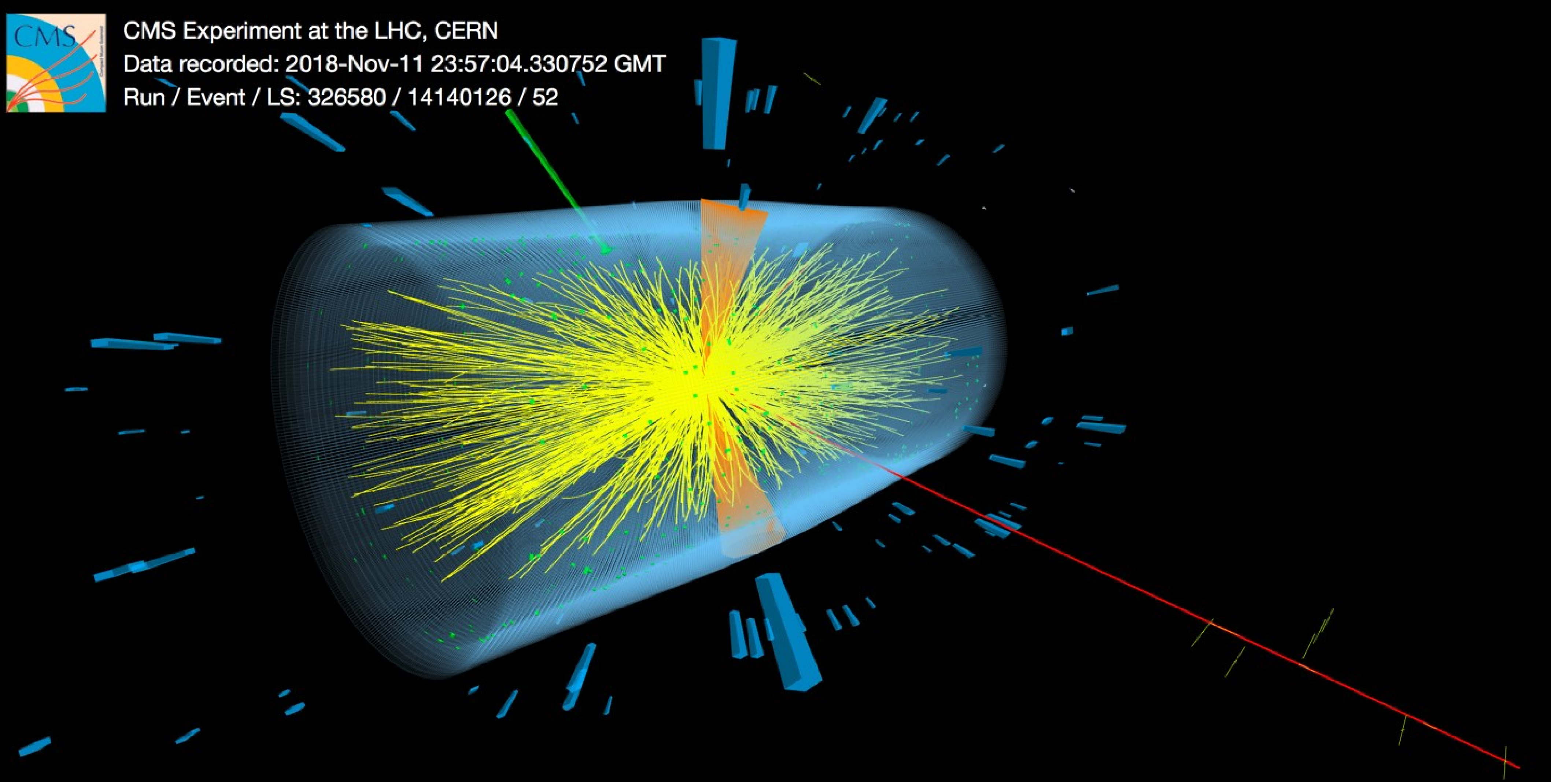


Inclusive $t\bar{t}$ cross section measurements at CMS

GK Krintiras – The University of Kansas

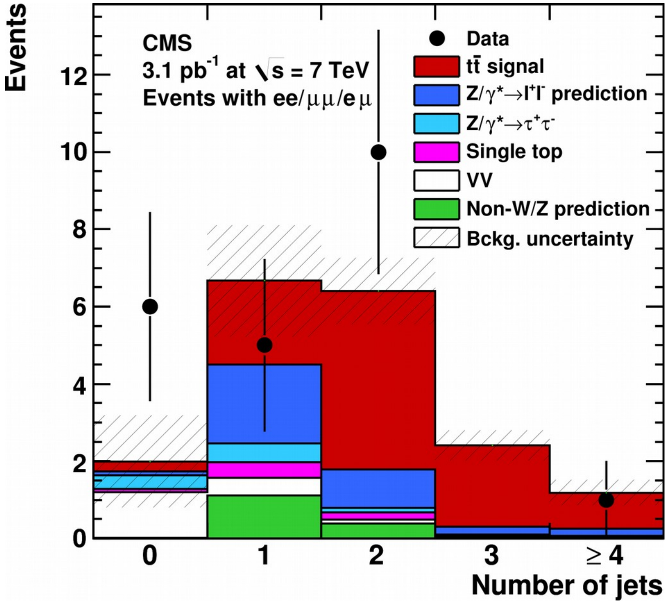
on behalf of the **CMS** Collaboration

U.S. DEPARTMENT OF
ENERGY
Office of
Science

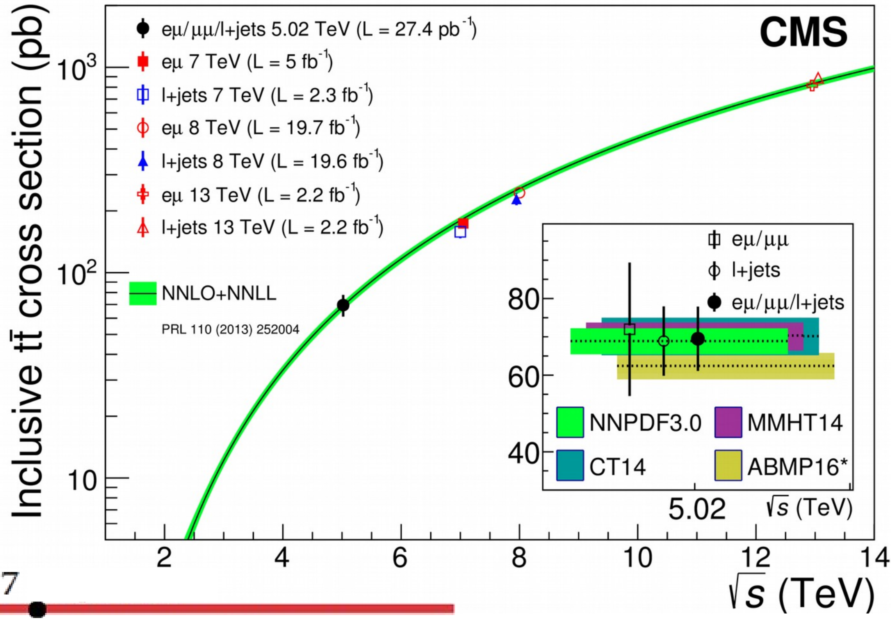
Up-to-date compilation: 4 √sNN & 2 systems @ LHC !

- A wealth of inclusive $t\bar{t}$ measurements since 2010
  - At 5.02, 7, 8, and 13 TeV
  - In dileptonic, semileptonic, and hadronic final states
  - In pp and pA collisions
- To place limits on SM (EW and QCD) parameters
  - Portal to BSM?
- Already in the era of systematically limited measurements
  - Even with the 2015/16 data set (~20% of Run 2)
  - Improve precision w/o spoiling accuracy

Phys. Lett. B 695 (2011) 424



JHEP 03 (2018) 115



1995 Top at Tevatron

2009 Top at LHC (7 TeV)

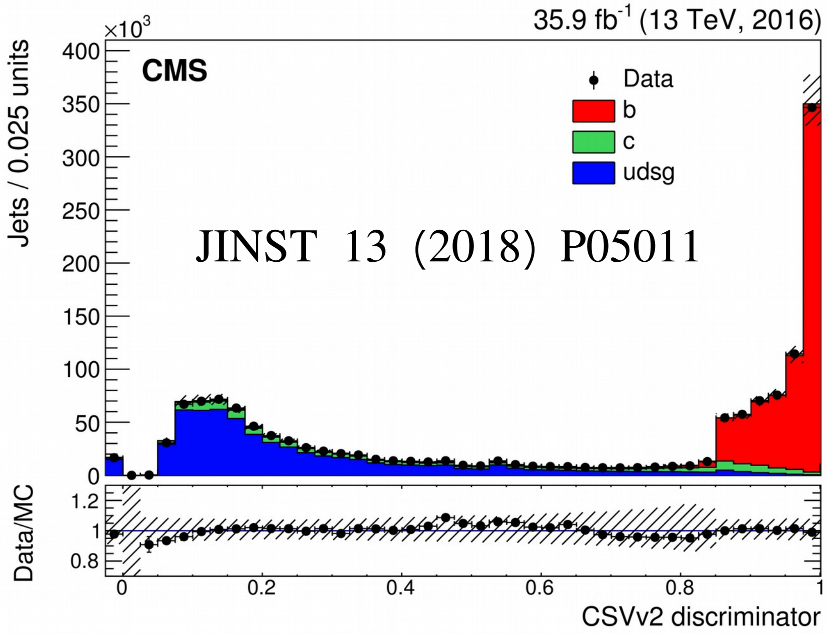
2015 Top at LHC (13 TeV)

2016 Top at LHC (5.02 TeV)

2017 Top at LHC (in nuclear matter)

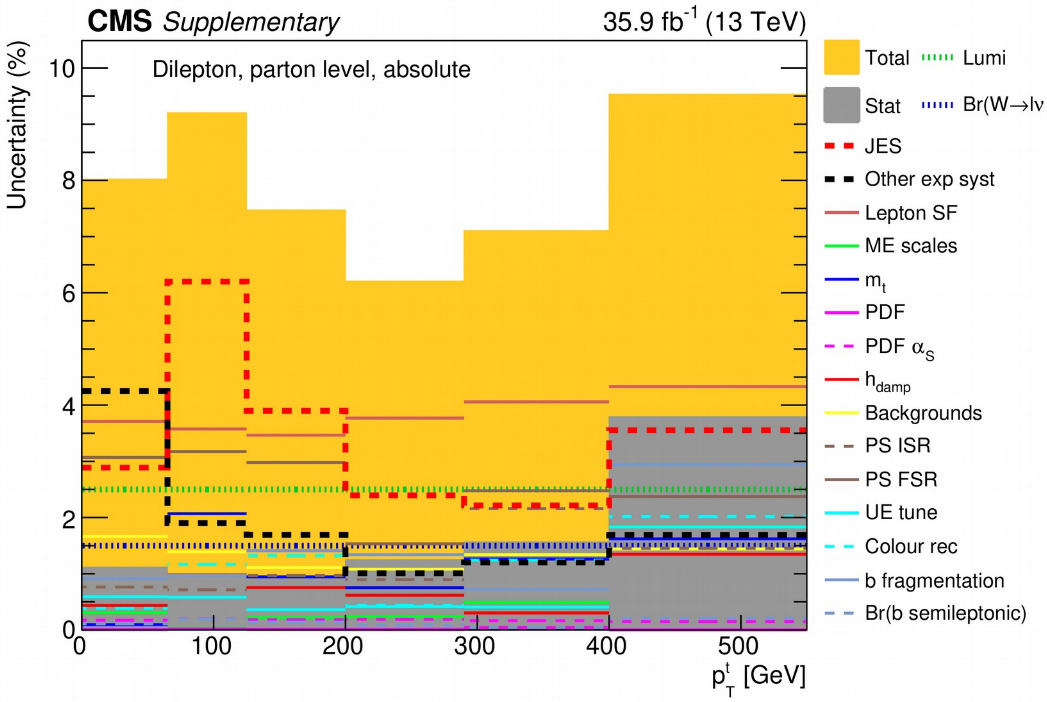
Experimental and theoretical challenges for $\sigma_{t\bar{t}}$

- Final states are complicated
  - All types of physics objects involved
    - Leptons, (<u>**b**</u>)jets, pTmiss
    - b tagging: main tool to control bkg.
- Experimental challenges
  - Jet energy scale (JES)
  - b tagging efficiency
  - Lepton trigger and identification
  - Absolute scale of luminosity
- Theoretical challenges
  - Proton PDF parametrization
  - Modeling (soft and hard) too
    - Greater impact on differential $t\bar{t}$



