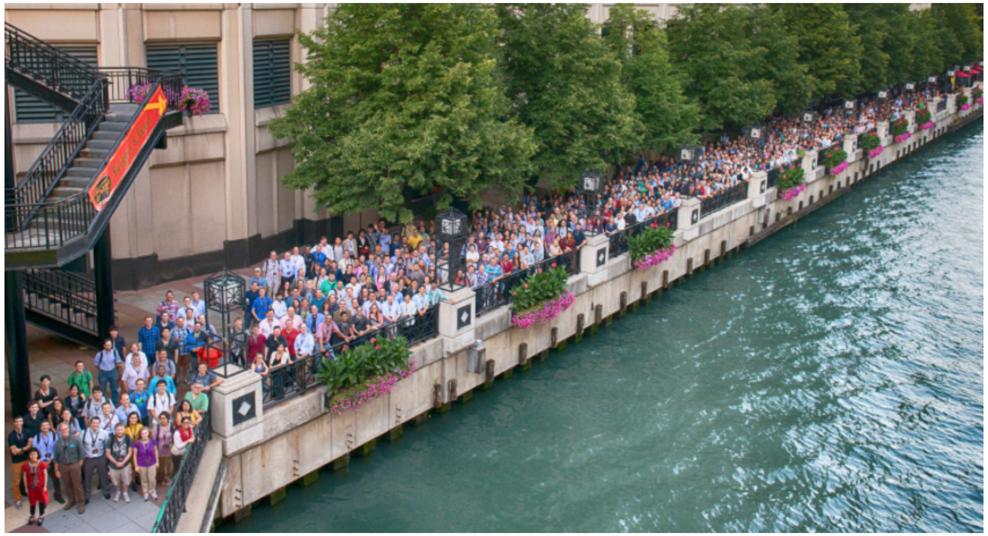
HIGHLIGHTS FROM ICHEP 2016 PART II:

JAMES KEAVENEY

LHC DISCUSSION, 05.09.2016

ICHEP 2016

- A snapshot of the field
  at a unique moment…
- Unprecedented media interest and public engagement



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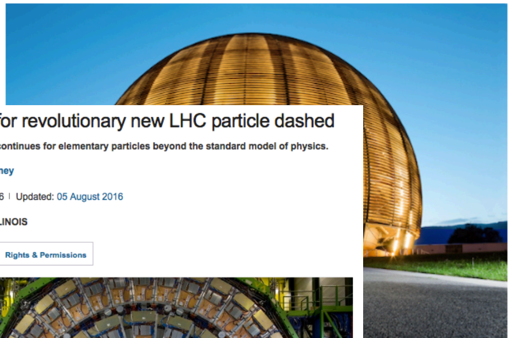
The End of the Beginning

Matthew Buckley

August 09, 2016



Hopes for revolutionary new LHC particle dashed

But the hunt continues for elementary particles beyond the standard model of physics.

Elizabeth Gibney

05 August 2016 | Updated: 05 August 2016

CHICAGO, ILLINOIS

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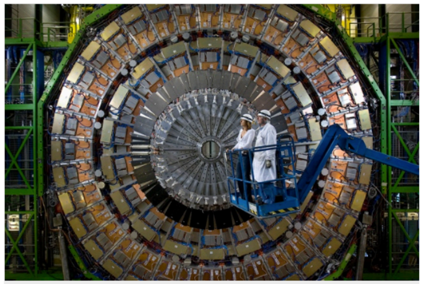


Stefano Dal Pozzolo/Contrasto/eyevine

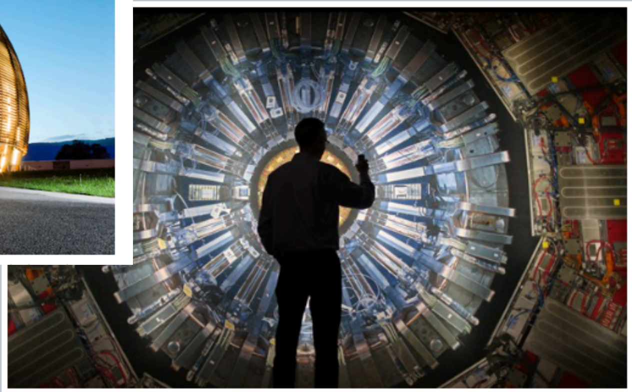
The CMS (pictured) was one of two experiments that saw a potential new particle late last year.

SCIENCE

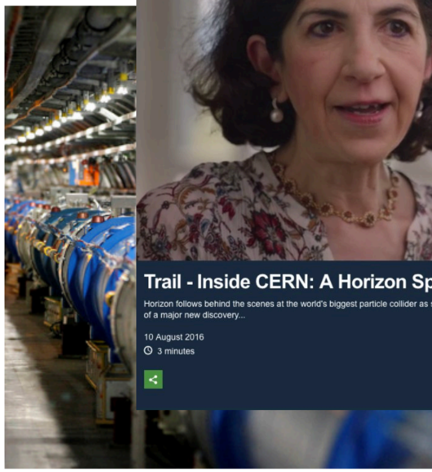
The Particle That Wasn't

By DENNIS OVERBYE AUG. 5, 2016

:ευση στο CERN - Δεν
)ηκε νέο σωματίδιο



Οι νέες σαμπάνιες δεν θα ανοίξουν ακόμη και τα νέα Νόμπελ θα πρέπει να περιμένουν, καθώς διαψεύσθηκαν οι προσδοκίες των φυσικών για την ανακάλυψη ενός νέου σωματιδίου στο Ευρωπαϊκό Κέντρο Πυρηνικών Ερευνών (CERN), τέσσερα χρόνια μετά την ανίχνευση του σωματιδίου Χιγκς.



erre Albouy/Reuters

Trail - Inside CERN: A Horizon Special

Horizon follows behind the scenes at the world's biggest particle collider as scientists think they are on the verge of a major new discovery...

