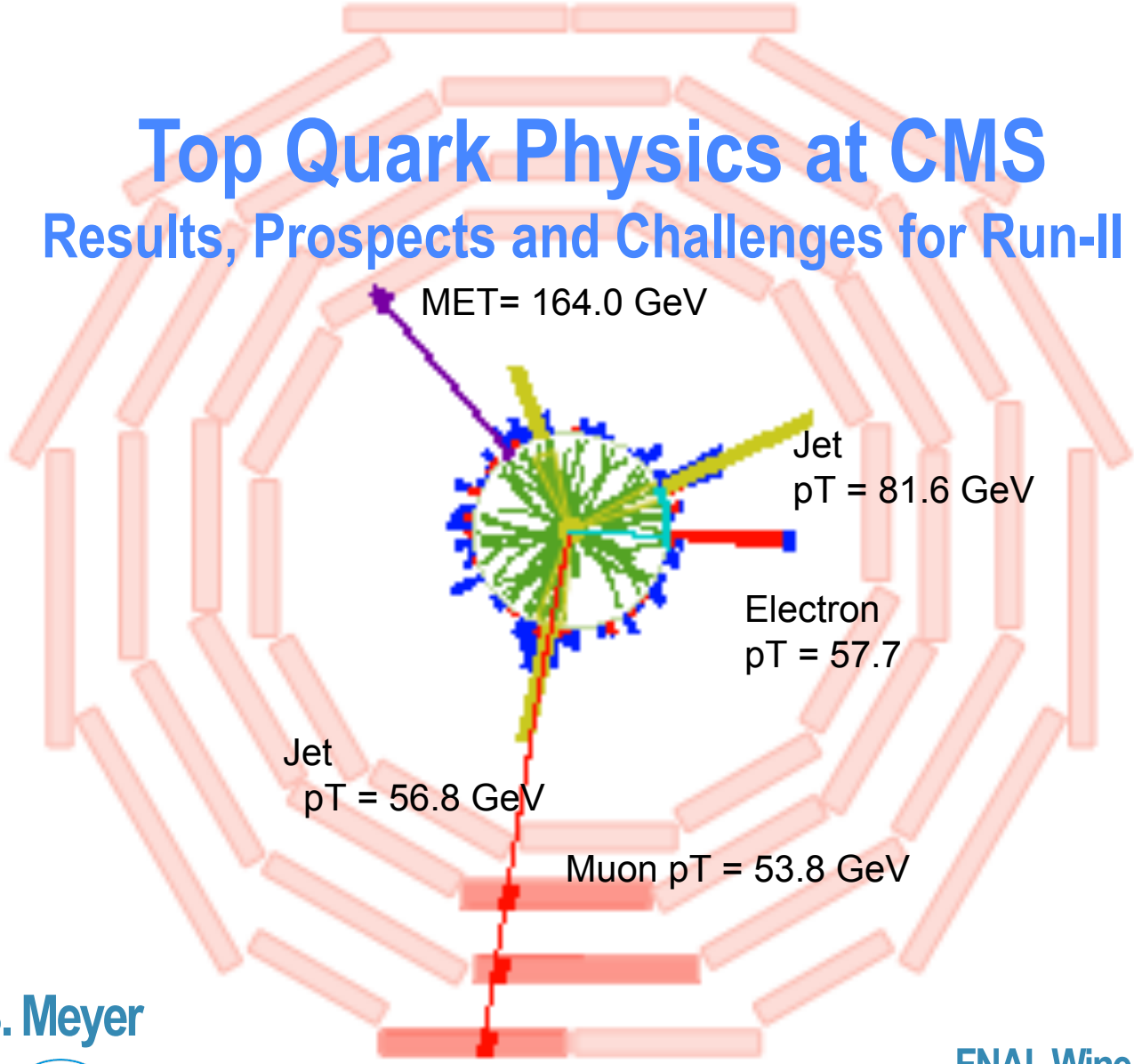
Top Quark Physics at CMS

Results, Prospects and Challenges for Run-II



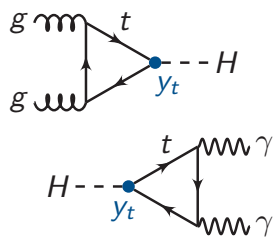
Andreas B. Meyer

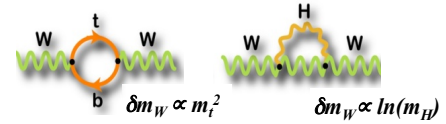
Karlsruher Institut für Technologie

DESY

FNAL Wine and Cheese
3 June 2016

Top Quark Physics





- **Heaviest known elementary particle**
  - Strong coupling to Higgs (EWK loops, gg → H)

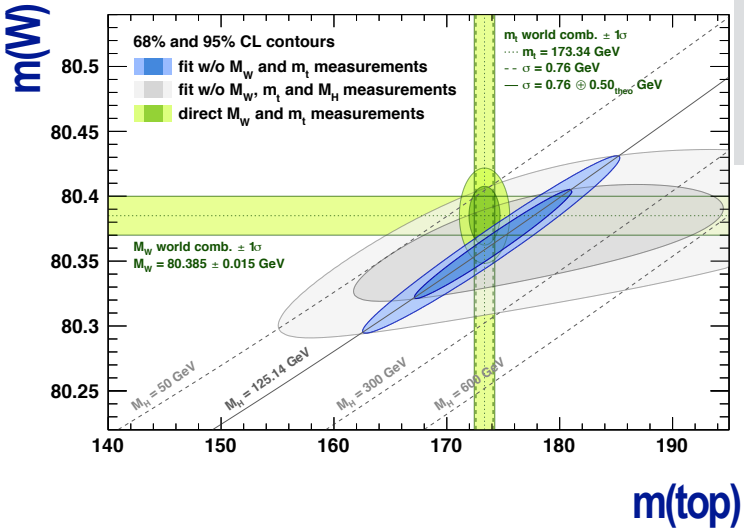
- **Timescales → unique features, bare quark**

$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production}\\ 10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime}\\ 10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization}\\ 10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip}\\ 10^{-21}\ \text{s}}}$$

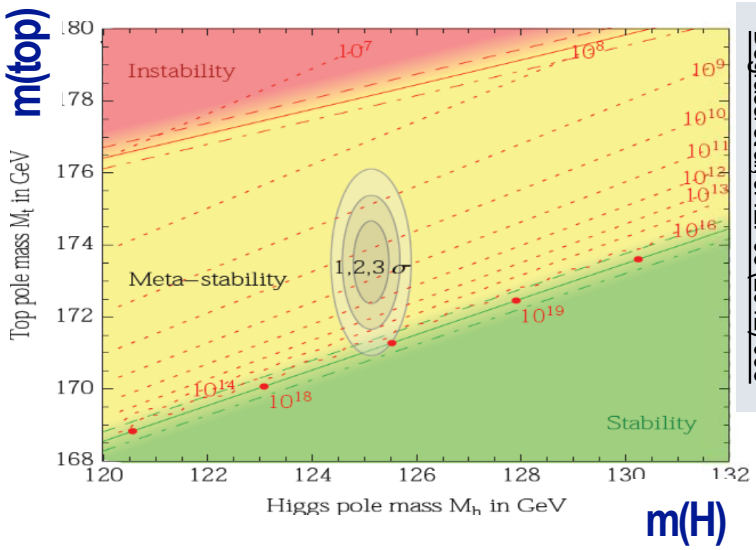
- **Precision measurements of SM parameters**

$$m_t,\ V_{tb},\ Y_t,\ \alpha_S,\ \textit{PDF}$$

- **Search for New Physics**
  - through precision measurements of top quark properties and couplings (esp. in case new physics would couple to mass)
  - top is background to many searches



arXiv:1407.3792



Degrassi et al. JHEP08 (2012) 098

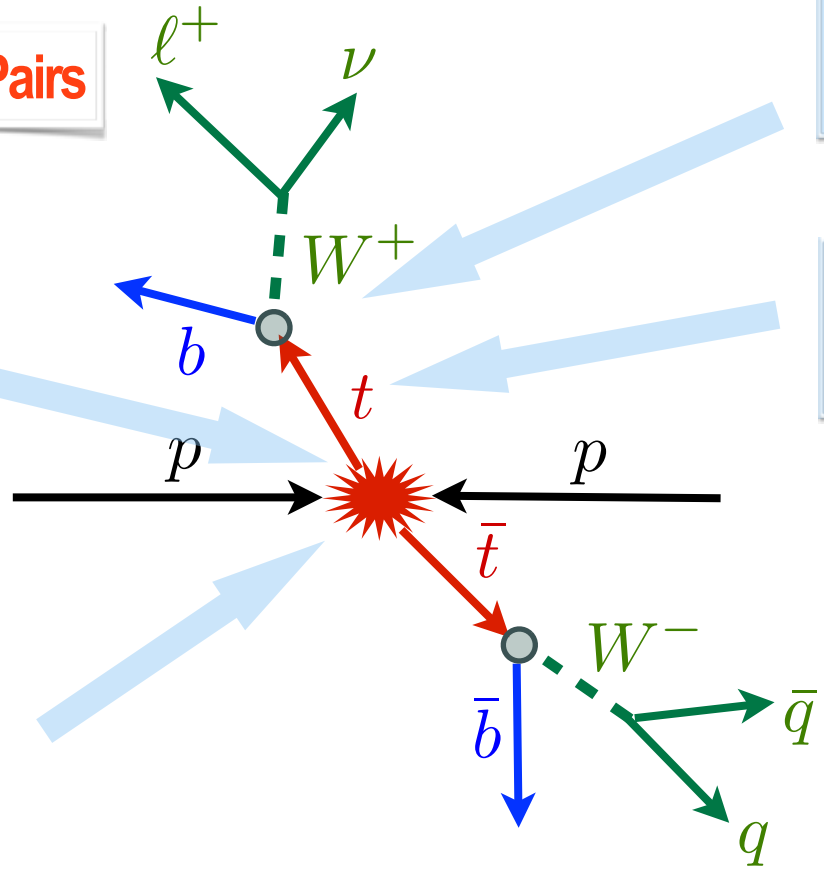
Top Quark Properties in Production and Decay

Top Quark Pairs

W-Helicity Fractions
Branching Ratios, V_{tb},
Rare Decays, FCNC

Spin Correlations
Polarisation
Asymmetries

Mass
Mass Difference,
Width, Charge



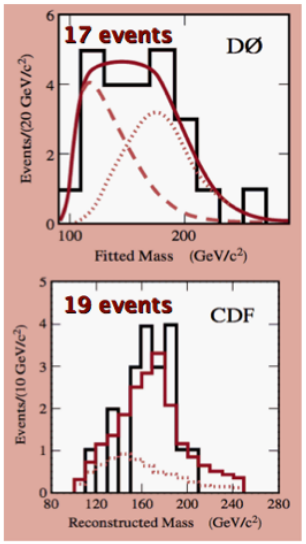
cross sections,
kinematics, QCD
parameters,
resonances,
new particles

EWK Single-Top Production

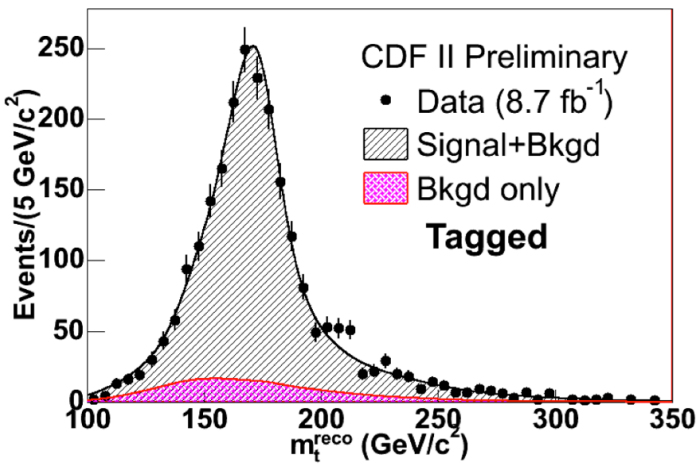
s, t, tW channel production,
Polarisation, V_{tb}, FCNC, W-helicity, mass

The Past

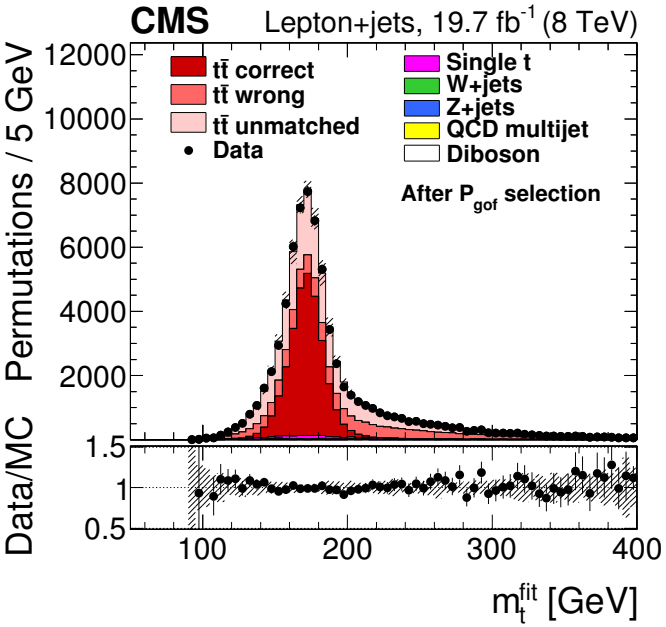
36 events



1000s of events



100000s of events

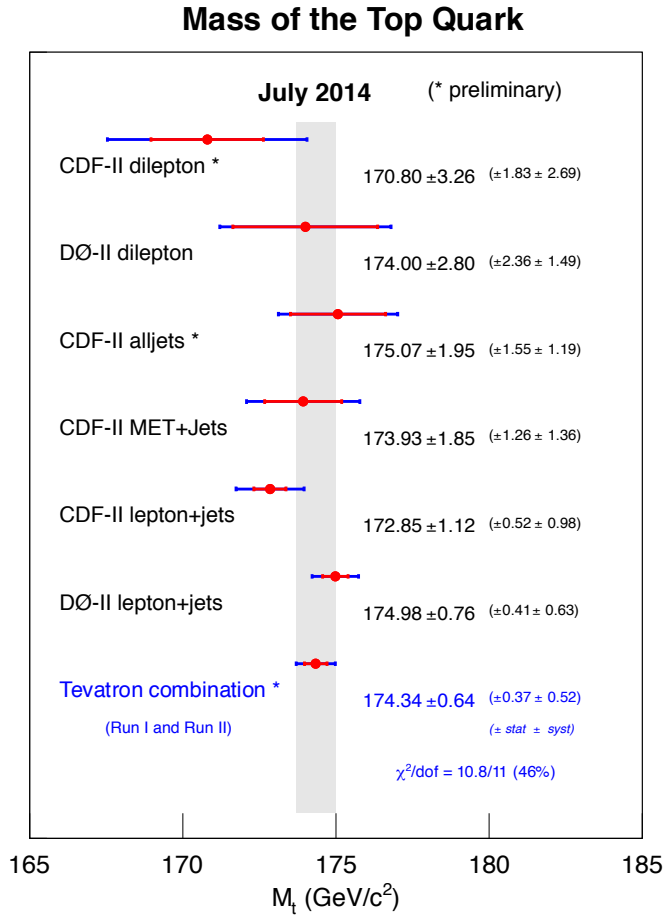


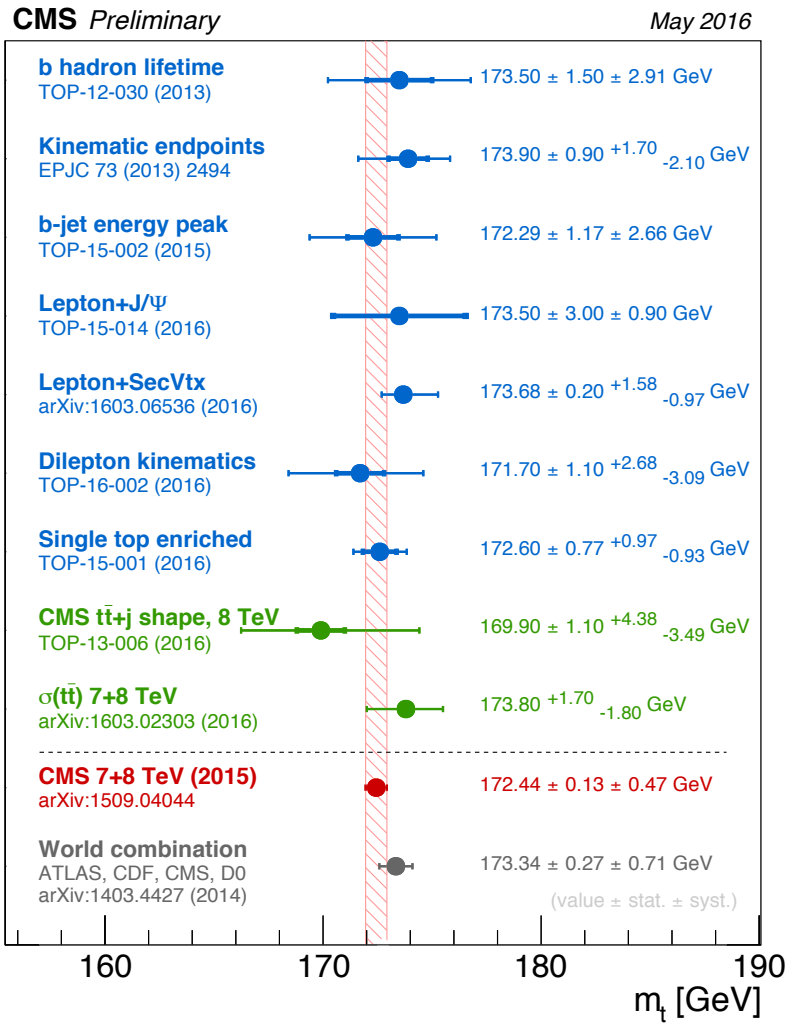
- **Tevatron $p\bar{p}$ 1.96 TeV**
  - discover
  - scrutinise and measure
  - establish top as SM quark
- **LHC Run-I pp (7 and 8 TeV)**
  - pp: complementary initial state
  - superior statistics ⟶ top factory

1995 — 2010 — 2012

The Present

Example: m(top)





Tevatron Run-I and Run-II Combination

$m_{top} = 174.34 \pm 0.64_{syst}$ GeV

CMS Run-I Combination

$m_{top} = 172.44 \pm 0.49_{syst}$ GeV

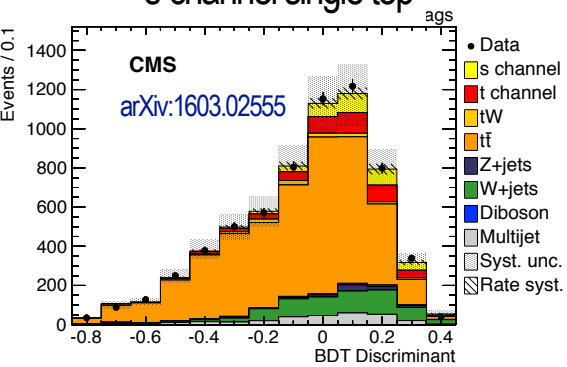
ATLAS Combination (8 TeV to come)

$m_{top} = 172.84 \pm 0.70_{syst}$ GeV

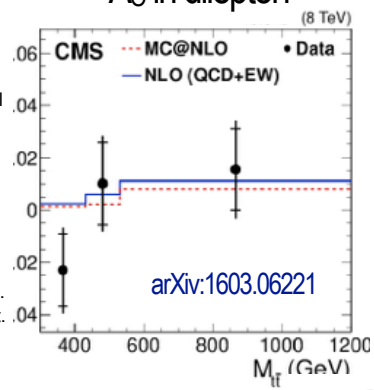
The Present

Many more results

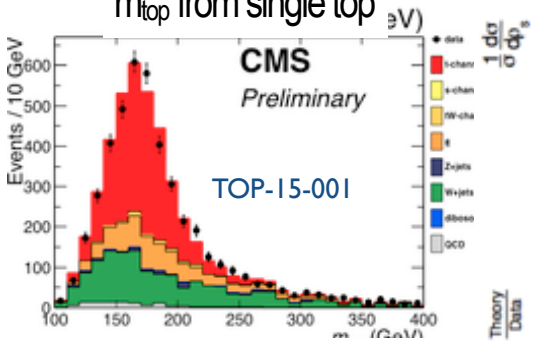
s-channel single top



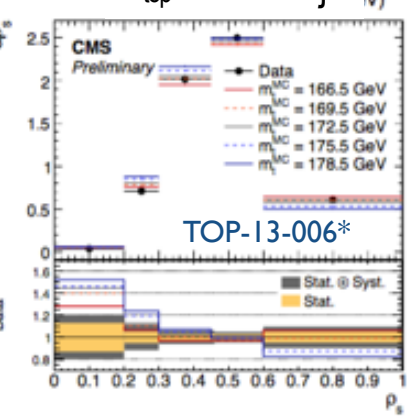
A_C in dilepton



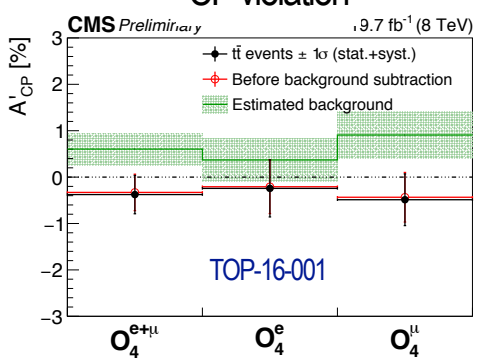
m_{top} from single top



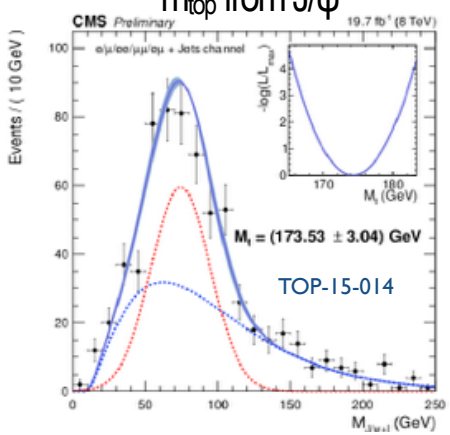
m_{top}^{pole} from tt+jet



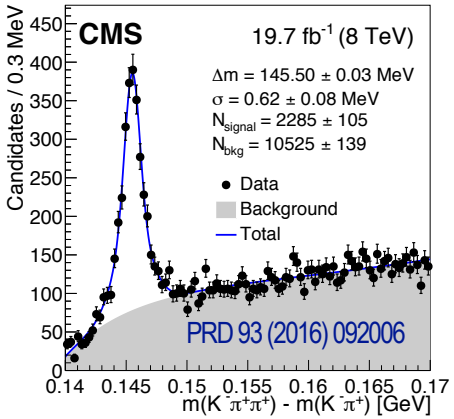
CP violation



m_{top} from J/ψ



m_{top} from 2ndry vertex



- **Tevatron and LHC Run-I Legacies →**
  - measurements of top quark cross sections, mass and properties at highest possible precision
- **LHC Run-II Early Analyses (13 TeV)**
  - rediscover
  - measure
  - tune

