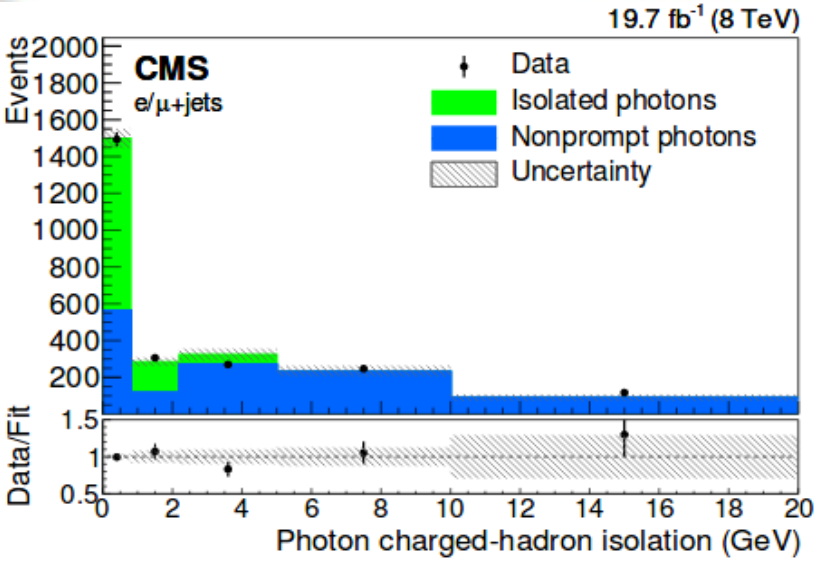
$t\bar{t} + \gamma$ (8 TeV)

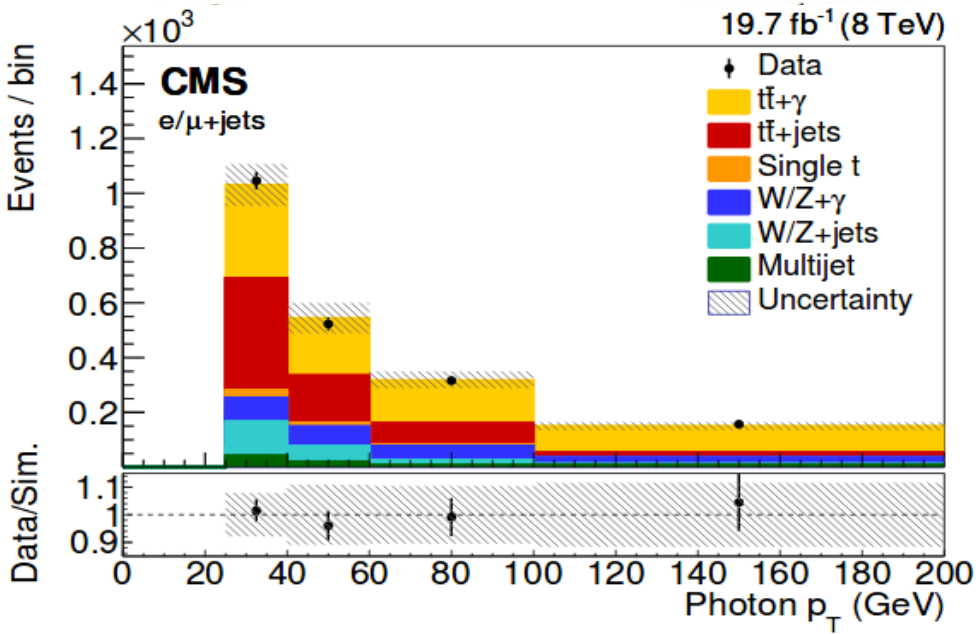
L. Lista (ICNFP2017)

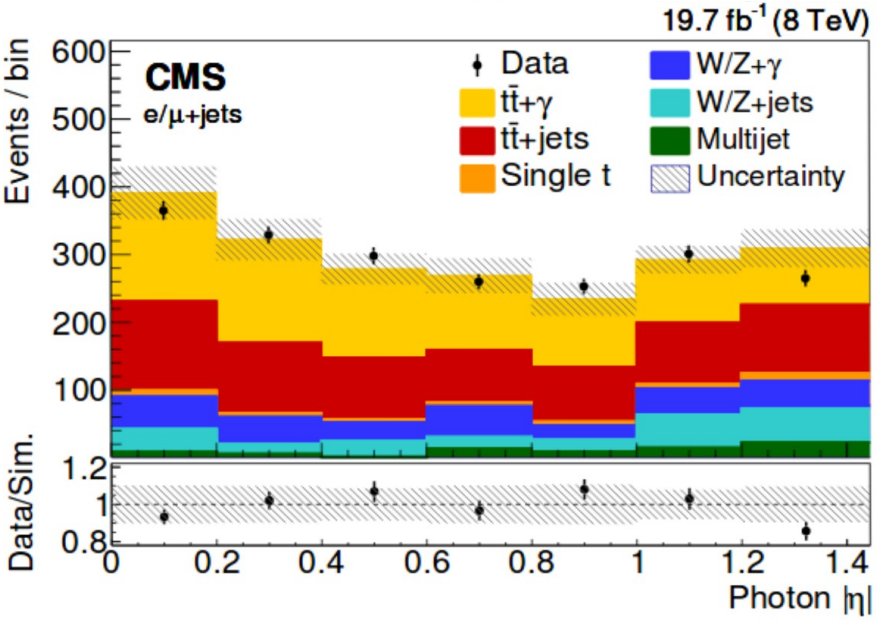
- Fiducial cross section in semilept. events with:
  - e: p_T > 35 GeV, $|\eta|$<2.5
  - μ: p_T > 26 GeV, $|\eta|$<2.4
  - γ: p_T > 25 GeV, $|\eta|$<1.44
  - p_T sum of ν > 20 GeV
- Photon isolation discriminates non-prompt photons

>=3jets

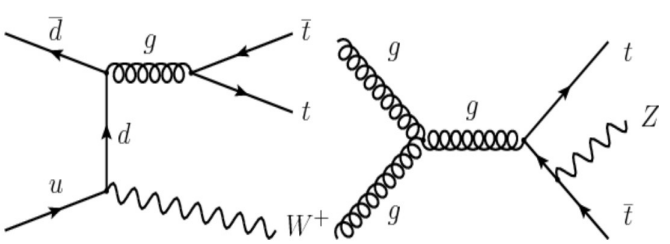
Category	$R=\sigma^{fid}_{t\bar{t}\gamma}/\sigma_{t\bar{t}}$	$\sigma^{fid}_{t\bar{t}\gamma}$(fb)	$\sigma_{t\bar{t}\gamma}\mathcal{B}$(fb)
e +jets	$(5.7 \pm 1.8)\times10^{-4}$	138 ± 45	582 ± 187
μ +jets	$(4.7 \pm 1.3)\times10^{-4}$	115 ± 32	453 ± 124
Comb.	$(5.2 \pm 1.1)\times10^{-4}$	127 ± 27	515 ± 108
Theory			592 ± 71(scale) ± 30(PDF)







- tt + V background to ttH
  - production **rates** 3/4 (W/Z) times **higher** @ 13TeV
    - Achieved 30/25 % (W/Z) precision in Run1
    - Achieved 33/30 % (W/Z) with part of 2016 dataset
  - update with **entire 2016 dataset** with most sensitive channels
    - syst. > stat. uncertainties
    - obtained **22/15 %** (W/Z) precision
    - consistent with NLO QCD predictions



JHEP 01 (2016), 0969

2lSS

$t\bar{t}W \to (bjj)(bjj)(jj)$
$t\bar{t}W \to (bjj)(bjj)(l\nu)$
$t\bar{t}W \to (bl\nu)(bjj)(l\nu)$
$t\bar{t}W \to (bl\nu)(bl\nu)(l\nu)$