10 August 2016

3 minutes

This clip is from

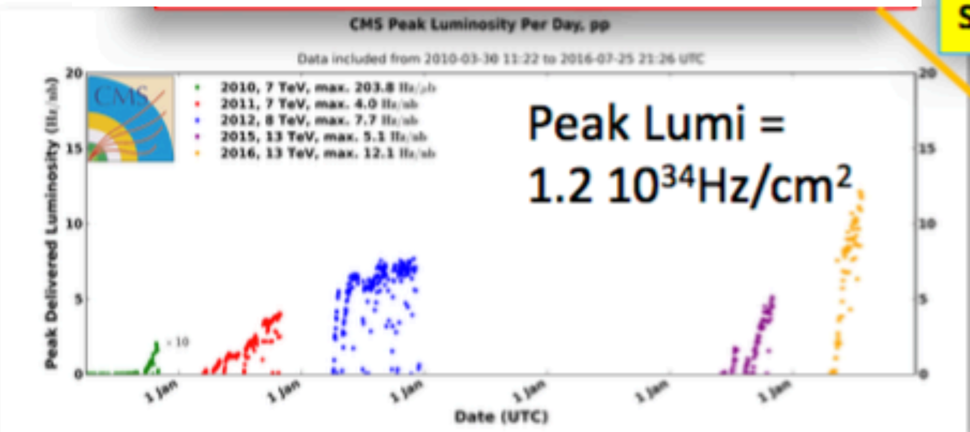
Horizon

2015-2016, Inside CERN

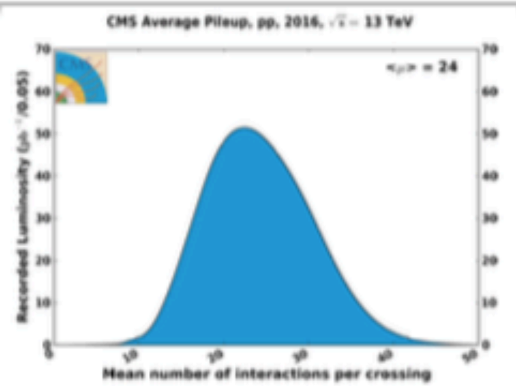
WHY? DATA, AND LOTS OF IT!

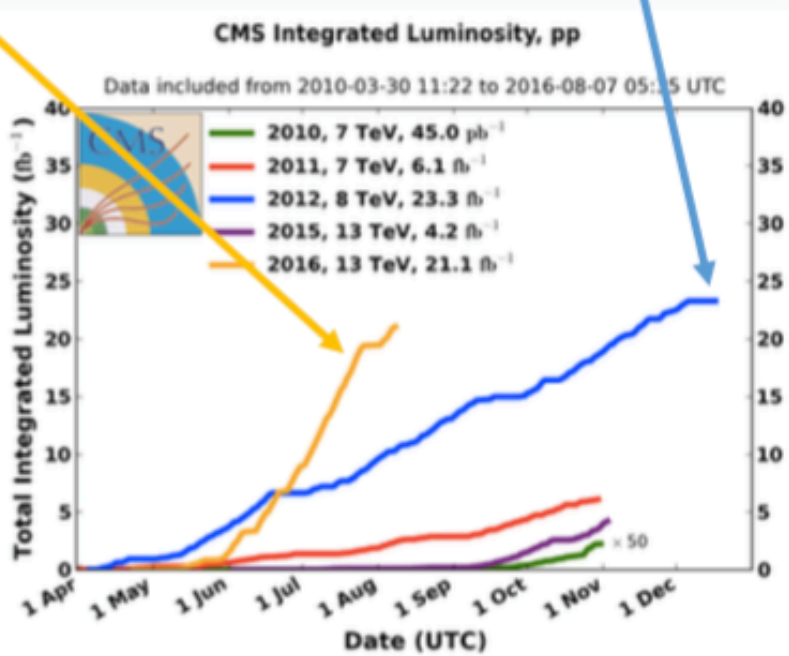
ICHEP 2016 DATASET

The estimate prior to the start of the 2016 campaign were to achieve something similar to the previous best (2012)



Pileup distribution for the data shown here





The unprecedented dataset led to a unique sense of excitement and expectation among experimentalists and theorists alike…

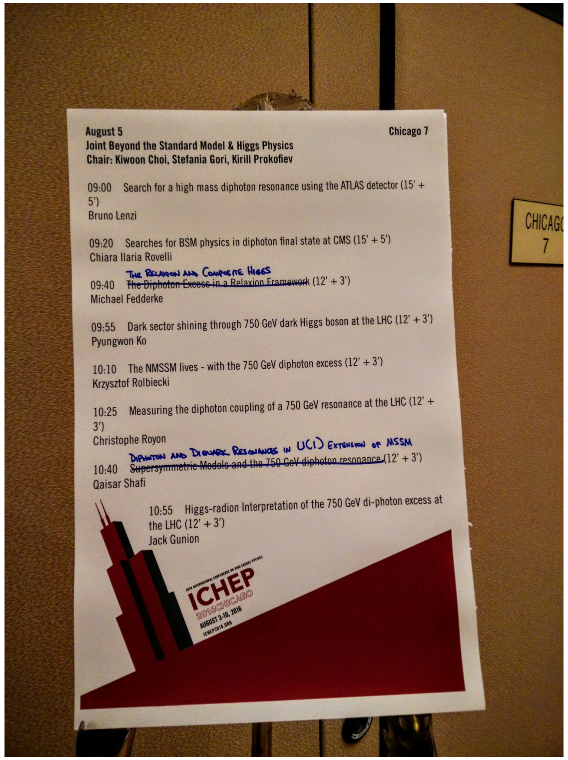
<u>but remember, this is still only 1% of the final LHC dataset</u>