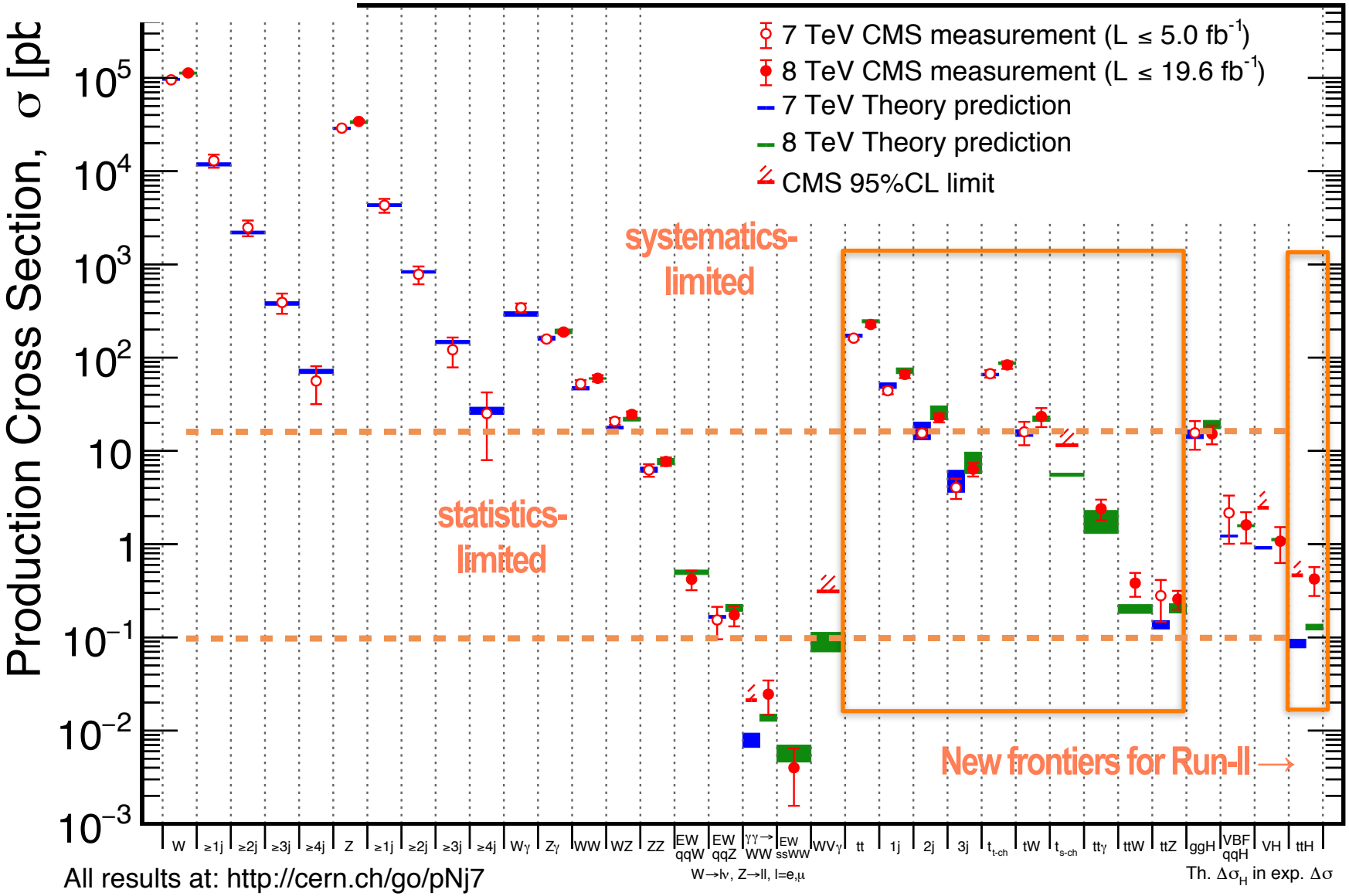
Top turns 21

2012 — 2015 — 2016

The Present

Run-I cross sections

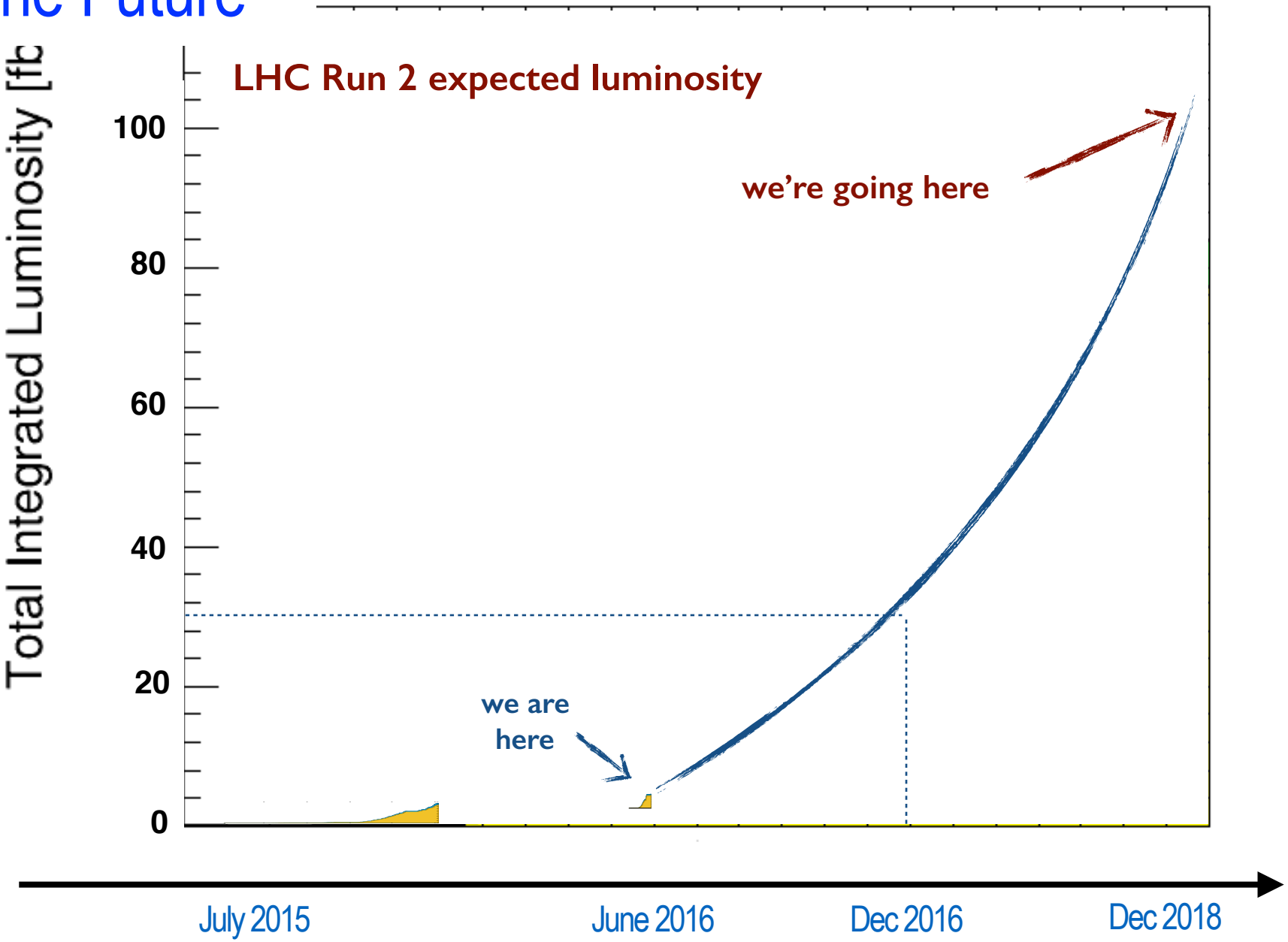
CMS Preliminary



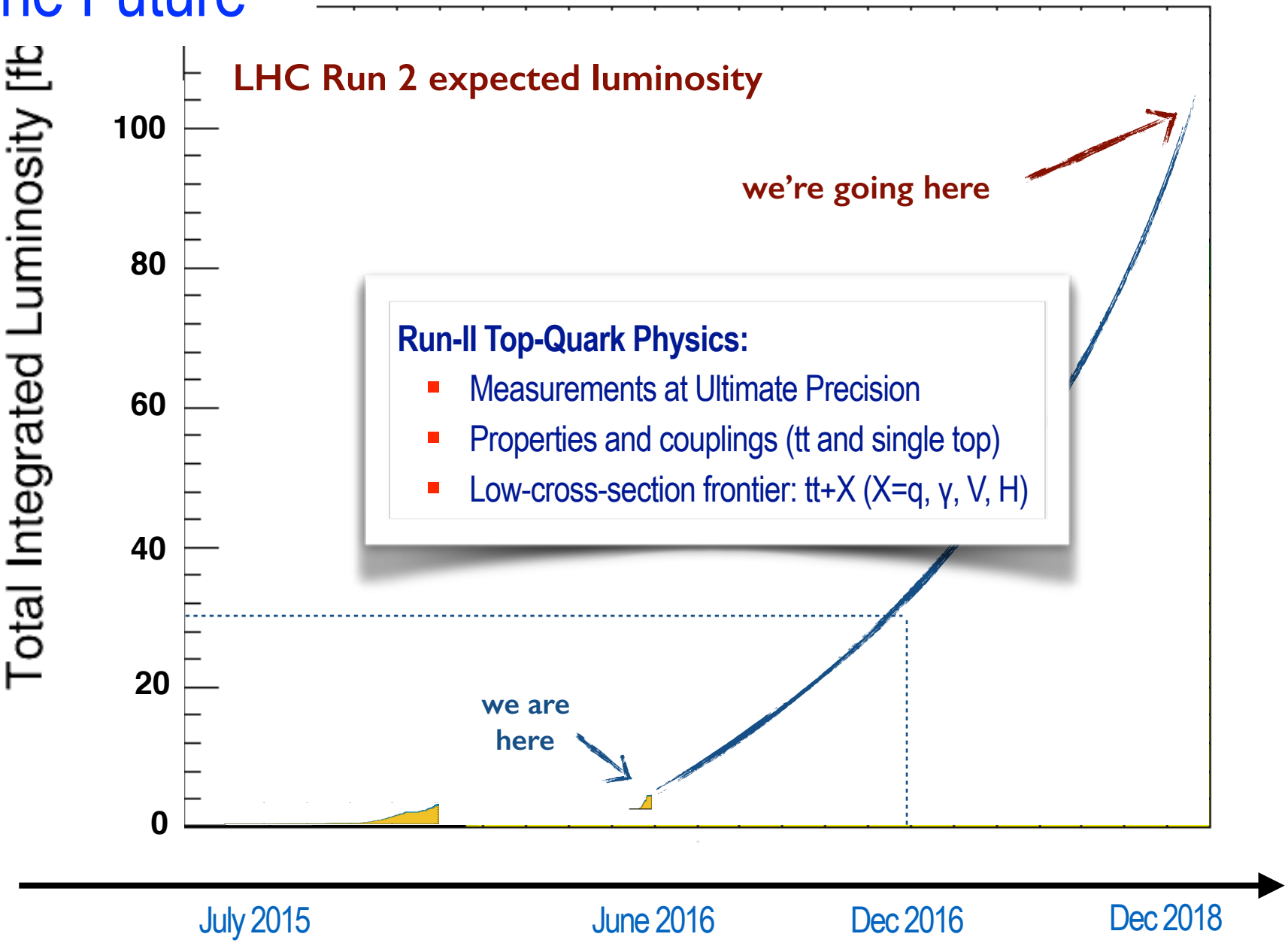
All results at: http://cern.ch/go/pNj7

The "Staircase-Plot"

The Future


LHC Run 2 expected luminosity
we're going here
we are here
Total Integrated Luminosity [fb
100
80
60
40
20
0
July 2015
June 2016
Dec 2016
Dec 2018

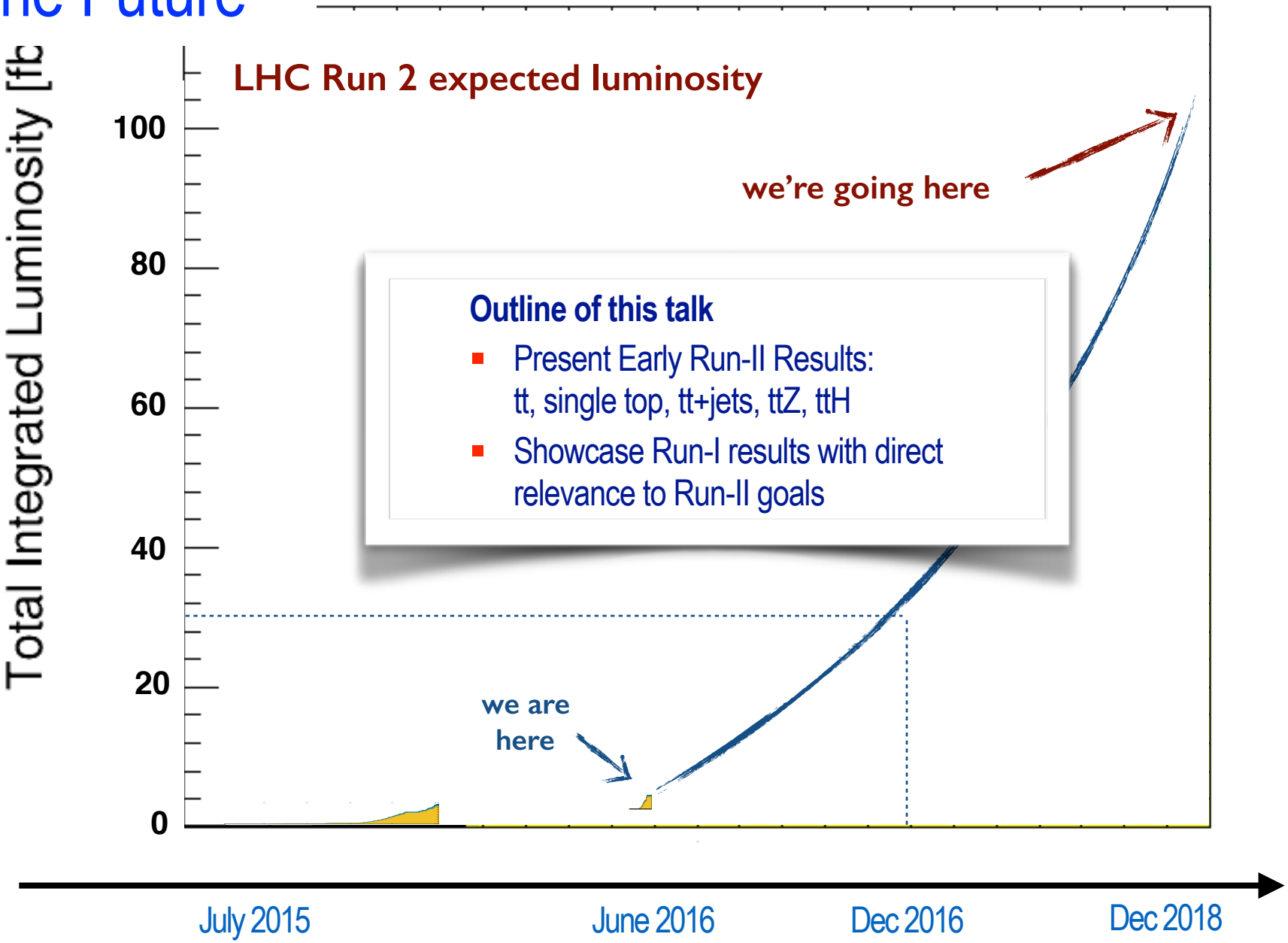
The Future



Run-II Top-Quark Physics:

- Measurements at Ultimate Precision
- Properties and couplings (tt and single top)
- Low-cross-section frontier: tt+X (X=q, γ, V, H)

The Future

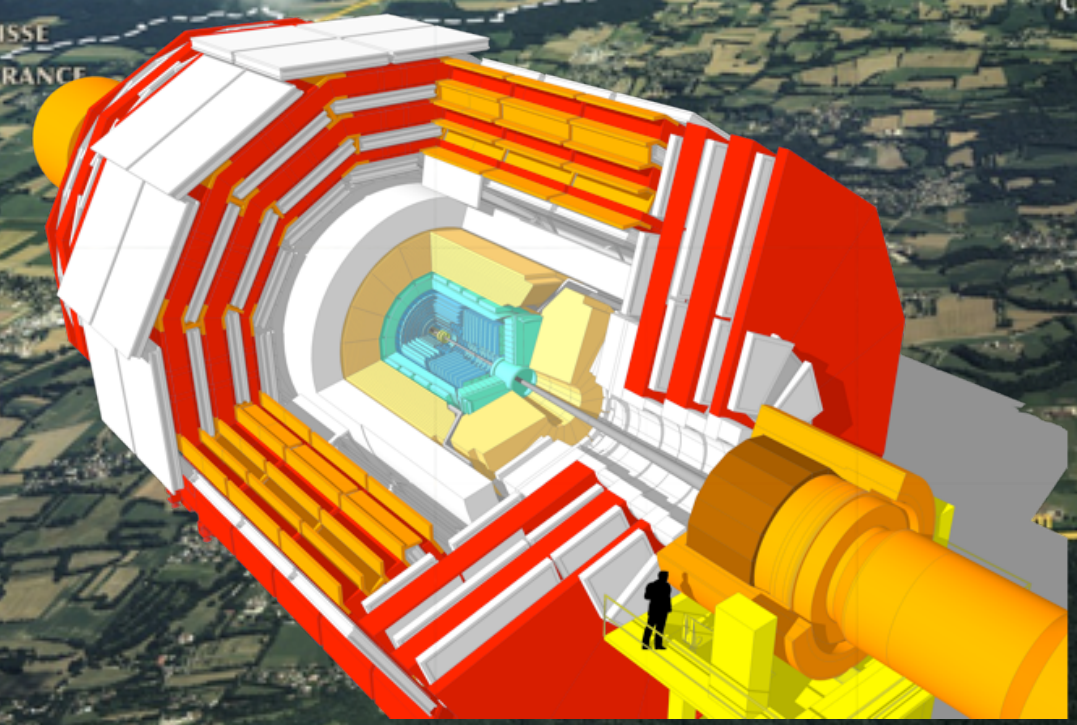


Outline of this talk

- Present Early Run-II Results: tt, single top, tt+jets, ttZ, ttH
- Showcase Run-I results with direct relevance to Run-II goals

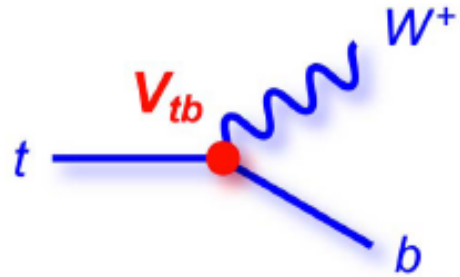
CMS Experiment

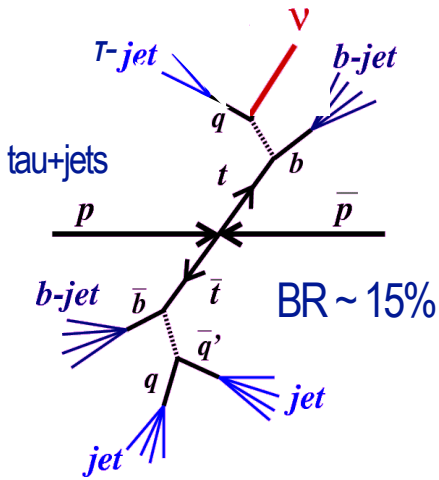
- Total Weight 14000 t
- Diameter 15 m
- Magnetic Field 3.8 T
- Silicon Pixel and Strip Trackers
- Crystal ECal, Brass HCal
- Muon Chambers, DT, RPC, CSC
- Trigger L1: 100kHz, ~500 Hz to tape

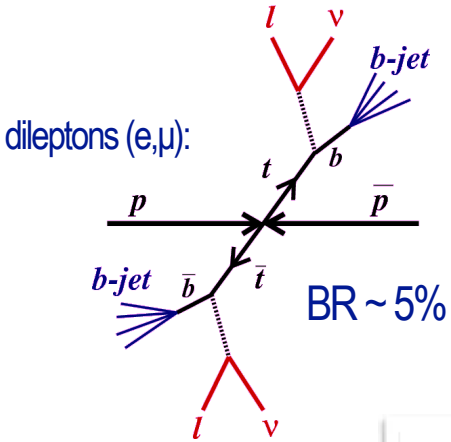


- **LHC Run-I ('10-'12): 25 fb^{-1}**
  - Peak inst. luminosity: 8 x 10^{33} cm^{-2}s^{-1}
    ~ 7000 top quark pairs per hour (8 TeV)
  - > 5,000,000 top each CMS and ATLAS
- **LHC Run-II ('15-'18): 100 fb^{-1} (13 TeV)**
  - **Expect 80,000,000 tt and 80,000 ttZ**

$t\bar{t}$ Event Signatures

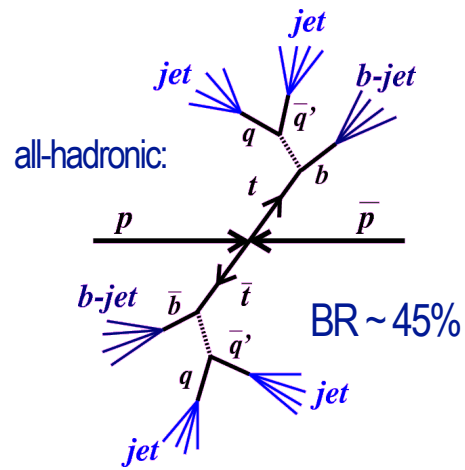


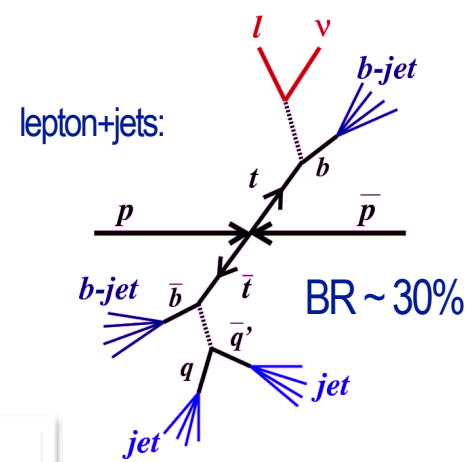




W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$
$\bar{c}s$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{u}d$					
τ^-	$e\tau$	$\mu\tau$	$\tau\tau$	tau+jets	
μ^-	$e\mu$	$\mu\mu$	$\mu\tau$	muon+jets	
e^-	ee	$e\mu$	$e\tau$	electron+jets	

dileptons



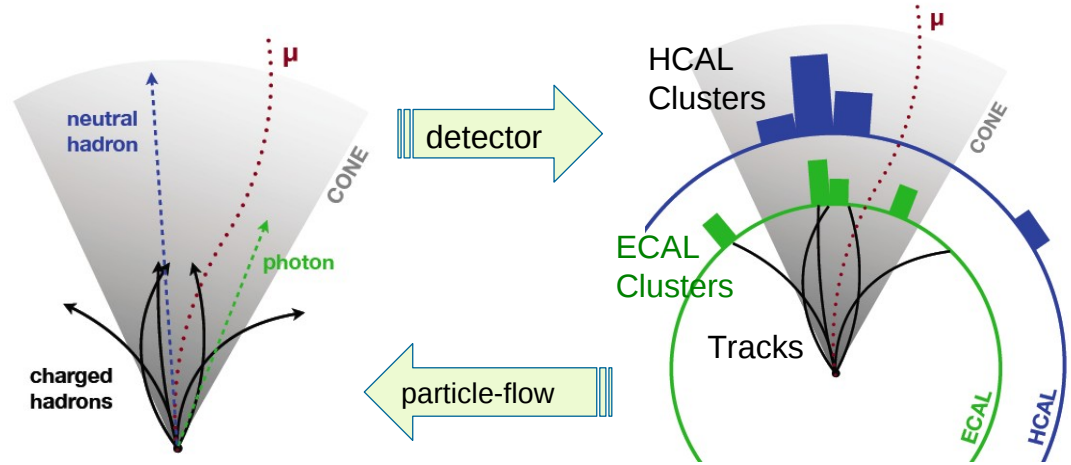


Top quark events have all experimental signatures: leptons, jets, b-jet, MET

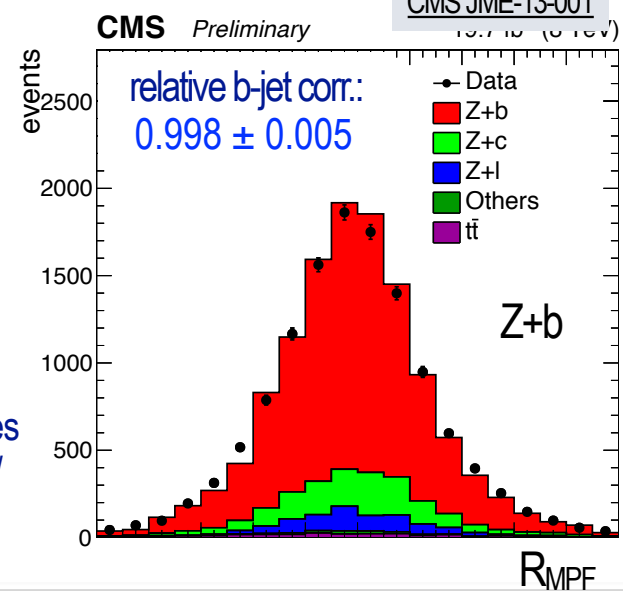
Experimental Ingredients

- **Particle Flow**
  - Holistic view of all detector information
  - Combination of tracker and calorimeter to obtain list of identified particles
- **Jet (and E_T^{miss})**
  - Resolution and scale mostly from γ-jet and Z-jet balance.
  - Event-by-event pile-up subtraction based on charged component
- **Isolated Leptons (e, μ or τ)**
  - Calibrations and efficiencies from dilepton resonances (Z, ϒ, J/ψ)
- **b-tagging**
  - Combination of several techniques (vertex, impact parameter, tracks/ leptons within jets)