JINST 13 (2018) P05011

JHEP 02 (2019) 149



Experimental and theoretical challenges for $\sigma_{t\bar{t}}$

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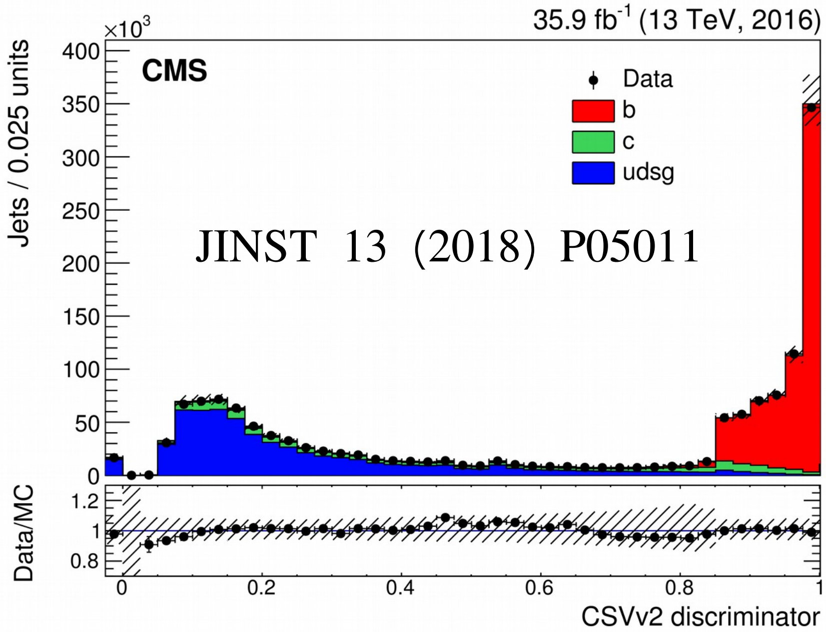
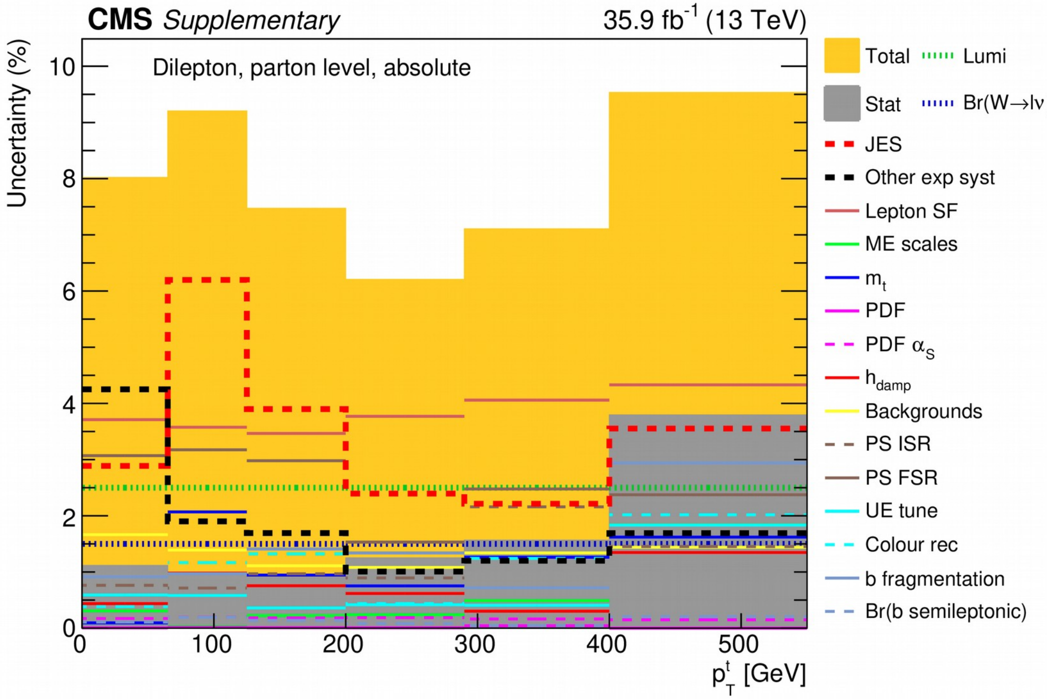

JINST 13 (2018) P05011

JHEP 02 (2019) 149

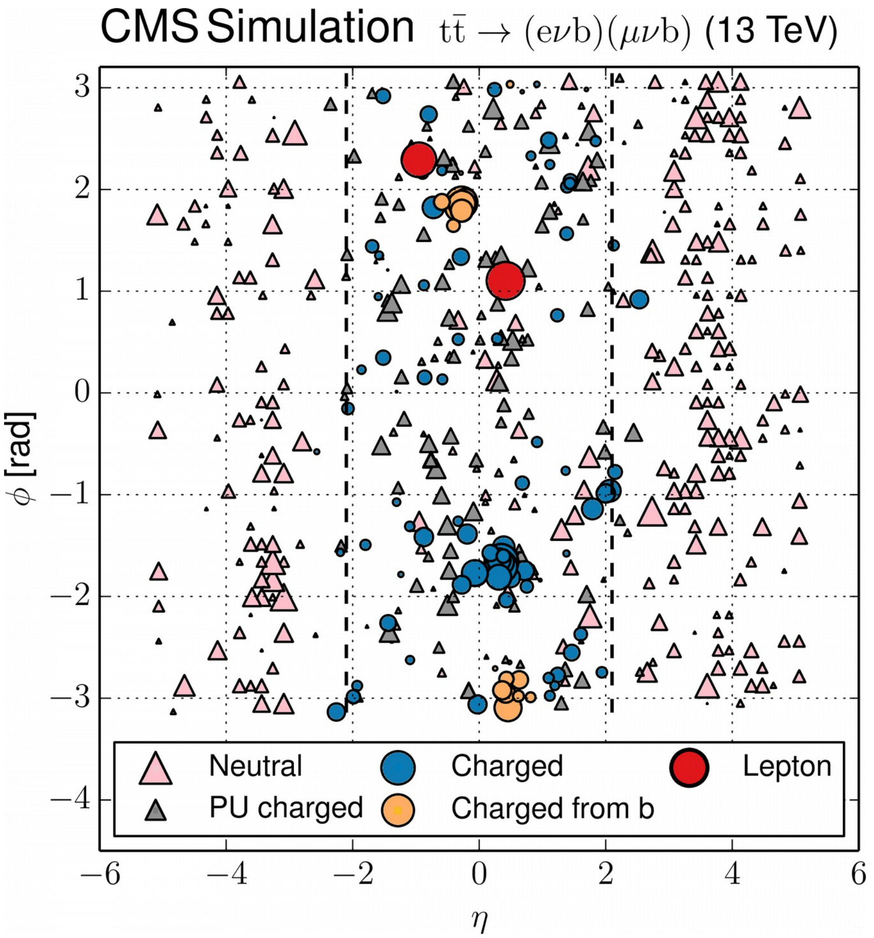


. to the talk from Otto

Measurements of tt̄ cross section: general procedure

- Performed in the “visible” phase space
- Categorized in bins of jet and b jet multiplicities
  - Template fits to counts and/or distributions
  - Exp. systematic uncertainty can be constrained
- Extrapolated to full phase space
  - Syst. uncertainty in $\mathcal{A}$ is added in quadrature $(\oplus)$
  - Introduces model dependence that can be checked
    - E.g., UE universality at the top mass scale

Eur. Phys. J. C 79 (2019) 123

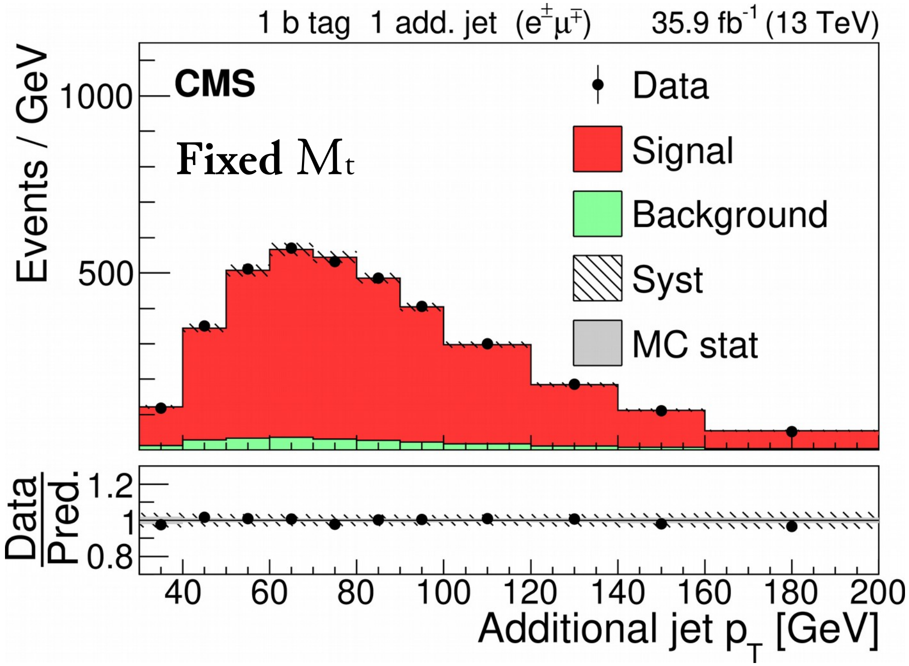


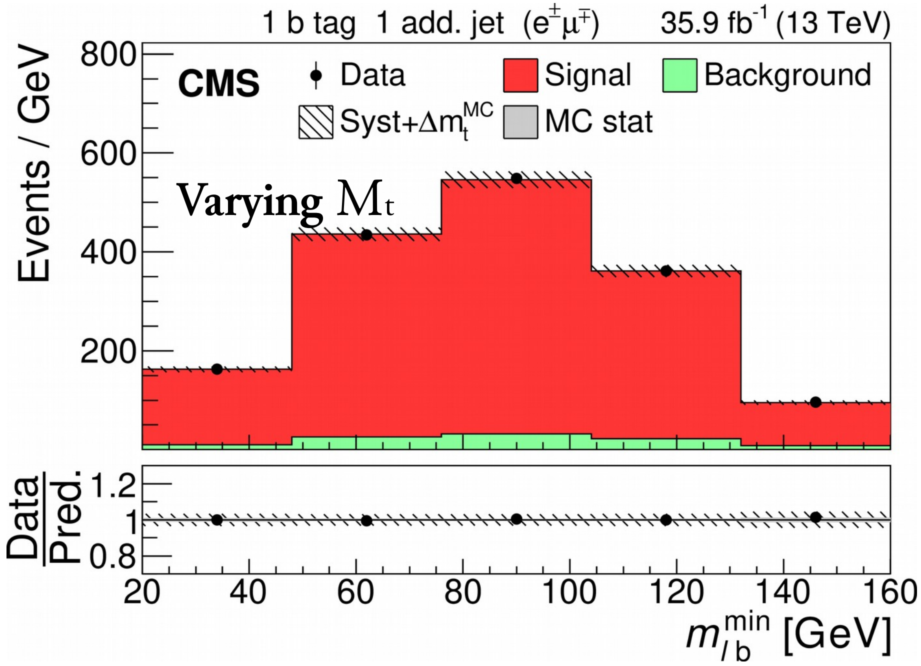
- “Golden” final states with ≥ 1 lepton + jets
  - All-hadronic: bkg dominated and more penalized by
    - JES, b tagging, and modeling uncertainty
    - MVA techniques are applied

The latest CMS inclusive $t\bar{t}$ measurement with 35.9/fb

- Performed with two different approaches
- At fixed M_t ($\equiv$172.5 GeV)
  - simultaneously in $e\mu$, $\mu\mu$, and ee
  - Minimize sensitivity to the data sample size
- Leaving M_t to vary
  - only in $e\mu$ to minimize the bkg. impact
  - cross section determined at best-fit M_t
- Used to independently extract the strong coupling and top mass
  - α_s is determined at NNLO
  - direct determination of M_t (pole and **running**)

Eur. Phys. J. C 79 (2019) 368

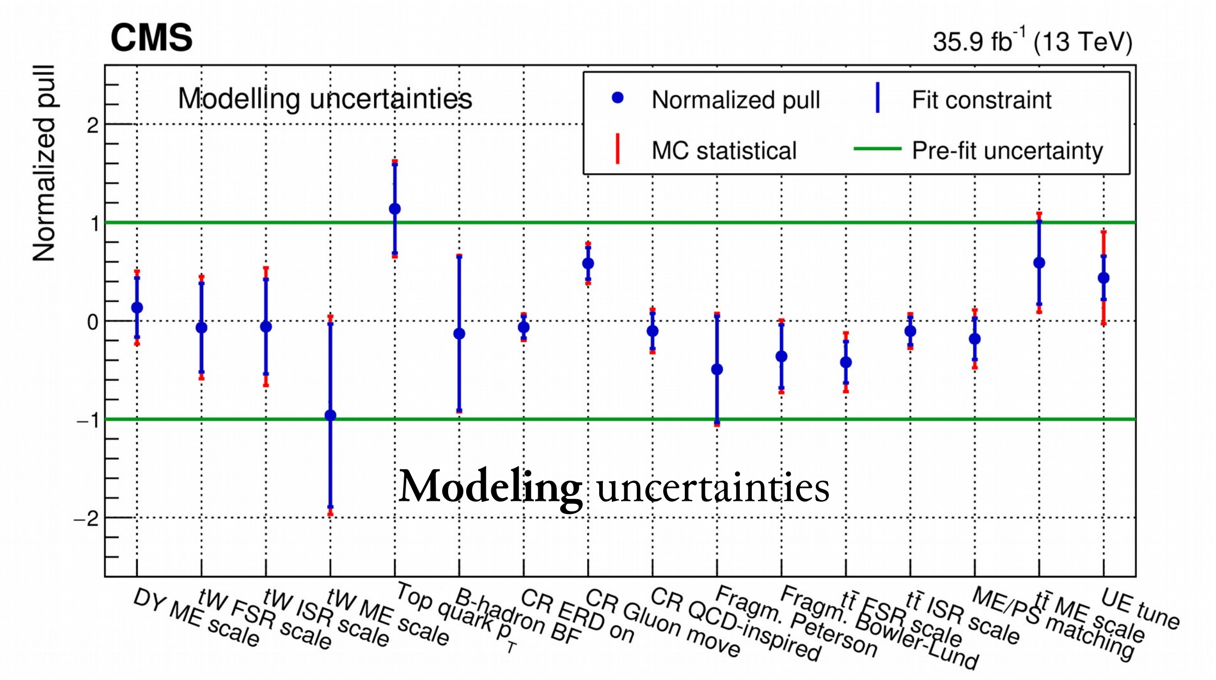




The latest CMS inclusive $t\bar{t}$ measurement with 35.9/fb

Eur. Phys. J. C 79 (2019) 368

- Fixed-M_t fit more precise (partly due to # of final states)
  - $t\bar{t}$ related unc. shows significant constraints
- Well in agreement with the varying-M_t fit