TODAY'S TALK

A selective take on the highlights –

Trying to cover both DESY-centric and less familiar topics

- 1. New ~~physics~~ observations from LHCb -
  - CP violation in the baryon/charm sectors
- 2. Top physics
  - Cross sections and mass
  - New ideas in top quark phenomenology
    - Top-philic Z', EFT at NLO
  - BSM-sensitive top quark measurements
  - Calibration of Monte-Carlo top mass
- 3. The latest on future HEP facilities
  - CEPC, ILC, FCC-ee…
- **For interesting results on neutrino oscillations at T2K, see the presentation here. LINK**



CP VIOLATION MEAUSREMENTS FROM LHCb

CP VIOLATION IN Λ_b^0 decays

- Initial discovery of CPV was in neutral K^0 decays
- Recently it has been observed in B0 B+, and B^0s decays,

  -> but never observed in the decays of any baryon

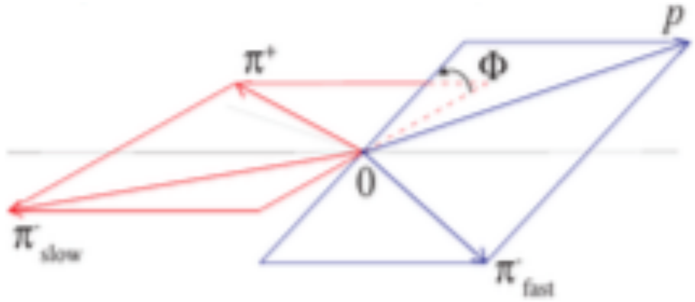
In the SM, decays of the Λ_b (bud) baryons to hadrons predicted to CP asymmetries **as large as 20%** for certain three-body decay modes

LHCb measures the asymmetries w.r.t of the 4-body decay

- $\Lambda_b \to p\pi^-\pi^+\pi^-$

The asymmetries are **CP-odd**, thus a non-zero result implies CP-violation.

CP VIOLATION IN Λ_b^0 decays



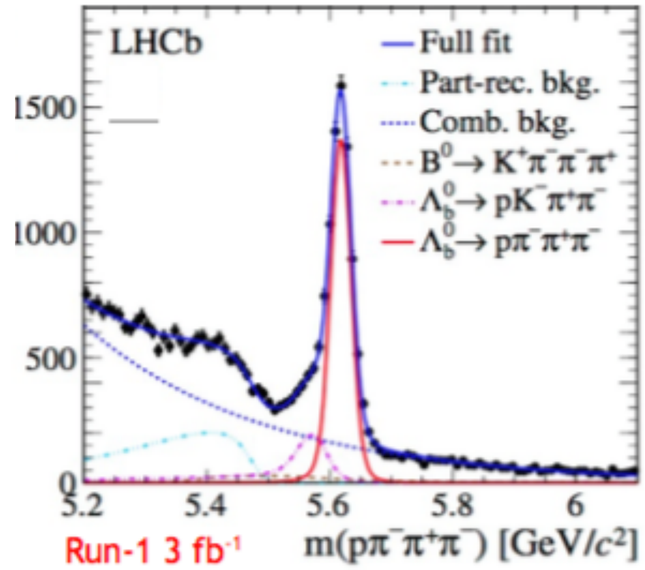
- Asymmetries as a function of the rela orientation between the decay planes formed by the pπ- and π+π- systems (Φ)

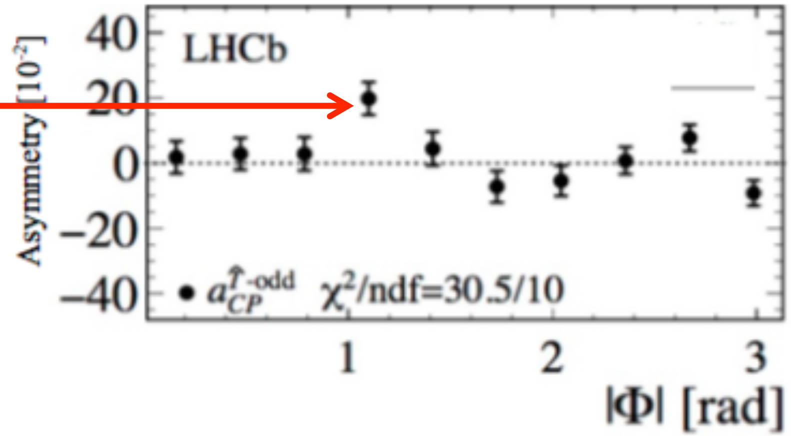
- 3fb−1 of at 7, 8 TeV data analysed.

- **CP violation at 3.3 sigma level**

- LHCb-PAPER-2016-030 in preparation

- 13 TeV results awaited with interest.