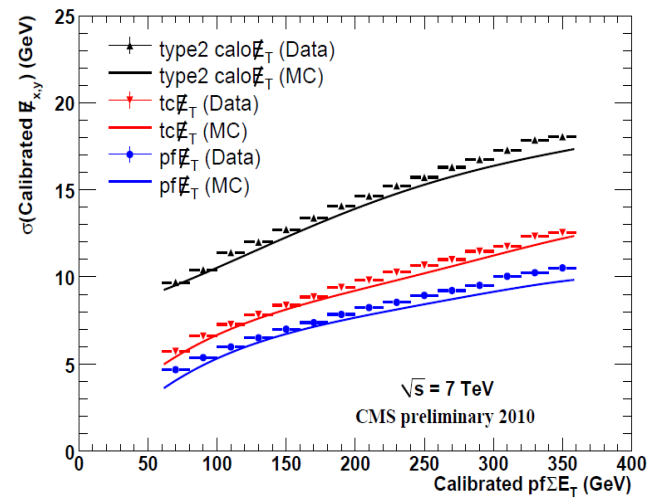
Particle Flow



CMS JME-13-001

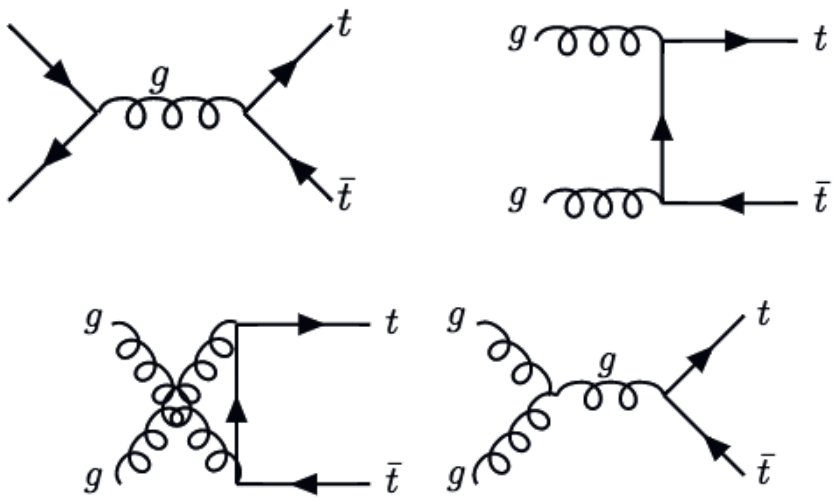


CMS DP-2012/012



Top quark physics: require high-precision leptons, jets and b-tagging

Top-Quark Pair Production



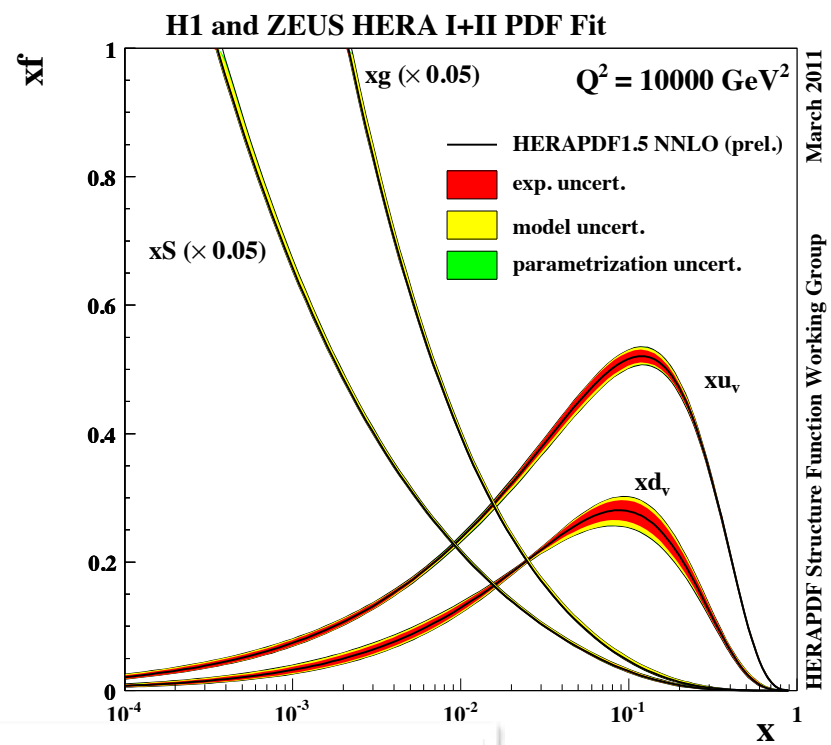
	LHC (13 TeV)	Tevatron
gg/gq	~90%	~15%
$q\bar{q}$	~10%	~85%

$$\sigma(7\ \text{TeV}) = 177\ \text{pb} \pm 7\%$$

$$\sigma(8\ \text{TeV}) = 253\ \text{pb} \pm 6\%$$

$$\sigma(13\ \text{TeV}) = 832\ \text{pb} \pm 5\%$$

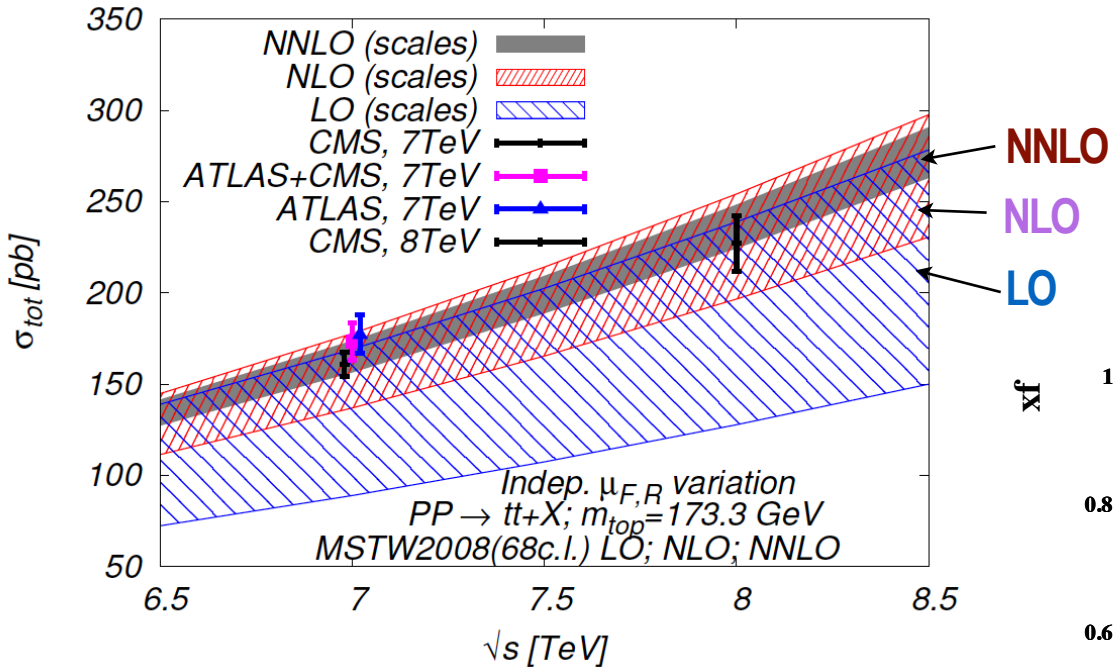
$$R_{13/8} = 3.28$$



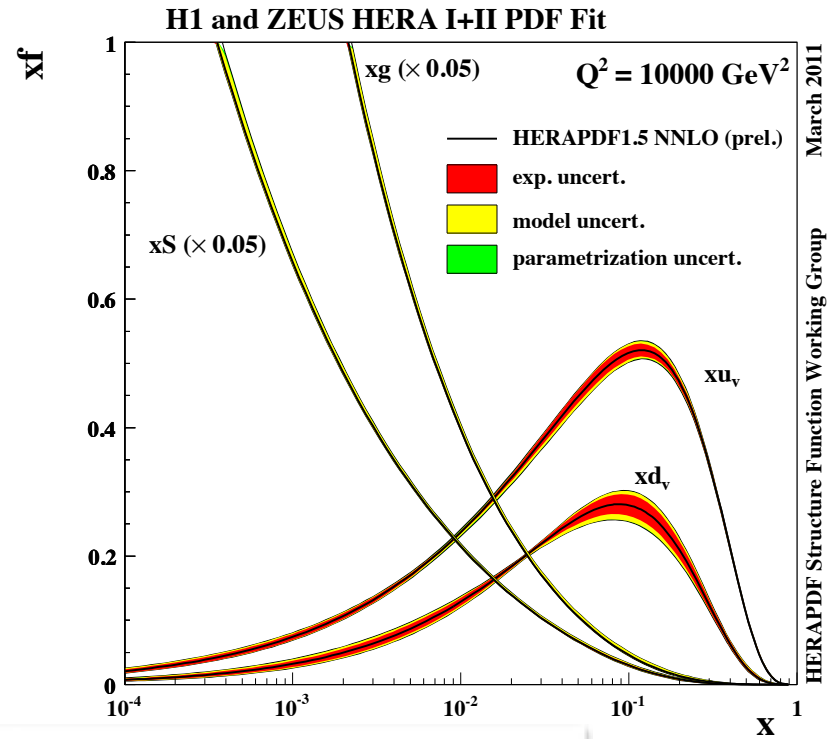
Top quark pair production at LHC predominantly from gluons

Top-Quark Pair Production

Czakon, Fiedler, Mitov PRL 110 (2013) 252004



	LHC (13 TeV)	Tevatron
gg/gq	~90%	~15%
$q\bar{q}$	~10%	~85%



$$\sigma(7\ \text{TeV}) = 177\ \text{pb} \pm 7\%$$

$$\sigma(8\ \text{TeV}) = 253\ \text{pb} \pm 6\%$$

$$\sigma(13\ \text{TeV}) = 832\ \text{pb} \pm 5\%$$

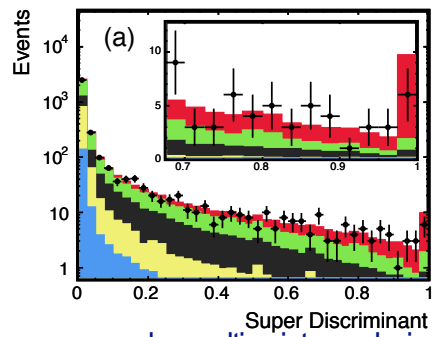
$$R_{13/8} = 3.28$$

Full NNLO available since early 2013 - scale and pdf uncertainties 2-3%

Single-Top Production

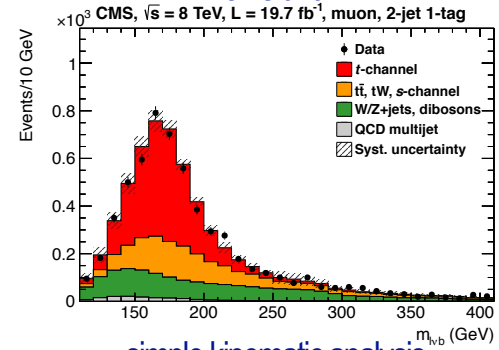
- Test of EW interactions
- V_{tb} / 4th generation / FCNC
- Sensitivity to b-PDF and u/d-PDF

CDF: 2009

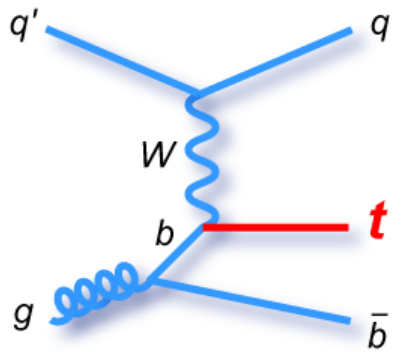


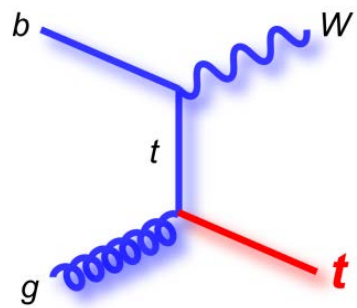
complex multivariate analysis

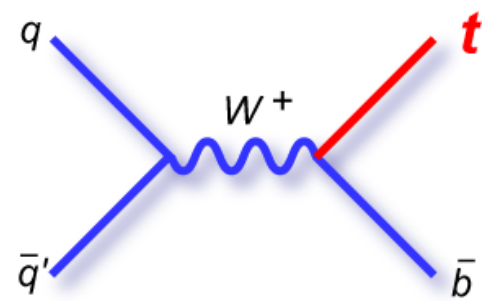
CMS 8 TeV



simple kinematic analysis







$\sigma(7\ \text{TeV}) = 64\ \text{pb} \pm 4.5\%$
$\sigma(8\ \text{TeV}) = 85\ \text{pb} \pm 4.4\%$
$\sigma(13\ \text{TeV}) = 217\ \text{pb} \pm 4.1\%$
$R_{13/8} = 2.6$

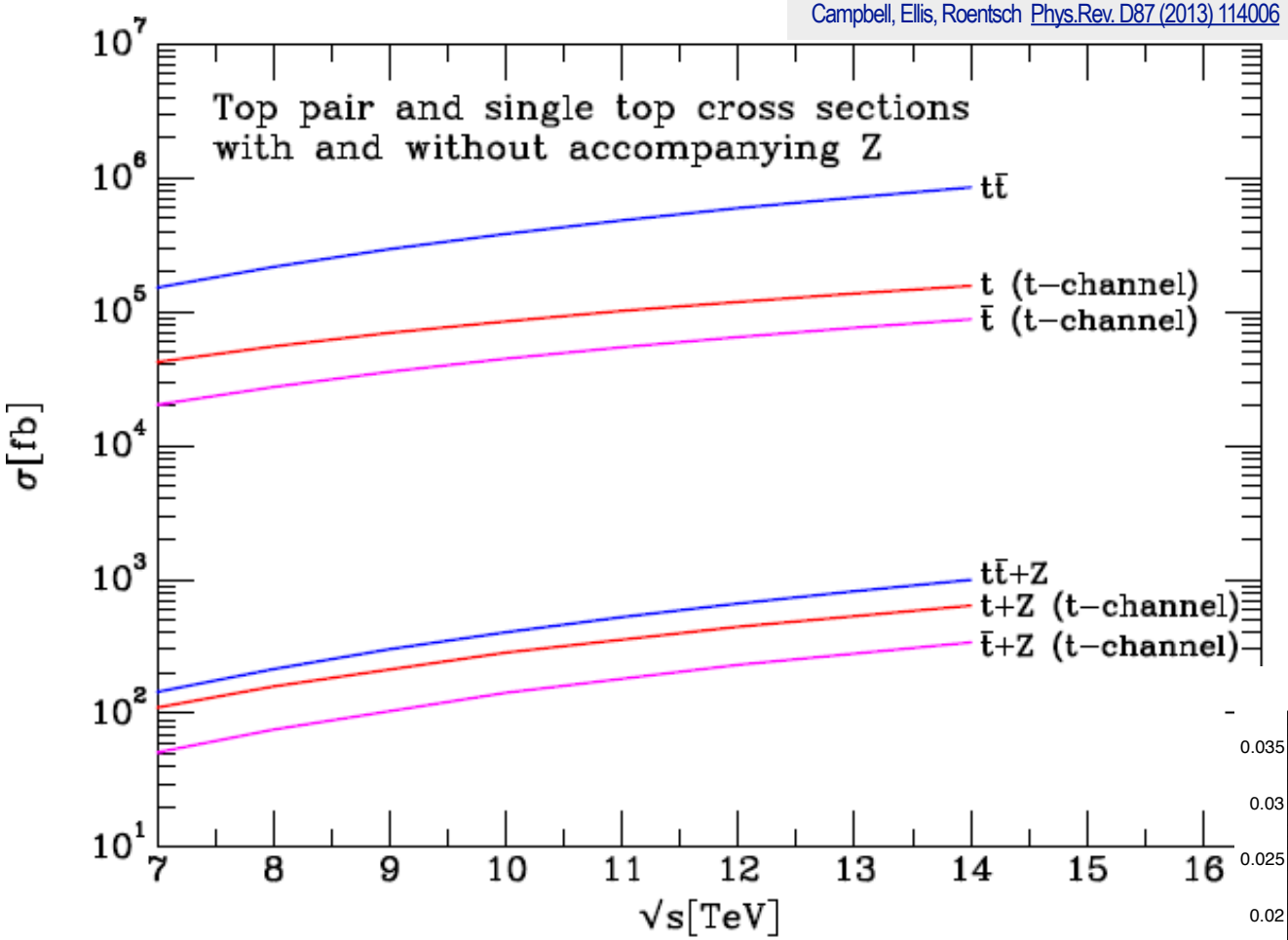
$\sigma(7\ \text{TeV}) = 15.7\ \text{pb} \pm 7.6\%$
$\sigma(8\ \text{TeV}) = 22.4\ \text{pb} \pm 6.8\%$
$\sigma(13\ \text{TeV}) = 71.7\ \text{pb} \pm 5.3\%$
$R_{13/8} = 3.2$

$\sigma(7\ \text{TeV}) = 4.3\ \text{pb} \pm 4.4\%$
$\sigma(8\ \text{TeV}) = 5.2\ \text{pb} \pm 4.2\%$
$\sigma(13\ \text{TeV}) = 10.3\ \text{pb} \pm 3.9\%$
$R_{13/8} = 1.9$

Single-top cross sections at Run-II are as large as the tt cross section at Run-I

Energy Dependence

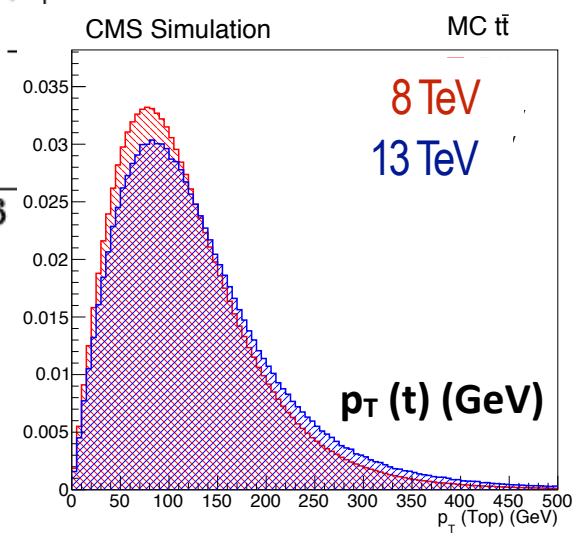
Campbell, Ellis, Roentsch Phys.Rev. D87 (2013) 114006



10 Hz (at 10^{34})

2 Hz (at 10^{34})

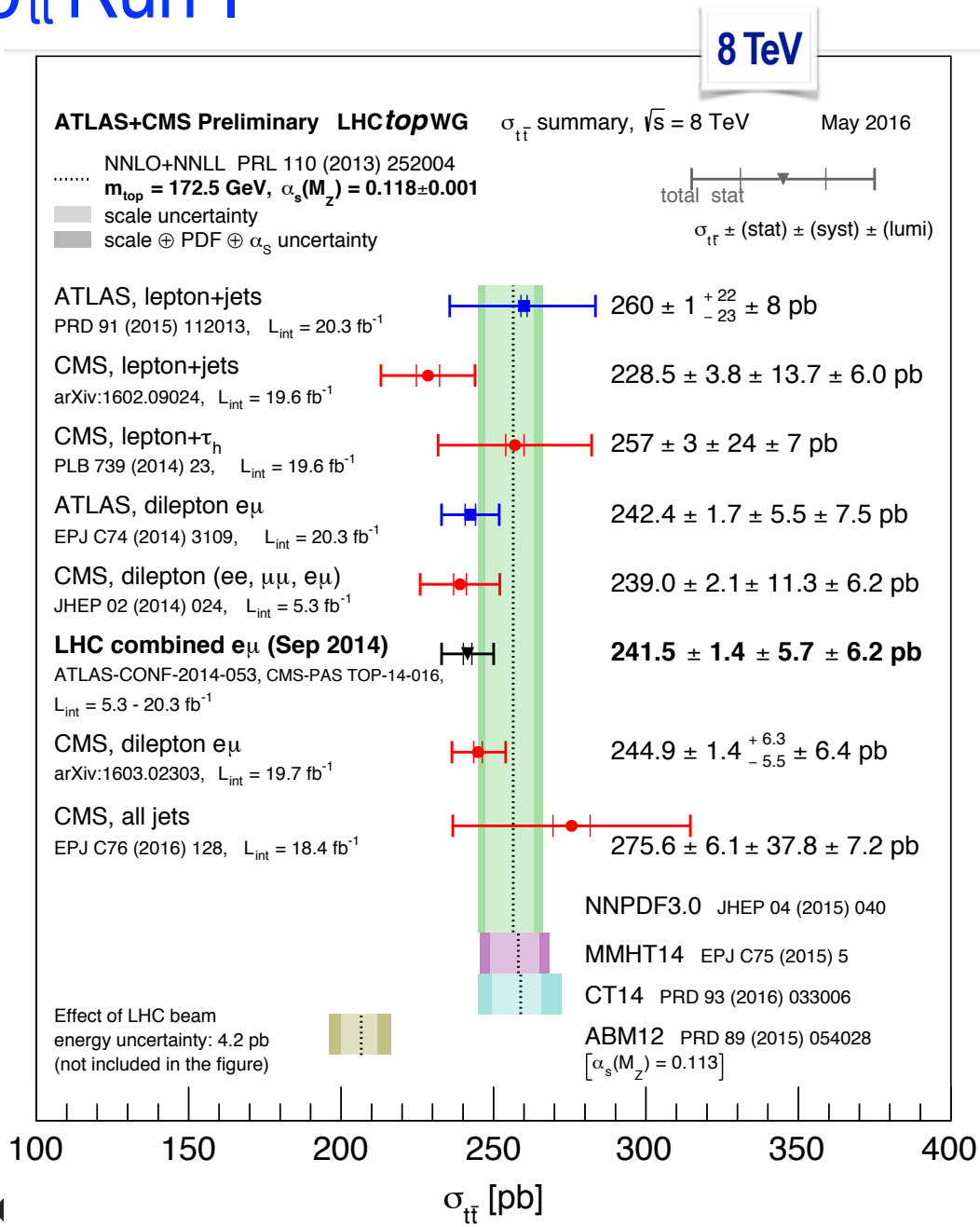
0.01Hz (at 10^{34})

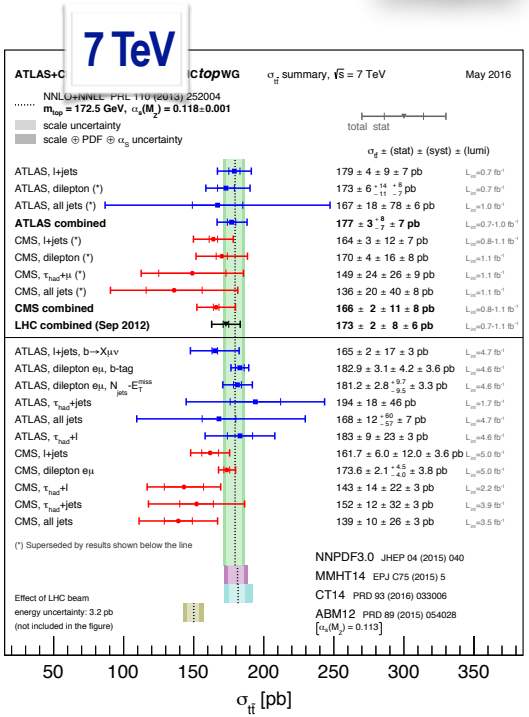


Cross section driven by rise of gluon density to low x:
→ bulk tt sample does not look substantially different

σ_{tt} Run-I

LHCtopWG

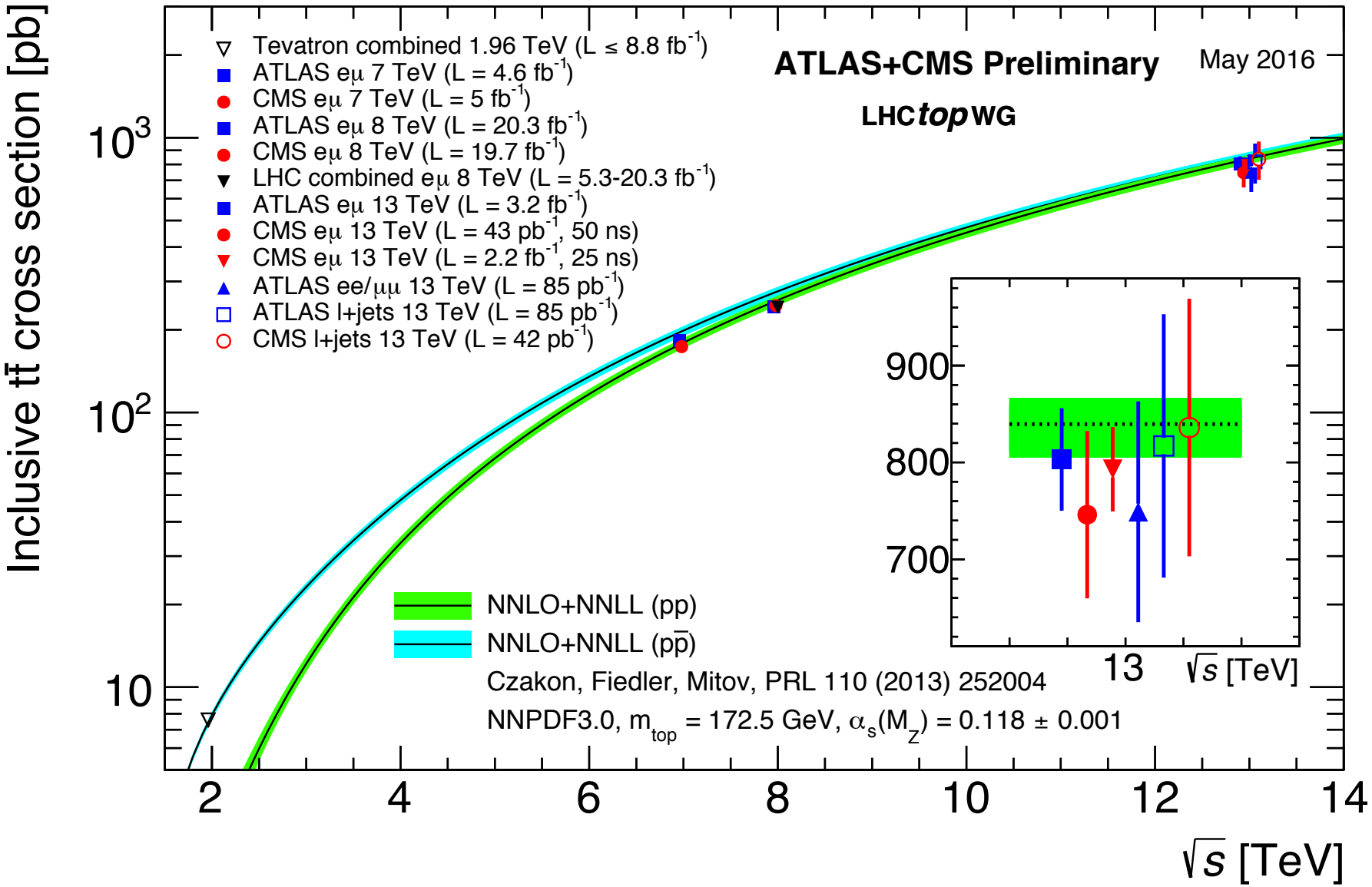




- eμ channel is most precise
  - high purity
  - high acceptance
- LHCtopWG Run-I combinations underway