$t\bar{t}Z \to (bjj)(bjj)(jj)$
$t\bar{t}Z \to (bjj)(bjj)(ll)$

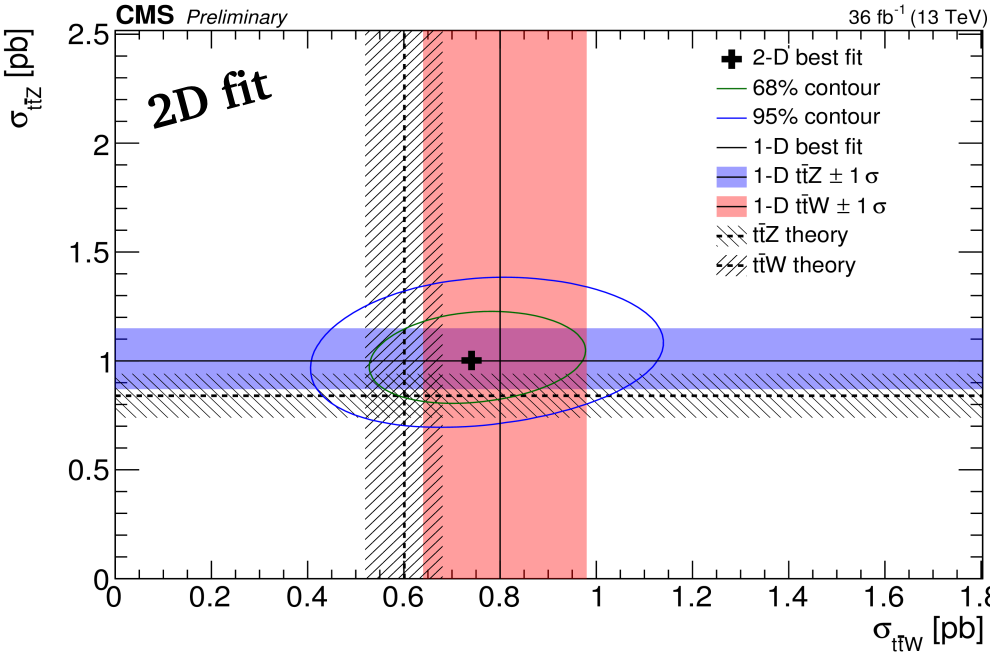
3l
4l

$t\bar{t}Z \to (bl\nu)(bjj)(ll)$
$t\bar{t}Z \to (bl\nu)(bl\nu)(ll)$

Run 2

TOP-17-005

Source	Uncertainty range	Impact on ttW cross-section	Impact on ttZ cross-section
Luminosity	2.5%	4%	3%
Jet Energy Scale/Resolution	2-5%	3%	3%
Trigger	2-4%	4-5%	5%
B tagging	1-5%	2-5%	4-5%
PU modeling	1%	1%	1%
Lepton ID, efficiency	2-7%	3%	6-7%
μ_R/μ_F scale choice	1%	<1%	1%
PDF choice	1%	<1%	1%
Nonprompt background	30%	4%	< 2%
WZ cross section	10-20%	<1%	2%
ZZ cross section	20%	-	1%
Charge misidentification	20%	3%	-
Rare SM background	50%	2%	2%
ttX background	10-15%	4%	3%
Stat. unc. for nonprompt	5-50%	4%	2%
Stat. unc. rare SM processes	20-100%	1%	< 1%
Total systematic	-	14%	12%



4/36 dim-6 operators passing the specific requirements

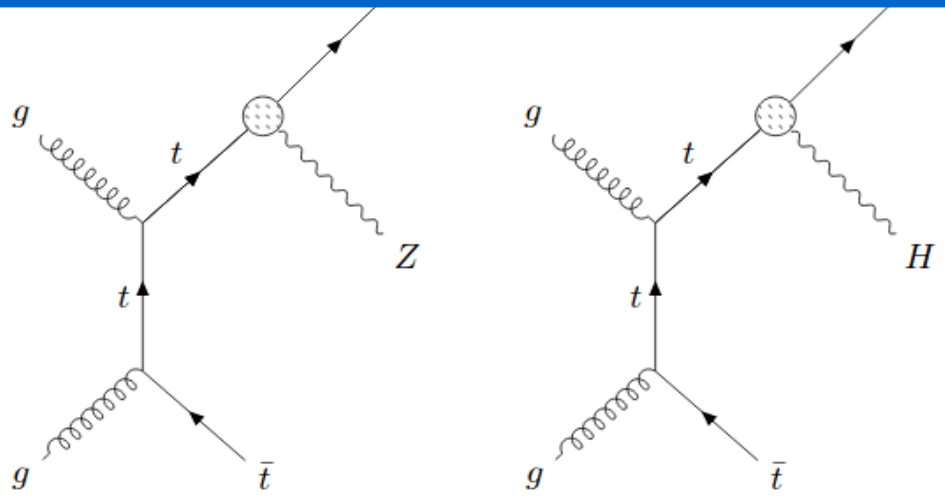


Figure 14: Leading order Feynman diagrams involving NP vertices due to the operator which is proportional to $\bar{c}_{uB}$, $\bar{c}_{uW}$, and $\bar{c}_{Hu}$ (left), and $\bar{c}_u$ (right).

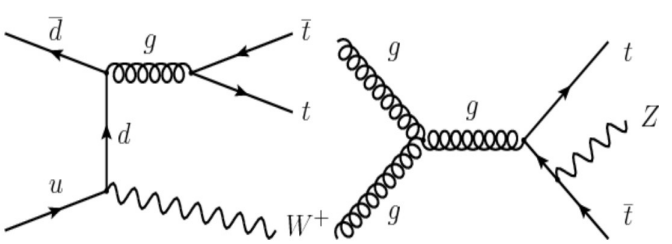
Wilson coefficient	1σ CL [TeV^{-2}]	2σ CL [TeV^{-2}]
$\lvert\bar{c}_{uB}/\Lambda^2\rvert$	[0.0, 1.5]	[0.0, 2.1]
$\lvert\bar{c}_u/\Lambda^2 + 10.9\ \text{TeV}^{-2}\rvert$	[2.3, 15.2]	[0.0, 18.6]
$\bar{c}_{uW}/\Lambda^2$	[-1.6, 1.5]	[-2.2, 2.1]
$\bar{c}_{Hu}/\Lambda^2$	[-9.1, -6.5] and [-1.6, 1.1]	[-10.1, 2.0]

Table 12: Expected 1σ and 2σ CL for this $t\bar{t}W$ and $t\bar{t}Z$ measurement, for selected Wilson coefficients.

Wilson coefficient	Best fit [TeV^{-2}]	1σ CL [TeV^{-2}]	2σ CL [TeV^{-2}]
$\lvert\bar{c}_{uB}/\Lambda^2\rvert$	1.6	[0.0, 2.3]	[0.0, 2.8]
$\lvert\bar{c}_u/\Lambda^2 + 10.9\ \text{TeV}^{-2}\rvert$	11.1	[2.7, 15.6]	[0.0, 19.1]
$\bar{c}_{uW}/\Lambda^2$	1.8	[-2.4, -0.8] and [0.7, 2.4]	[-3.0, 2.9]
$\bar{c}_{Hu}/\Lambda^2$	-9.4	[-10.3, -8.1] and [0.1, 2.1]	[-11.2, -6.6] and [-1.5, 3.0]

Table 13: Observed best-fit values determined from this $t\bar{t}W$ and $t\bar{t}Z$ measurement, along with corresponding 1σ and 2σ CL intervals for selected Wilson coefficients.

- *tt* + V background to *tt*H
  - production **rates** 3/4 (W/Z) times **higher** @ 13TeV
    - achieved 30% / 25% (W/Z) precision in Run1
    - achieved 35% precision for ttZ with 2015 dataset
  - update with **2016 dataset** with most sensitive channels
    - stat. ≈ syst. uncertainties
    - obtained **33%** / **30%** (W/Z) precision
    - consistent with NLO QCD predictions



JHEP 01 (2016), 0969

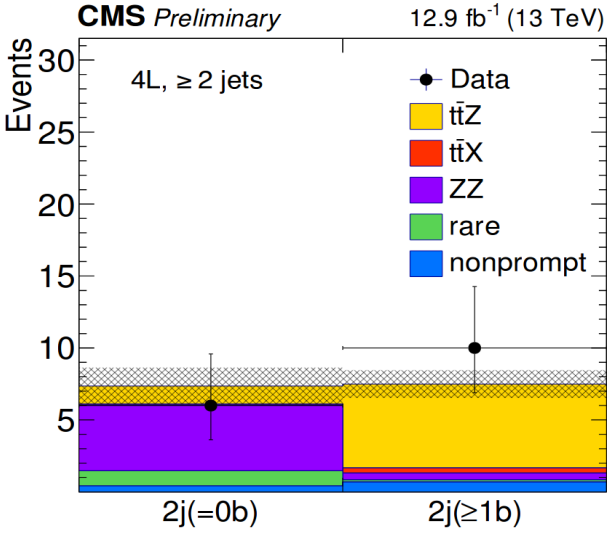
2lSS

$t\bar{t}W \to (bjj)(bjj)(jj)$
$t\bar{t}W \to (bjj)(bjj)(l\nu)$
$t\bar{t}W \to (bl\nu)(bjj)(l\nu)$
$t\bar{t}W \to (bl\nu)(bl\nu)(l\nu)$