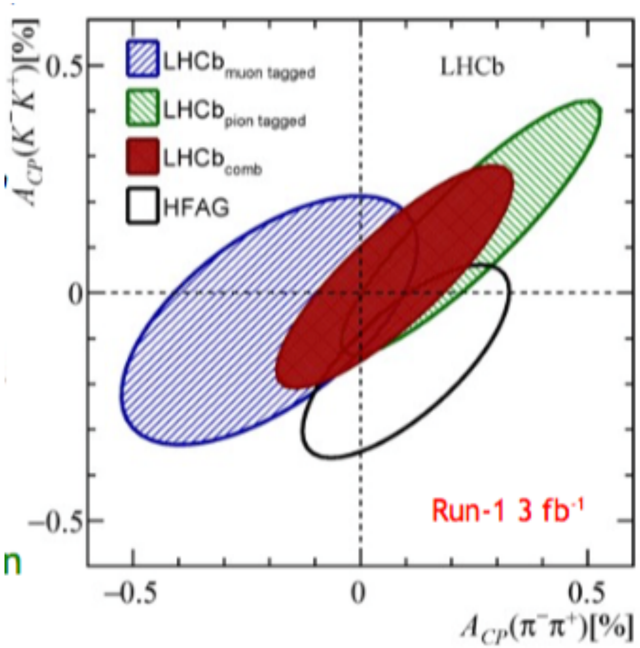




CP VIOLATION IN CHARM DECAYS

- CP violation in charm sector expected to be very small in SM
  - But can be enhanced by new physics

$$\frac{N(D^0 \to f) - N(\overline{D}^0 \to \bar{f})}{N(D^0 \to f) + N(\overline{D}^0 \to \bar{f})}$$ with $f = K^+K^-$



LHCb-PAPER-2016-035 in preparation

- Combining with a previous result (B→DμX decays), the most precise CP violation measurement in charm meson decay from a single experiment is obtained -

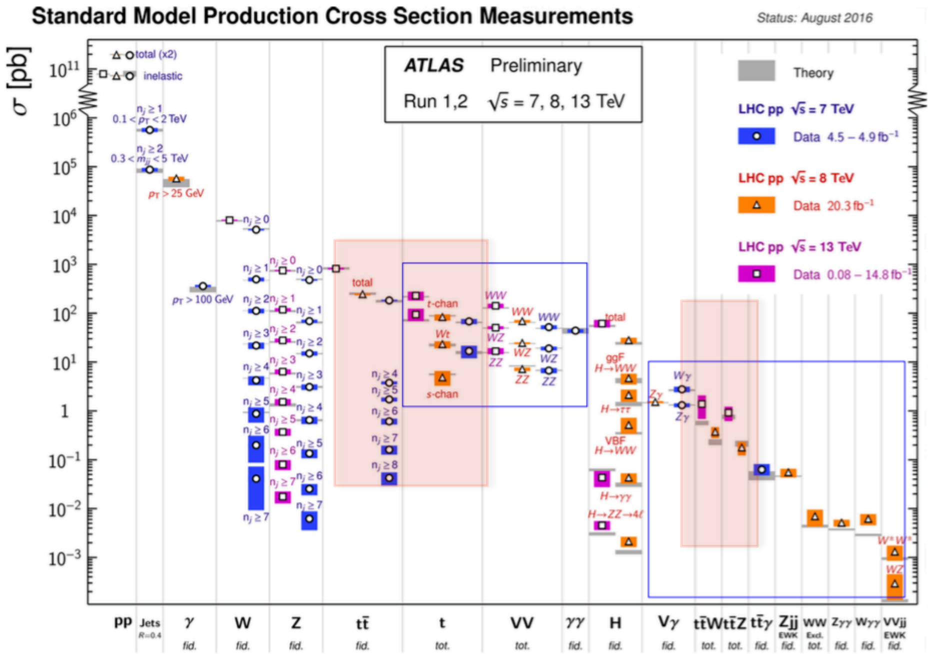
$$A_{CP}(K^-K^+) = (0.04 \pm 0.12\,(\text{stat}) \pm 0.10\,(\text{syst}))\%$$

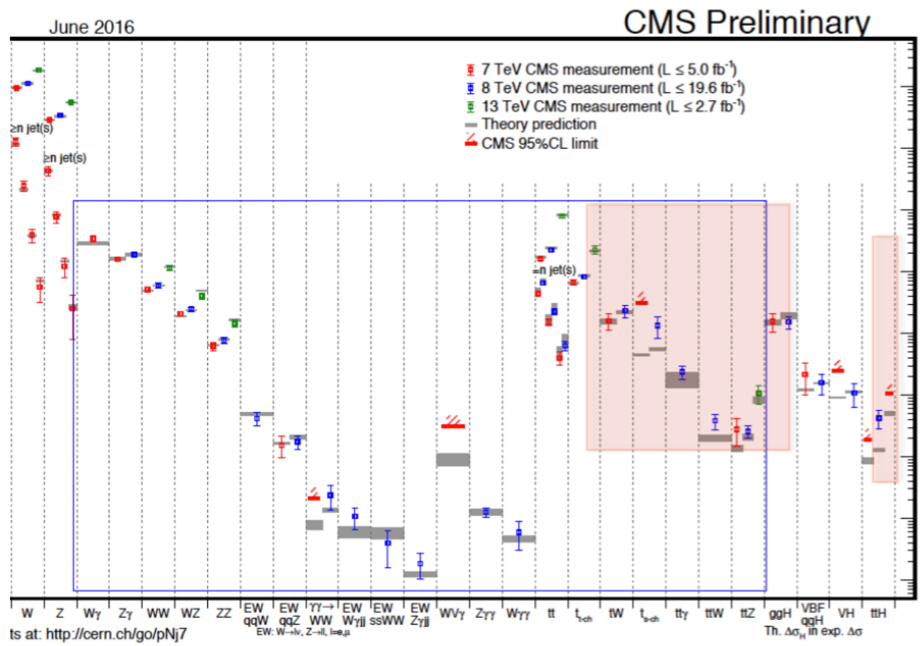
Still consistent with no CPV -> no hint of new physics.