Modeling uncertainties

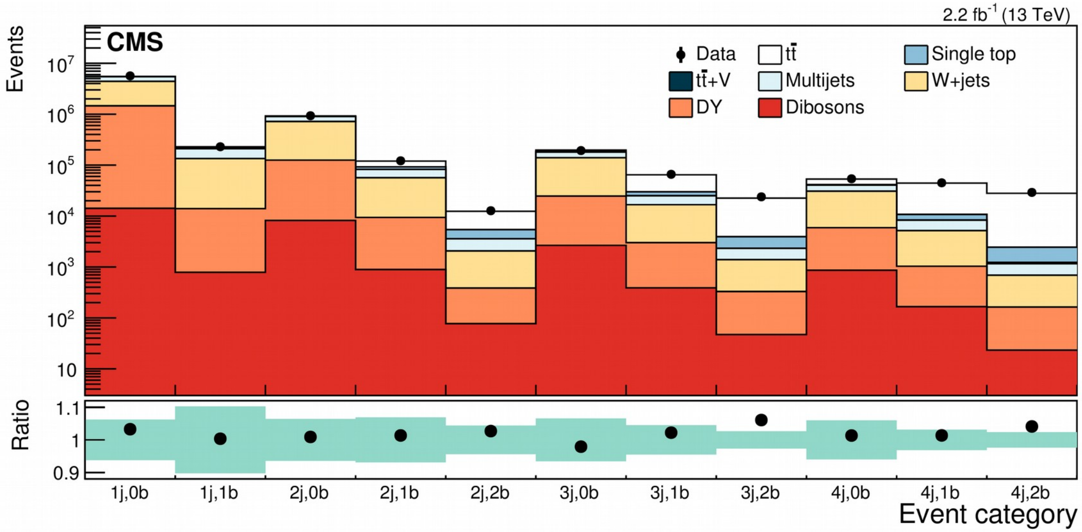
The most **dominant** ones

Source	Uncertainty [%]
Lep id/iso	2.0
PDF	1.1
tW bkgd	1.1
Lumi	2.5
MC stat	1.1
Total $\sigma_{t\bar{t}}^{vis}$	3.8
Extrapolation	⊕
PDF	$\pm^{0.8}_{0.6}$
Top quark p_T	$\mp^{0.5}_{<0.1}$
Total $\sigma_{t\bar{t}}$	4.0

Total (extrapolated) cross-section

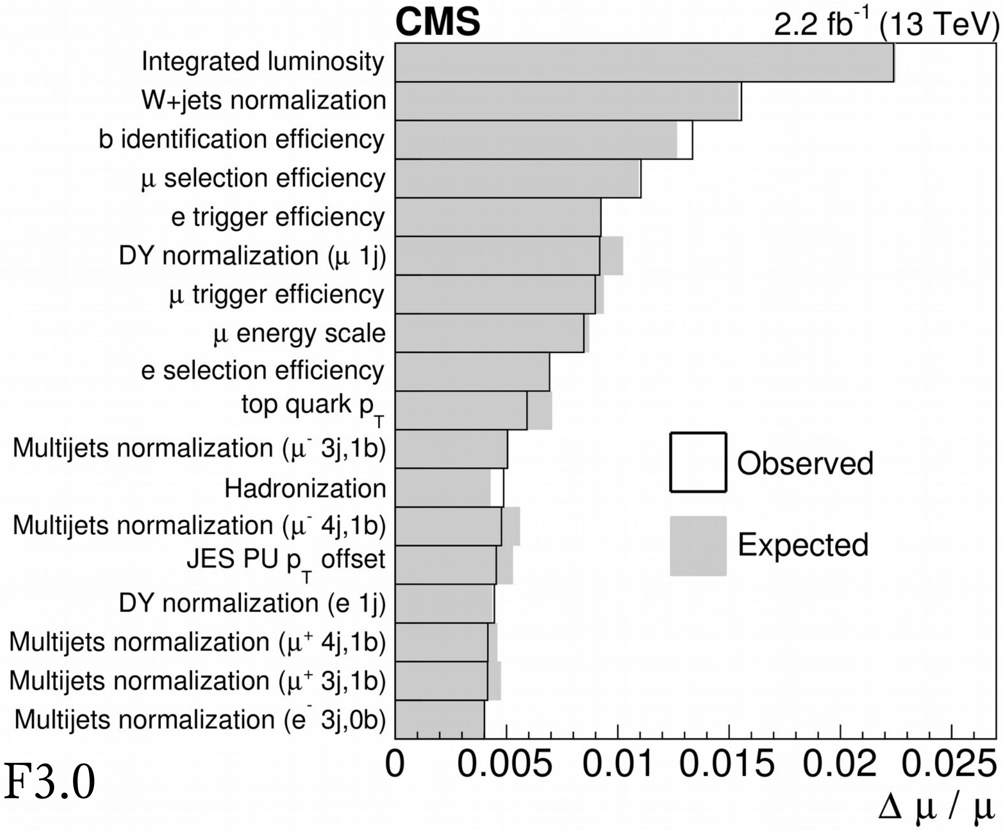
Fixed m_{top}: $\sigma_{t\bar{t}} = 803 \pm 2(\text{stat}) \pm 25(\text{syst}) \pm 20(\mathit{lumi})$ pb. Tot unc: 4%

The semileptonic $t\bar{t}$ measurement at 13 TeV



- Events split in 11×4 orthogonal categories
  - 2 from lepton flavor and 2 from charge
- M(lepton,b) distribution used
  - Discriminate $t\bar{t}$ against bkg.
- Dominated by exp. syst. uncertainty (3.6⊕1.6)%
  - Integrated luminosity
  - W+jets normalization & b tagging

JHEP 09 (2017) 051



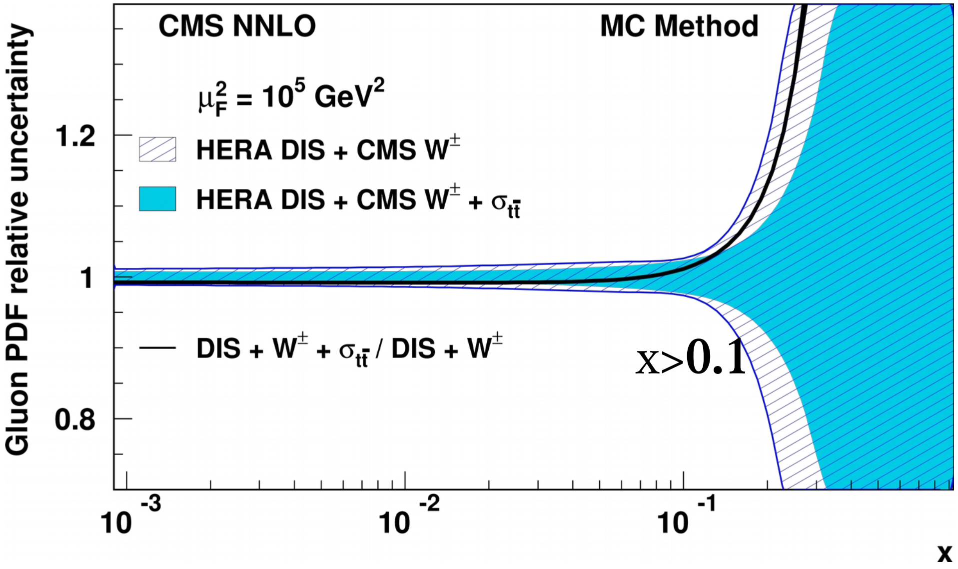
- Used to extract M_t at NNLO
  - In agreement with Run 1 combination
  - CT14 (no $t\bar{t}$ data) compatible with NNPDF3.0

Constraining SM parameters and proton PDFs

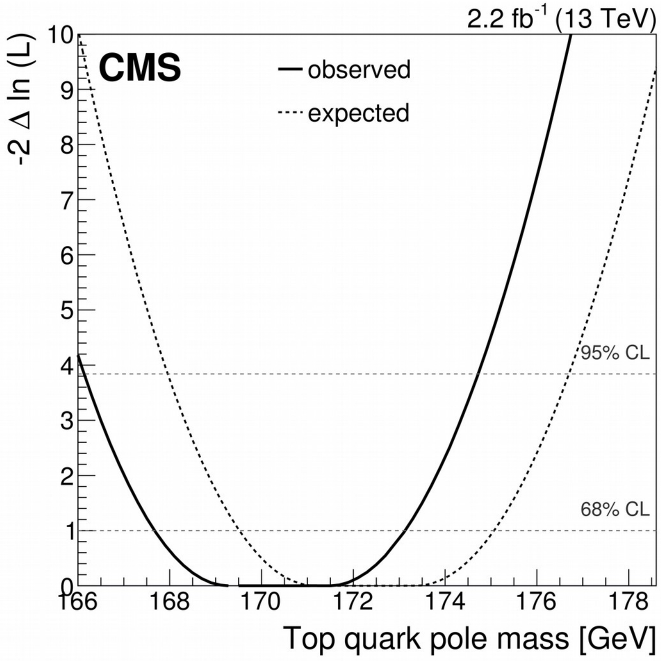
- The inclusive $t\bar{t}$ cross section depends on
  - M_t, α_s, and gluon PDF
- Proton PDF constrained from $d^n\sigma_{t\bar{t}}/d^nX_i$, n≥1
  - Mainly gluon but potentially also valence PDFs
  - Consistency checks from inclusive $\sigma_{t\bar{t}}$
- α_s is known with <1% precision
  - What about accuracy?

- Can we claim that M_t is unambiguously defined?
  - avoid interpretation problems of M_t in MC generation?
  - can be determined in a well defined theoretical scheme?
  - consistency test of SM?

JHEP 03 (2018) 115



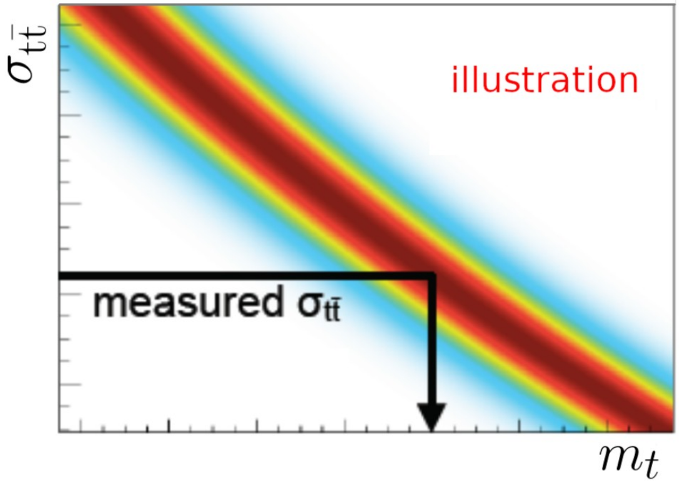
JHEP 09 (2017) 051



Use measured $\sigma_{t\bar{t}}$ to extract M_t

- Simultaneous fit of $\sigma_{t\bar{t}}$ and M_t from the MC generation
  - The two fit parameters are almost independent (12% corr.)
  - Input and best-fit values of M_t in agreement
- The best-fit $\sigma_{t\bar{t}}$ is then used to determine a QFT M_t
  - In running scheme, fixing α_s at input values from PDFs
    - The most precise direct determination of $M_t(M_t)$ to date
  - In the pole scheme with NNLO+NNLL accuracy
    - Convergence of the perturbative series impacts scale variations

PRL 116 (2016) 162001

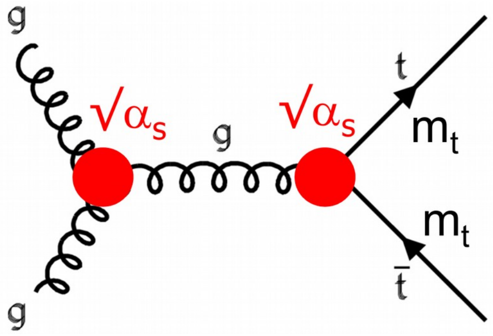


Eur. Phys. J. C 79 (2019) 368

PDF set	$m_t(m_t)$ [GeV]	m_t^{pole} [GeV]
ABMP16	$161.6 \pm 1.6\ (\text{fit} + \text{PDF} + \alpha_S)\ ^{+0.1}_{-1.0}\ (\text{scale})$	$169.9 \pm 1.8\ (\text{fit} + \text{PDF} + \alpha_S)\ ^{+0.8}_{-1.2}\ (\text{scale})$
NNPDF3.1	$164.5 \pm 1.6\ (\text{fit} + \text{PDF} + \alpha_S)\ ^{+0.1}_{-1.0}\ (\text{scale})$	$173.2 \pm 1.9\ (\text{fit} + \text{PDF} + \alpha_S)\ ^{+0.9}_{-1.3}\ (\text{scale})$
CT14	$165.0 \pm 1.8\ (\text{fit} + \text{PDF} + \alpha_S)\ ^{+0.1}_{-1.0}\ (\text{scale})$	$173.7 \pm 2.0\ (\text{fit} + \text{PDF} + \alpha_S)\ ^{+0.9}_{-1.4}\ (\text{scale})$
MMHT14	$164.9 \pm 1.8\ (\text{fit} + \text{PDF} + \alpha_S)\ ^{+0.1}_{-1.1}\ (\text{scale})$	$173.6 \pm 1.9\ (\text{fit} + \text{PDF} + \alpha_S)\ ^{+0.9}_{-1.4}\ (\text{scale})$

Use measured $\sigma_{t\bar{t}}$ to extract α_s and $M_t(M_t)$

- α_s and $M_t(M_t)$ calculated at PDF input $M_t(M_t)$ and α_s, respectively
  - The most precise α_s – at M_Z scale – from $\sigma_{t\bar{t}}$ to date
  - Comparable precision at any $M_t(M_t)$ within [160.5,165.0] GeV
    - similar uncertainty contributions from measured $\sigma_{t\bar{t}}$ and PDFs