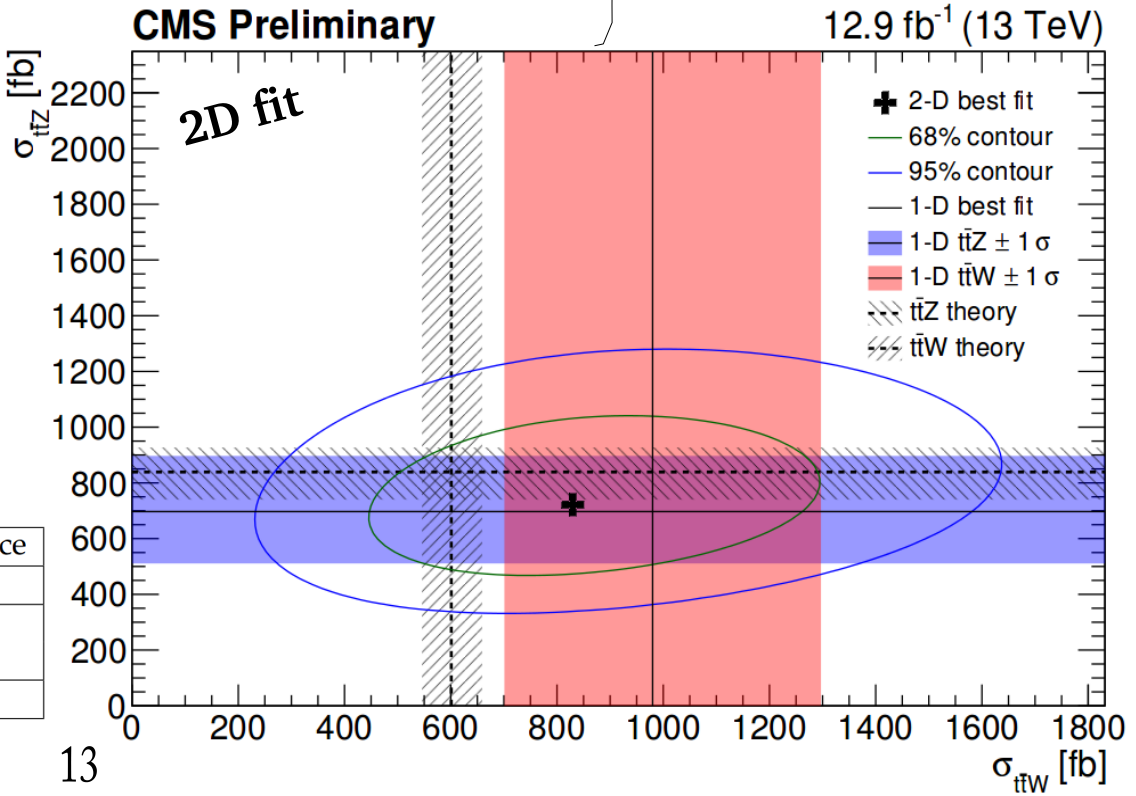
3l
4l

$t\bar{t}Z \to (bjj)(bjj)(jj)$
$t\bar{t}Z \to (bjj)(bjj)(ll)$
$t\bar{t}Z \to (bl\nu)(bjj)(ll)$
$t\bar{t}Z \to (bl\nu)(bl\nu)(ll)$

Run 2



TOP-16-017



Channel	Expected significance	Observed significance
2ℓ*ss* analysis (tt̄W)	2.6	3.9
3ℓ analysis (tt̄Z)	5.4	3.8
4ℓ analysis (tt̄Z)	2.4	2.8
3ℓ and 4ℓ combined (tt̄Z)	5.8	4.6

reducible (faking b jets)

- tt+jets measurement for understanding $ttjj$ and $ttbb$ in ttH(bb) process

irreducible

  - in dilepton channel with extra MET and Z-mass veto in same-flavors
    - $N_{jets} \geq 4$, at least two b-tagged (both with CSVv2M)
    - DY estimated from data

arXiv:1705.10141 (submitted to PLB)

  - in the visible (measured best) and full phase space (facilitates theory comparison)
    - $t\bar{t}jj$: two leptons, at least 4 jets → at least 2 b-jets
    - $t\bar{t}b\bar{b}$: $t\bar{t}jj$ → at least 4 b-jets
    - $t\bar{t}bj$: $t\bar{t}jj$ → exactly 3 b-jets
    - $t\bar{t}c\bar{c}$: $t\bar{t}jj$ → 2 b-jets, and at least 2 c-jets
    - $t\bar{t}LF$: $t\bar{t}jj - t\bar{t}b\bar{b} - t\bar{t}bj - t\bar{t}c\bar{c}$

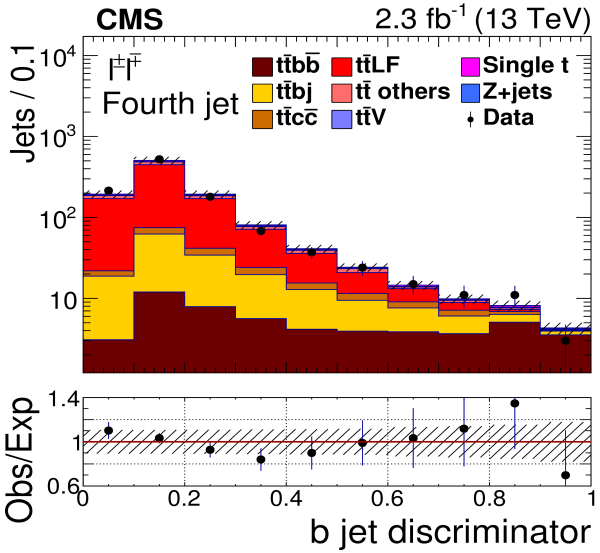
Visible phase space
- ratio: $R_{Vis} = \sigma(t\bar{t}b\bar{b})_{Vis}/\sigma(t\bar{t}jj)_{Vis} = R_{RECO} \times \frac{\epsilon_{t\bar{t}jj}}{\epsilon_{t\bar{t}b\bar{b}}}$
- cross section: $\sigma_{Vis} = N/(\epsilon\mathcal{L})$

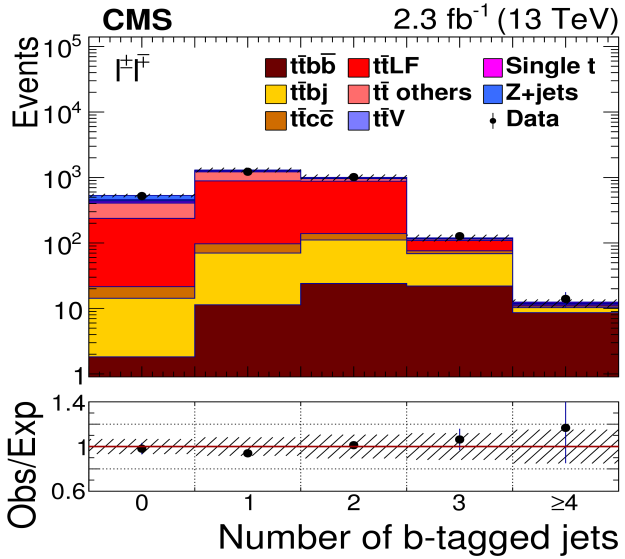
Full phase space
- ratio: $R_{Full} = \sigma(t\bar{t}b\bar{b})_{Full}/\sigma(t\bar{t}jj)_{Full} = R_{Vis} \times \frac{\mathcal{A}_{t\bar{t}jj}}{\mathcal{A}_{t\bar{t}b\bar{b}}}$
- cross section: $\sigma_{Full} = \sigma_{Vis}/\mathcal{A}$

Process	Efficiency ϵ	Acceptance $\mathcal{A}$
$t\bar{t}b\bar{b}$	27 %	2.2 %
$t\bar{t}jj$	12 %	2.0 %

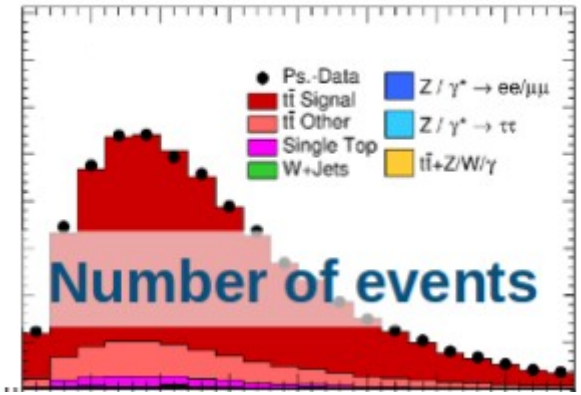
  - sim fit to CSV of third and fourth (in b-tagging order) jets

$$f(k,R) = k \cdot N_{t\bar{t}jj} \cdot [R \cdot N^{norm}_{t\bar{t}b\bar{b}} + R' \cdot N^{norm}_{t\bar{t}bj} + (1-R-R') \cdot N^{norm}_{t\bar{t}LF/t\bar{t}c\bar{c}}] + N^{MC}_{bkg} + N^{Data-driven}_{bkg}$$



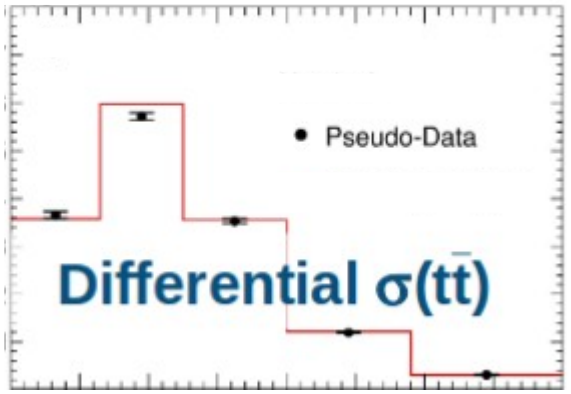


Source	$\sigma_{t\bar{t}b\bar{b}}$	$\sigma_{t\bar{t}jj}$	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
Pileup	0.4	<0.1	0.4
JES & JER	7.8	7.4	2.6
b tag (b quark flavour)	19	4.7	19
b tag (c quark flavour)	14	1.3	14
b tag (light flavour)	14	9.8	9.7
Ratio of ttbb and ttbj	2.6	0.5	2.6
Background modelling	3.8	3.5	1.6
$t\bar{t}c\bar{c}$ fraction in the fit	5.2	1.9	4.8
Lepton trigger/identification	3.0	3.0	0
MC generator	9.4	6.2	3.0
μ_F and μ_R scale	2.0	2.0	1.0
scale in PS	13	9.9	10
PDFs	0.5	0.5	<0.1
Efficiency ($t\bar{t}c\bar{c}$ fraction)	0	1.3	1.3
Jet multiplicity modelling	5.0	5.0	5.0
Top quark p_T modelling	0.8	0.3	0.5
Simulation (statistical)	1.5	1.5	1.5
Integrated Luminosity	2.3	2.3	0
Total uncertainty	34	19	28