TOP PHYSICS

TOP PHYSICS – THE STATE OF THE ART

- The Standard Model extremely successful in predicting the cross sections of processes with top quarks: tt, t , tW, ttZ, ttW, ttγ…

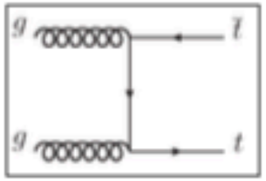


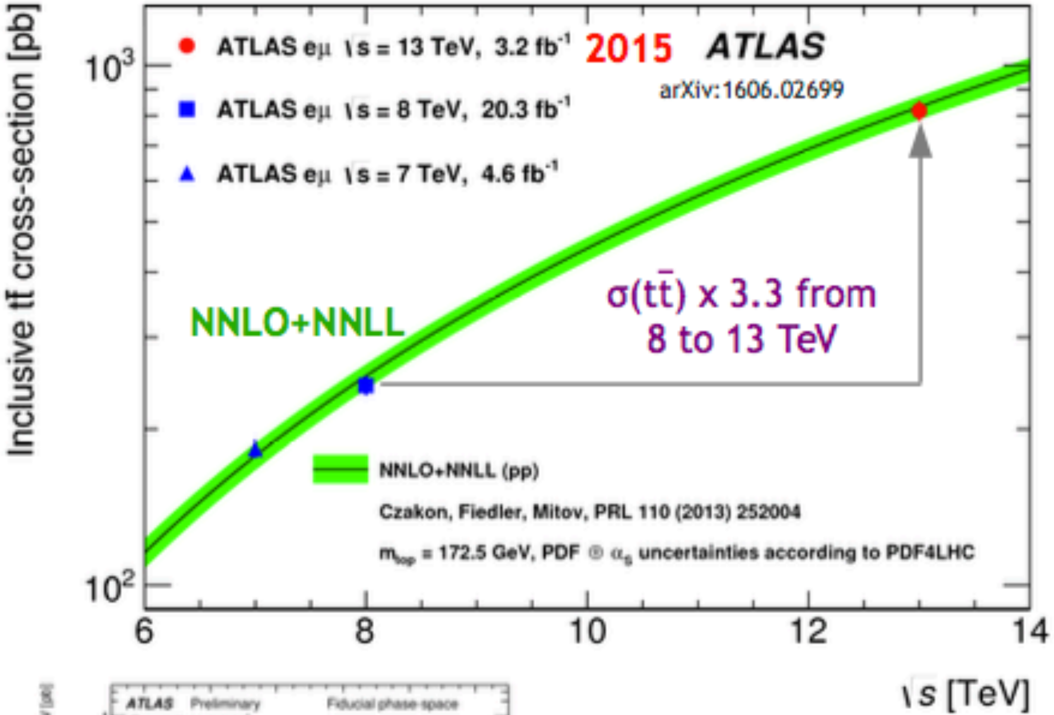


Experimental precision now ~ theory (NNLO+NNLL) precision:

- Deep probe of pQCD
- Extraction of fundamental parameters (M_t, σ_s, PDFs)
- Check for hints of new physics, constrain background for searches
- Huge stats allow new corners of the phase space to be explored…

$t\bar{t}$ Production

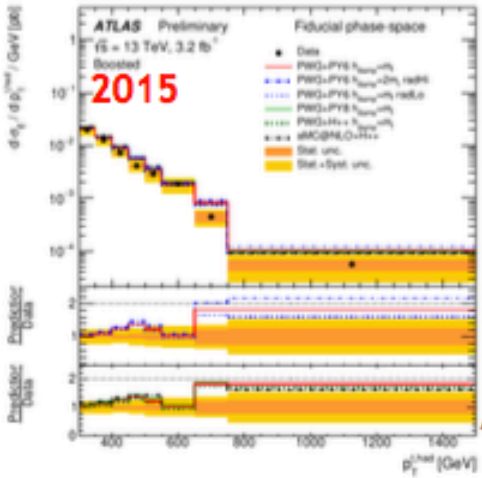




Single and double b-tagged $t\bar{t} \to b e \nu \bar{b} \mu \nu$ events allow to measure $t\bar{t}$ cross-section and b-tagging efficiency simultaneously

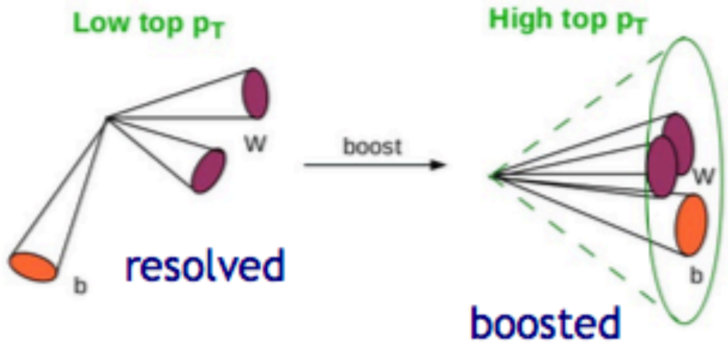
Precision ±(3.9-4.4)% (7-13 TeV) betters NNLO+NNLL predictions (~5%)

High $t\bar{t}$ statistics → detailed studies of production properties



ATLAS-CONF-2016-040

ℓ+jet channel high-p_T differential cross-section from boosted analysis (also resolved)