σ_{tt} (Tevatron, Run-I and Run-II)

LHCtopWG



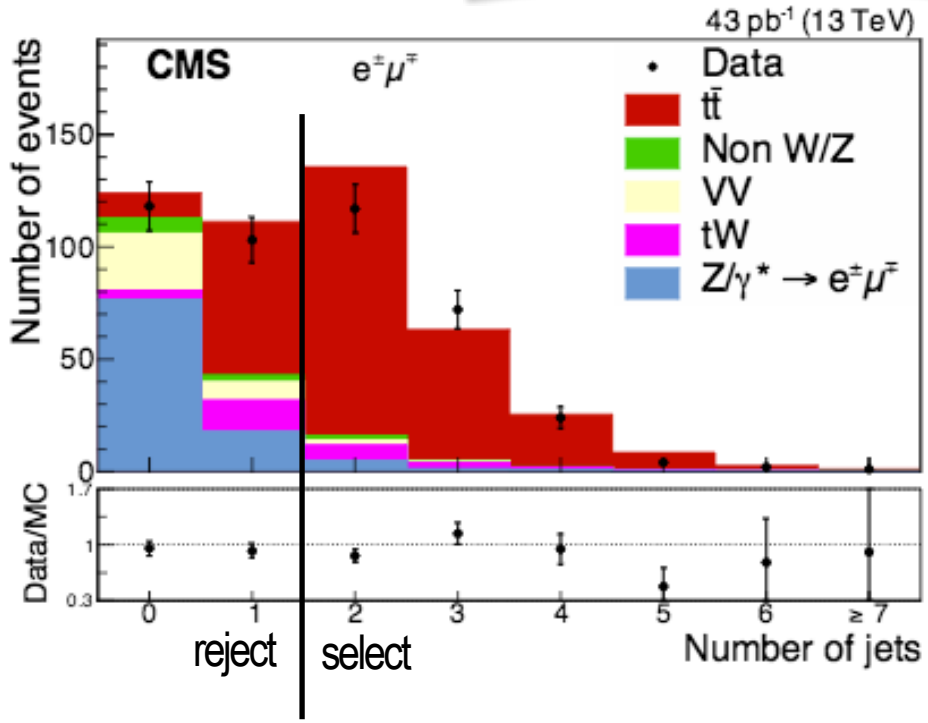
σ_{tt} Run-II: the first 42 pb^{-1} (July '15)

Phys. Rev. Lett. 116, 052002 (2016)

Published in October 2015
3rd CMS Paper on Run-II

- Opposite-charge eμ + 2 jets (no b-tag)
- Simple cuts → very pure tt sample
- DY background from data
- tW background dominant

Source	$\Delta\sigma/\sigma$ (%)
Statistics	7.8
Luminosity	4.8
Trigger/selection	5.6
Signal modelling	2.6
PDF	2.4
Backgrounds	2.1



$$\sigma_{tt} = 746 \pm 58_{stat} \pm 53_{syst} \pm 36_{lumi}\ \text{pb}$$

$\Delta\sigma/\sigma \approx 11\%$

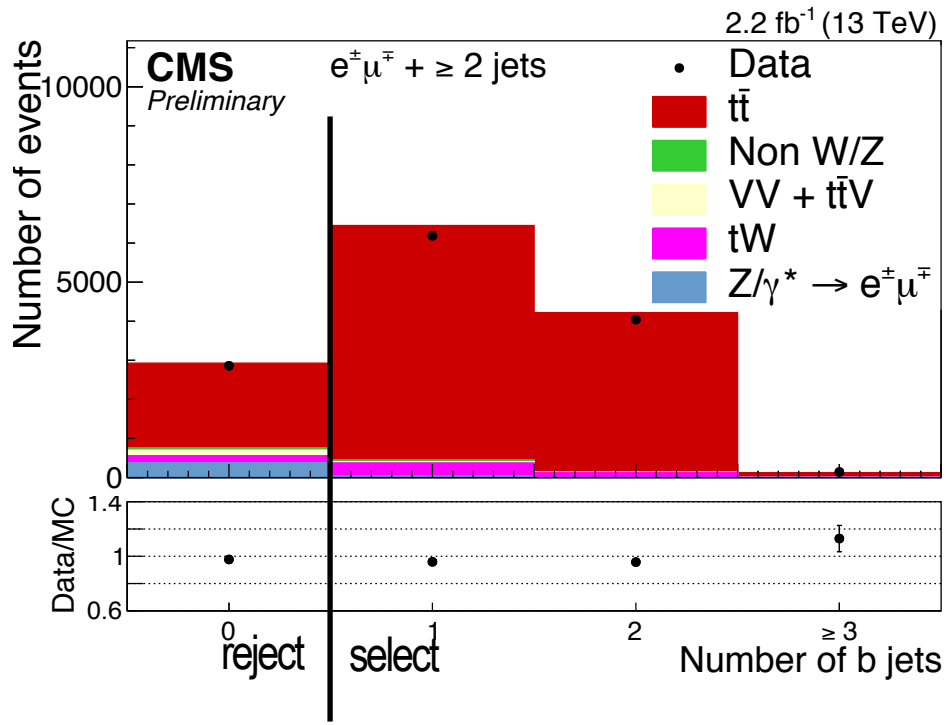
Still statistics limited

σ_{tt} Run-II: the full 2015 dataset

TOP-16-005

Spring 2016

- Opposite-charge eμ + 2 jets (1 b-tag)
- Simple cuts → very pure tt sample
- DY background from data
- tW background dominant



Source	$\Delta\sigma/\sigma$ (%)
Statistics	1.0
Luminosity	2.7
Trigger/selection	2.5
Signal modelling	2.6
PDF	0.6
Backgrounds	1.5

$\sigma_{tt} = 793 \pm 8_{stat} \pm 38_{syst} \pm 21_{lumi}$ pb

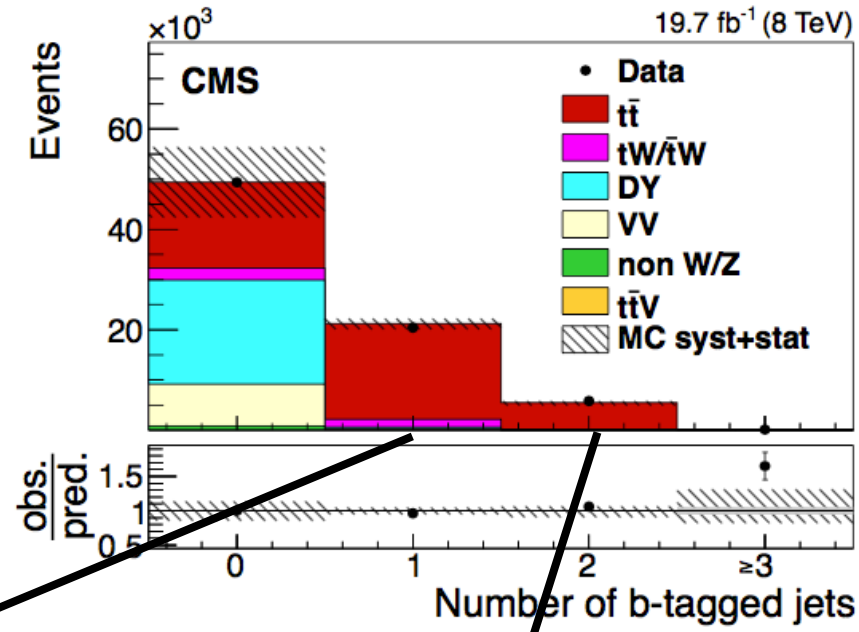
$\Delta\sigma/\sigma \approx 5.6\%$

Shrink systematics further with more data

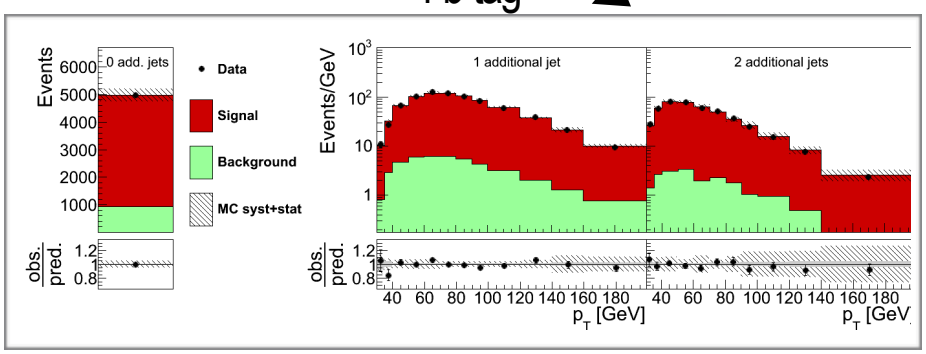
σ_{tt} Run-I Legacy

arXiv:1603.02303

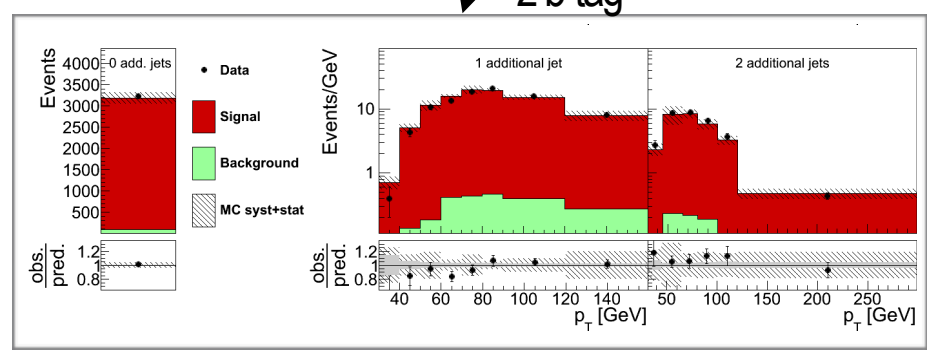
- Opposite-charge eμ
- 12 categories of N_{jet} and $N_{b\text{-}tag}$
- Constrain backgrounds and systematics in visible phase space
- Extrapolate to full phase space



1 b-tag



2 b-tag



$\sigma_{tt\ (7\ TeV)} = 173.6 \pm 2.1_{stat} + 4.5\text{-}4.0_{syst} \pm 3.8_{lumi}$ pb

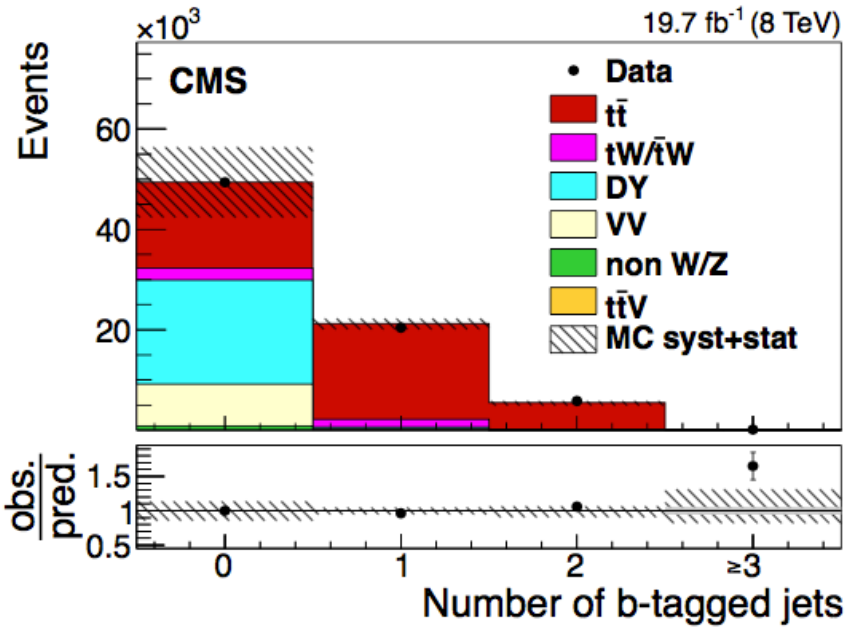
$\sigma_{tt\ (8\ TeV)} = 244.9 \pm 1.4_{stat} + 6.3\text{-}5.5_{syst} \pm 6.4_{lumi}$ pb

$\Delta\sigma/\sigma \approx 3.7\%$

σ_{tt} Run-I Legacy

arXiv:1603.02303

Source	$\Delta\sigma/\sigma$ (%)
Trigger	1.2
Lepton ID	1.5
Jet Energy Scale	0.8
Drell-Yan Bg.	1.4
b-tag	0.5
Luminosity	2.6
Total visible	3.6
Scale (extrap.)	0.2
ME/PS (extrap.)	0.2
Top pt (extrap.)	0.5
PDF (extrap.)	0.1



- Detector response: constrain systematics from experiment within fiducial phase space
- Acceptance: Unconstrained theory uncertainties for extrapolation to full phase space

$\sigma_{tt\ (7\ TeV)} = 173.6 \pm 2.1_{stat} + 4.5\text{-}4.0_{syst} \pm 3.8_{lumi}$ pb

$\sigma_{tt\ (8\ TeV)} = 244.9 \pm 1.4_{stat} + 6.3\text{-}5.5_{syst} \pm 6.4_{lumi}$ pb

$\Delta\sigma/\sigma \approx 3.7\%$

σ_{tt} Run-II: Challenges

arXiv:1603.02303

Source	$\Delta\sigma/\sigma$ (%)
Trigger	1.2
Lepton ID	1.5
Jet Energy Scale	0.8
Drell-Yan Bg.	1.4
b-tag	0.5
Luminosity	2.6
Total visible	3.6
Scale (extrap.)	0.2
ME/PS (extrap.)	0.2
Top pt (extrap.)	0.5
PDF (extrap.)	0.1

Run-II Shopping List

- Experimental
  - Trigger (OR with single lepton triggers)
  - Lepton ID (beat down systematics with statistics)
  - Backgrounds (additional fit categories)
  - Luminosity
  - Also measure tt/Z ratio and tt+tW cross sections
- Theory
  - NLO+PS Monte Carlos (LHE weights to reduce statistical effects and increase sample sizes)
  - PYTHIA8, Herwig7, EvtGen
  - improved MC tuning
  - improved PDF

$$\sigma_{tt\ (7\ TeV)} = 173.6 \pm 2.1_{stat} + 4.5\text{-}4.0_{\ syst} \pm 3.8_{lumi}\ pb$$

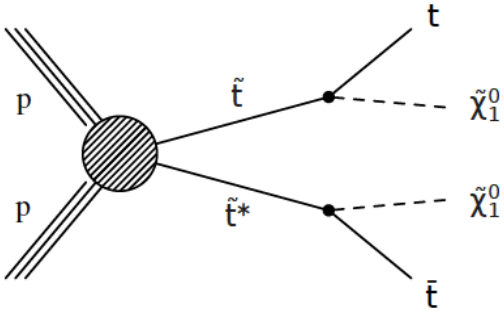
$$\sigma_{tt\ (8\ TeV)} = 244.9 \pm 1.4_{stat} + 6.3\text{-}5.5_{\ syst} \pm 6.4_{lumi}\ pb$$

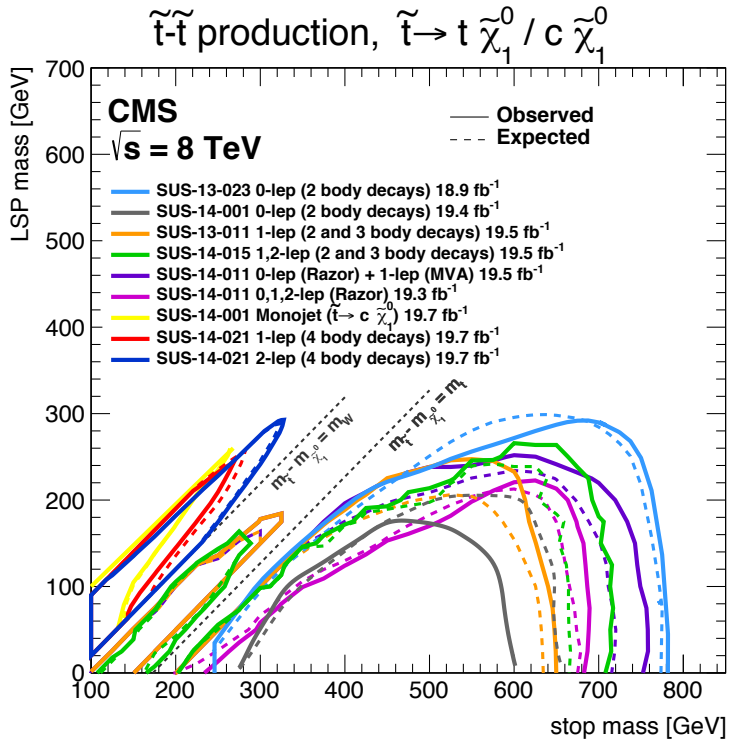
$\Delta\sigma/\sigma \approx 3.7\%$

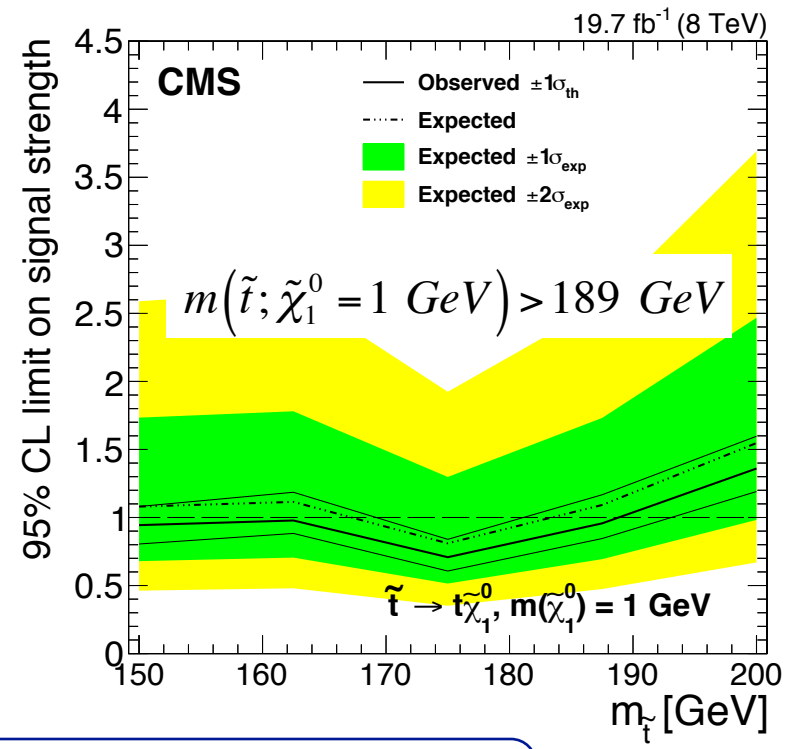
σ_{tt} Run-I Legacy: Stop Limit

arXiv:1603.02303

- Simplified model with two parameters (m_{stop} and m_{χ})
- Light stop production σ(MSSM) ~15% of σ_{tt}
- Precision cross section measurement can fill gap at $m_{top} \approx m_{stop}$







$\sigma_{tt\ (7\ TeV)} = 173.6 \pm 2.1_{stat} + 4.5\text{-}4.0_{\ syst} \pm 3.8_{lumi}$ pb

$\sigma_{tt\ (8\ TeV)} = 244.9 \pm 1.4_{stat} + 6.3\text{-}5.5_{\ syst} \pm 6.4_{lumi}$ pb

$\Delta\sigma/\sigma \approx 3.7\%$

σ_{tt} Run-I Legacy: Pole Mass

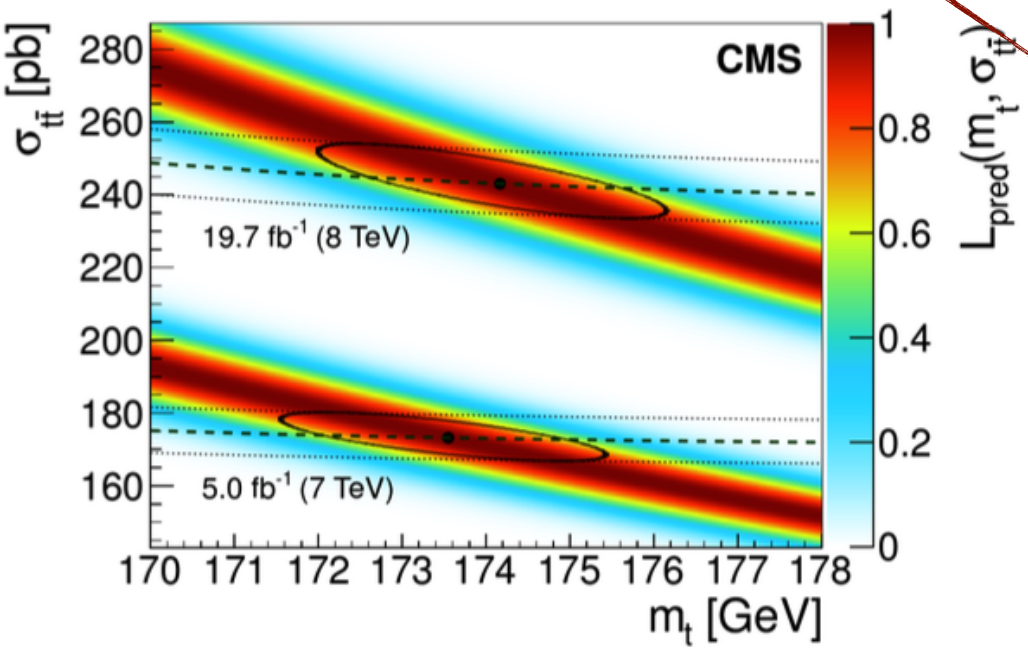
arXiv:1603.02303

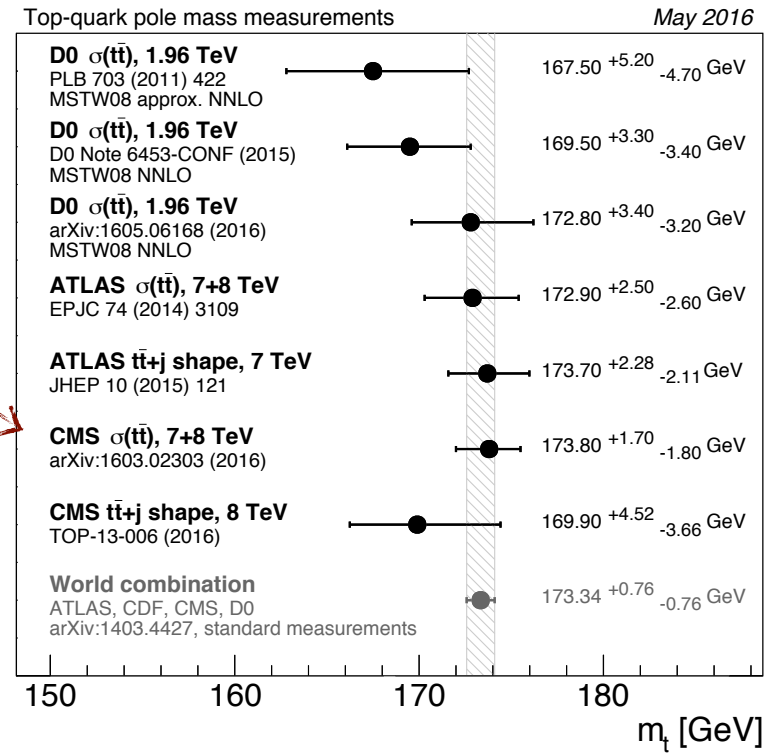
With current $\delta\sigma_{theory}^{NNLO} \approx 5.5\%$: could reach $\delta m_t^{pole} \approx 0.5\%$ with $\delta\sigma_{exp} = 2\%$

- From cross section extract top quark mass within theoretically well defined scheme (e.g. pole mass)
- Assume α_S and PDF and compare to NNLO