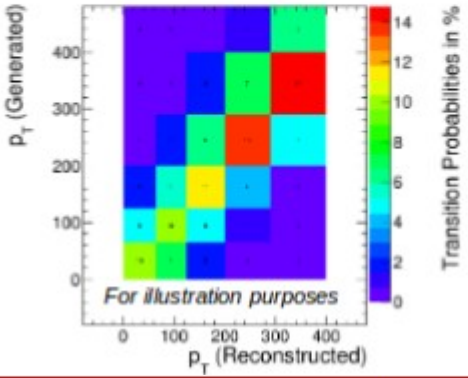


Response matrix A_{ij}

$\frac{1}{\sigma}\frac{d\sigma}{dp_T^t}$ [GeV^{-1}]



bin-by-bin correlations

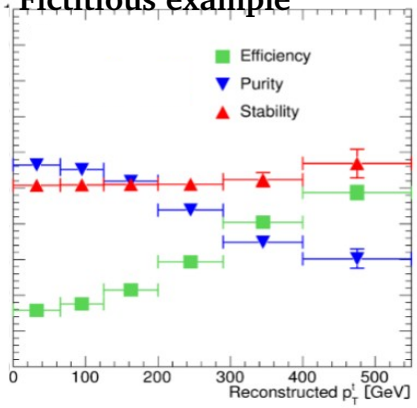


$$\frac{1}{\sigma}\frac{d\sigma}{dX_i} = \frac{1}{\sigma}\frac{unfold\left(N^X_{data,i} - N^X_{BG,i}\right)}{\Delta^i_X \cdot \int \mathscr{L}\, dt}$$

binning

- chosen to limit migration effects
  - based on purity and/or stability

Fictitious example



$$p_i = \frac{N_i^{rec\,\&\,gen}}{N_i^{rec}}$$

$$s_i = \frac{N_i^{rec\,\&\,gen}}{N_i^{gen}}$$

e.g. Regularized Unfolding

- Unfolding → χ^2-minimization problem
  - non-physical fluctuations removed by regularization

unfolding — regularization

$$\chi^2 = (\vec{N} - A\cdot\vec{x})^T\, COV_{\vec{N}}^{-1}\, (\vec{N} - A\cdot\vec{x}) - \tau^2 \cdot K(\vec{x})$$

  - τ the regularization parameter
  - selected at e.g. minimum of $\bar{\rho}$

Phase space

- correct back to parton or particle level
  - parton level: facilitates theory comparison
  - particle level: theo. uncertainties reduced

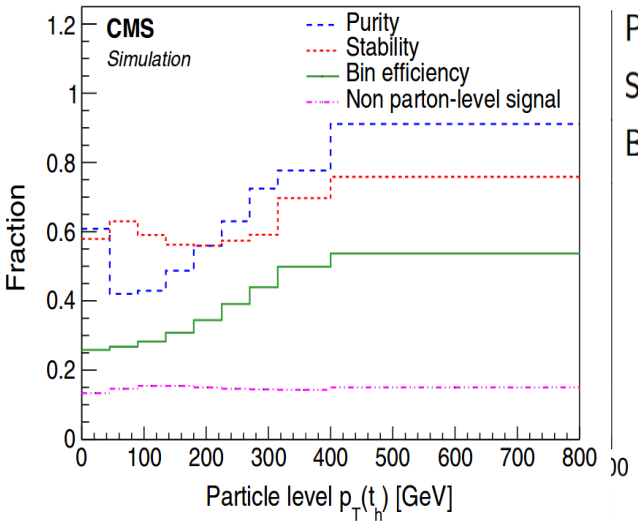
- Differential *tt* measurement as function of P_T^l, P_T^j, P_T^t, y^t, $P_T^{t\bar{t}}$, $y^{t\bar{t}}$, $M^{t\bar{t}}$, and $\Delta\phi^{t\bar{t}}$
  - in dilepton channel with extra MET and Z-mass veto in same-flavors
    - $N_{jets} \geq 2$, at least one *b*-tagged
    - leptons from prompt τ decay are treated as background
  - **particle** level definition expected not to rely of MC implementation and tuning
    - same kinematical requirements as imposed on the reconstructed objects
    - pseudo W: dressed lepton + prompt neutrino
    - pseudo top: dressed leptons + prompt neutrinos + *b* jets **arXiv:1708.07638**

Object	Definition	Selection criteria
Prompt neutrino	neutrinos not from hadron decay	none
Dressed lepton	anti-k_T jet with a distance parameter of 0.1 using electrons, muons and photons not from hadron decay	$p_T > 20$ GeV, $\|\eta\| < 2.4$
b quark jet	anti-k_T jet with a distance parameter of 0.4 using all particles and ghost B hadrons not including any neutrinos nor particles used in dressed leptons	$p_T > 30$ GeV, $\|\eta\| < 2.4$ with ghost B hadrons

typical uncertainties

Uncertainty source	Particle level [%]	Parton level [%]
Statistical	0.24 – 0.70	0.37 – 0.70
Pileup modeling	0.02 – 0.57	0.10 – 0.51
Trigger efficiency	0.03 – 0.74	0.06 – 0.85
Lepton efficiency	0.06 – 0.94	0.09 – 1.0
JES	0.14 – 2.0	0.31 – 1.8
JER	0.04 – 1.2	0.29 – 0.94
b jet tagging	0.12 – 1.2	0.32 – 1.2
Background	0.16 – 2.3	0.10 – 1.4
PDFs	0.15 – 1.2	0.17 – 1.0
MC generator	0.66 – 12	1.8 – 10
Fact./renorm.	0.10 – 4.7	0.21 – 4.6
Top quark mass	0.49 – 2.0	0.73 – 4.2
Top quark p_T	0.03 – 0.96	0.04 – 1.3
Hadronization	0.70 – 6.0	0.49 – 8.3
Total systematic uncertainty	1.7 – 17	3.3 – 13

- Differential *tt* measurement at parton and particle level
  - in *l+jets* with exact one lepton and
    - $N_{jets} \geq 4$, at least two *b*-tagged (one CSVv2M and one CSVv2L)
  - particle level definition similar to **arXiv:1708.07638** (see previous slide)
    - *l+jets* event at particle level not necessarily *l+jets* event at parton level

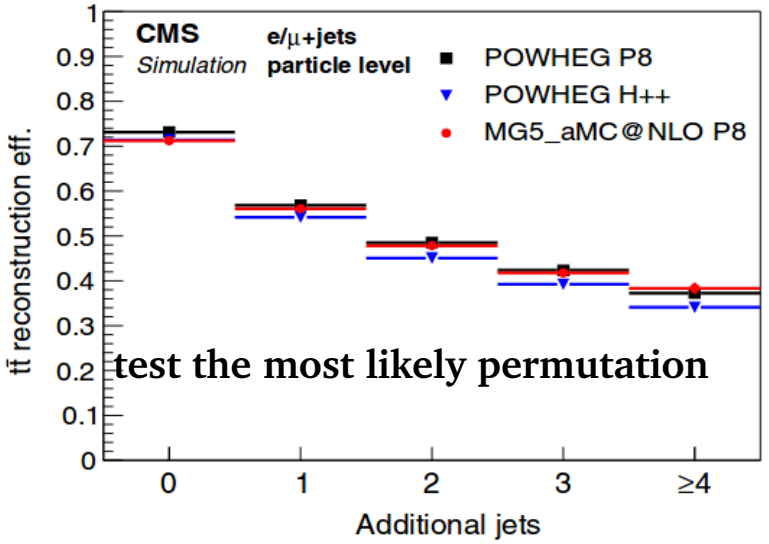


Purity: fraction at parton level in same particle level bin.

Stability: fraction at particle level in same parton level bin.

Bin efficiency: ratio of particle objects and parton level objects in same bin.

PRD 95, 092001 (2017)



test the most likely permutation

POWHEG vs aMC@NLO

typical uncertainties

Source	Particle level [%]	Parton level [%]
Statistical uncertainty	1–5	1–5
Jet energy scale	5–8	6–8
Jet energy resolution	<1	<1
$\vec{p}_T^{miss}$ (non jet)	<1	<1
b tagging	2–3	2–3
Pileup	<1	<1
Lepton selection	3	3
Luminosity	2.7	2.7
Background	1–3	1–3
PDF	<1	<1
Fact./ren. scale	<1	<1
Parton shower scale	2–5	2–9
POWHEG+PYTHIA8 vs. HERWIG++	1–5	1–12
NLO event generation	1–5	1–10
m_t	1–2	1–3

- Inclusive and differential *tt* measurement in resolved and boosted regimes in *all jets*

TOP-16-013

Resolved	Boosted
lepton veto	lepton veto
AK4 jets	AK8 jets
$p_T > 30$ GeV and $\|\eta\| < 2.4$	$p_T > 200$ GeV, $\|\eta\| < 2.4$, $m_{SD} > 50$ GeV
$N_{jets} \geq 6$	$N_{jets} \geq 2$
$H_T > 500$ GeV, $p_T^{(6)} > 45$ GeV	$p_T^{(1)} > 450$ GeV
at least two b-tagged jets	both jets should contain one b-tagged subjet
$\Delta R_{bb} > 2.0$	$\mathcal{F} > 0$
kin. fit probability > 0.02	$150 < m_{SD}^{(1)} < 200$ GeV
$150 < m_t < 200$ GeV	