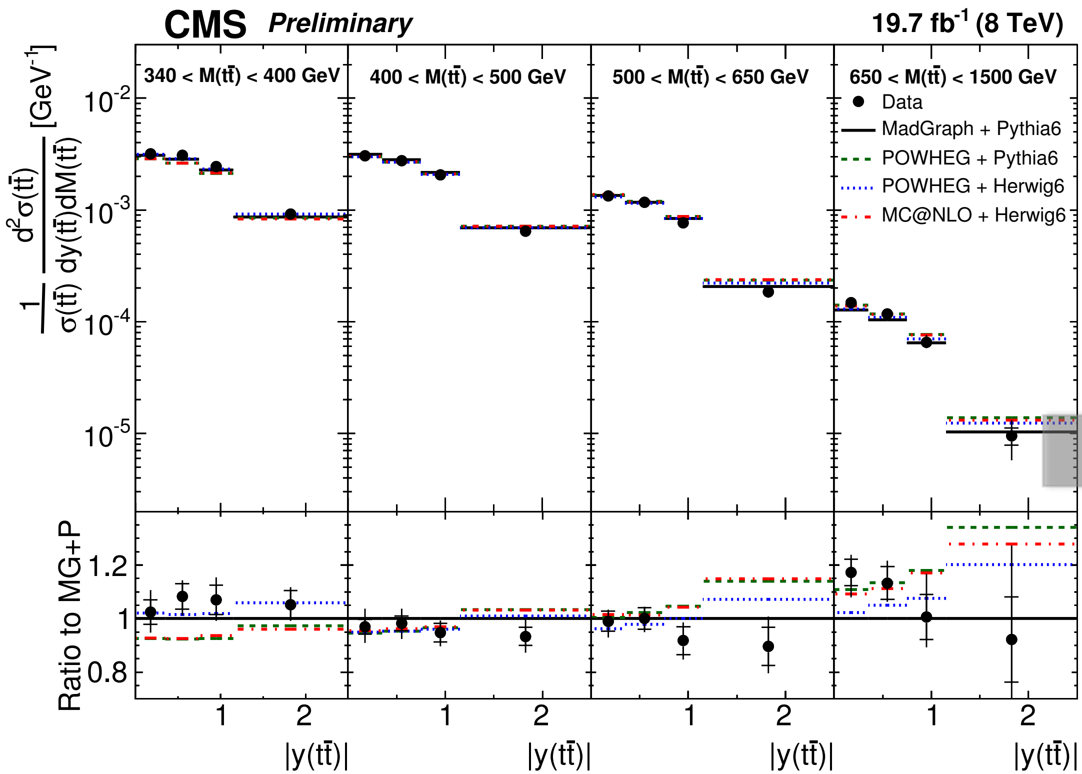
2D differential σ_{tt}

CMS-TOP-14-013

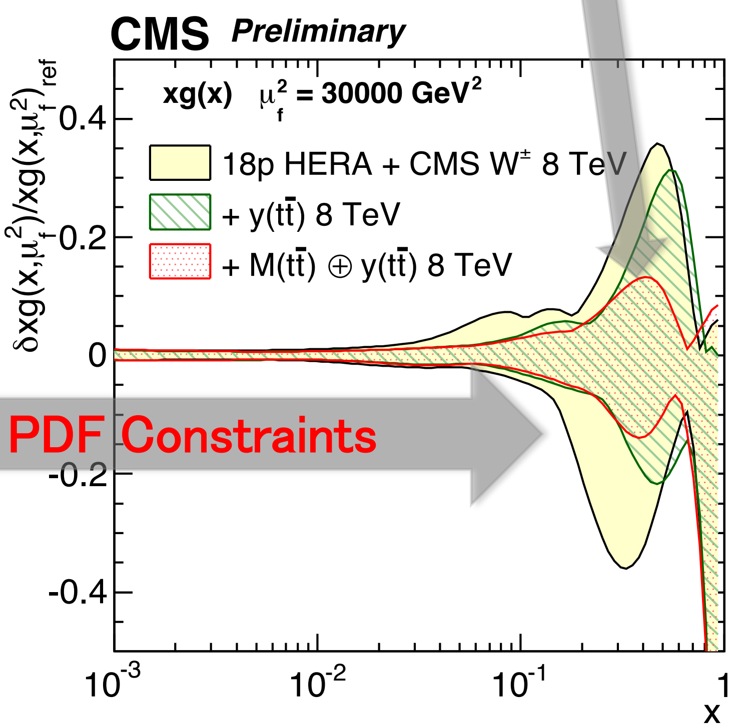
Double-differential tt cross sections at 8 TeV

- first measurement of this type
- bin tt events in two variables e.g., $Pt_{top} - y_{top}$, $M_{tt} - y_{tt}$
- $M_{tt} - y_{tt}$ especially sensitive to PDFs
- 2D distributions provide stronger PDFs constraints than 1D