$\Delta m/m = 1\%$

$$m_t^{pole} = 173.8^{+1.7}_{-1.8}\ (\text{GeV})$$





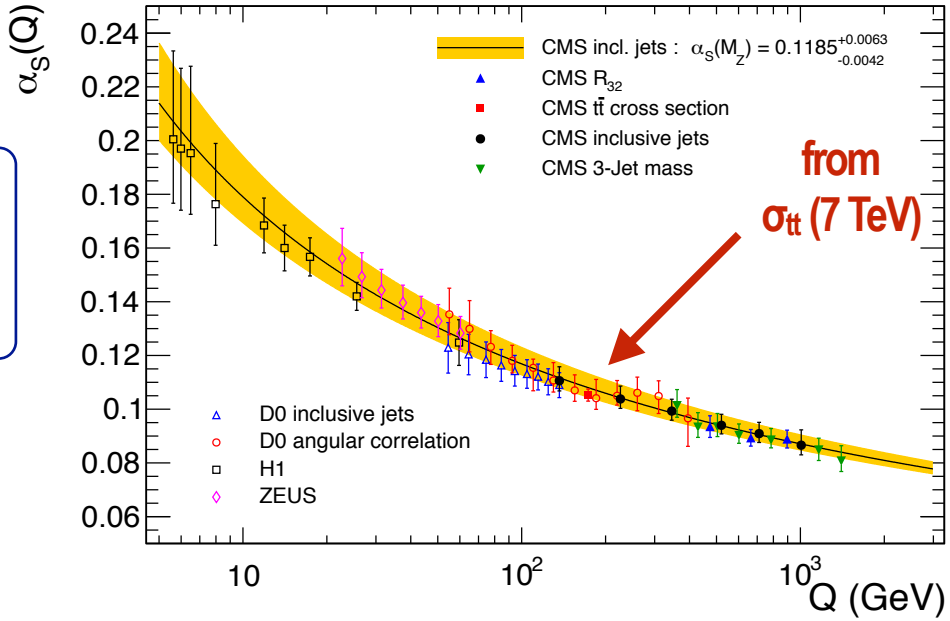
Pole mass measurements numerically consistent with standard top mass measurements

σ_{tt}: α_S and PDF

PLB 728(2013) 496

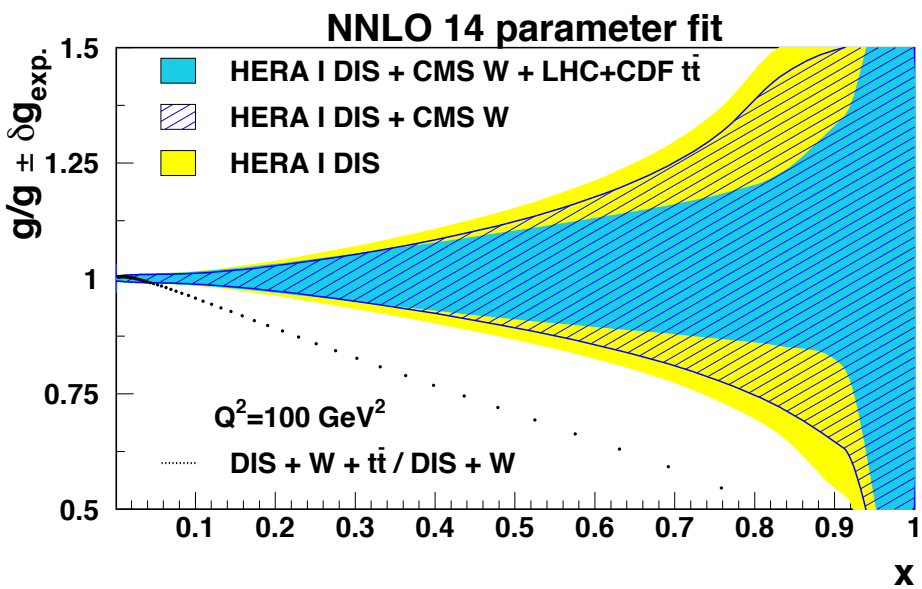
$$\alpha_s(m_Z) = 0.1151^{+0.0033}_{-0.0032}$$

for fixed m_{top} = 173.2 ± 1.4 GeV and NNPDF2.3



EPJC 75 (2015) 288

- Competitive measurement of α_S
- Demonstrated constraint of gluon density at high x
- Run-II: Aim to constrain quark masses, α_S, and PDF simultaneously



JHEP 1501 (2015) 082

Differential measurements and calculations at NNLO are available

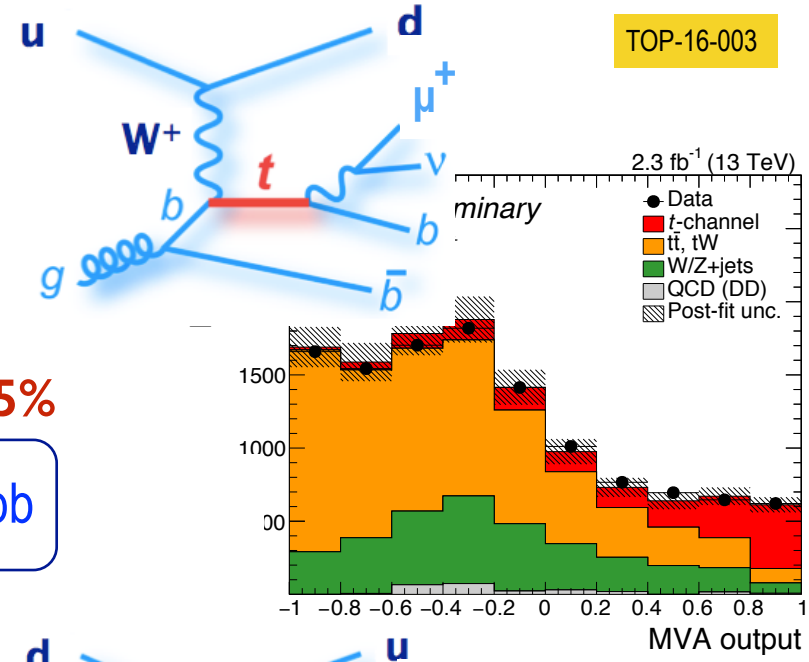
Run-II Single-top quark

TOP-16-003

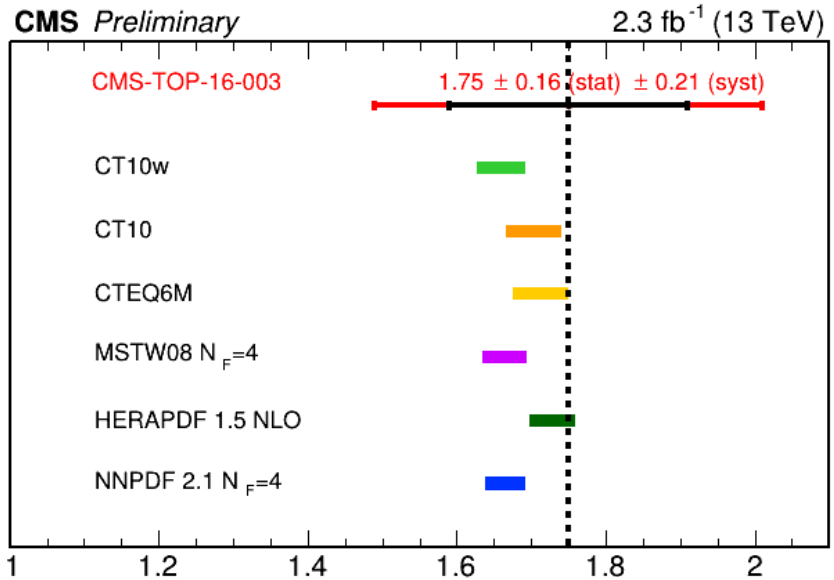
- **First cross section measurements**
  - 1μ + 2 jets + 1 b-tag
  - Neural Net
  - bg from control regions (3j1b, 3j0b)

$\Delta\sigma/\sigma \approx 15\%$

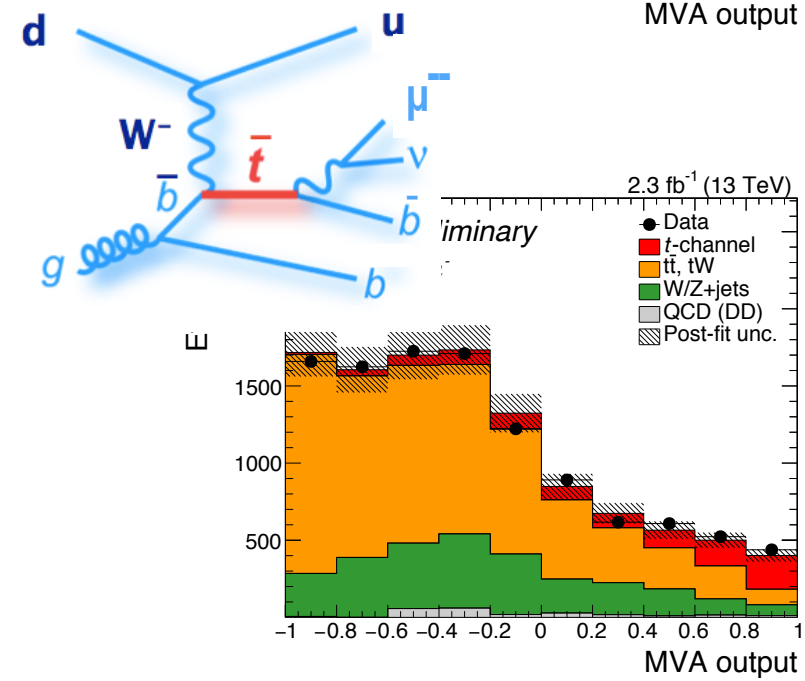
$$\sigma_{t(13\ \mathrm{TeV})} = 228 \pm 9_{stat} \pm 14_{exp} \pm 28_{theo} \pm 6_{lumi}\ \mathrm{pb}$$



- **Constraints on u- and d-quark ratio**



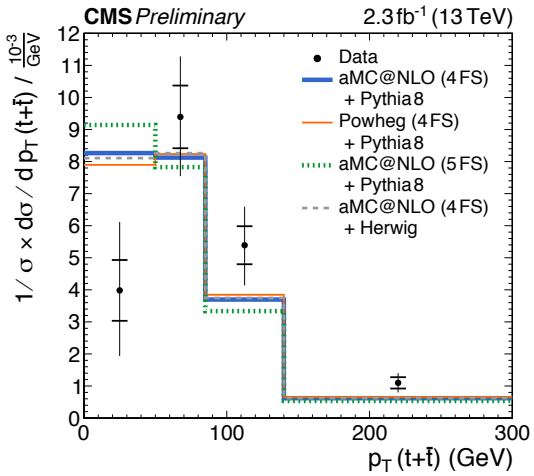
$R = \sigma(t)/\sigma(\bar{t})$

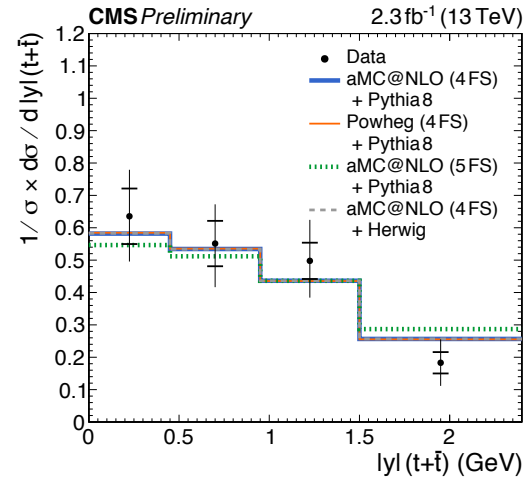


Differential Single-Top Measurements

TOP-16-004

- Run-II Early Analyses: Very first differential measurement available
- Most properties measurements rely on precise differential cross sections

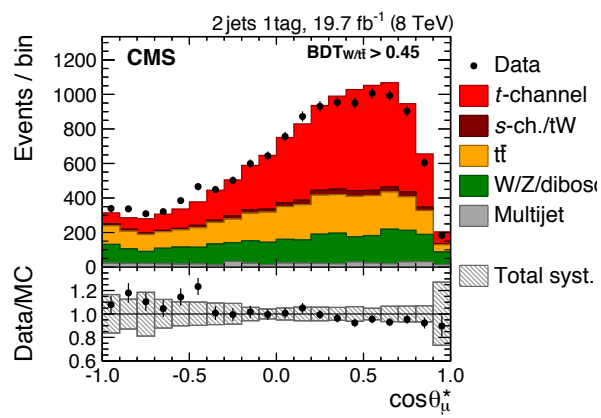


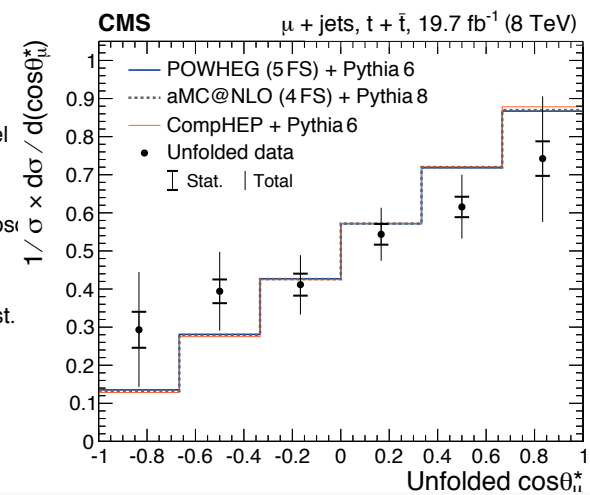


JHEP 04 (2016) 073

- **Example from Run-I**: Single-top quark polarisation
  - V-A: expect top quarks to be highly polarised: $A_P^{theo} = 0.44$
  - Possible depolarisation due to BSM

$$A_p = 0.26 \pm 0.03_{stat} \pm 0.10_{syst}$$

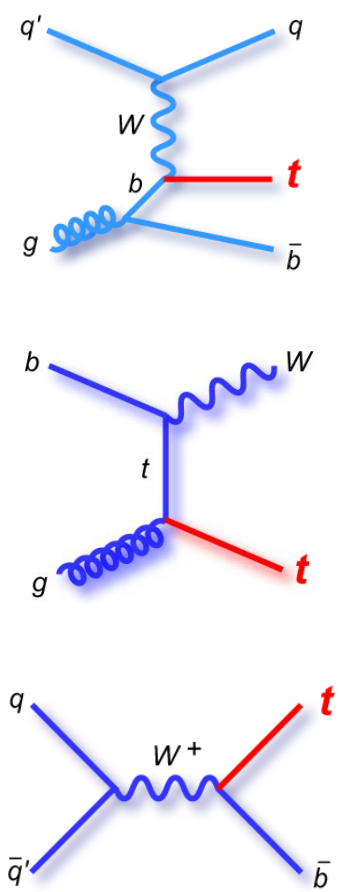


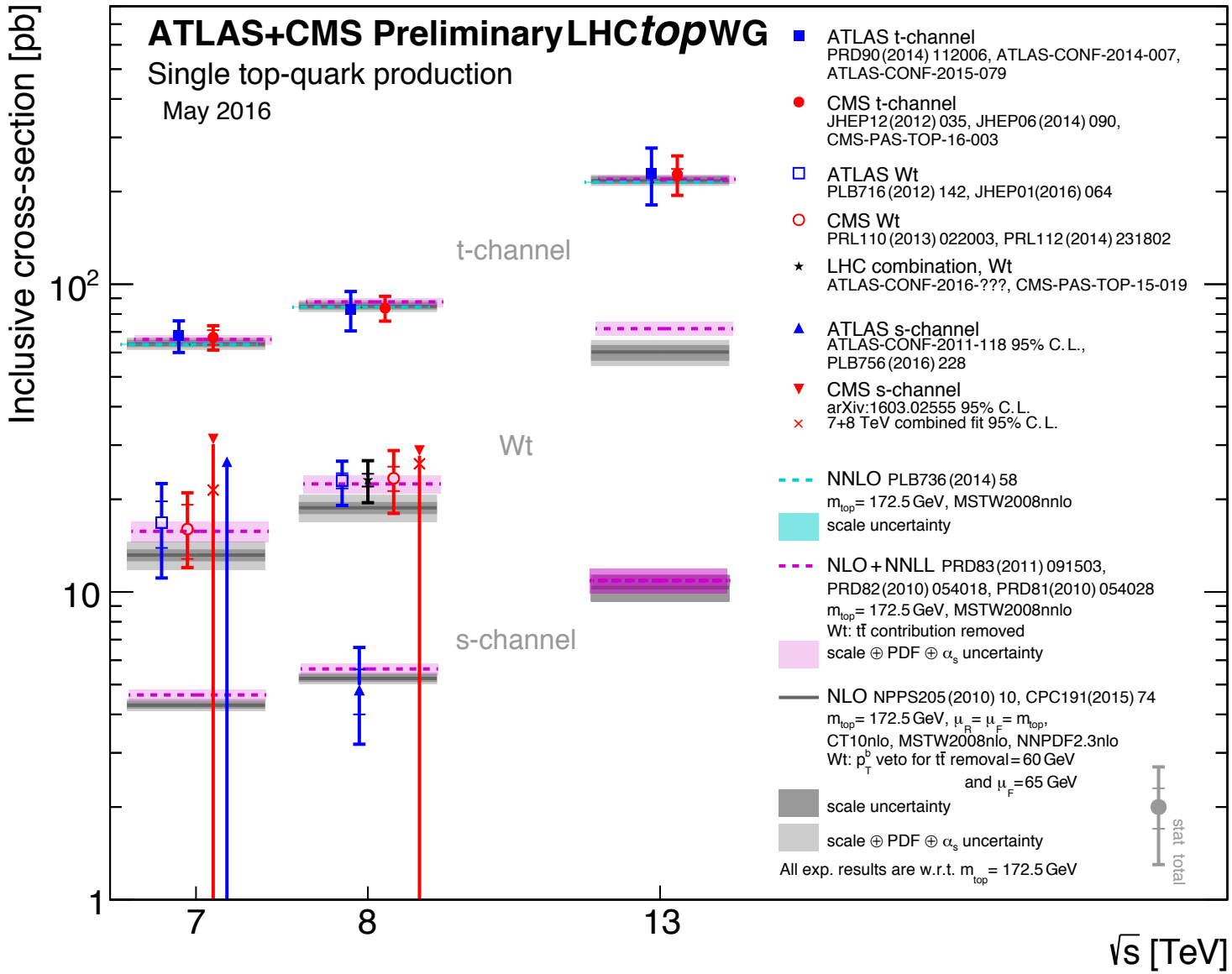


A whole program of detailed studies (differential distributions, mass, properties, couplings) lies ahead

Single-Top Quark Cross Sections

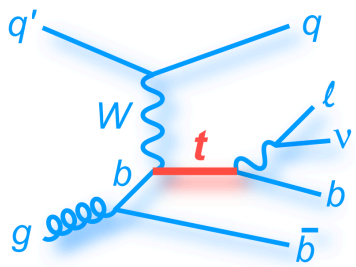
LHCtopWG

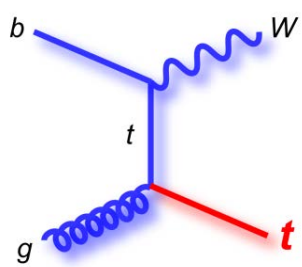




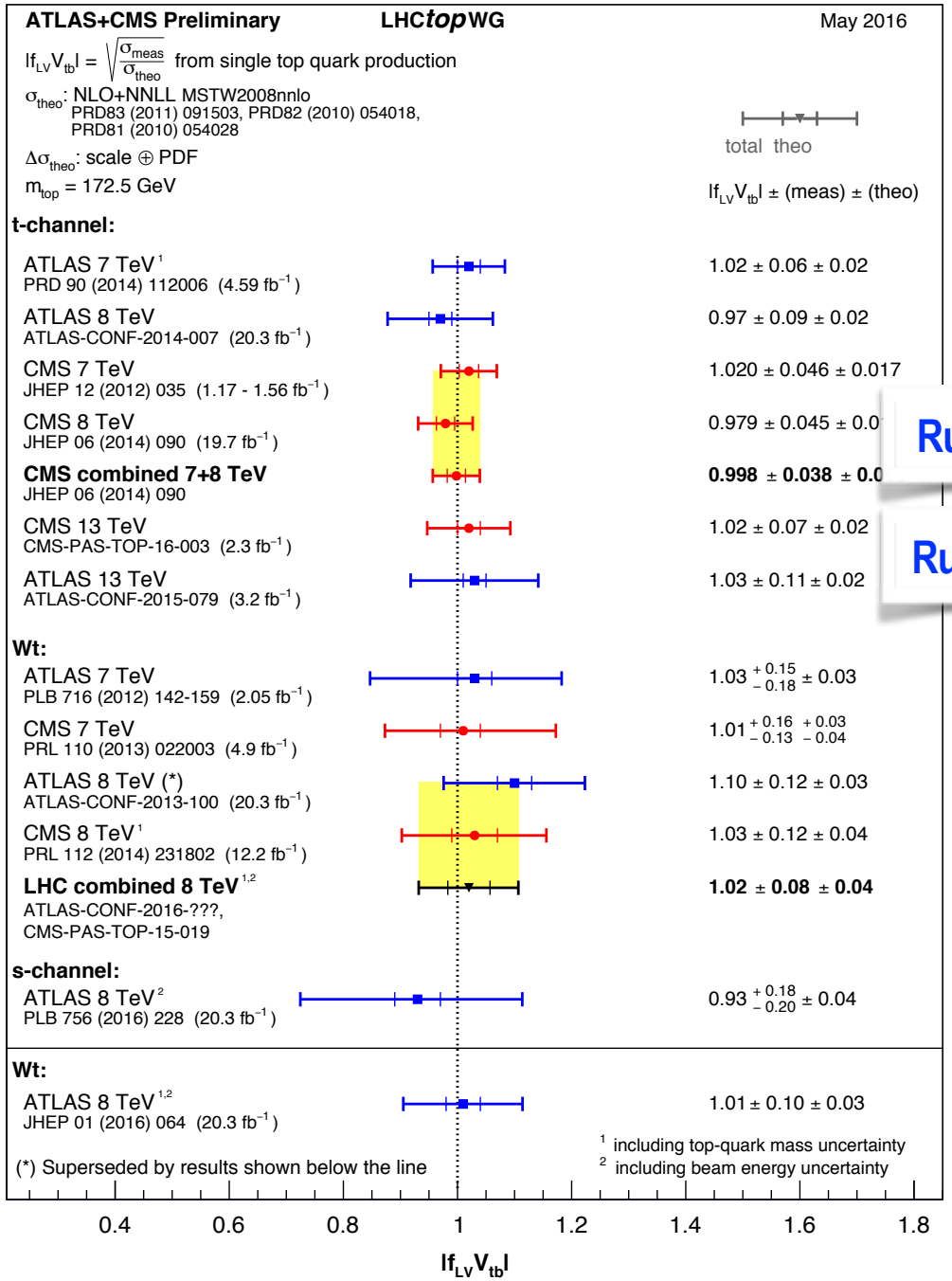
V_{tb}

- V_{tb} enters in production and decay $\rightarrow \sigma \propto |V_{tb}|^2$





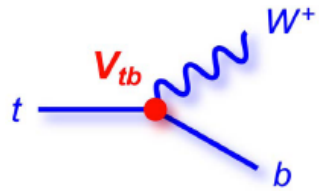
LHCtopWG



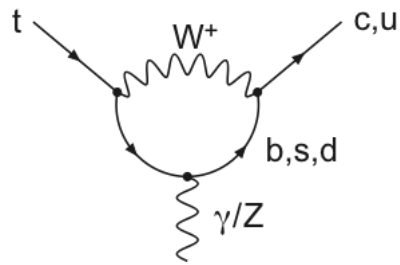
Run-I: $\delta V_{tb} \approx 4\%$

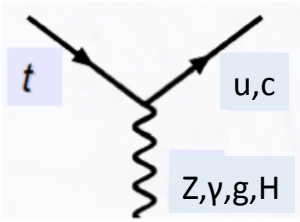
Run-II: $\delta V_{tb} \approx 7\%$

V_{tb} and FCNC

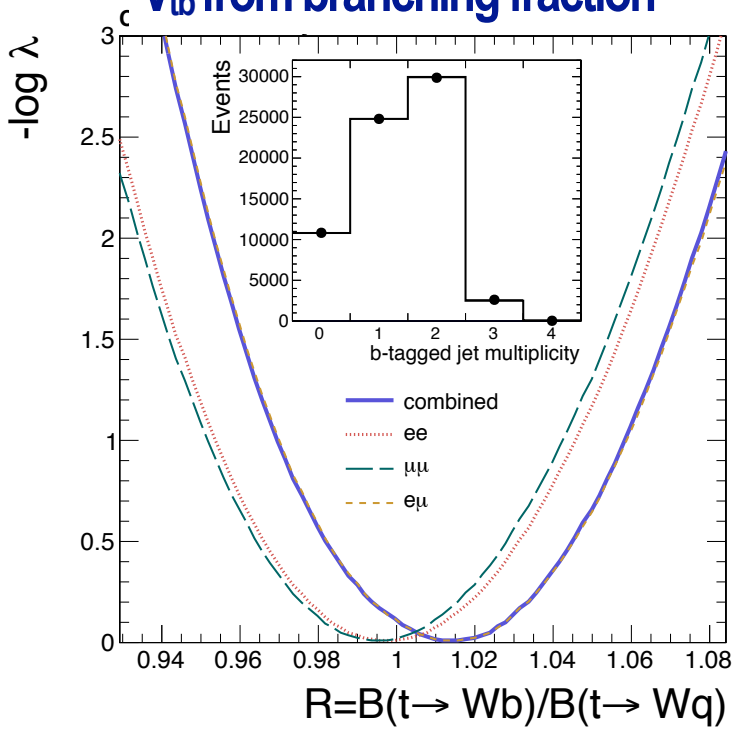


PLB 736 (2014) 33

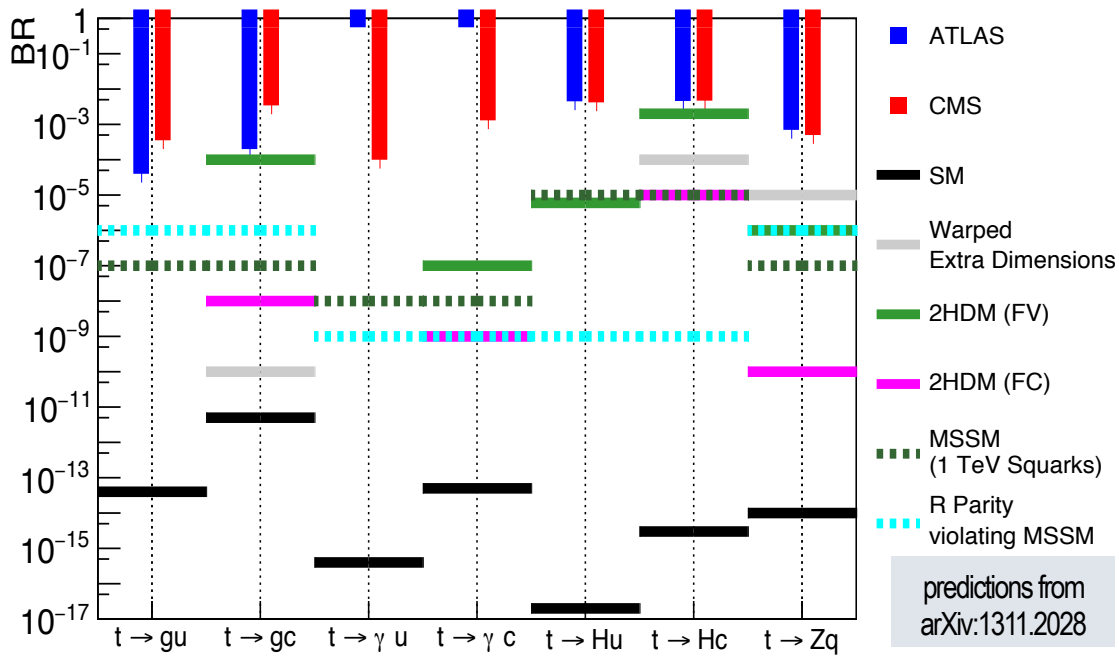




V_{tb} from branching fraction



FCNC



predictions from arXiv:1311.2028

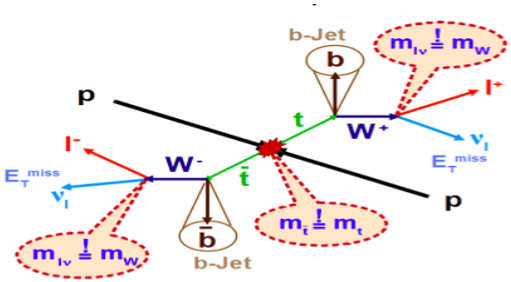
From top quark decays assuming CKM unitarity: $V_{tb} > 0.972$ at 95%CL