93% purity

85% purity

Fisher discriminant with τ_3/τ_2 and τ_3/τ_1

k → *R* jet constituent

$$\tau_i = \frac{1}{\sum_k p_{T,k} R} \sum_k p_{T,k} \min\left(\Delta R_{1k}, \Delta R_{2k}, \ldots \Delta R_{ik}\right)$$

$$m_{SD} = \text{¿} \frac{\min\left(p_{T,1}, p_{T,2}\right)}{p_{T,1} + p_{T,2}} > z_{cut} \cdot \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

z_{cut} and b model parameters

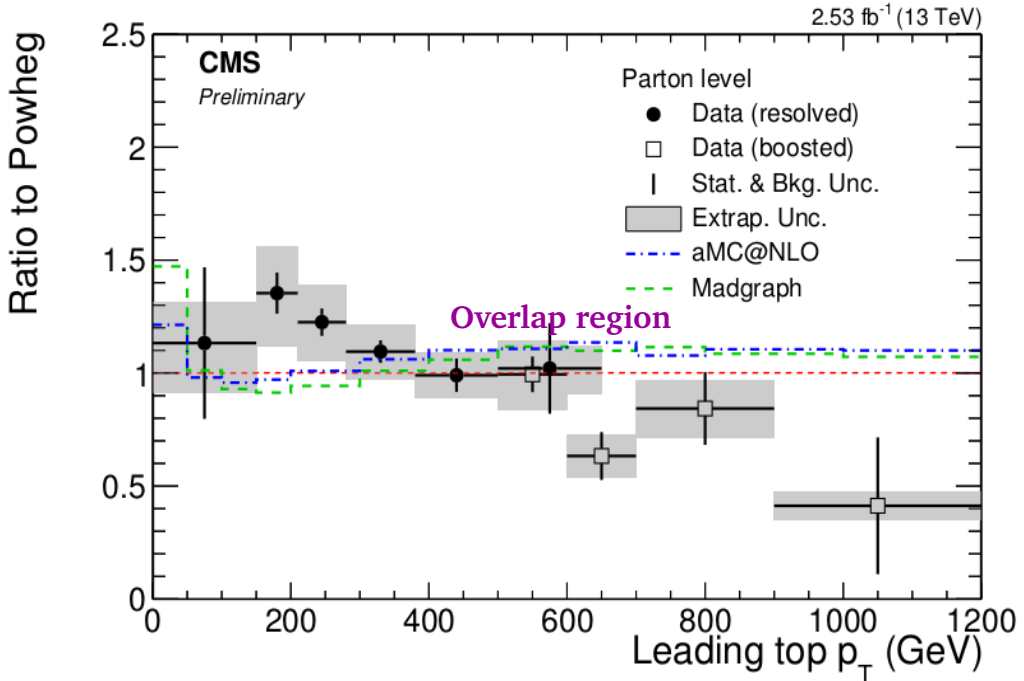
- perform a template fit $D(m_t) = N_S \cdot S(m_t) + N_B \cdot B(m_t)$

  - QCD (dominant bkg.) extracted from 0 *b*-tagged CR
  - Differential measurement in $150 < m_t < 200$

m_t after accounting for the most probable combination (kin. fit probability) of jets

boosted

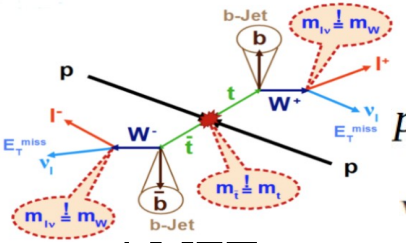
m_{SD} of the leading *fat* jet



inclusive

Analysis	Resolved	Boosted
Source	(%)	(%)
QCD background modeling	$-1.0, +6.6$	$-2.7, +2.4$
Subdominant backgrounds	± 4.0	± 4.0
Jet energy scale	$-8.2, +9.0$	$-1.8, +1.6$
Jet energy resolution	$-0.7, +0.8$	$\pm < 1$
b tagging	$-5.5, +6.2$	$-10.5, +12.9$
Trigger efficiency	$-2.9, +3.2$	$-1.1, +0.9$
Scale (μ_F and μ_R)	$-1.5, +0.0$	$-1.5, +0.0$
PDF	± 1.0	± 1.0
Parton shower	$-5.0, +2.5$	$-7.0, +3.0$
NLO generator	± 2.0	± 7.0
Total systematic	$-12.4, +14.1$	$-15.4, +15.8$
Statistical	± 3.0	± 6.3
Integrated luminosity	± 2.7	± 2.7

- Double differential tt measurement in $e\mu$



$$p^{top}_{x,y,z} = \frac{1}{w}\sum_{i=0}^{100} w_i \cdot (p^{top}_{x,y,z})_i$$

$$w_i = w_i(l_1 b_1) \cdot w_i(l_2 b_2)$$

  - $N_{jets} \geq 2$ at least one b-tagged (CSVL)
    - momenta of neutrinos constrained by m_t, m_W and MET
    - jets and leptons smeared to recover events with no solution (95% efficiency)
  - overall good description, tension relative to LO/NLO MC (similar to slide 9)
    - good description at NLO of $y(t)$-$p_T(t)$, $M(t\bar{t})$-$y(t)$ and $M(t\bar{t})$-$y(t\bar{t})$ with latest PDFs for CT14, MMHT2014, NNPDF3.0, CJ15
    - large scale unc. for $M(t\bar{t})$-$\Delta\eta(t\bar{t})$, $M(t\bar{t})$-$p_T(t\bar{t})$, $M(t\bar{t})$-$\Delta\phi(t\bar{t})$
    - improved description of $y(t)$-$p_T(t)$ with approx. NNLO
    - PDF parametrisation: 18p HERAPDF style at starting scale $\mu^2_{f0} = 1.9$ GeV^2, $f_s = 0.4$:

$$xg(x) = A_g x^{B_g}(1-x)^{C_g}(1+E_g x^2+F_g x^3) - A'_g x^{B'_g}(1-x)^{C'_g}$$
$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+D_{u_v} x+E_{u_v} x^2)$$
$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}$$
$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1+D_{\bar{U}} x+F_{\bar{U}} x^3)$$
$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}$$

Additional constrains: (small-x, $x \to 1$)

$$A_{\bar{U}} = A_{\bar{D}}(1-f_s),\ B_{\bar{U}} = B_{\bar{D}},\ C'_g = 25$$
$$\int_0^1 [\sum_i (q_i(x)+\bar{q}_i(x)) + g(x)]x dx = 1$$
$$\int_0^1 [u(x)-\bar{u}(x)]dx = 2,$$
$$\int_0^1 [d(x)-\bar{d}(x)]dx = 1$$

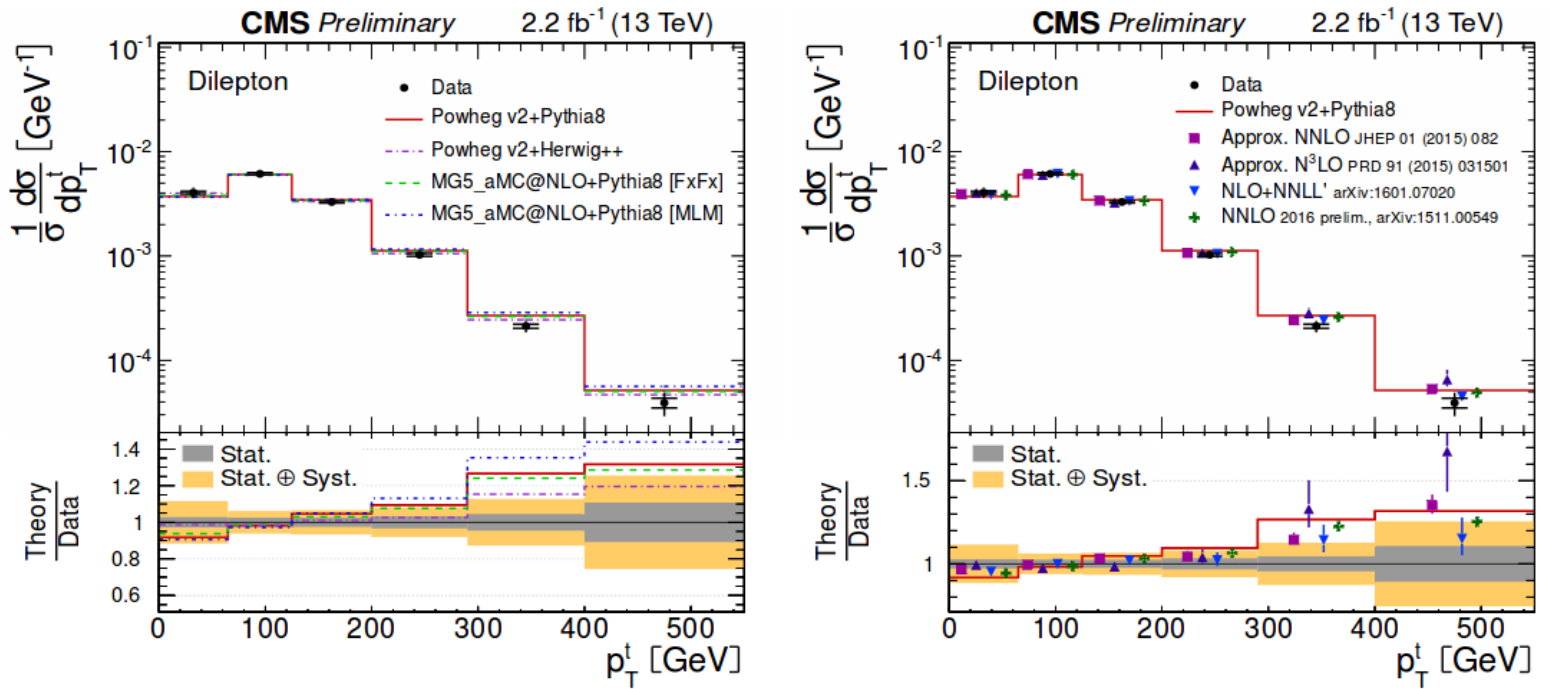
    - PDF uncertainties: fitting ($\Delta\chi^2 = 1$), model (f_s, M_c, M_b, Q^2_{min}) and parametrisation (μ^2_{f0}, D, E, F)
    - $y(t)$-$p_T(t)$, $M(t\bar{t})$-$y(t)$, $M(t\bar{t})$-$y(t\bar{t})$ can be used in PDF fit