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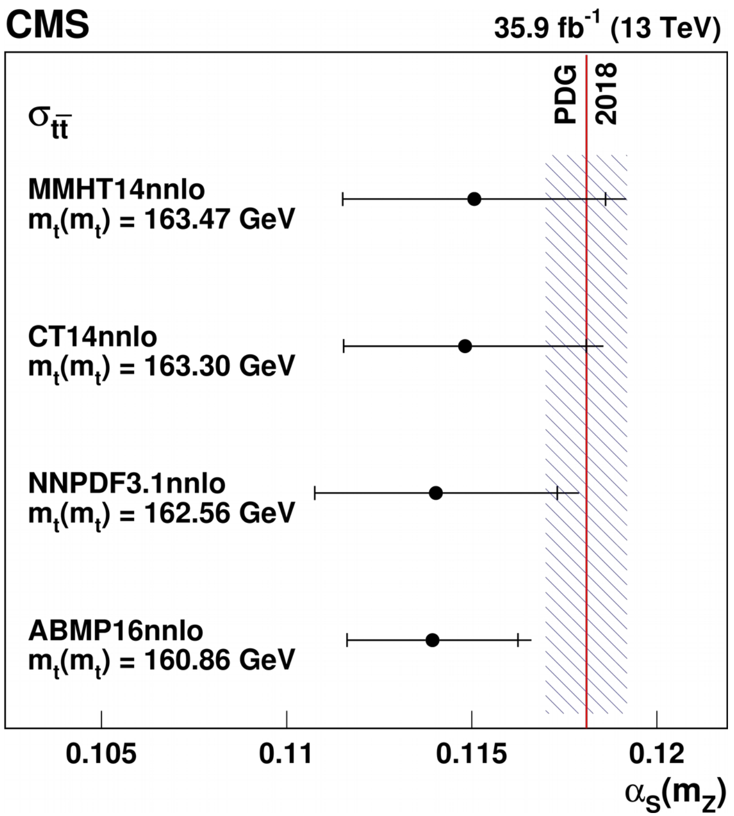
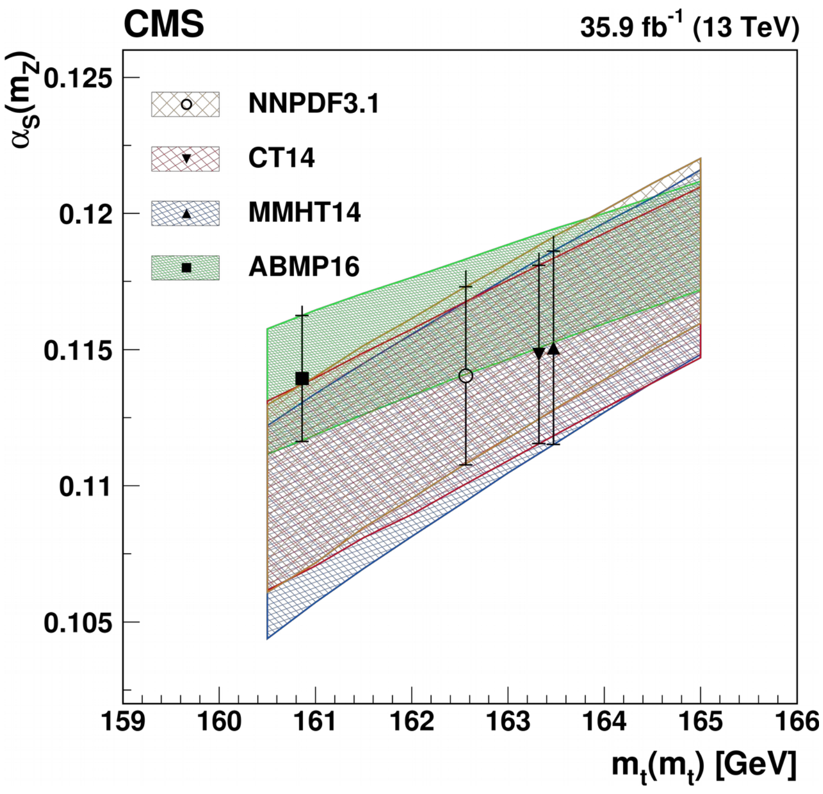
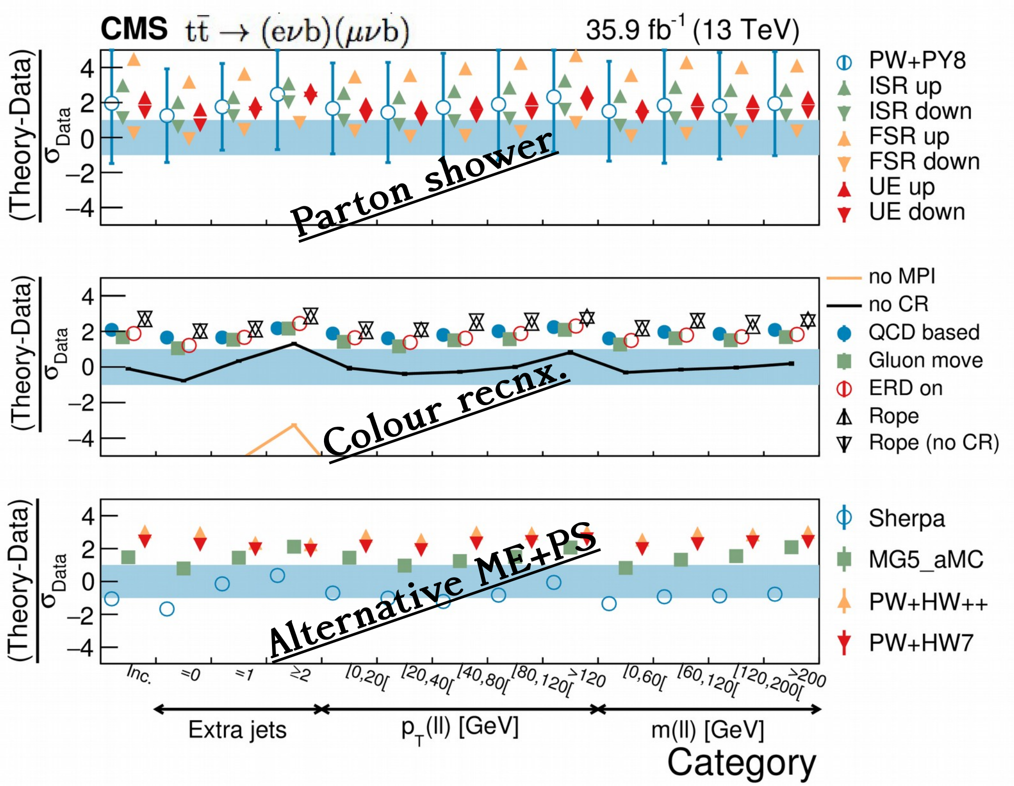


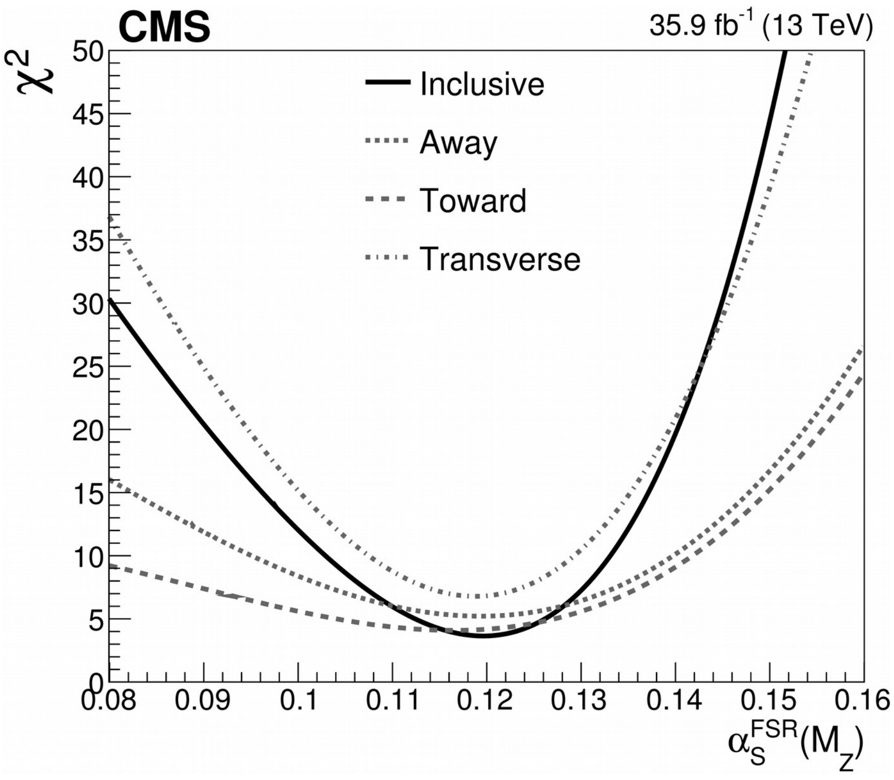


Can we *improve* the modeling of tops?

- Crucial to “monitor” soft QCD reminiscent effects in heavy quark hadroproduction
  - Tune in situ the default settings for event generation?
    - Dependence on hadronization models and UE seen in boosted regimes too, e.g., B2G-18-002
  - E.g., data disfavor default effective strong coupling for FSR in PYTHIA8 (Monash)
    - Similar trends seen for jet substructure observables in $\sigma_{t\bar{t}}$ events

Eur. Phys. J. C 79 (2019) 123





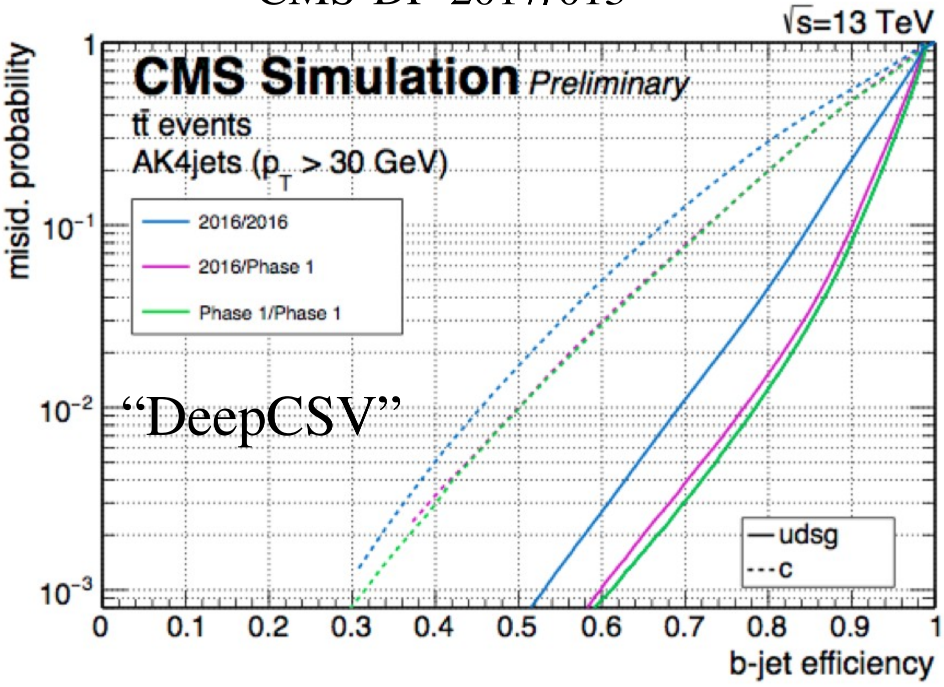
Nch ≡ particles **not** associated with the tt decay and the b tagged jets

Improvements in b tagging & QCD rejection

- Use of advanced MVAs allows for quicker and “wiser” processing of b tagging info
  - Combine a large number of input features
  - Handle low-level info
  - Detector upgrades boost performance, e.g., CMS Phase 1 pixel detector

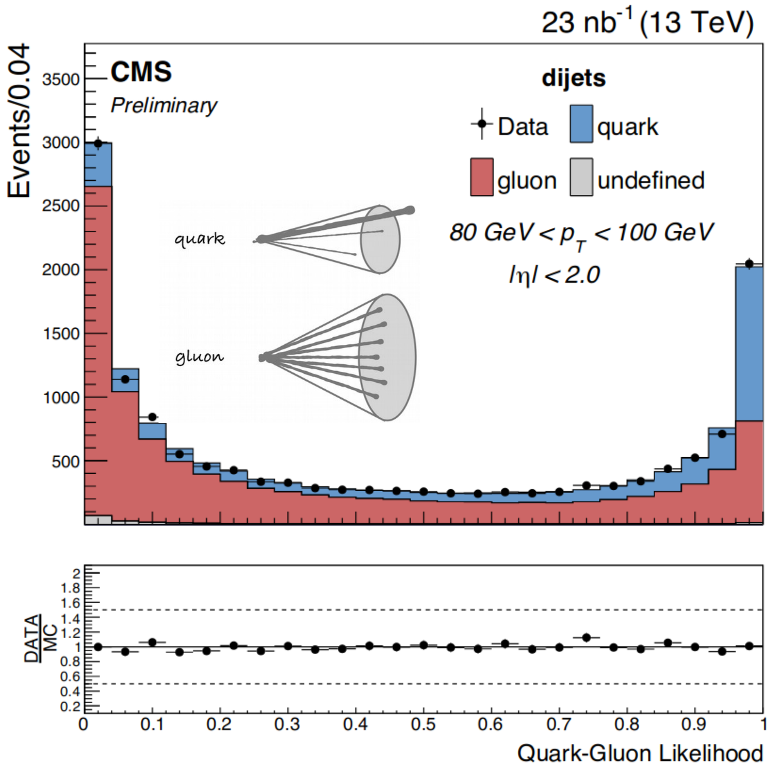
- Evolve discriminators capable of distinguishing quark- vs gluon-like jets
  - Beneficial, e.g., in $t\bar{t}$ +HF studies