Many FCNC results available, closing in on some BSM models, statistics limited → expect significant improvements in Run-II

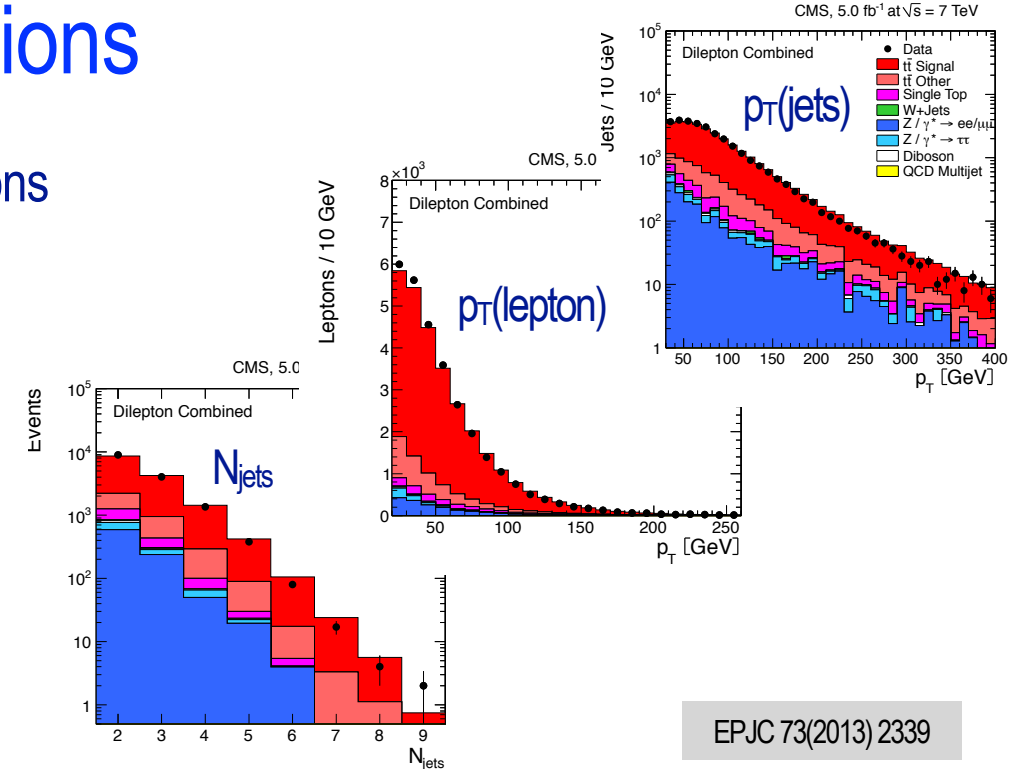
Differential $t\bar{t}$ Cross Sections

- Measure top quark kinematic distributions
  - Scrutinize theory predictions and models
  - Acceptances, efficiencies
  - Sensitivity to new physics
  - Goal: simultaneously determine m_{top}, α_S, PDF

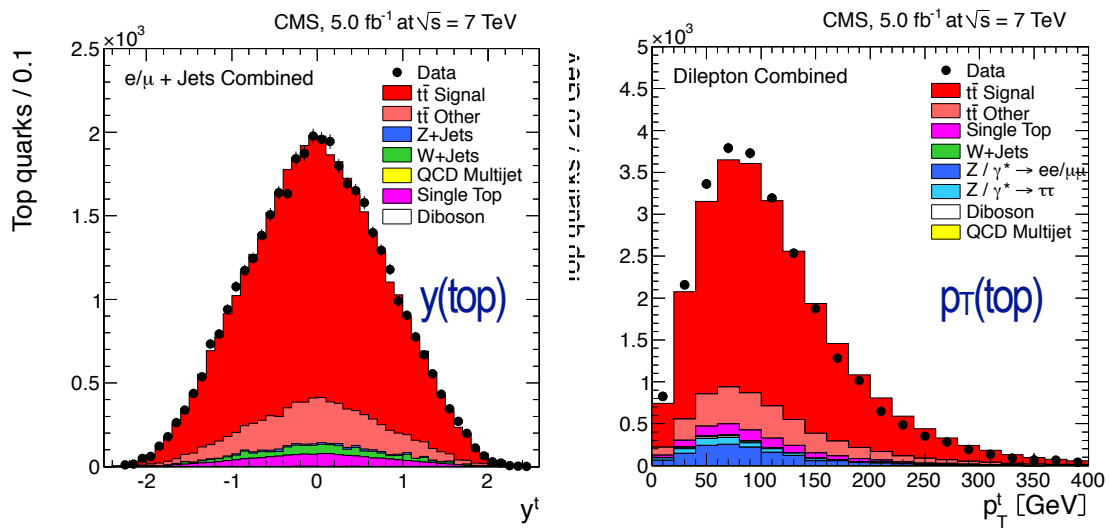
- Main analysis ingredients:
  - Kinematic reconstruction



  - Unfolding for comparison with fixed order calculations



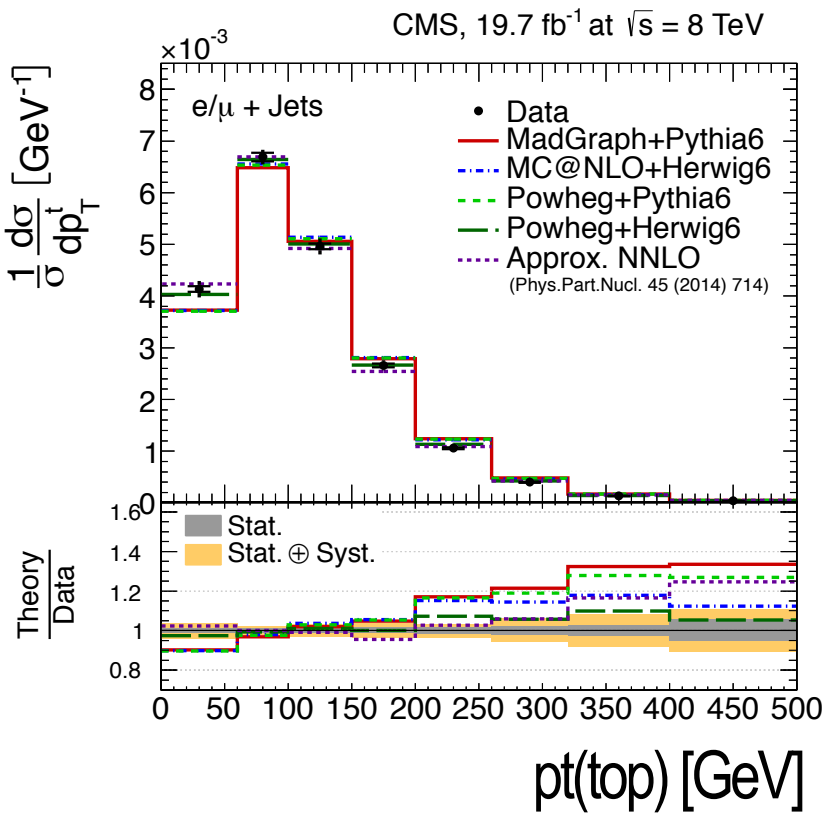
EPJC 73(2013) 2339



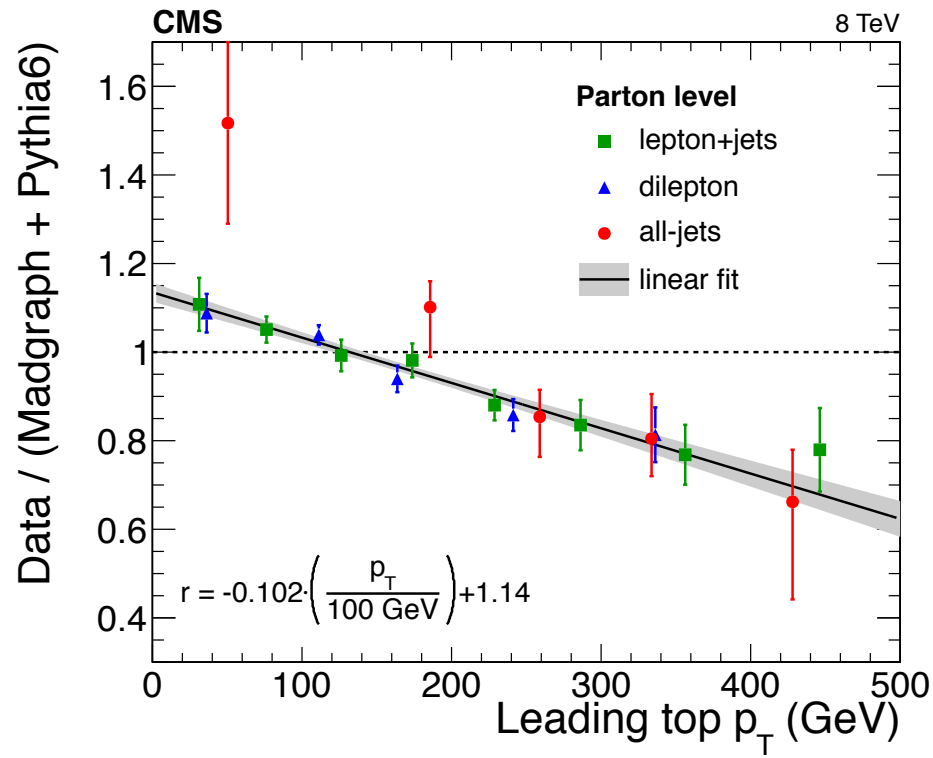
Differential distributions: p_T(top)

A discovery at Run-I

Eur. Phys. J. C 75 (2015) 542



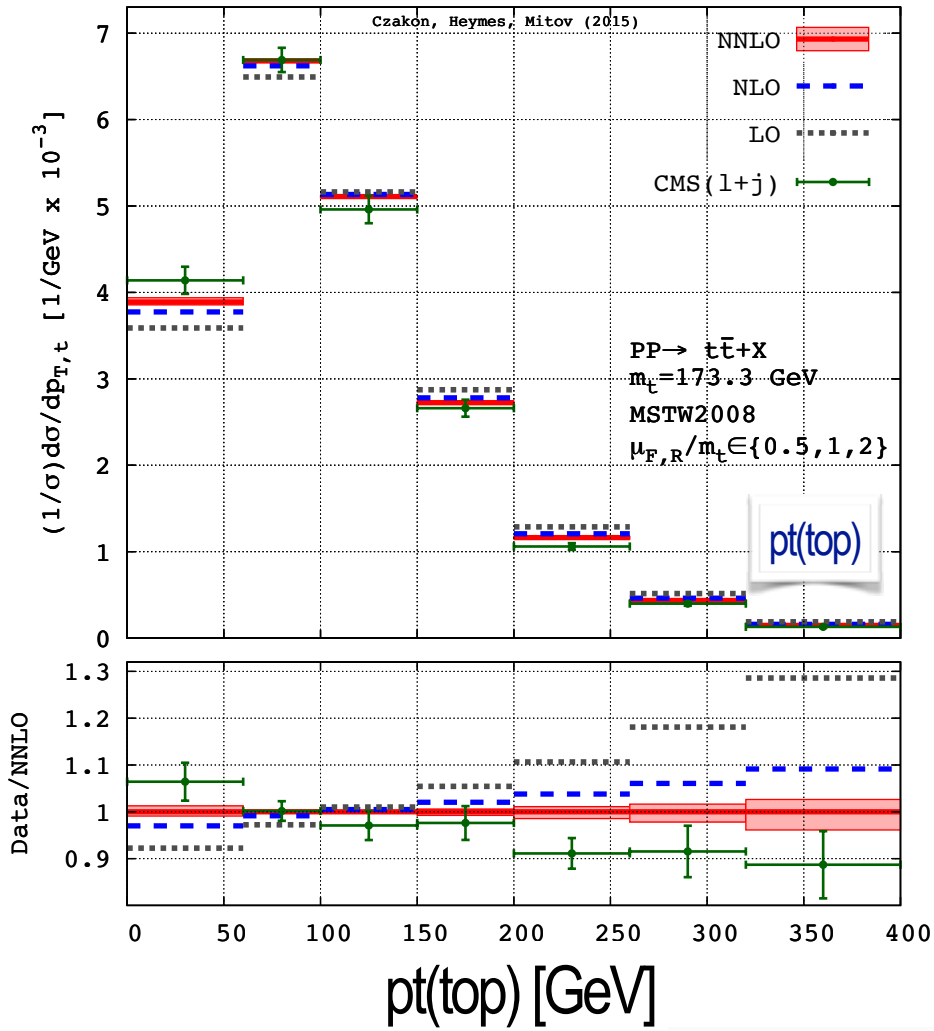
Eur. Phys. J. C 76 (2016) 128



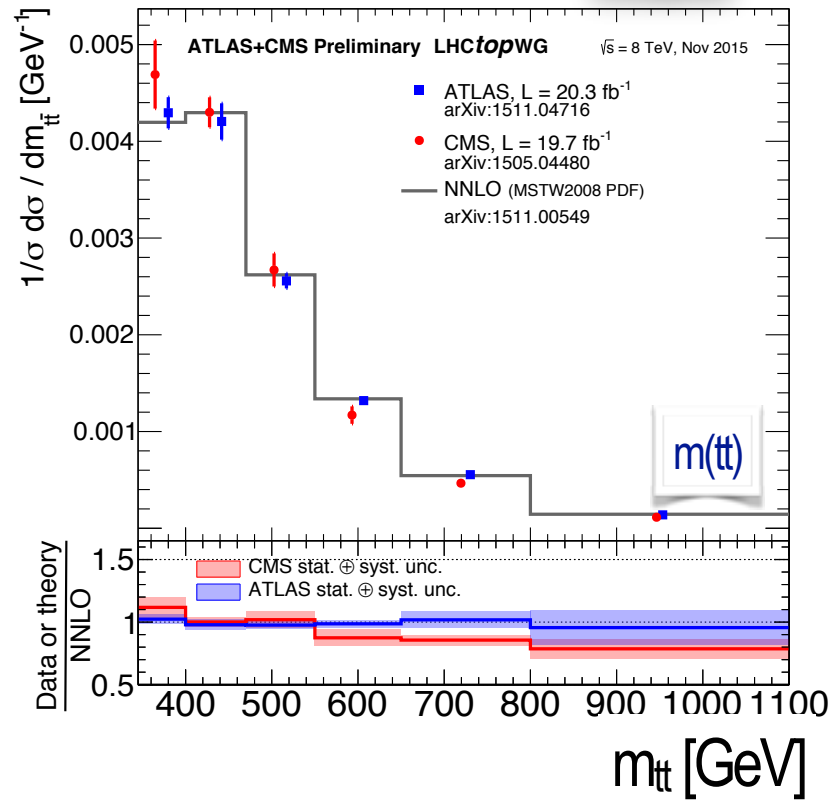
Measurements in dilepton, l+jets and all-jet final states
NLO calculations and most MC do not describe pt-spectrum, all other distributions look good

Differential $t\bar{t}$ at full NNLO

Czakon, Mitov, Heymes, PRL 116, 082003 (2016)



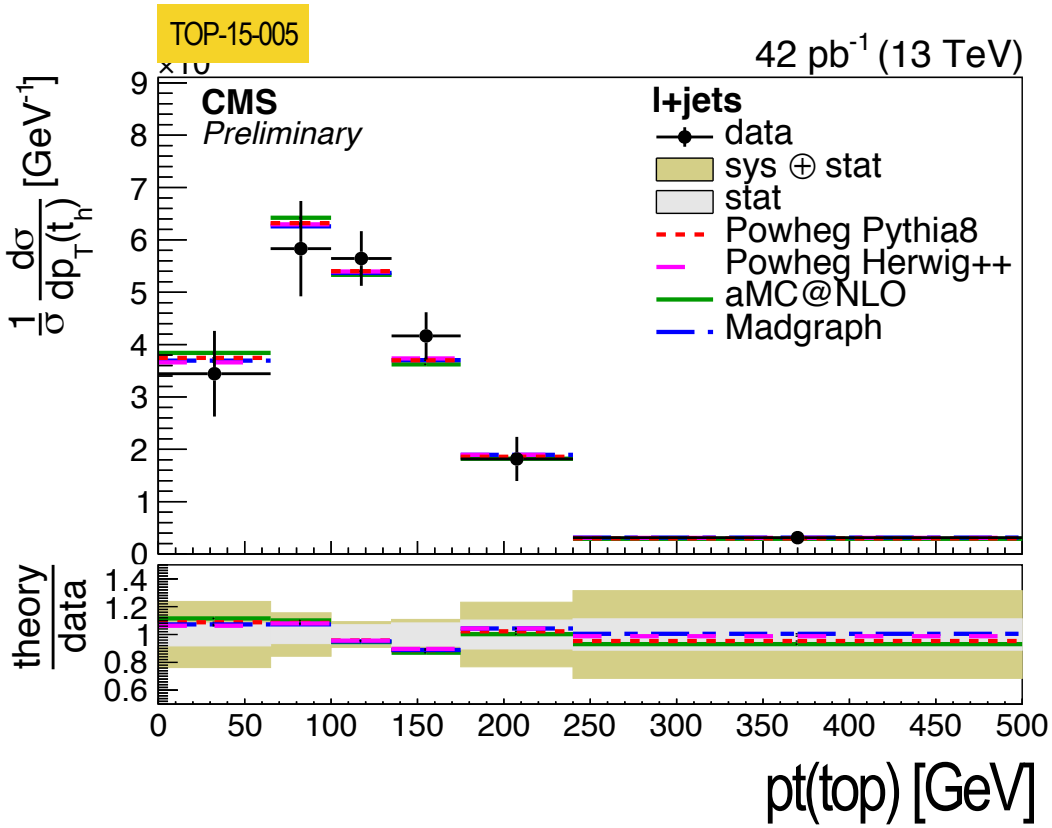
LHCtopWG

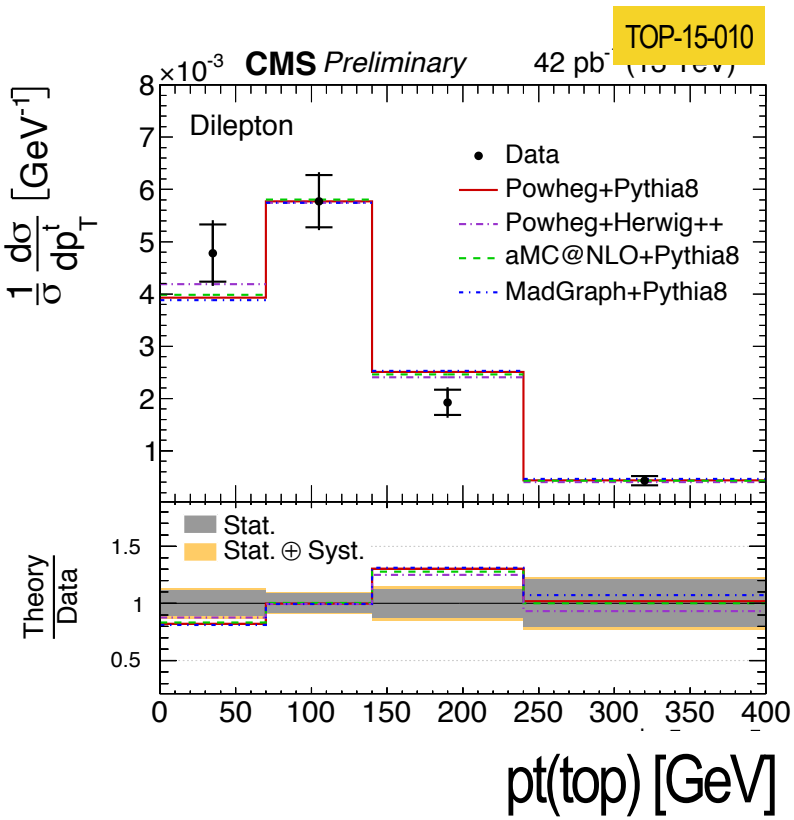


- k-factor between NNLO and NLO depending on pt(top), but not on other observables, m(tt), y(tt)
- One of the unexpected features of SM physics discovered in Run-1
- Data in use for PDF fits

CMS and ATLAS data well described by NNLO

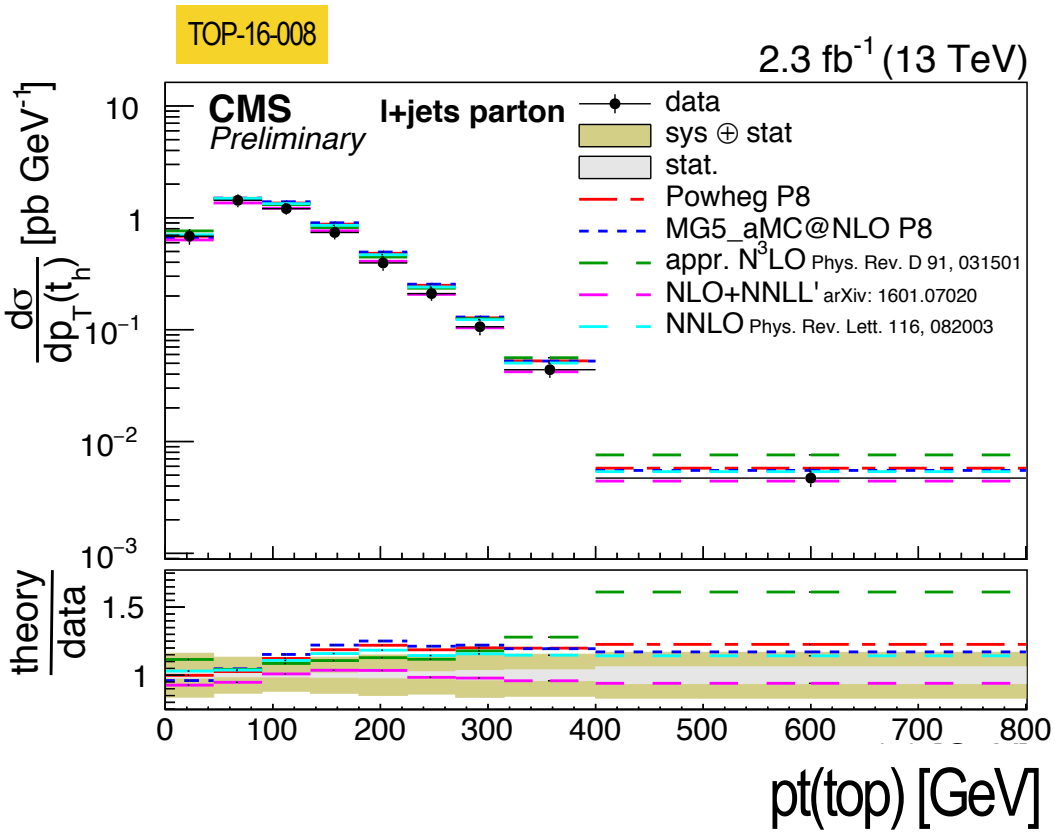
Run-II Early Analyses: the first 42 pb^{-1}