Significant reduction of uncertainty at high-x



PDF Constraints



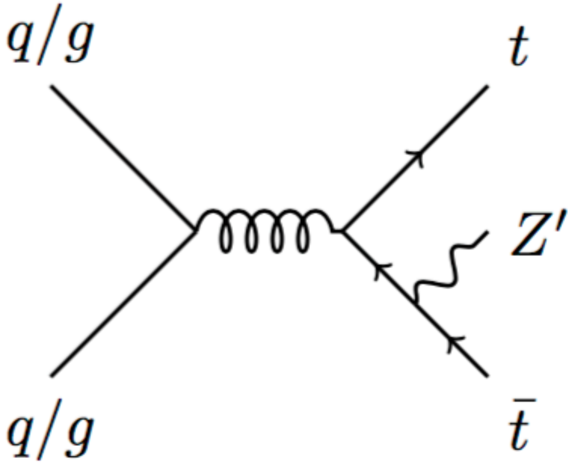
TOPS AND DARK MATTER

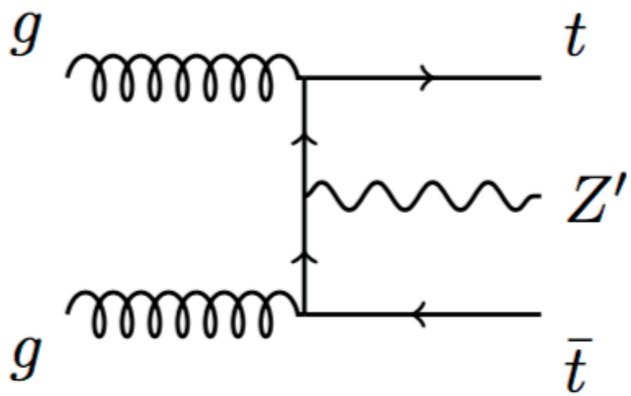
– novel collider phenomenology (JHEP 1606 (2016) 110 [1512.00471])

-> Slight deviation in combined ATLAS+CMS ttH signal strength:

$\mu = \sigma / \sigma_{SM} = 2.3^{+0.7}_{-0.6}$ (driven by CMS same-sign dilepton channel)

- Attempt to explain excess with Top-philic Z' model



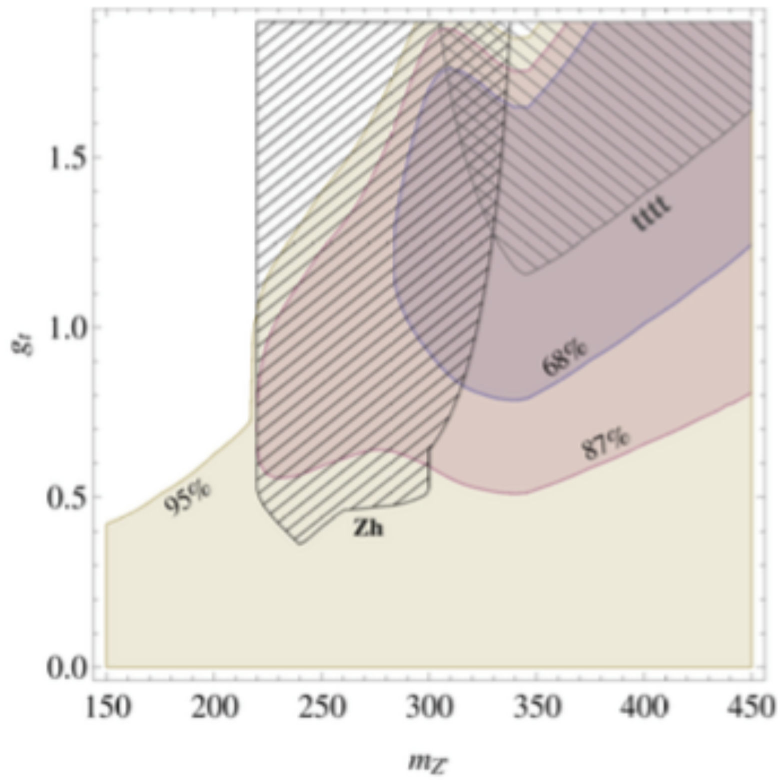


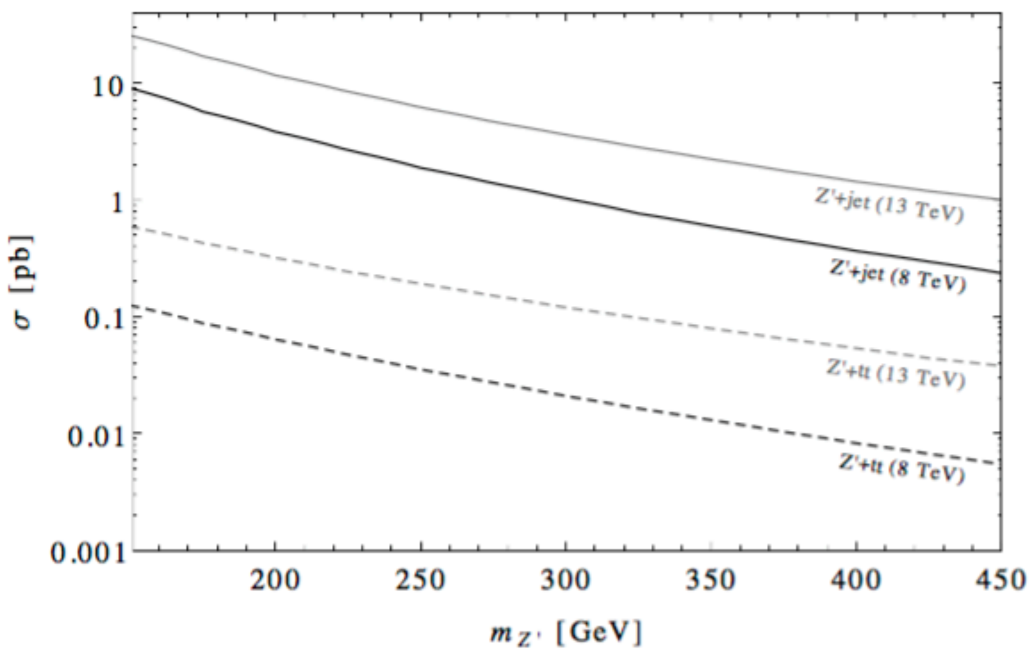
Potentially interesting signature(s)…
e.g. Boosted ttbar + resolved ttbar?