CMS-DP-2017/013



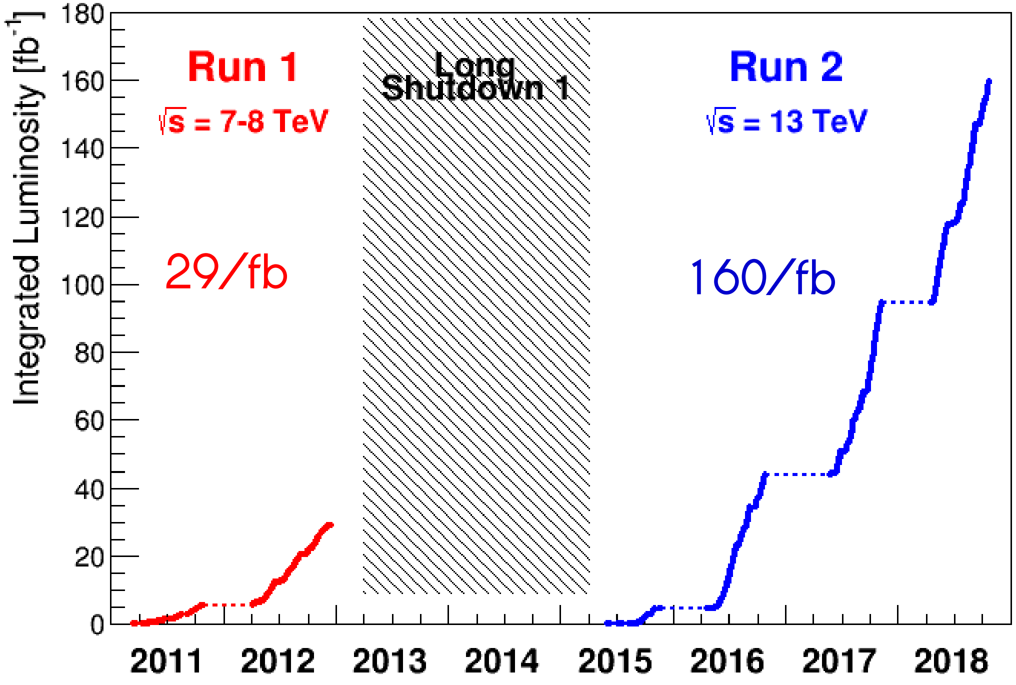
“DeepCSV”

CMS-DP-2016/070



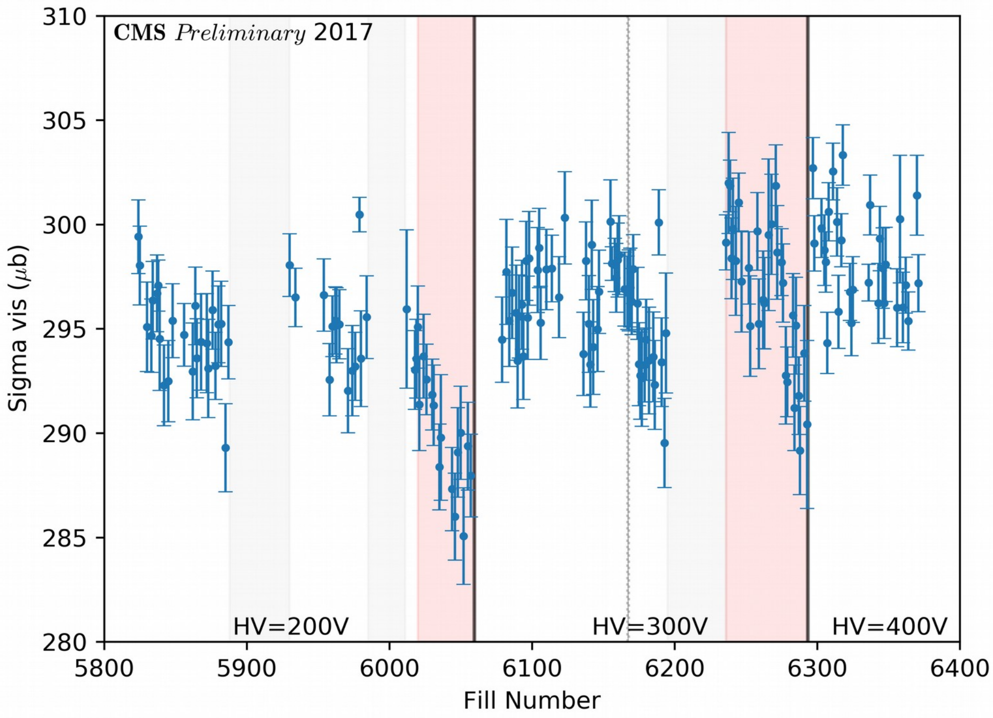
Luminosity: “a blessing and a curse”

- LHC comfortably surpassed the target of 150 /fb with Run 2 pp data at 13 TeV
  - This is a **collider** FOM for delivering statistically significant data samples
- The precise knowledge of the absolute luminosity scale is of equal importance
  - This is a **synergy** among LHC & experiments
  - We can – for the moment – measure it with O(2-4%), depending on the colliding species



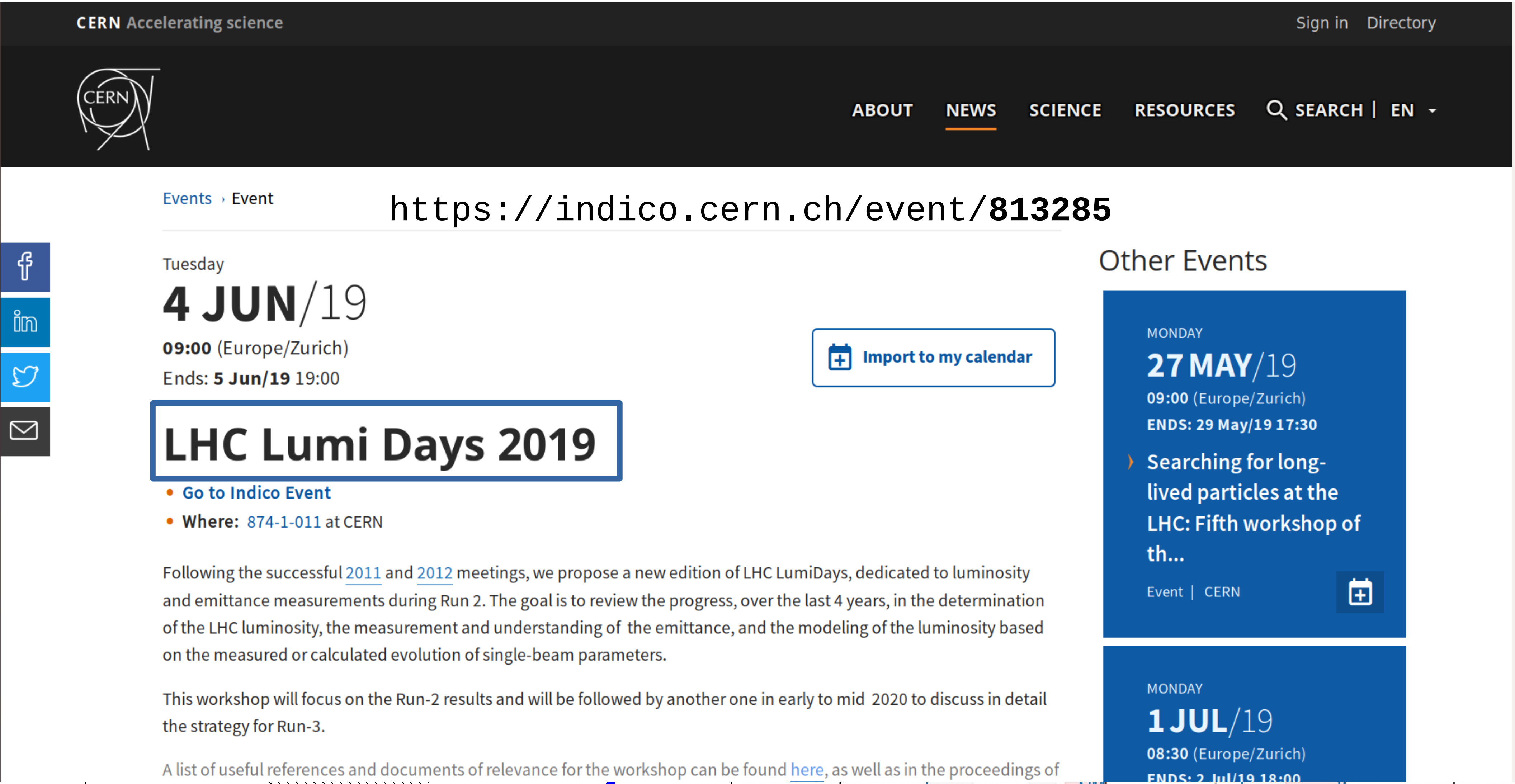
Plot from the LHC Coordination Info page

Mini-vdM scans during the whole year!



CMS-DP-2018/011

4-5th June: LHC-wide workshop dedicated to Lumi



`https://indico.cern.ch/event/`**`813285`**

Tuesday

4 JUN/19

09:00 (Europe/Zurich)

Ends: **5 Jun/19** 19:00

LHC Lumi Days 2019

- **Go to Indico Event**
- **Where:** 874-1-011 at CERN

Following the successful 2011 and 2012 meetings, we propose a new edition of LHC LumiDays, dedicated to luminosity and emittance measurements during Run 2. The goal is to review the progress, over the last 4 years, in the determination of the LHC luminosity, the measurement and understanding of the emittance, and the modeling of the luminosity based on the measured or calculated evolution of single-beam parameters.

This workshop will focus on the Run-2 results and will be followed by another one in early to mid 2020 to discuss in detail the strategy for Run-3.

A list of useful references and documents of relevance for the workshop can be found here, as well as in the proceedings of

Other Events

MONDAY

27 MAY/19

09:00 (Europe/Zurich)

ENDS: 29 May/19 17:30

Searching for long-lived particles at the LHC: Fifth workshop of th...

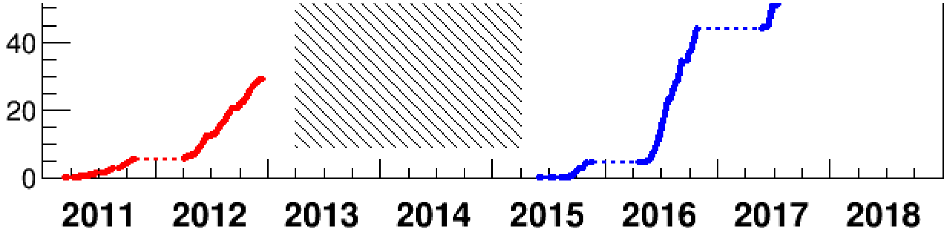
Event | CERN

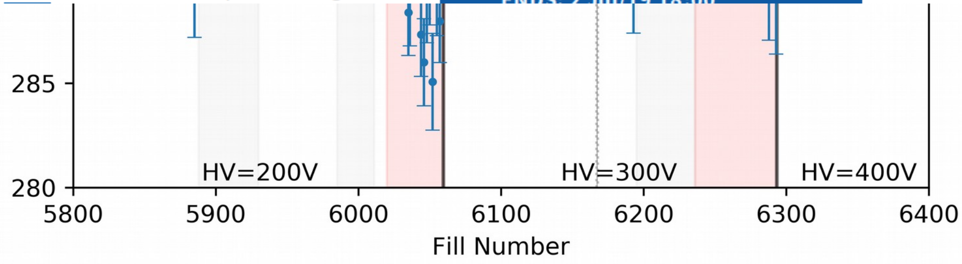
MONDAY

1 JUL/19

08:30 (Europe/Zurich)

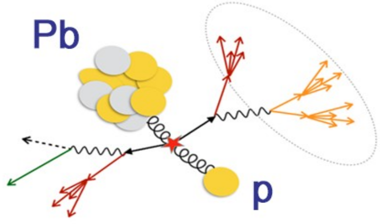
ENDS: 2 Jul/19 18:00

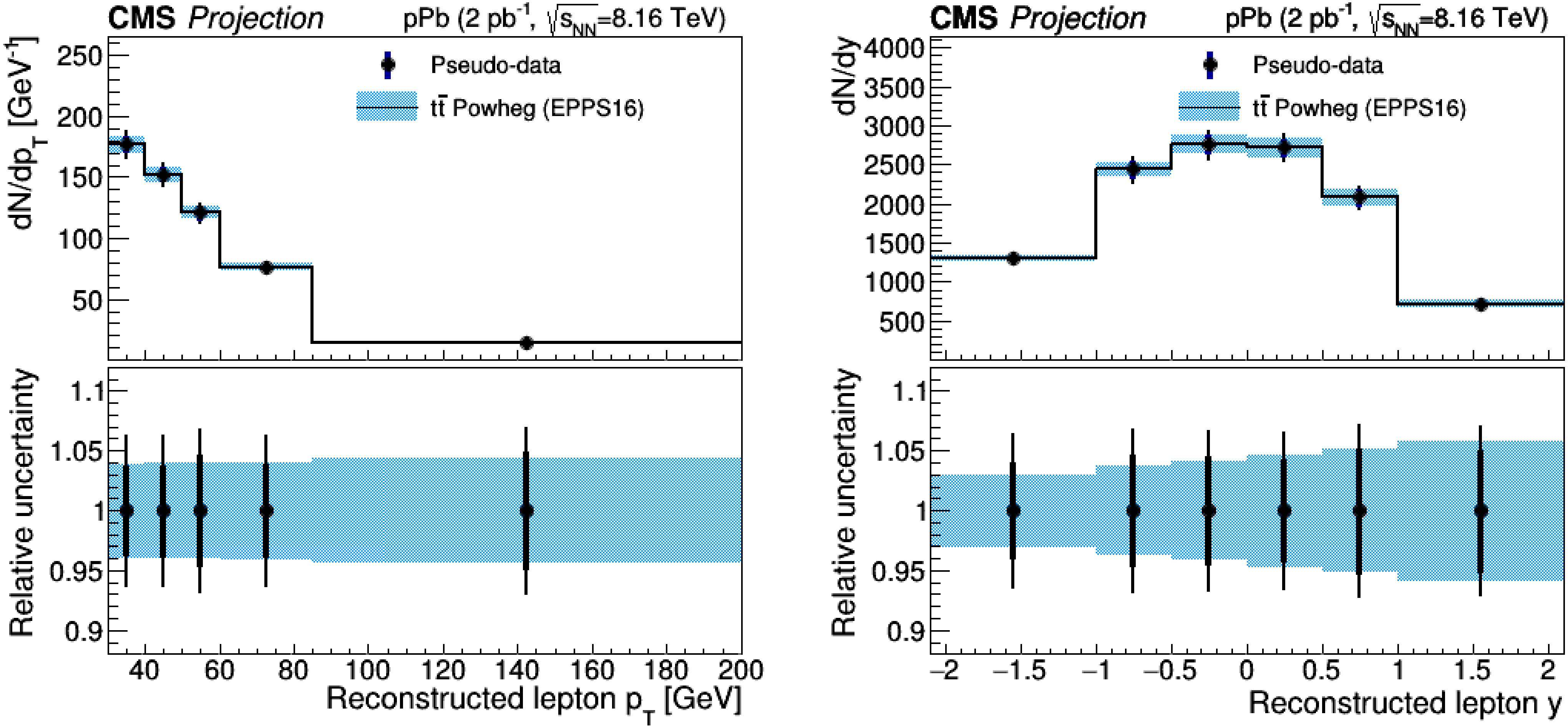




Future physics opportunities for high-density QCD

- Runs 3+4 and High-Luminosity LHC era: ×10 of proton-lead collisions
  - To substantially reduce the uncertainty in the $\sigma_{t\bar{t}}$ measurement
  - Even $d\sigma_{t\bar{t}}/dX$ possible → constraining nuclear gluon PDF