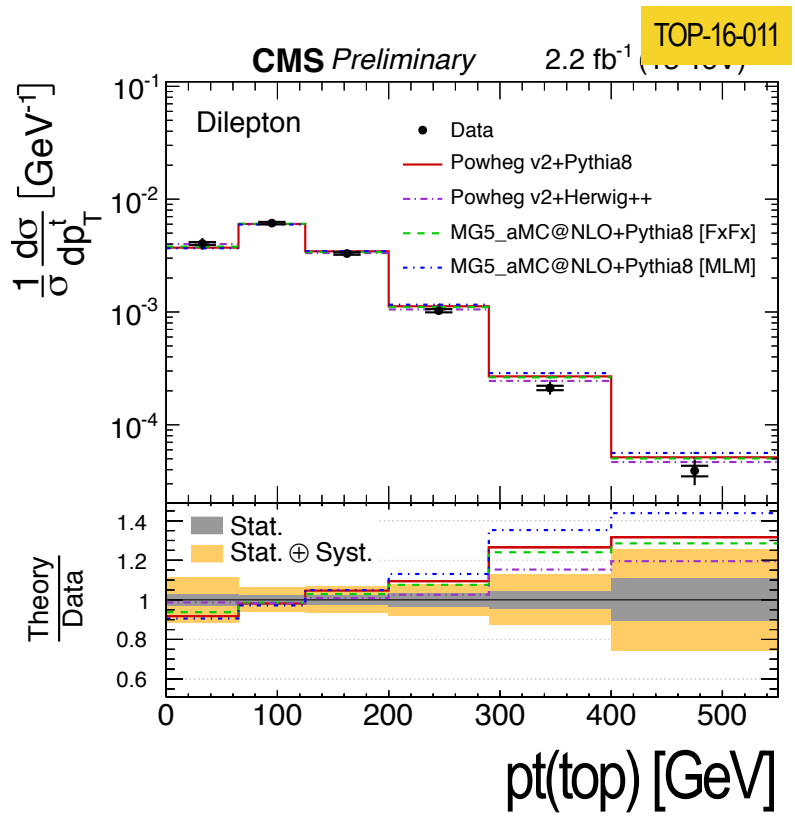




Very first results were made public in September 2015: still statistics limited

Run-II Early Analyses: the full 2015 dataset



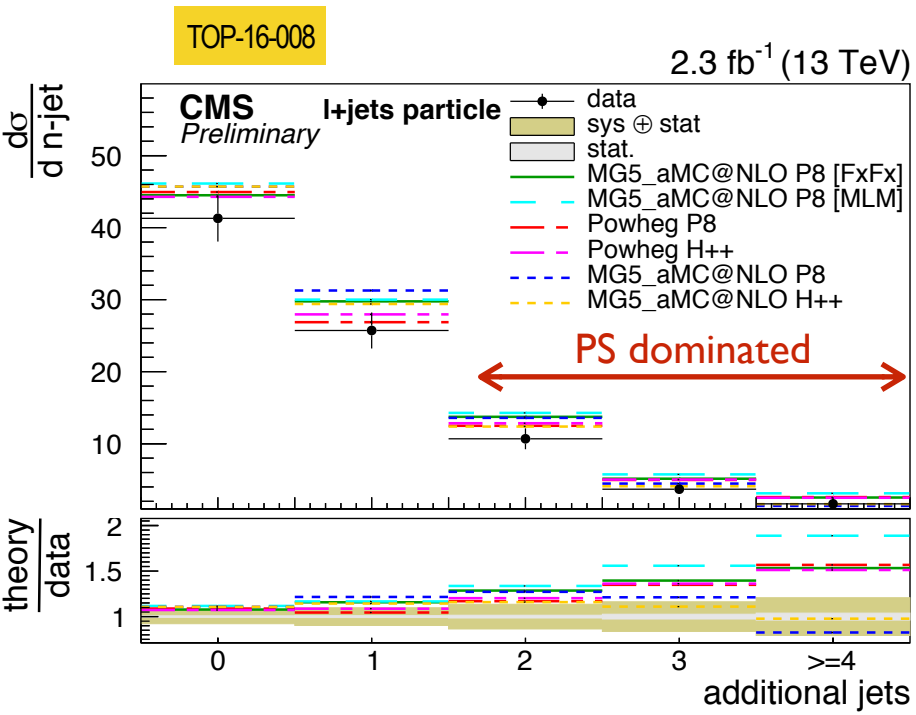


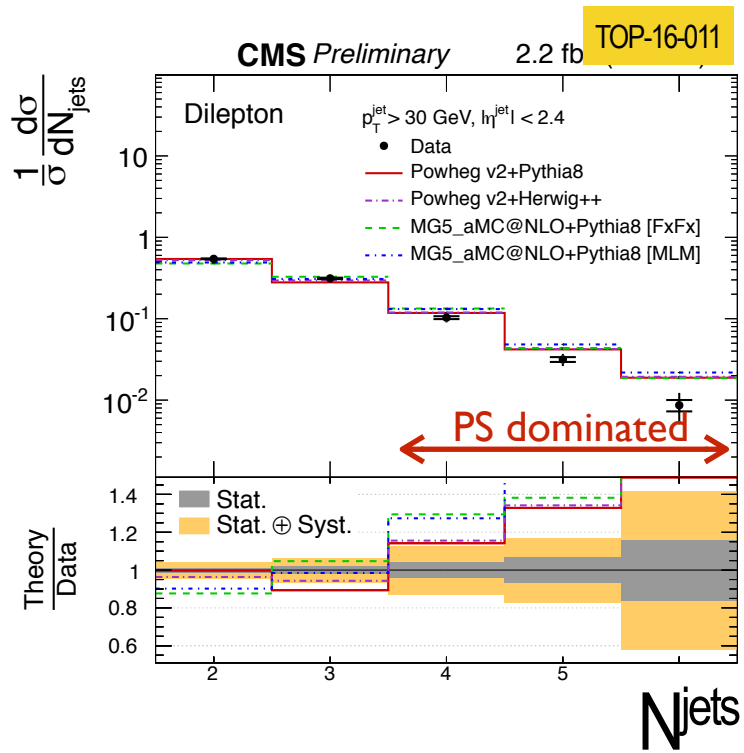
See same pt(top) trend as in Run-I

Full 2015 statistics: already running up against systematics wall

Run-II Early Analyses: $t\bar{t}$+jets

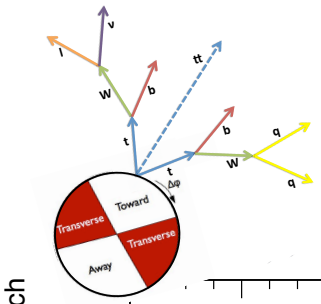
- tt+jets is dominant background in many new-physics searches and in ttH
- Investigate MC description of radiation
- CMS 2015 default: NLO+parton shower (Pythia8) using Monash-based tune CUETP8M1



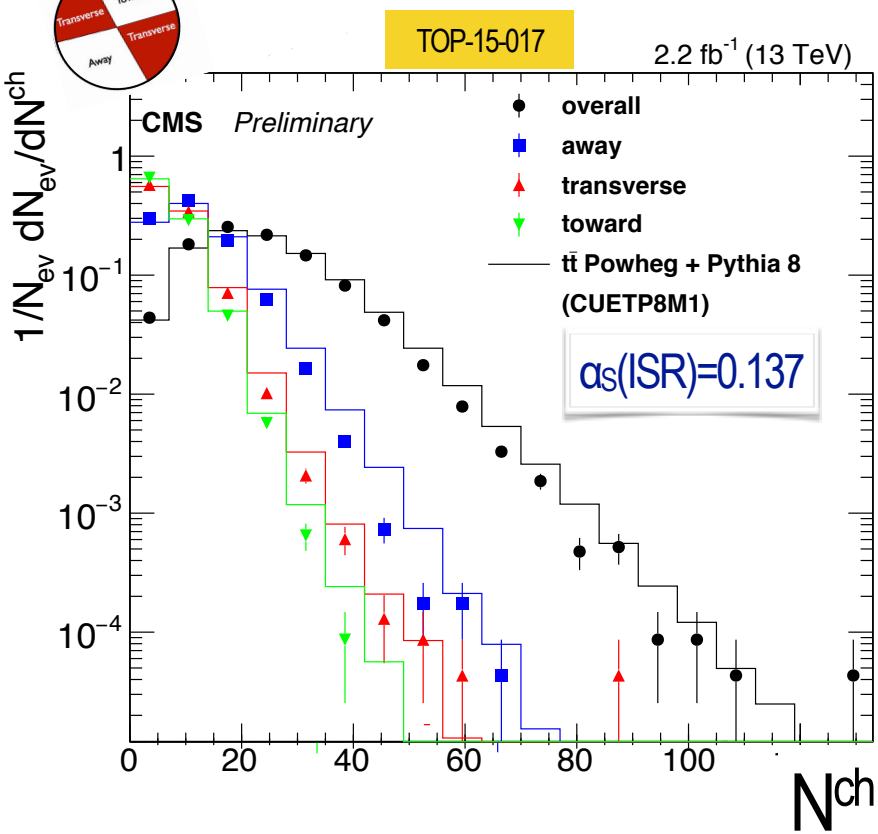


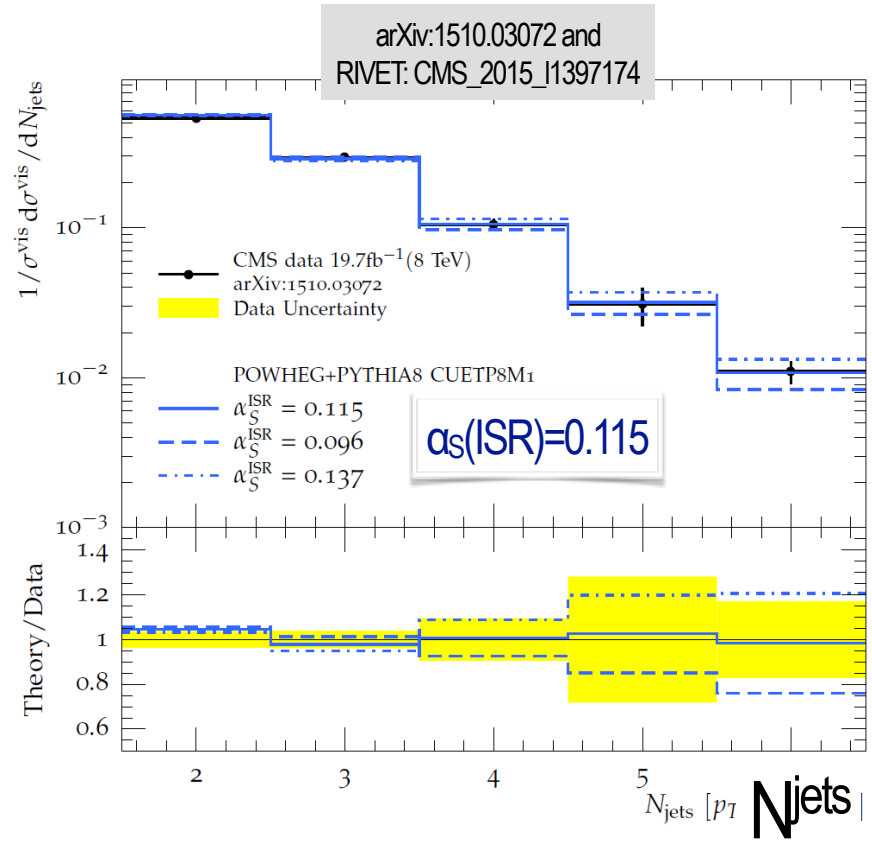
Current generation of NLO+PS MC predicts too much gluon radiation

Run-II Early Analyses: UE and tuning of α_S(ISR)



- Charged particle multiplicities in different event hemispheres → UE
- Use Run-I and Run-II data to tune basic PS parameters - here: α_S(ISR)



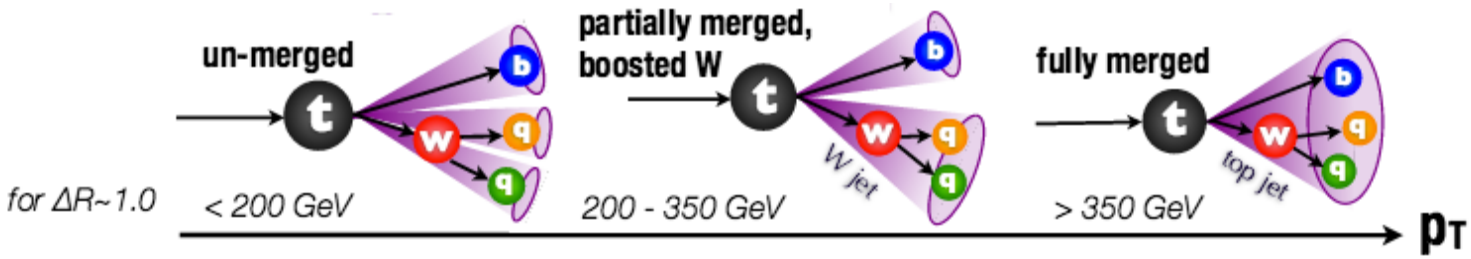


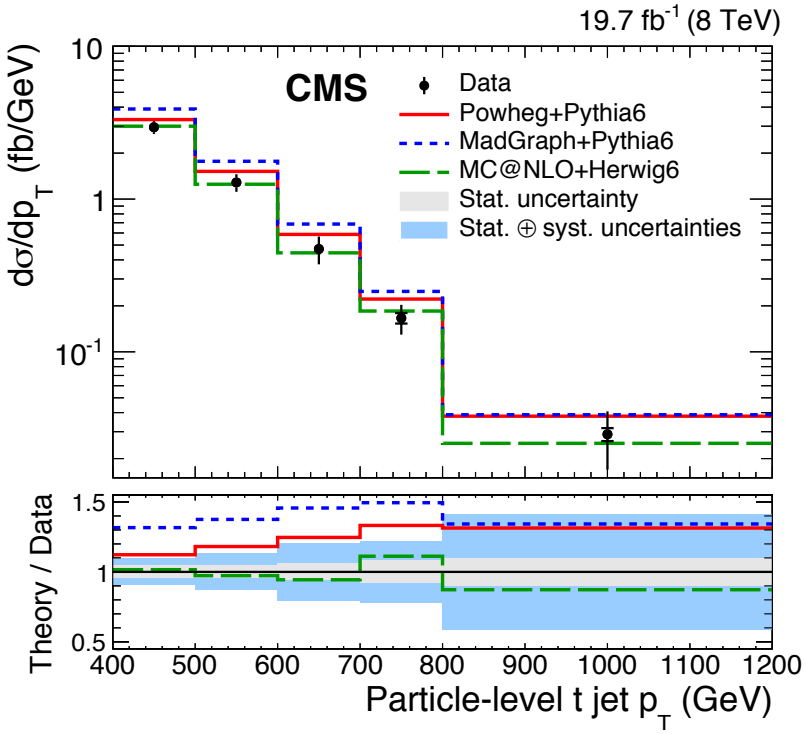
Charged particle spectra prefer scale-up variation, i.e. lower α_S

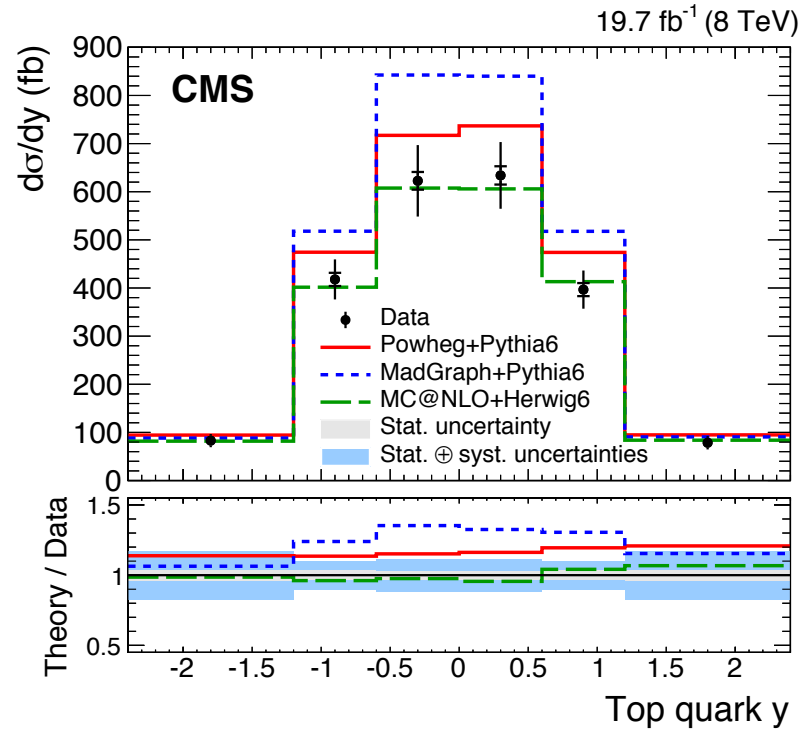
Improved description for both Run-I and Run-II: α_S(ISR) = 0.115

Boosted Regime: $t\bar{t}$ cross sections

arXiv:1605.00116





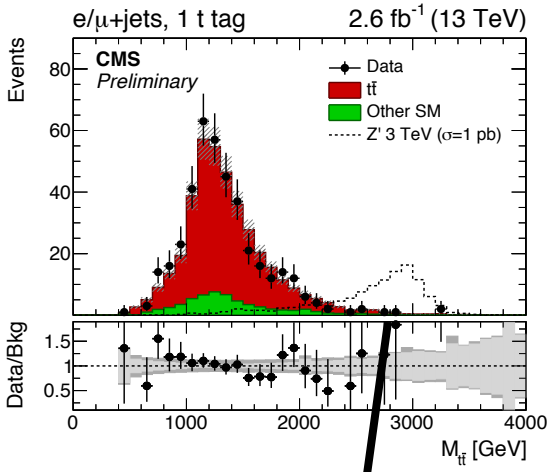


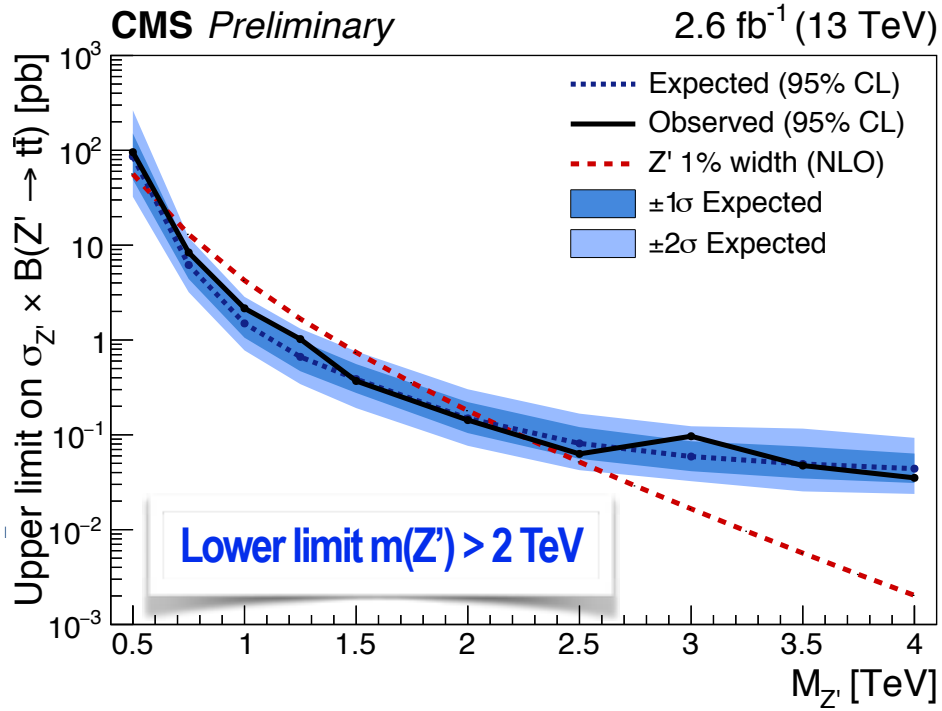
pt(top) trend continues to high pt

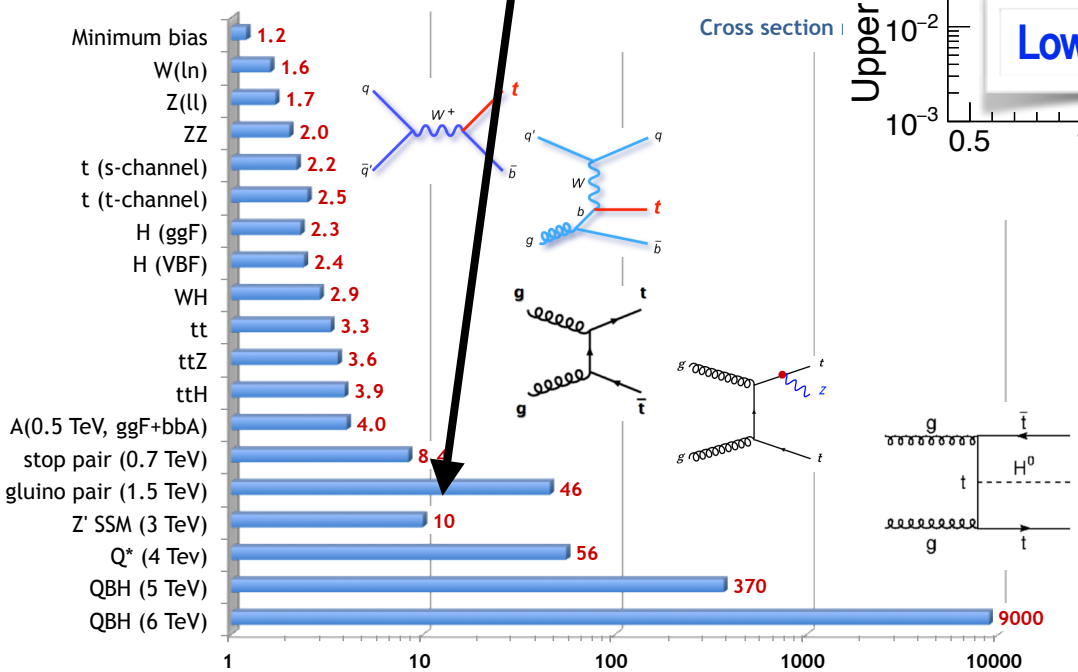
Run-II: enhanced cross sections in boosted regime

Boosted Regime: Z'→$t\bar{t}$ search

B2G-15-002



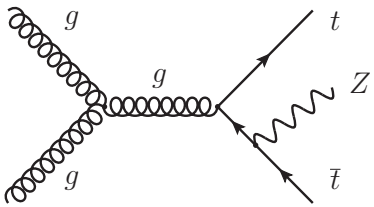


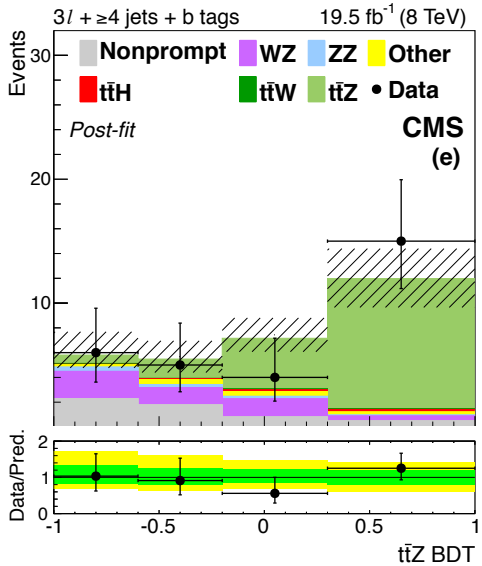


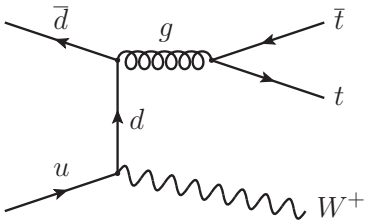
13/8 TeV cross section ratio
Factor 10 for Z' (3 TeV):
→
Limit from complete Run-I
re-established with first 2015 data