TOP-14-013

- Differential *tt* measurement in dilepton channel
  - at parton: p_T (t or $\bar{t}$), y(t or $\bar{t}$) and m($t\bar{t}$) and particle level: jet multiplicity
    - $N_{jets} \geq 2$, at least one *b*-tagged (CSVv2L)
    - extra MET and Z-mass veto in same-flavors
    - DY estimated from data

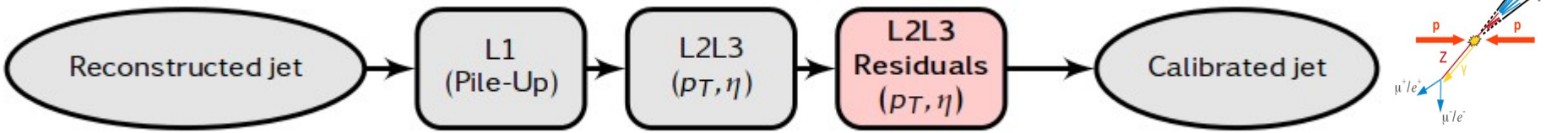
TOP-16-011

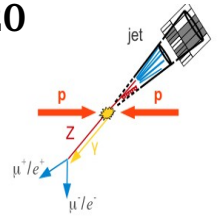
  - kinematic *tt* reconstruction as in TOP-14-013 (see previous slide)
    - results in ~90% efficiency and ~80% purity in *tt* dilepton events
  - Object definition at parton level similar to TOP-16-007
    - phase space definition closely follows the (detector level) event selection



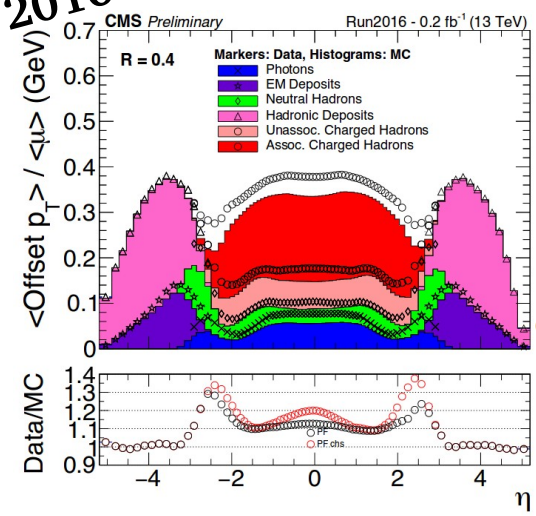
JET and MET performance in Run2 (I)

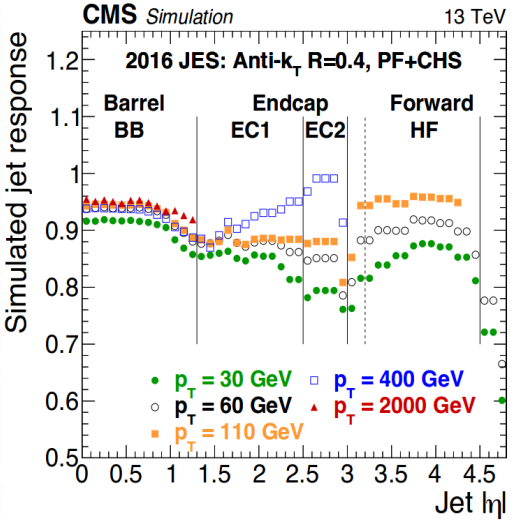
CMS-DP-2016-020

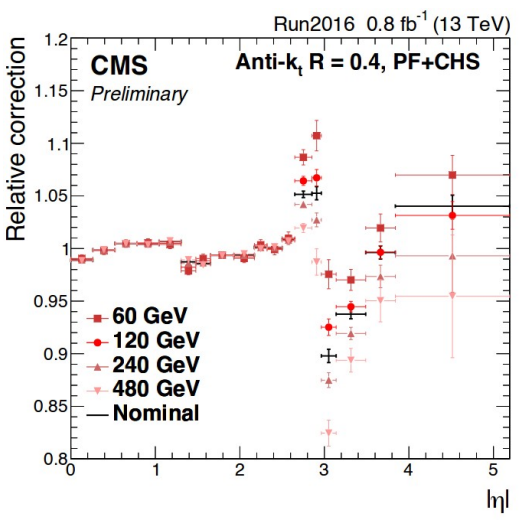


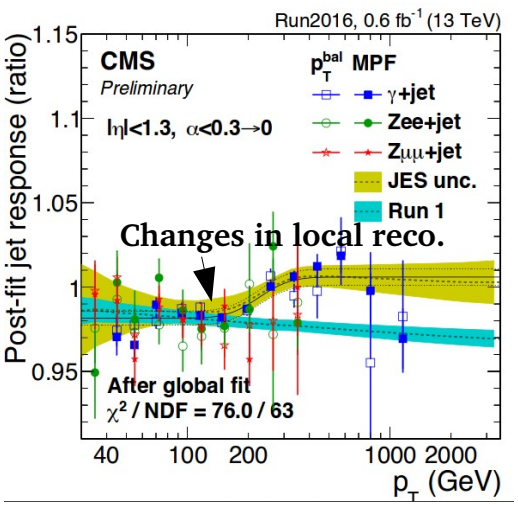


2016









Data/MC comparison for the average offset per additional pileup interaction (μ)

Derived with Random Cone method from ZeroBias data (random triggers in the presence of bunch crossing) vs NeutrinoGun simulation

Stronger p_T-dependence in Endcaps and HF

Drop in response

- at 3<|η|<3.2 due to gaps
- at |η|>4.5 due to acceptance

back-to-back dijets events

(*tag jet* in the barrel, *probe jet* free to scan the whole detector)

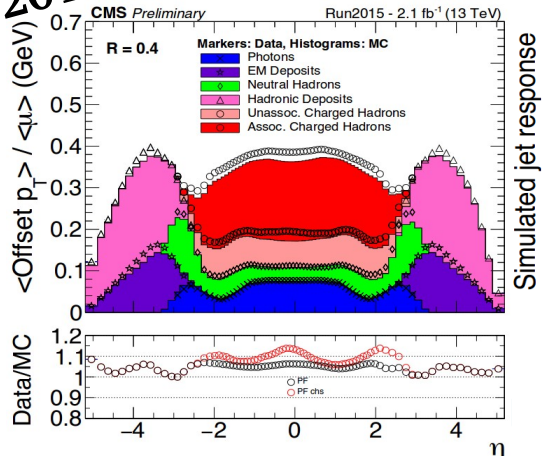
response of *probe jet* relative to *tag jet*

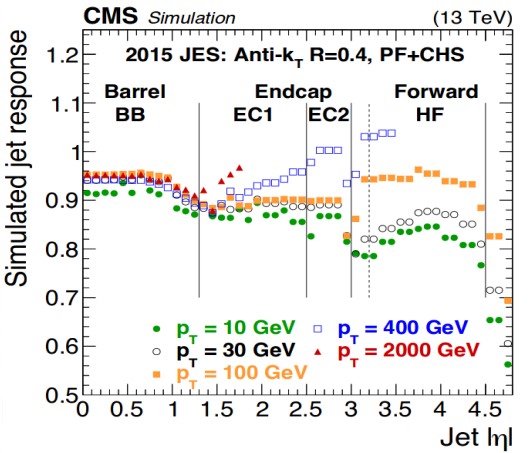
(calibrate the response of a jet at a given η to the one for jets in |η|<1.3)

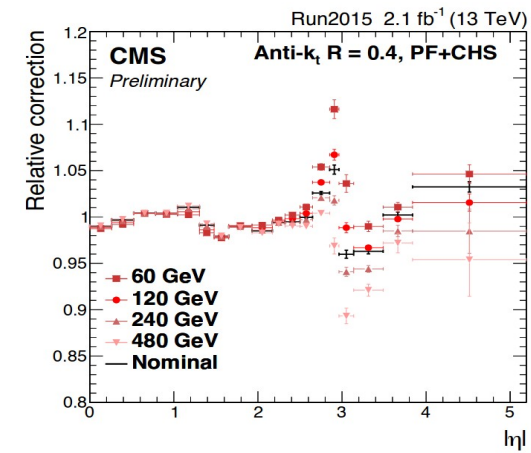
Data/MC comparison for the jet response dependency on the jet p_T

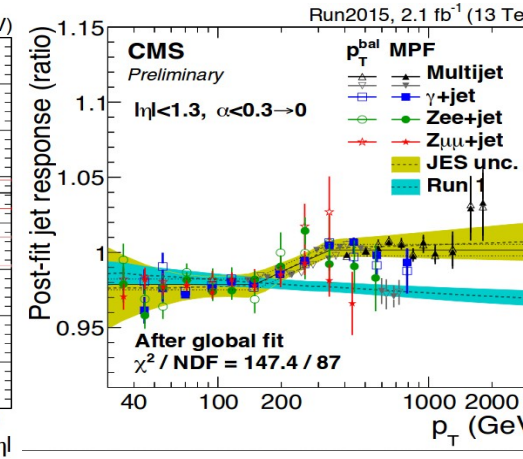
Combination of three samples, γ+jet, Z(→μμ)+jet, Z(→ee)+jet