CMS-PAS-**FTR**-18-027
(High-Luminosity LHC Yellow Report)

“I like the dreams of the future better than the history of the past”

- LHC is undoubtedly a top quark factory
  - Allowed for $t\bar{t}$ observation even in “exotic” systems, e.g., proton-lead collisions
  - Factories could make defective products – “With Great Power Comes Great Responsibility”

- Level of precision already reached (~4%) for measuring $\sigma_{t\bar{t}}$ at 13 TeV is **impressive**
  - Special care for not quoting artificial constraints
    - e.g., nuisance parameter fits with treatment of statistical limitation of templates
  - Going below not easy – **multitask process** with main ones identified, e.g., luminosity calibration

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- A rich and thorough program for interpreting the results
  - Both in terms of SM parameters and BSM physics
  - $\sigma_{t\bar{t}}$ **complemented** with a varietety of measurements, e.g., differential studies

- Top modeling has a direct impact on $\sigma_{t\bar{t}}$ and extracting top quark properties, in general
  - crucial to understand **soft physics** even in something high-Q^2 scale like $t\bar{t}$

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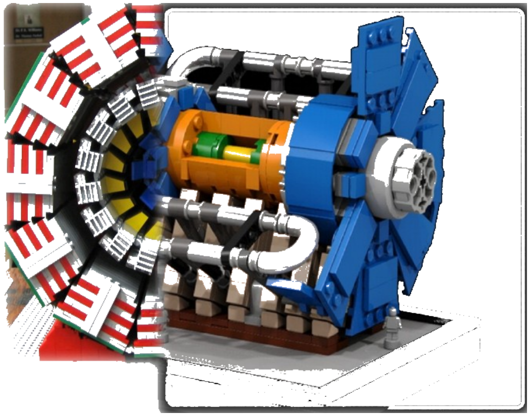
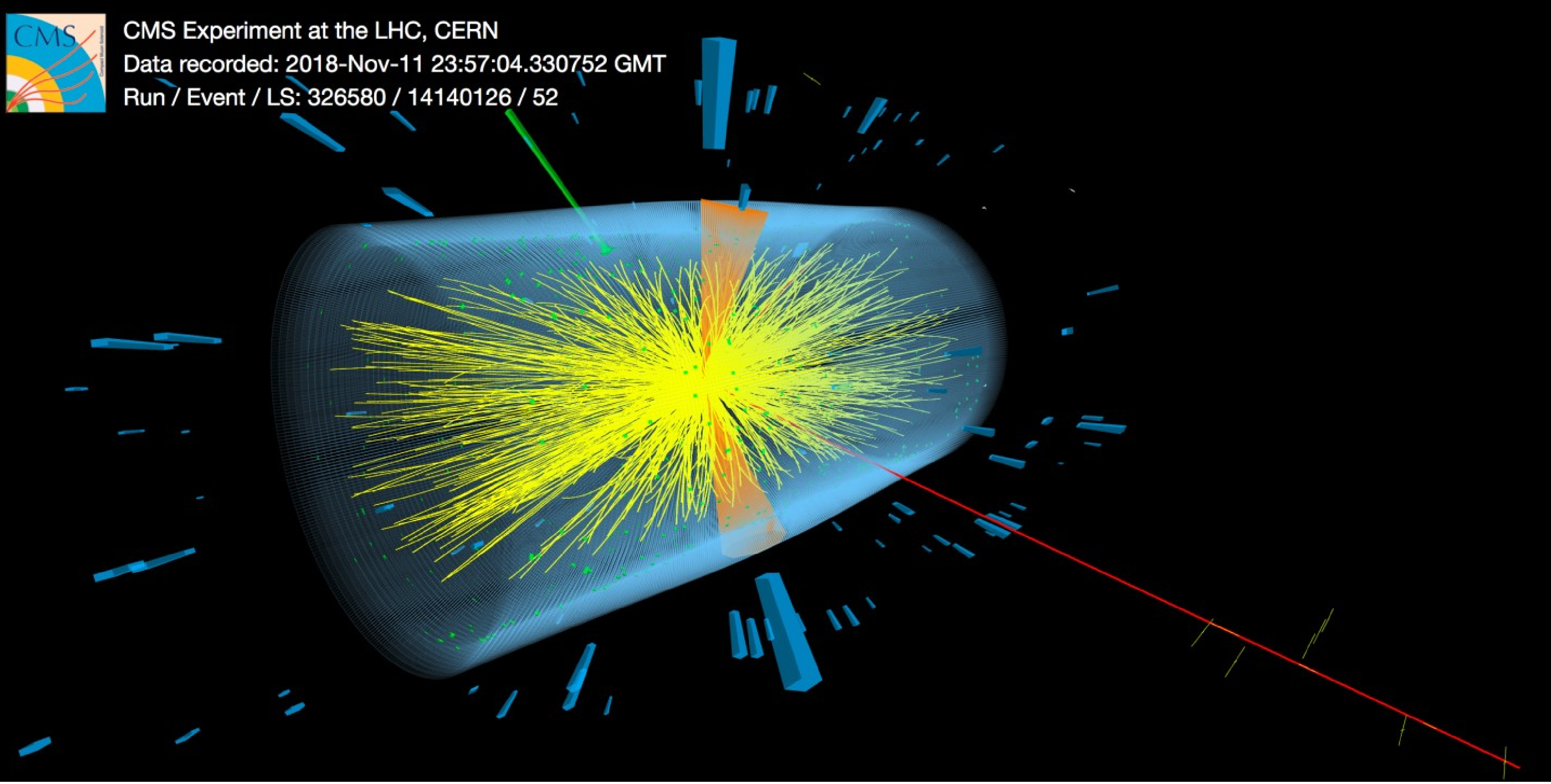
  - crucial to understand soft physics even in something high-Q^2 scale like $t\bar{t}$

- On our way to **precision tests** in the top quark sector
  - Pivotal steps already performed combining ATLAS+CMS
  - Tools independently developed to combine input measurements
  - Share efforts in bottleneck areas, e.g., MC sample production




CMS Experiment at the LHC, CERN
Data recorded: 2018-Nov-11 23:57:04.330752 GMT
Run / Event / LS: 326580 / 14140126 / 52

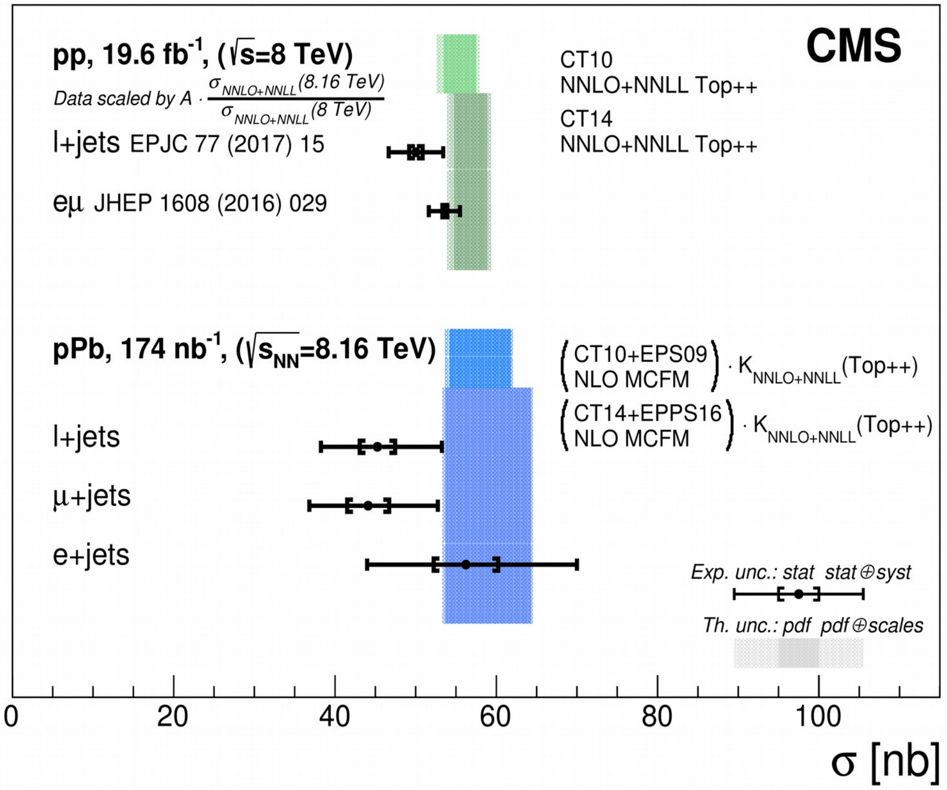
Questions?

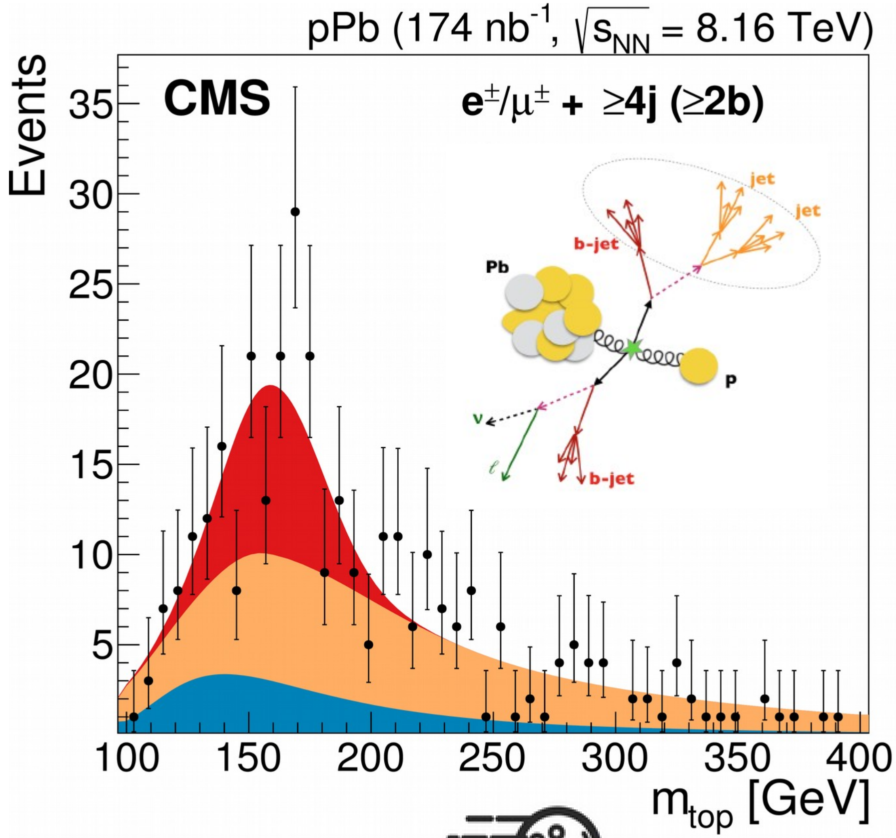
S slides

HIN & TOP & LUM synergy paid off

- Succeeded to give a nice deliverable to the community **once more** after pp 5.02 TeV
  - First study of top quark in nuclear collisions
    - using **two channels** that enhance credibility
    - the measurement paves the way for **dedicated** future studies, and
    - contributes to the **longevity** of nuclear collision program @ LHC and post-LHC

PRL **119** (2017) 242001





Common object selection - CMS

Single lepton and dilepton triggers

- $p_T(e) > 27$ GeV or $p_T(\mu) > 24$ GeV
- ee: $p_T(e) > 23(12)$ GeV, $\mu\mu$: $p_T(\mu) > 17(8)$ GeV
- $e\mu$: $p_T(e) > 23$, $p_T(\mu) > 8$ GeV or $p_T(\mu) > 23$, $p_T(e) > 12$ GeV

Particle-flow (PF) algorithm

- Combine information from various detectors
- Identify each individual particle
- Leading (subleading) leptons: $p_T > 25(20)$ GeV, $|\eta| < 2.4$
- Reject e in $1.44 < |\eta| < 1.57$
- Relative Isolation $\sum_{\Delta R=0.3(0.4)}^{PF} p_T / p_T^{e(\mu)} < 6(15)\%$
- Reject $m_{\ell\bar{\ell}} < 20$ GeV, $76 < m_{\ell\bar{\ell}} < 106$ GeV

Jets and b-tagging

- anti-k$_t$ clustering $\Delta R = 0.4$ radius
- Calibrated (p_T,η), in situ correction, pileup offset
- $p_T > 30$ GeV, $|\eta| < 2.4$
- Hadronised b-quarks identified w/ secondary vertex algorithms