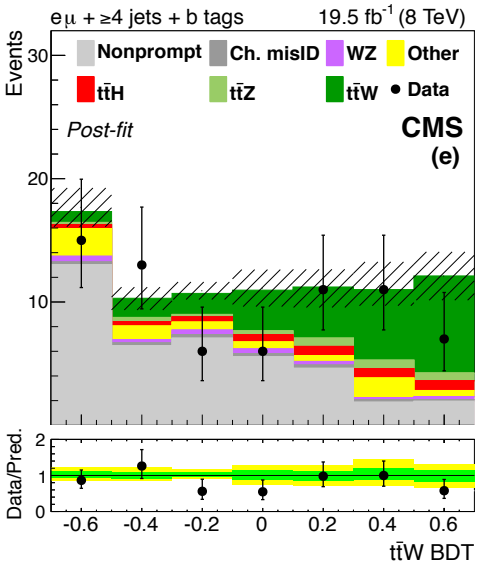
$t\bar{t}Z$ and $t\bar{t}W$

J. High Energy Phys. 01 (2016) 096





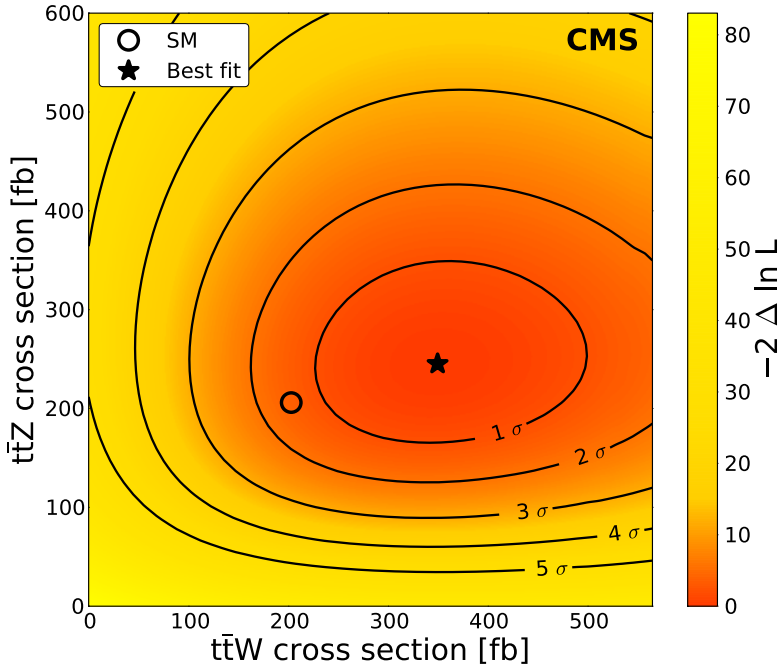




- Five multi-lepton event categories: 2ℓ OS, 2ℓ SS, 3ℓ ttZ, 3ℓ ttW, 4ℓ
- Kinematic reconstruction followed by MVA Profile likelihood fit to extract signal strength
- Also in paper: first constraints on ttZ couplings and several dim-6 operations

ttZ: 6.4 (5.7)σ obs (exp)

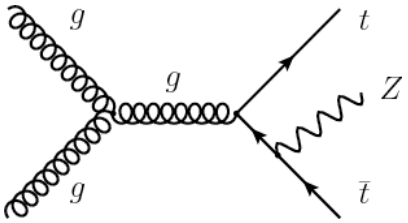
ttW: 4.8 (3.5)σ obs (exp)

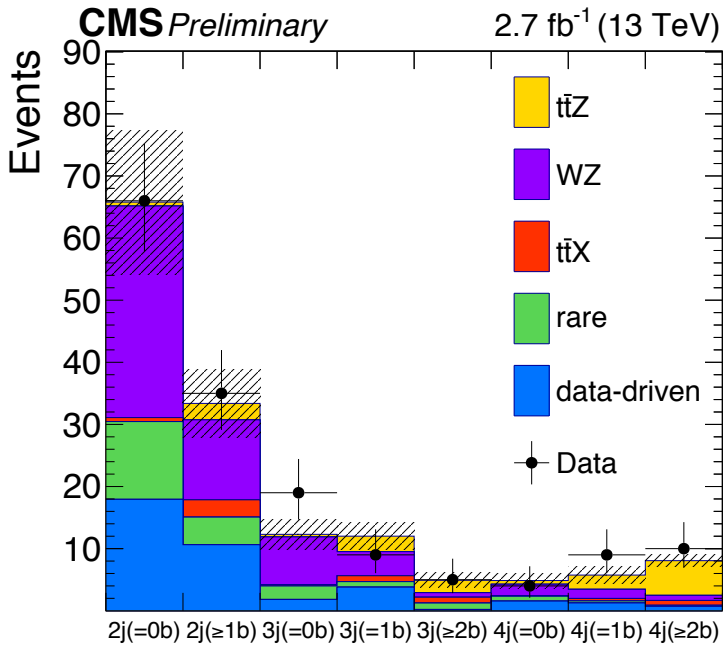


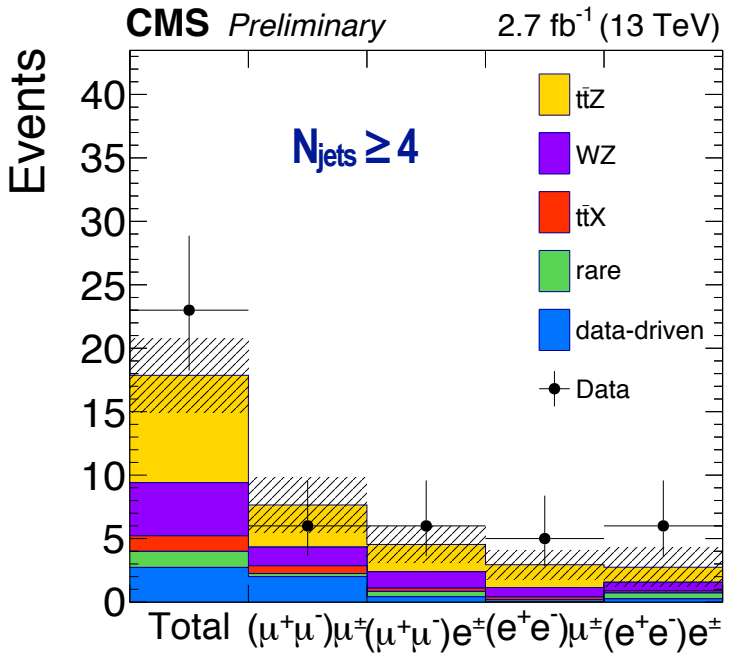
Run-II Early Analyses: $t\bar{t}$+Z

TOP-16-009

- ttZ cross section ~4 times higher than at 8 TeV
- Count 3- and 4-lepton events in eight categories of jets and b-jets





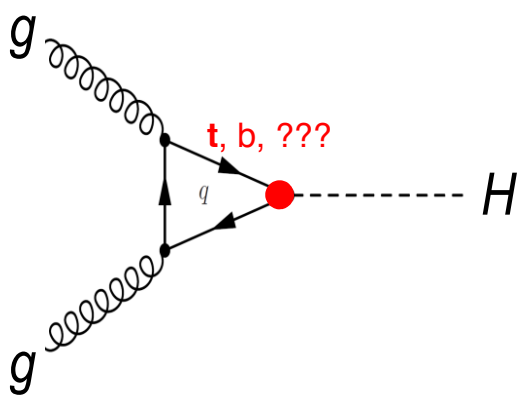


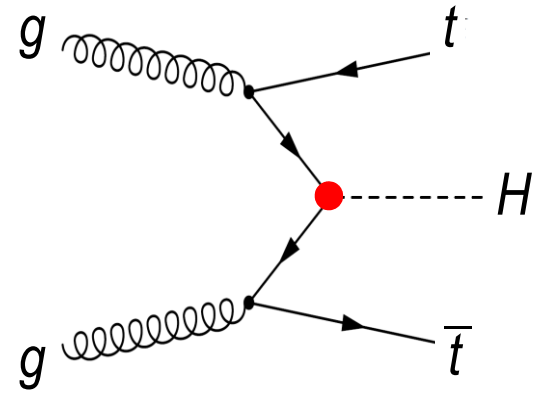
$\sigma_{ttZ\ (13\ TeV)}$ = 1065 $^{+352}_{-313}{}_{stat}$ $^{+168}_{-142}{}_{syst}$ **fb**

Significance = 3.6 (3.1) σ obs (exp.)

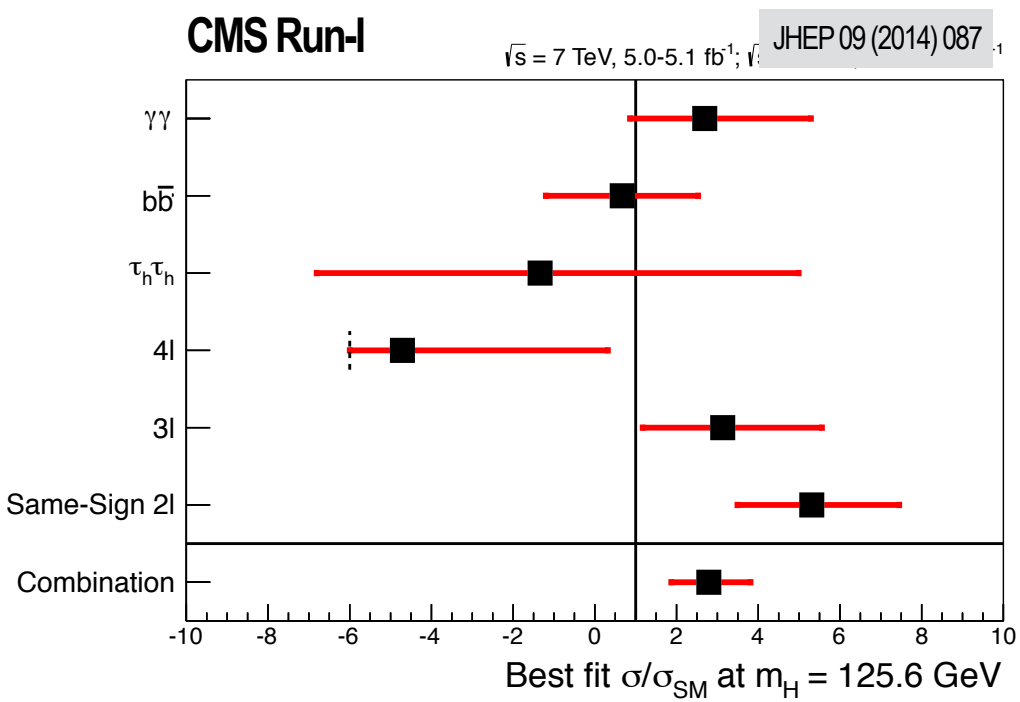
Signal strength = 1.27 ± 0.4_{stat} ± 0.2_{syst}

$t\bar{t}$+Higgs





Break up top-quark loop → measure Y_t directly



ttH (NLO)	Cross section
7 TeV	89 fb
8 TeV	133 fb
13 TeV	507 fb

x3.8

Run-II Early Analyses: $t\bar{t}$+Higgs

HIG-15-005
HIG-15-008
HIG-16-004

H→multileptons

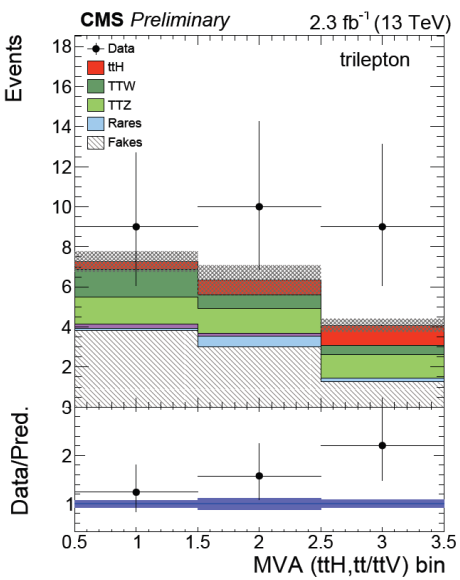
- 2ℓ(ss) or 3ℓ + > 2jets (1b-tag)
- MVA in categories, Separate trainings against tt and ttV
- Diboson bg from control regions

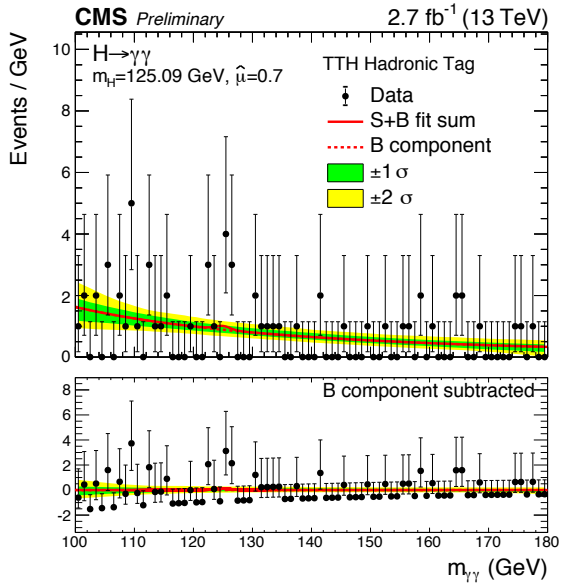
H→ γγ

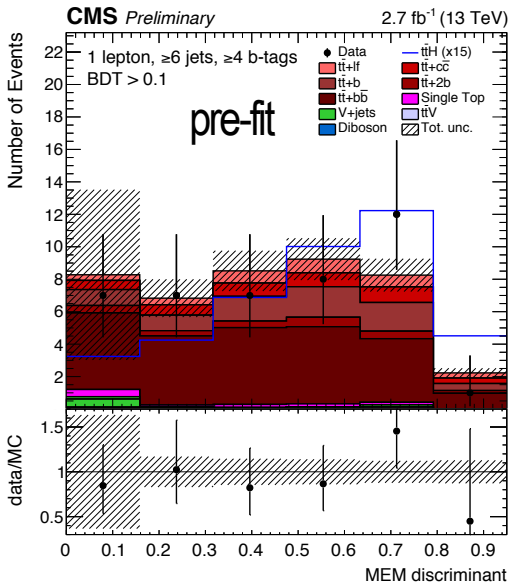
- Background low, clear mass peak
- One category of H→ γγ analysis
- Critical: calibration

H→bb

- dominant background from ttbb
- combined matrix element method and BDT







$$\hat{\mu}_{\text{obs}} = 0.6^{+1.4}_{-1.1}$$

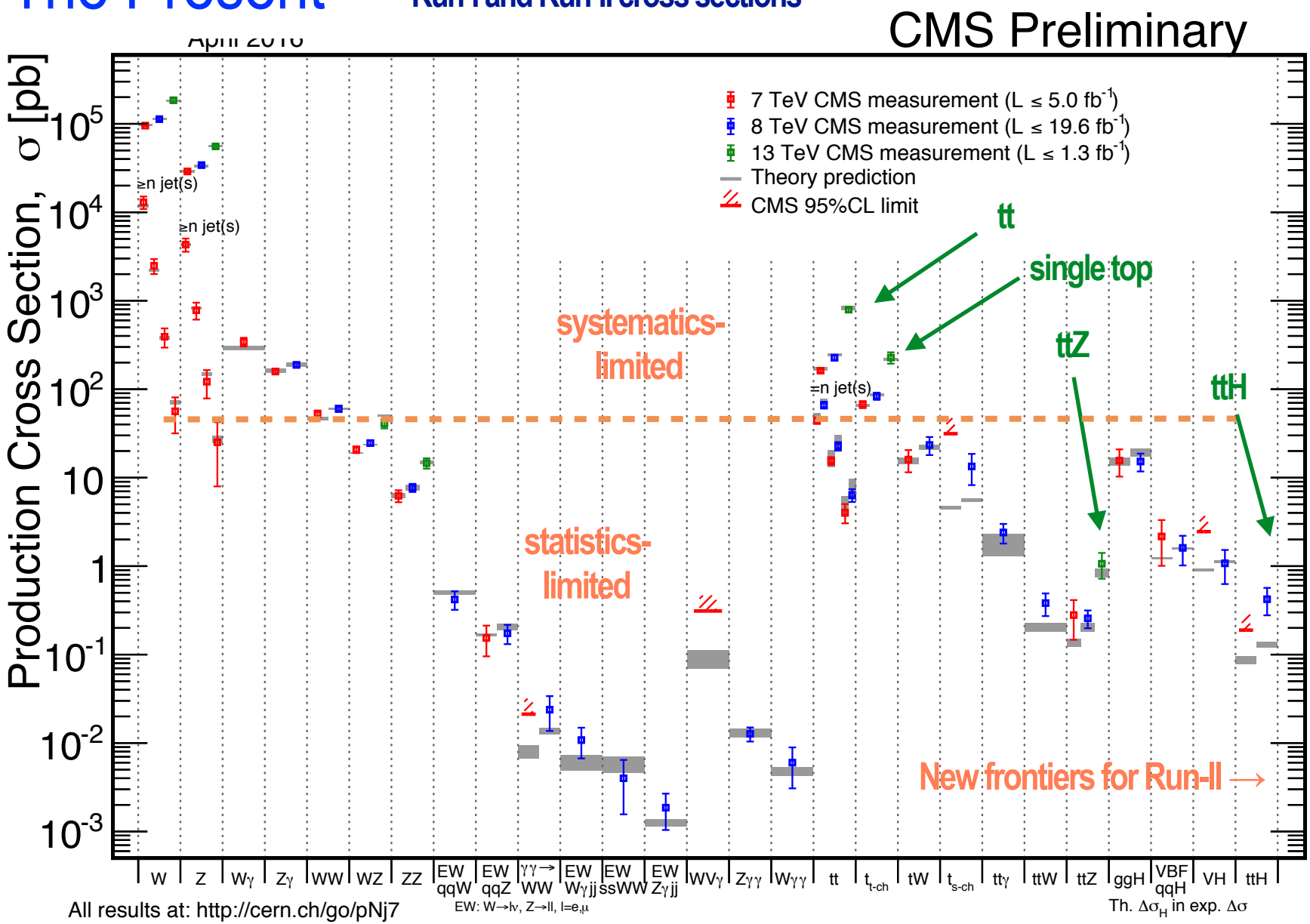
$$\hat{\mu}_{\text{obs}} = 3.8^{+4.5}_{-3.6}$$

$$\hat{\mu}_{\text{obs}} = -2.0^{+1.8}_{-1.8}$$

If ttH complies with SM expectation expect discovery very soon

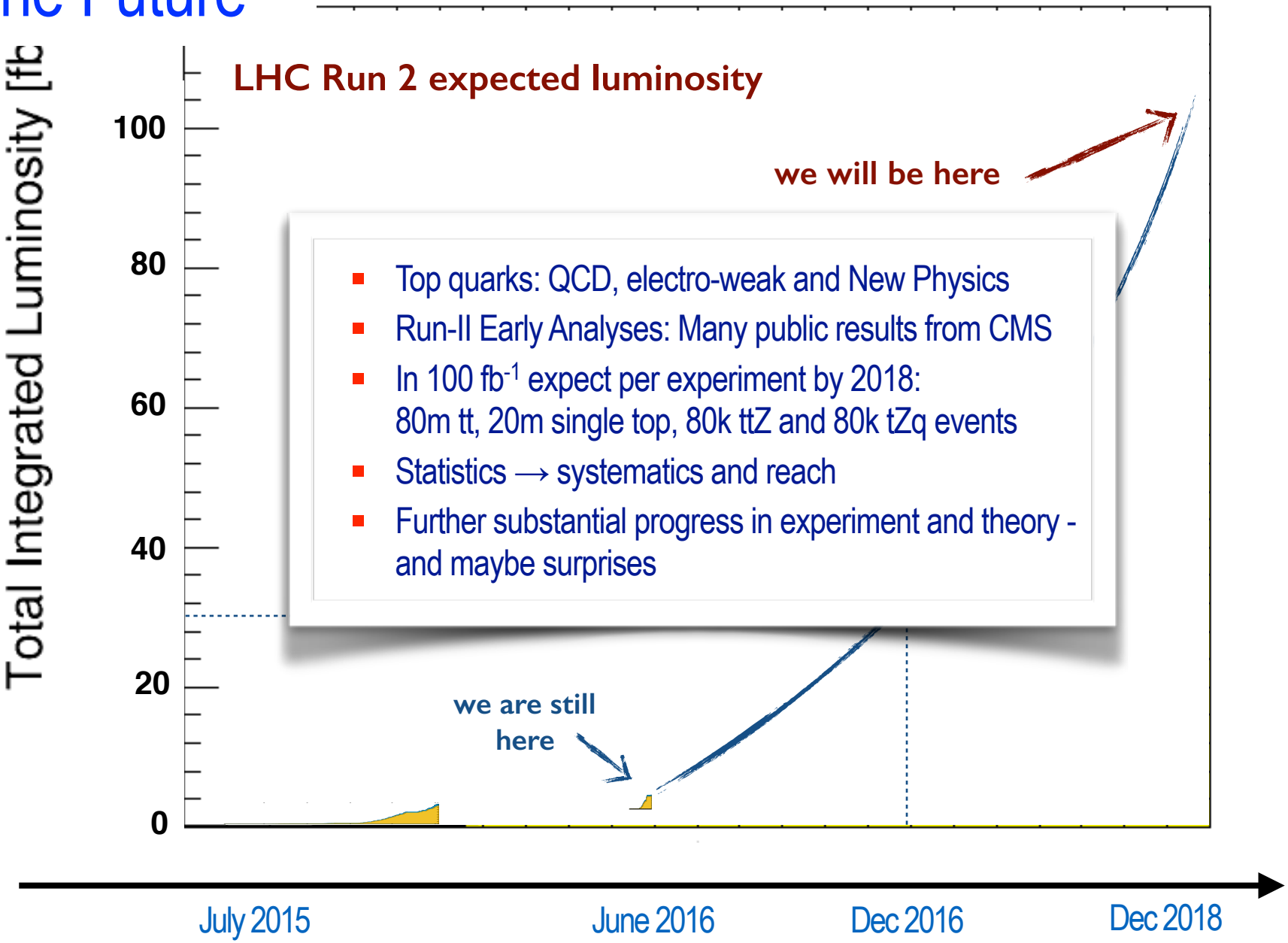
The Present

Run-I and Run-II cross sections

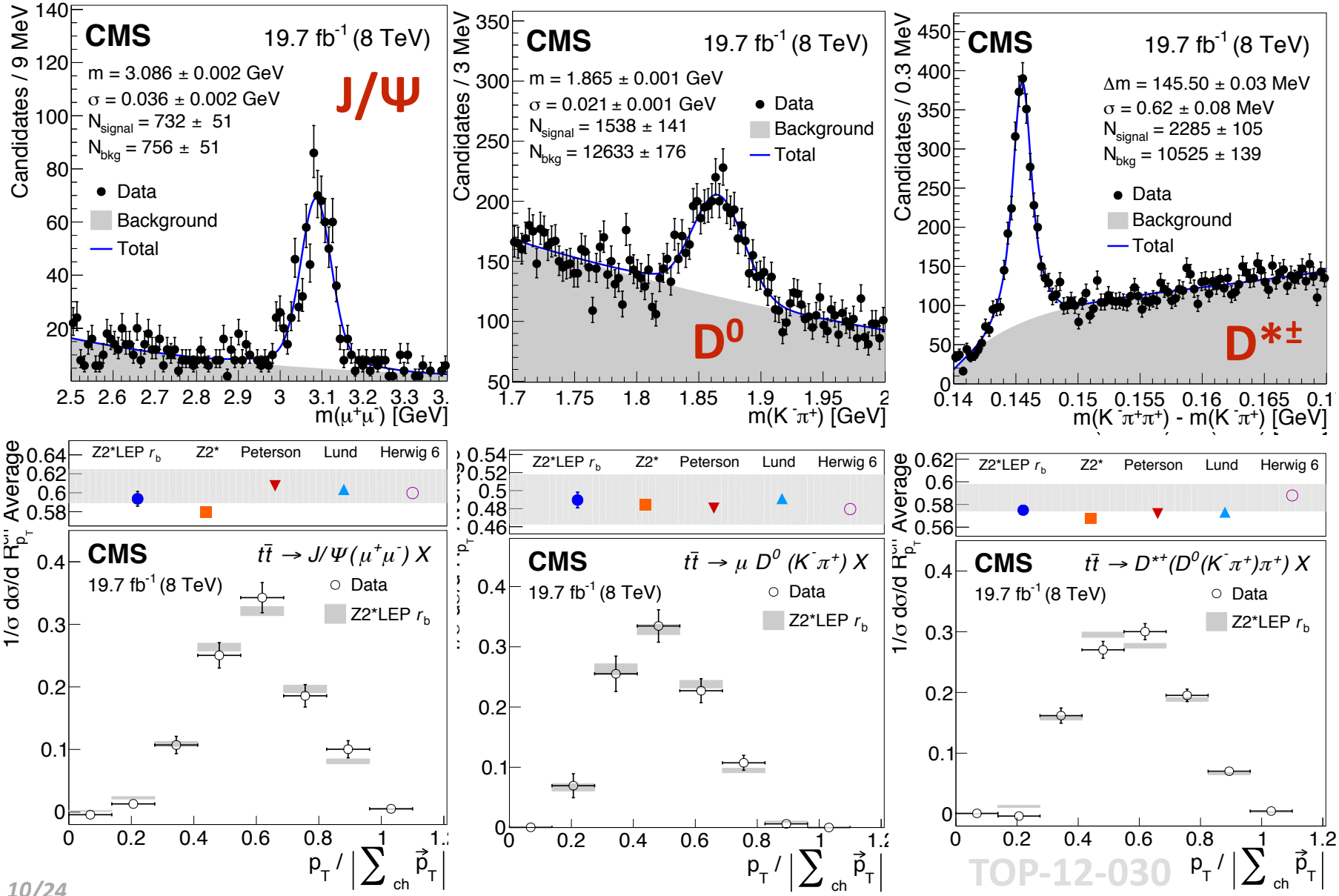


All results at: http://cern.ch/go/pNj7

The Future



- Top quarks: QCD, electro-weak and New Physics
- Run-II Early Analyses: Many public results from CMS
- In 100 fb^{-1} expect per experiment by 2018:
  80m tt, 20m single top, 80k ttZ and 80k tZq events
- Statistics ⟶ systematics and reach
- Further substantial progress in experiment and theory - and maybe surprises

Backup

Charm Mesons from Top Decays