2015



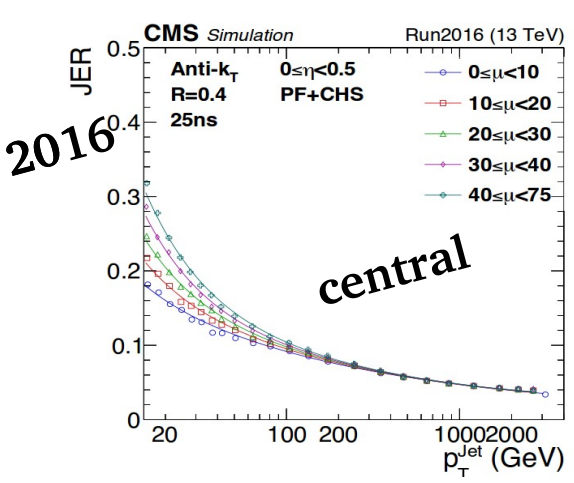


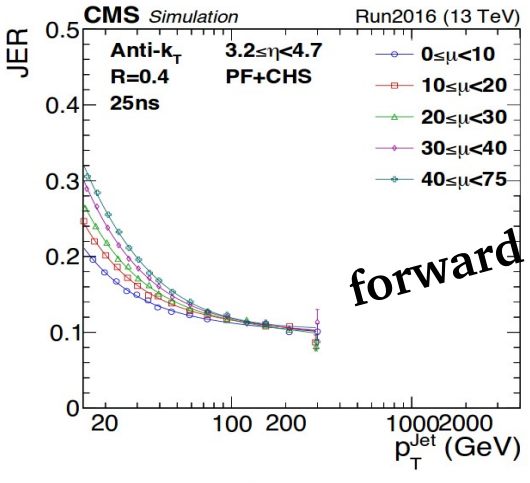




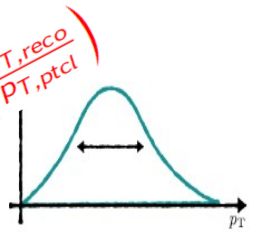
JET and MET performance in Run2 (II)

2016





$$JER = \sigma\left(\frac{p_{T,reco}}{p_{T,ptcl}}\right)$$

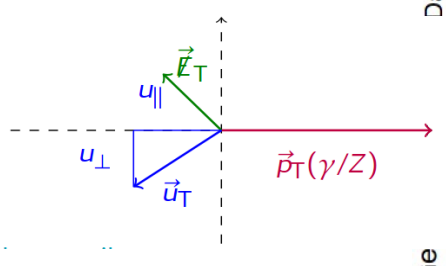


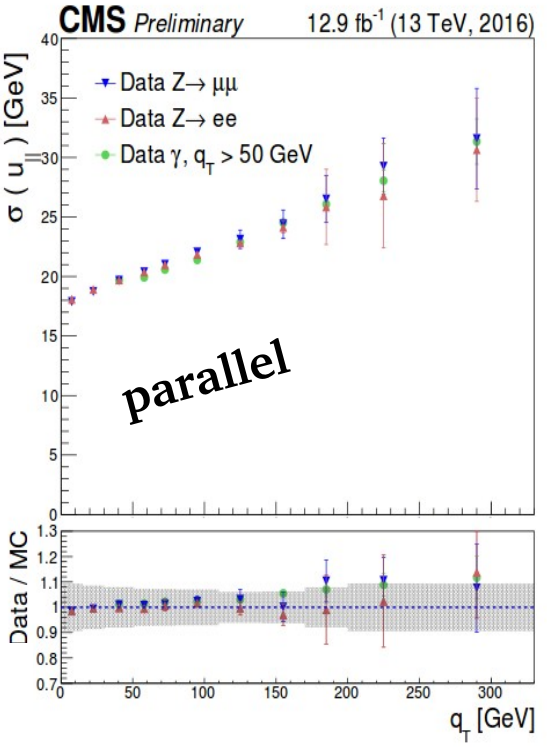
Resolutions stable against pileup

Better than 10% (5%) resolution above p_T=100 GeV (1 TeV)