S. Grancagnolo,
DIS19

Typical event generation setup in CMS

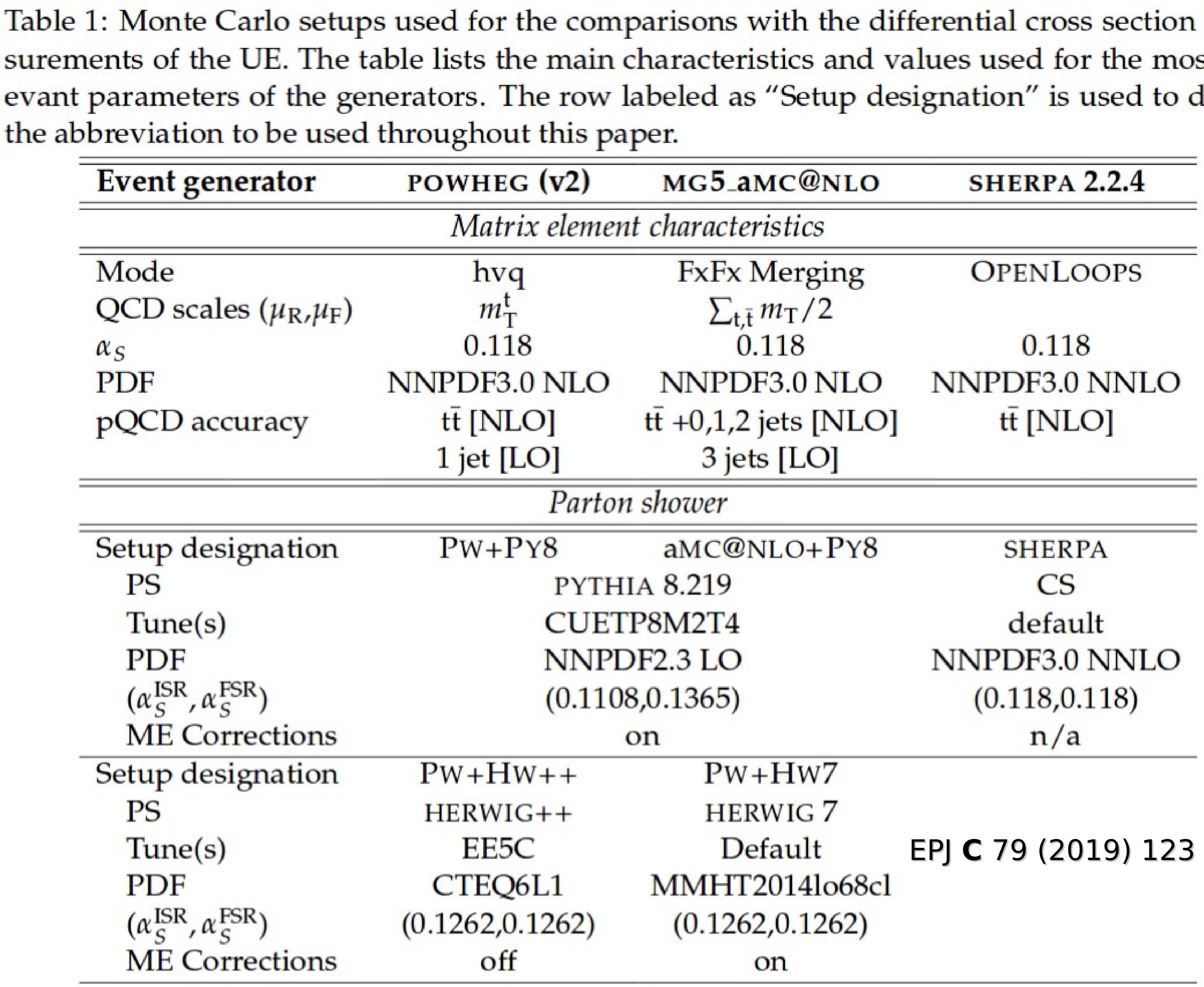


Table 1: Monte Carlo setups used for the comparisons with the differential cross section measurements of the UE. The table lists the main characteristics and values used for the most relevant parameters of the generators. The row labeled as “Setup designation” is used to define the abbreviation to be used throughout this paper.

Event generator	**POWHEG (v2)**	**MG5_aMC@NLO**	**SHERPA 2.2.4**
		Matrix element characteristics	
Mode	hvq	FxFx Merging	OPENLOOPS
QCD scales (μ_R,μ_F)	m_T^t	$\sum_{t,\bar{t}} m_T/2$	
α_S	0.118	0.118	0.118
PDF	NNPDF3.0 NLO	NNPDF3.0 NLO	NNPDF3.0 NNLO
pQCD accuracy	$t\bar{t}$ [NLO] 1 jet [LO]	$t\bar{t}$ +0,1,2 jets [NLO] 3 jets [LO]	$t\bar{t}$ [NLO]
		Parton shower	
Setup designation	PW+PY8	aMC@NLO+PY8	SHERPA
PS	PYTHIA 8.219		CS
Tune(s)	CUETP8M2T4		default
PDF	NNPDF2.3 LO		NNPDF3.0 NNLO
(α_S^{ISR}, α_S^{FSR})	(0.1108,0.1365)		(0.118,0.118)
ME Corrections	on		n/a
Setup designation	PW+HW++	PW+HW7	
PS	HERWIG++	HERWIG 7	
Tune(s)	EE5C	Default	
PDF	CTEQ6L1	MMHT2014lo68cl	
(α_S^{ISR}, α_S^{FSR})	(0.1262,0.1262)	(0.1262,0.1262)	
ME Corrections	off	on	

EPJ **C** 79 (2019) 123

Factorized PS/Hadronization uncertainties in CMS

Source	Handle	Weights	Variation	Note/Reference	Dedicated studies
Shower scales	ISR scale (SpaceShower:renormMultFac) FSR scale (TimeShower:renormMultFac)	~~No~~ *YES* ~~No~~	0.5-2.0 0.5-2.0	FSR variations can be scaled down by √2 from LEP	TOP-15-011, TOP-16-021, TOP-17-13, TOP-17-015, …
ME-PS Matching	hdamp	No	hdamp=$1.58m_t$ $+0.66-0.59\ m_t$	see TOP-16-021	Starting scale variations for MG5_aMC@NLO still to be studied
Soft QCD	UE parameters	No	*CP5 (2017)* CUETP8M2T4(2016) up/down	See TOP-16-021 MPI & CR strength doesn't affect resonance decays	TOP-17-015
Color reconnection (odd clusters)	MPI based, QCD-inspired, gluon move	No	different models	CR affecting resonance decays	TOP-17-13, TOP-17-015
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

Other planned Run 1 legacy publications

- Combination analyses in progress:
  - **Single top channels (t, tW and s) + V_{tb}**

    arXiv:1902.07158
    - To include 7 and 8 TeV combinations per channel
    - V_{tb} from ratio of measured and prediction cross sections
    - Paper in collaboration internal reviews
  - **Inclusive top pair cross sections at 7 and 8 TeV**
    - To include 7 and 8 TeV cross-sections and their ratio
    - Also considering extraction of α_s and top pole mass
    - Paper in preparation
- Other combinations
  - **Top mass:** preparatory discussions and studies ongoing
  - **Differential ttbar** distributions (started with comparisons)
    - 8 TeV at parton level
    - 13 TeV at particle level
  - **W helicity** and/or constraints on anomalous couplings and EFTs

A non-exhaustive list of top quark-antiquark properties

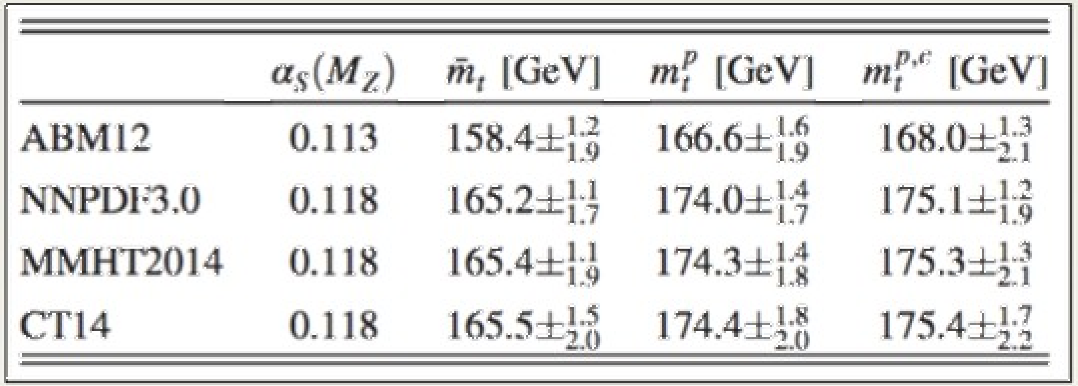
	Property	Result (most precise or most recent)	Uncertainty	Journal Link (or Preprint)/ Conf. note
"Intrinsic"	Charge	0.64 e	0.02 (stat) ± 0.08 (syst) e	**JHEP 11 (2013) 031**
	Mass (kinematic extraction)	172.44 GeV	0.13 (stat) ± 0.47 (syst) GeV	**PRD 93 (2016) 072004**
	Mass difference	-0.15 GeV	0.19 (stat) ± 0.09 (syst) GeV	**PLB 770 (2017) 50**
	Width (direct method)	1.76 GeV	0.33 (stat) $^{+0.79}_{-0.68}$ (syst) GeV	**EPJ C 78 (2018) 129**
	Width (indirect method)	1.36 GeV	0.02 (stat) $^{+0.14}_{-0.11}$ (syst) GeV	**PLB 736 (2014) 33**
	Spin (polarization)	Not uniquely defined variables		**JHEP 03 (2017) 113** **PRD 93 (2016) 052007**
"Production"	Spin (correlation fraction)	1.20	0.05 (stat) ± 0.13 (syst)	**PRL 114 (2015)142001**
	Rapidity cut-independent charge asymmetry	0.0055	0.0023 (stat) ± 0.0025 (syst)	**1709.05327**
	Colour flow Underlying event	No "one-fits-all" prediction		**EPJ C 78 (2018) 847** **EPJ C 79 (2019) 123**
	Gauge and Yukawa couplings	Wilson $\tilde{c}$ compatible with 0 μ_t strength: 1.18	+0.31-0.27 (tot)	**JHEP 04 (2018) 033** **1809.10733**
"Decay"	W boson helicity fractions	F_0 = 0.709 F_L = 0.299 F_R = -0.008	0.012 (stat) +0.015-0.014 (syst) 0.008 (stat) +0.013-0.012 (syst) 0.006 (stat) ± 0.012 (syst)	**EPJ C 77 (2017) 264**

- We know some properties well, but several key properties remain poorly understood
    - modeling uncertainties typically dominant or important source

Mitigate dependence on MC mass & improve interpretation !

Well-defined m_t:

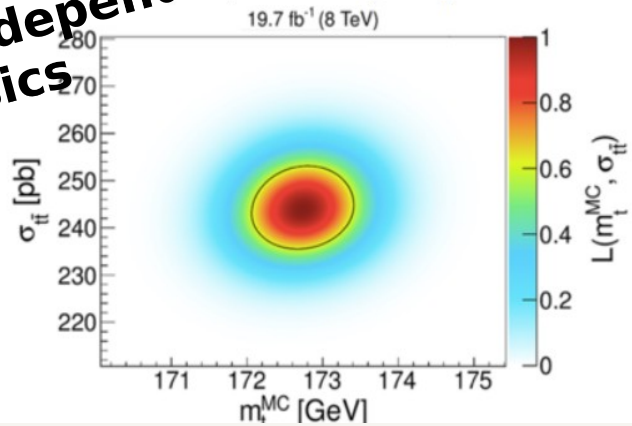
- Without assuming any relation to m_t(MC)
- Higher precision than accounting for slope (CMS/ATLAS/Tevatron)
- Consistently lower for ABM
- About 1 GeV difference between directly measured and converted pole mass
  → sizeable corrections beyond NNLO



	$\alpha_S(M_Z)$	$\bar{m}_t$ [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

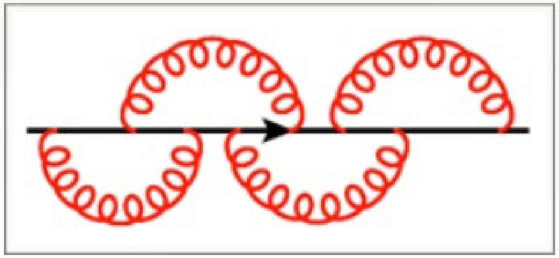
Absorb MC mass dependence → Improved physics interpretation



J. Kieseler

- 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

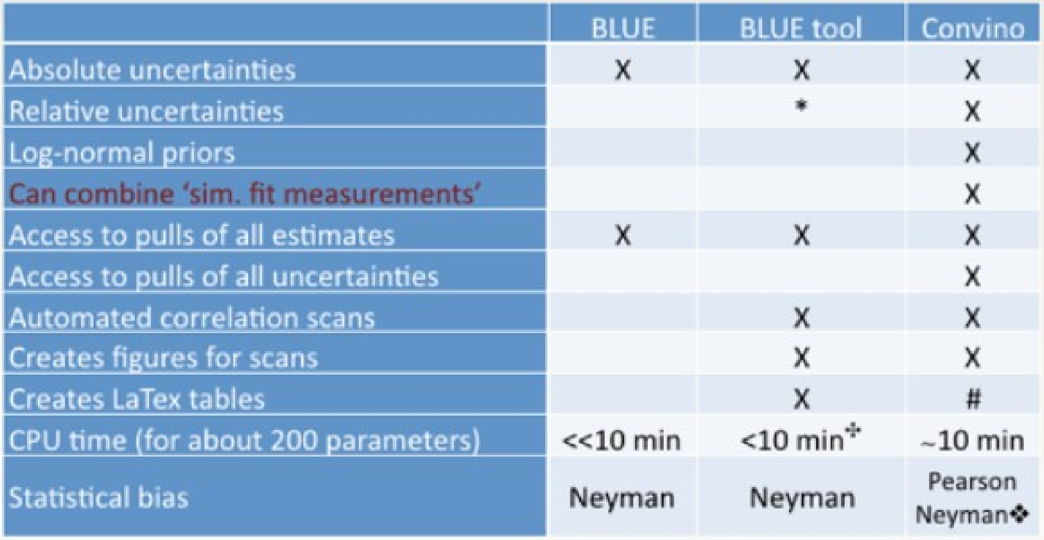


$$m_t^{\text{pole}}(k) = m_t^{\overline{\text{MS}}}(\mu)\left[1 + \sum_{n=1}^{k} c_n \left(\frac{\mu}{m_t^{\overline{\text{MS}}}(\mu)}\right) \alpha_S^n(\mu)\right]$$

Summary/Outlook

New program for combination of (differential) quantities

- Maximum-likelihood approach
- Accounts for correlations between uncertainties within and in-between measurements



	BLUE	BLUE tool	Convino
Absolute uncertainties	X	X	X
Relative uncertainties		*	X
Log-normal priors			X
Can combine 'sim. fit measurements'			X
Access to pulls of all estimates	X	X	X
Access to pulls of all uncertainties			X
Automated correlation scans		X	X
Creates figures for scans		X	X
Creates LaTex tables		X	#
CPU time (for about 200 parameters)	<<10 min	<10 min✣	~10 min
Statistical bias	Neyman	Neyman	Pearson Neyman❖

- Models data-driven constraints
- Incorporates BLUE [1,2] functionality and adds possibilities

- Provides simple user interface (text-based or C++ classes directly interfaced to ROOT classes)
- Direct graphical representation of output

- Pre-compiled binaries on CERN lxplus:
  /afs/cern.ch/user/j/jkiesele/public/Convino
  /afs/cern.ch/user/j/jkiesele/public/Convino/docu/manual.pdf *

- Actively working on performance improvements and additions

Monte-Carlo Top Quark Mass Parameter

Why is there an non-trivial issue in the the interpretation of m_t^{MC} ?

- Picture of **“top quark particle”** does not apply (non-zero color charge!)
  - m_t is a scheme-dependent parameter of a perturbative computation

    → In which scheme do MC event generators calculate ?
  - **Hadronization effects** (affect all methods in a similar way, particularly important for direct method)
  - **Relation of m_t^{MC} to any field theory mass** definition can be affected by different contributions: (let’s consider pole mass just for convention)

$$m_t^{\mathrm{MC}} = m_t^{\mathrm{pole}} + \Delta_m^{\mathrm{pert}} + \Delta_m^{\mathrm{non-pert}} + \Delta_m^{\mathrm{MC}}$$

pQCD contribution:

- Perturbative correction
- Depends on MC parton shower setup

Non-perturbative contribution:

- Effects of hadronization model
- May depend on parton shower setup

Monte Carlo shift:

- Contribution arising from systematic MC uncertainties
- E.g. color reconnection, b-jet modeling, finite width, ...
- Should be covered by ‘MC uncertainty’ or better negligible

A. H. Hoang
TOP18

Monte-Carlo Top Quark Mass Parameter

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$$m_t^{\mathrm{MC}} = m_t^{\mathrm{pole}} + \Delta_m^{\mathrm{pert}} + \Delta_m^{\mathrm{non-pert}} + \Delta_m^{\mathrm{MC}}$$

  - There is general agreement that Δ_m^{pert} and , $\Delta_m^{\mathrm{non\text{-}pert}}$ can exist, but has been a controversy how important and relevant they are.

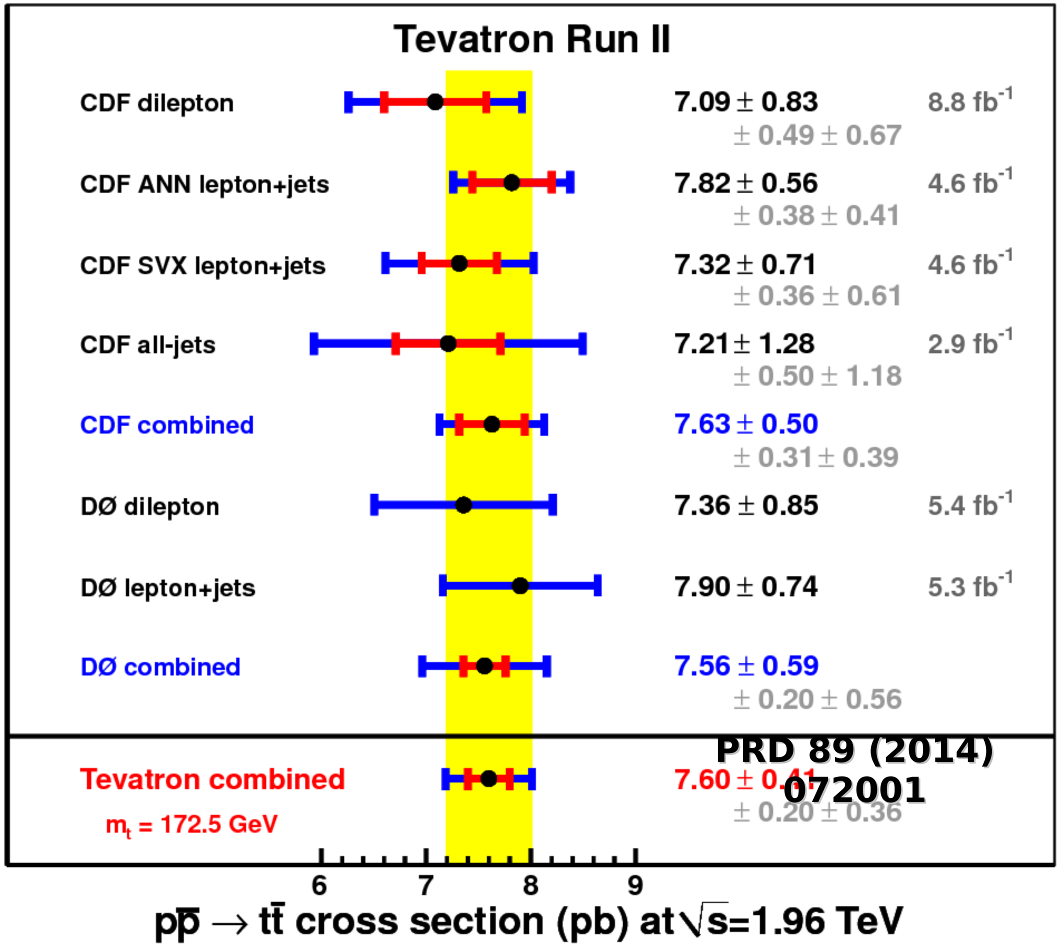
    Discussions have been qualitative over many years:

    View B: Δ_m's can be at the level of 0.5 GeV, $\Delta_m^{\mathrm{pert}} \sim Q_0\, \alpha_S(Q_0)$ [Q_0 = shower cut]

    AHH, Stewart, arXiv;:0808.0222; AHH. arXiv:1412.3649

    View C: Δ_m^{pert} likely negligible, $\Delta_m^{\mathrm{non\text{-}pert}} \sim \Delta_{\mathrm{QCD}}$ Nason, arXiv:1712.02796

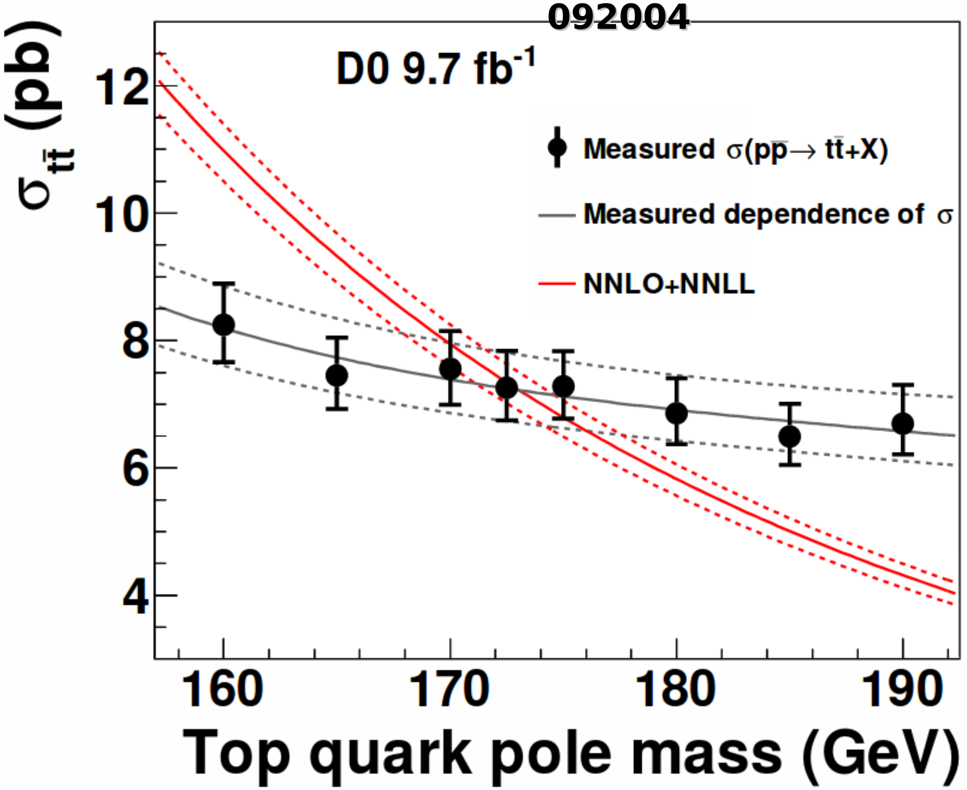
Updated measurement from D0 including 9.7fb-1



PRD 89 (2014) 072001

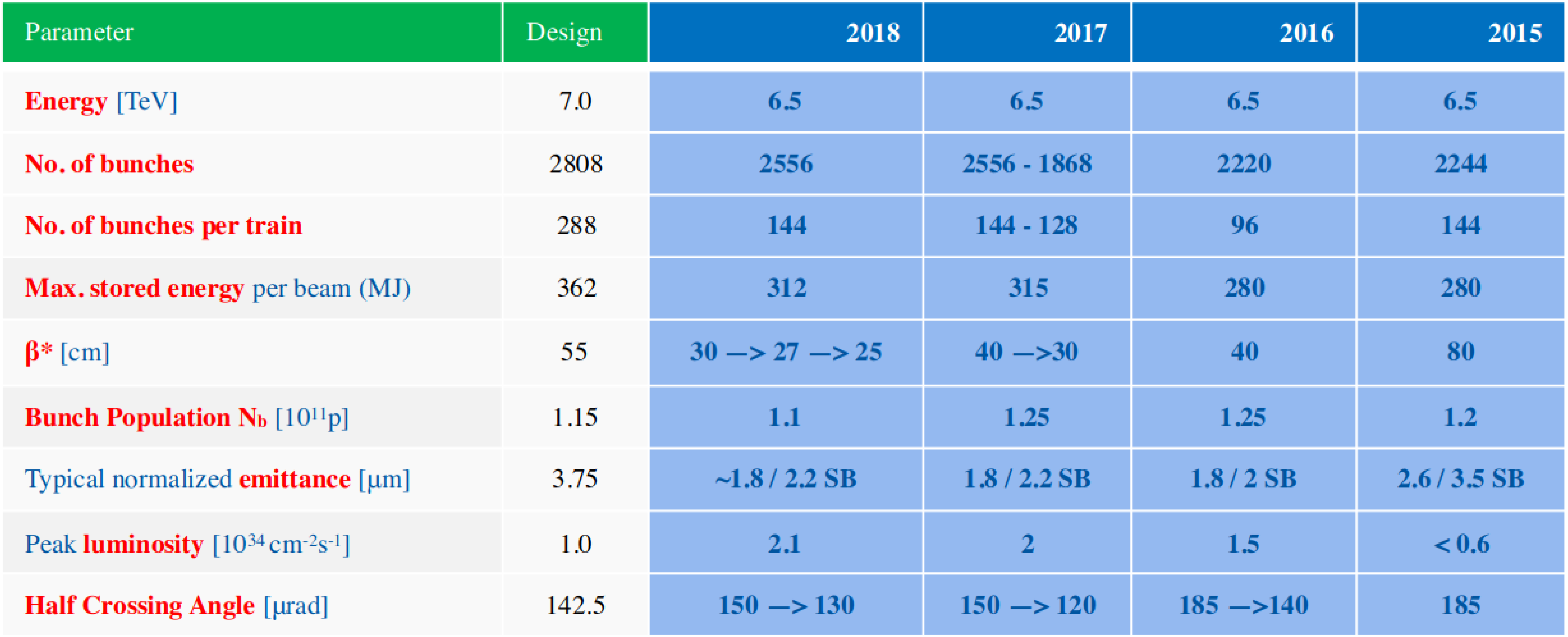
$$\sigma_{t\bar{t}} = 7.26 \pm 0.13(\text{stat})^{+0.57}_{-0.50}(\text{syst})\ \ \text{pb}$$

PRD 94 (2016) 092004



$$m_t = 172.8 \pm 1.1(\text{theo})^{+3.3}_{-3.1}(\text{exp})\ \ \text{GeV}$$

Summary Run 2



Parameter	Design	2018	2017	2016	2015
Energy [TeV]	7.0	6.5	6.5	6.5	6.5
No. of bunches	2808	2556	2556 - 1868	2220	2244
No. of bunches per train	288	144	144 - 128	96	144
Max. stored energy per beam (MJ)	362	312	315	280	280
β* [cm]	55	30 —> 27 —> 25	40 —>30	40	80
Bunch Population N_b [10^{11}p]	1.15	1.1	1.25	1.25	1.2
Typical normalized **emittance** [μm]	3.75	~1.8 / 2.2 SB	1.8 / 2.2 SB	1.8 / 2 SB	2.6 / 3.5 SB
Peak **luminosity** [10^{34} cm^{-2}s^{-1}]	1.0	2.1	2	1.5	< 0.6
Half Crossing Angle [μrad]	142.5	150 —> 130	150 —> 120	185 —>140	185

Excellent Run 2 despite the different events encountered along the way. Thanks to all the involved teams we always found a way to push to new limits.

160fb-1 for Run 2 and a rich physics program

B.Salvachua,
9th Evian workshop