Degradation of 50% at p_T=20 GeV for very high pileup

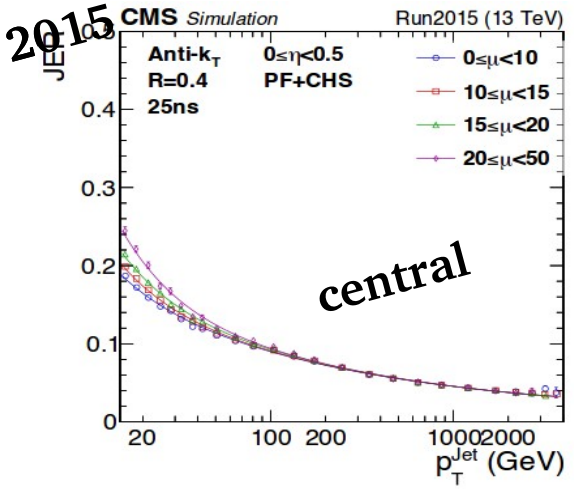
CMS-DP-2016-020

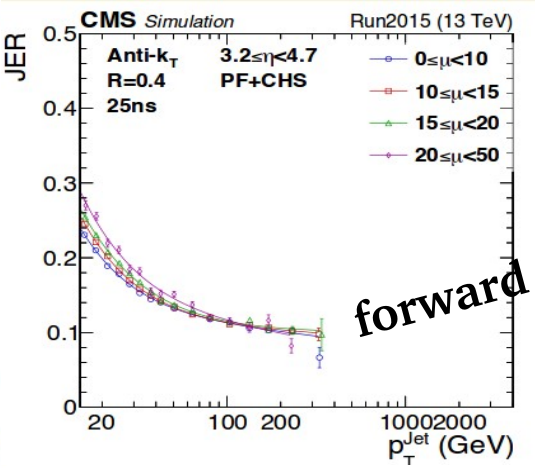


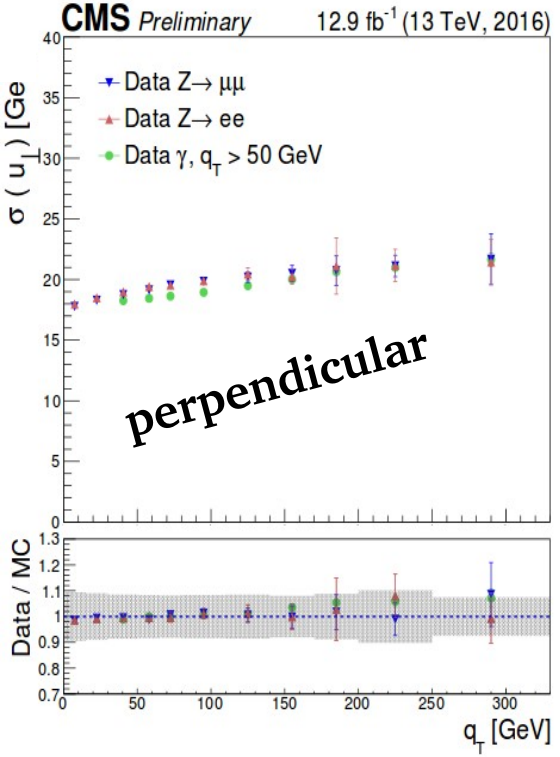


JME-16-004

2015

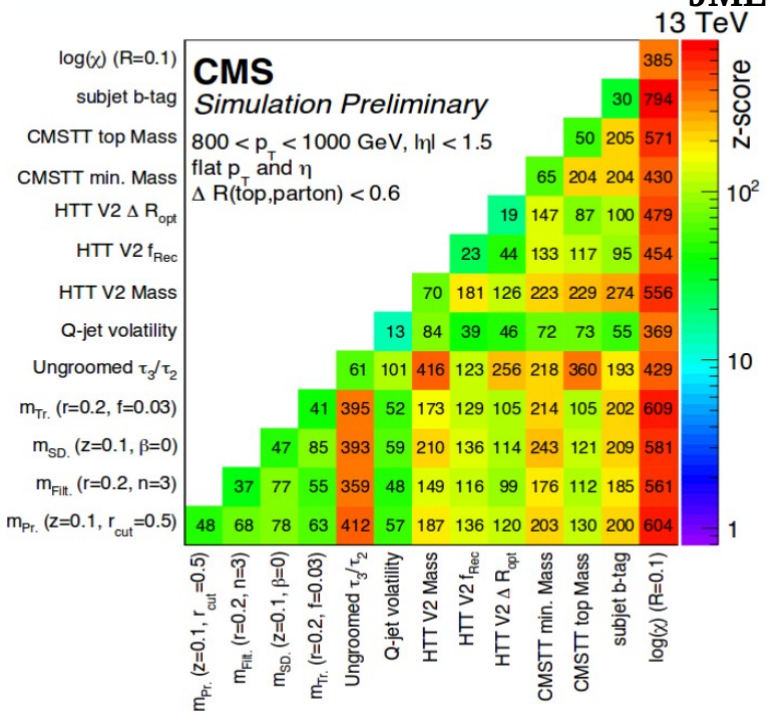


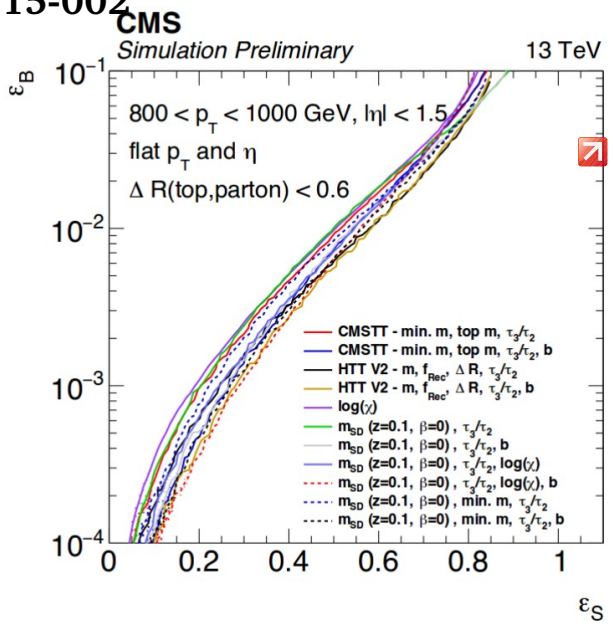




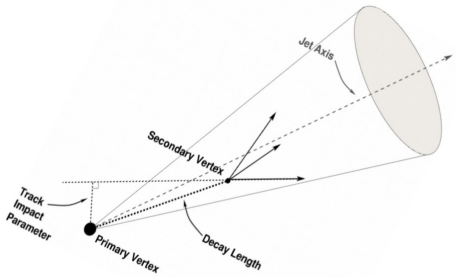
t- and *b*-tagging in Run2

JME-15-002

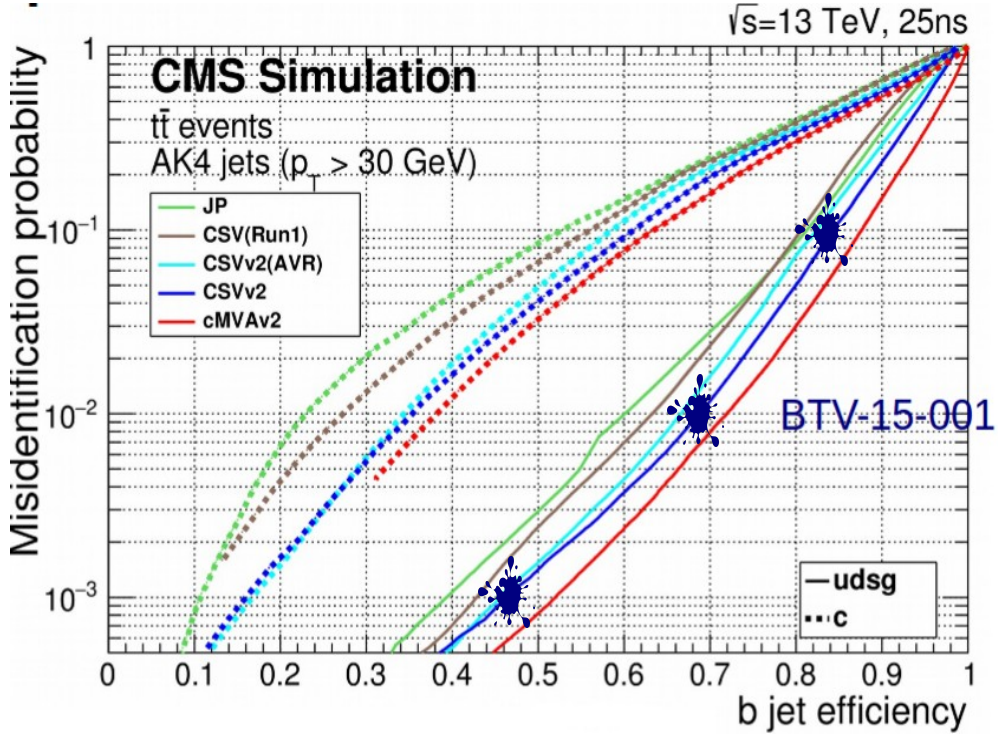




- Identify best variable combinations
  - z score: 1/bkg.eff at sig.eff=30%
    - comb. with τ_i promising
    - best combs. perform equally well



- Combined SV algorithm
  - real, pseudo and no vtx. cases
    - Improved performance to Run1
    - CSVv2 ~8% better at 1% mis-ID



PUPPI

- Various methods are studied for pileup mitigation in Run 2
  - example: PUPPI (**P**ile**U**p **P**er **P**article **I**dentification)
    - use knowledge of origin of PU charged particles to deduce information on neutral PU component
    - reweight neutrals according to their probability to originate from PU
  - intuitive correction for jet substructure observables

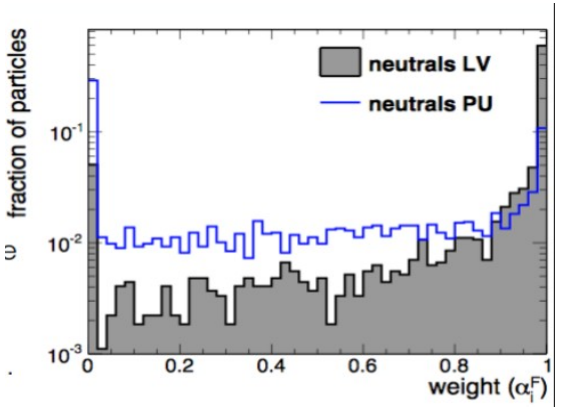
Defines α of each particle (i)
using other particles (j) around it.
For example

$$\alpha_i = \log \sum_{j \in \text{event}} \frac{P_T^j}{\Delta R_{ij}} \Theta(R_{\min} < \Delta R_{ij} < R_0)$$

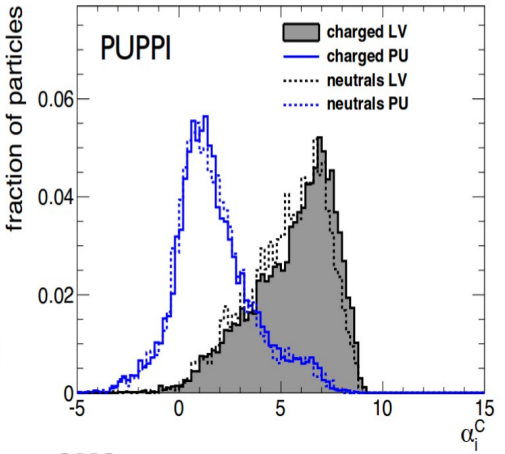
PT sum weighted with distance

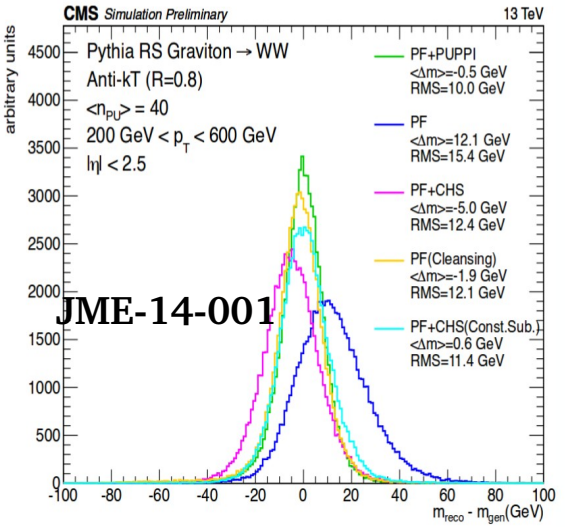
Step function to take into account only particles around it.

Transforms the distribution of α in a weight

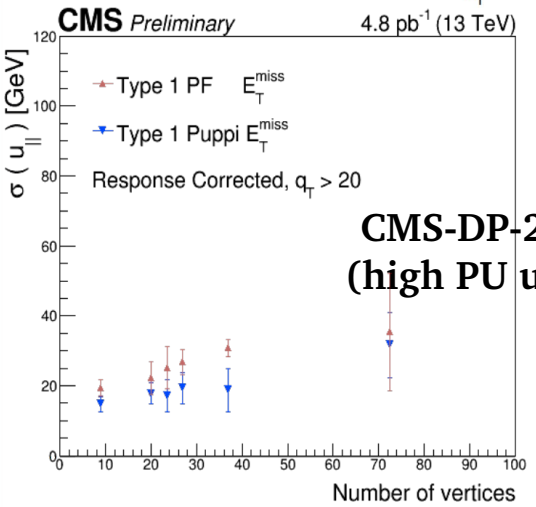


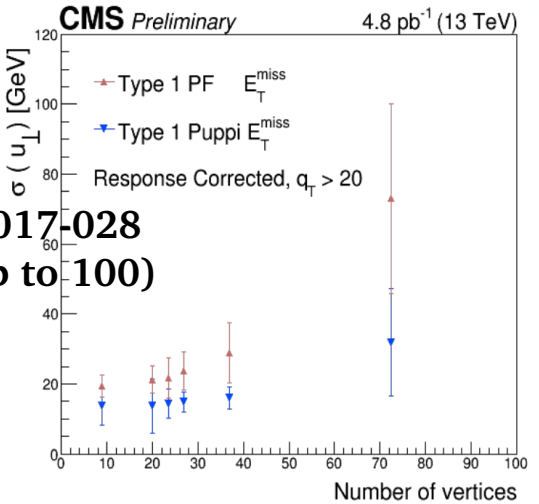
[Bertolini et al., JHEP 1410, 59 (2014)]





JME-14-001





CMS-DP-2017-028
(high PU up to 100)