TOPS AND DARK MATTER

– novel collider phenomenology (JHEP 1606 (2016) 110 [1512.00471])

- Observables based on tttt, Zh, DM relic density, Galactic γ excess, sensitive to Z' model parameters
  - Apply constraints and deduce best fit Z' mass and Z'-top coupling





Seems to deserve a dedicated LHC search

TOPS AND DARK MATTER

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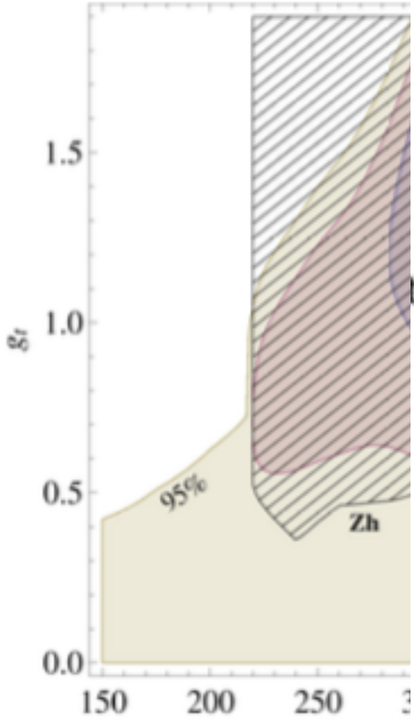
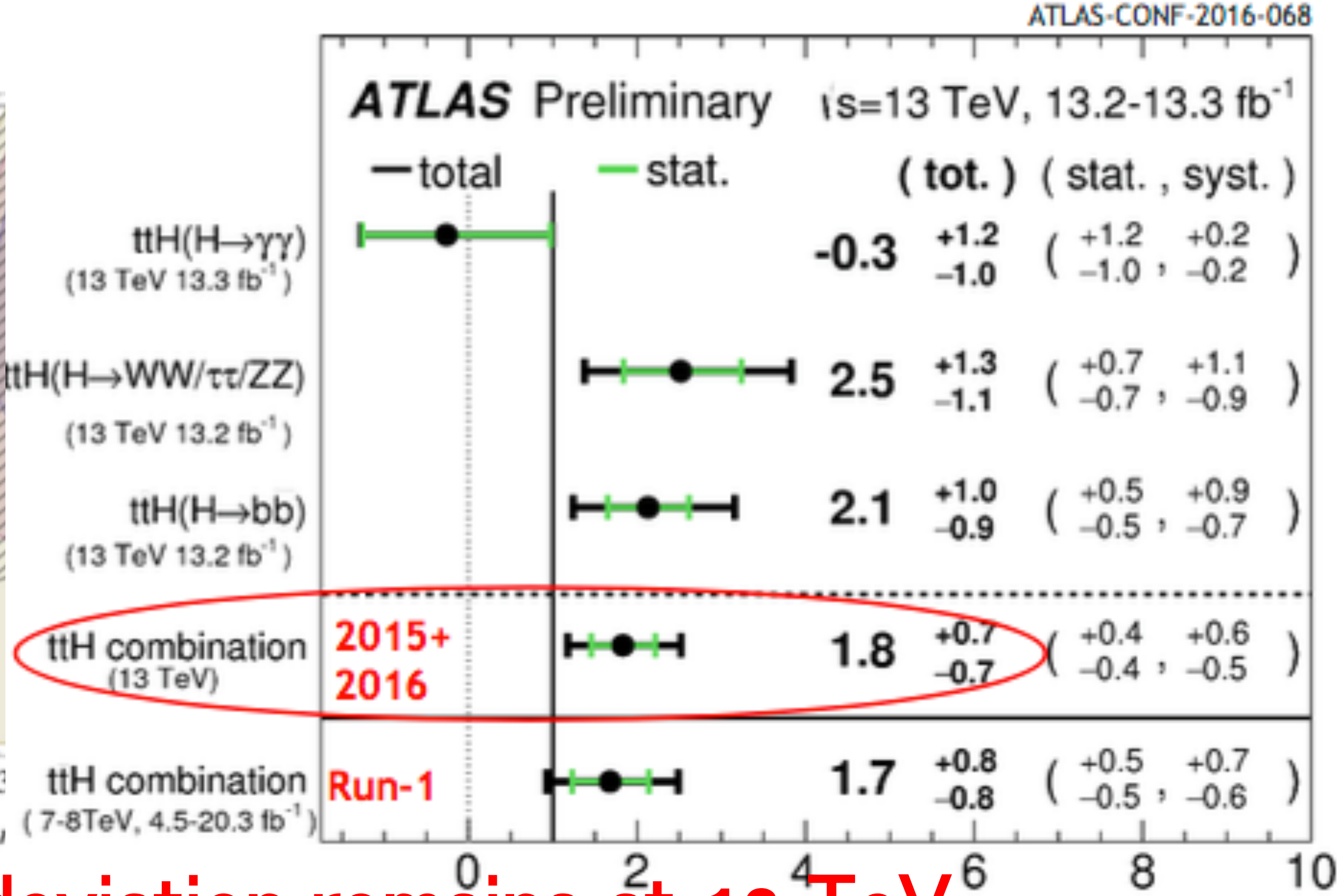




Hint of deviation remains at 13 TeV

TT + Z/W AT 13 TEV

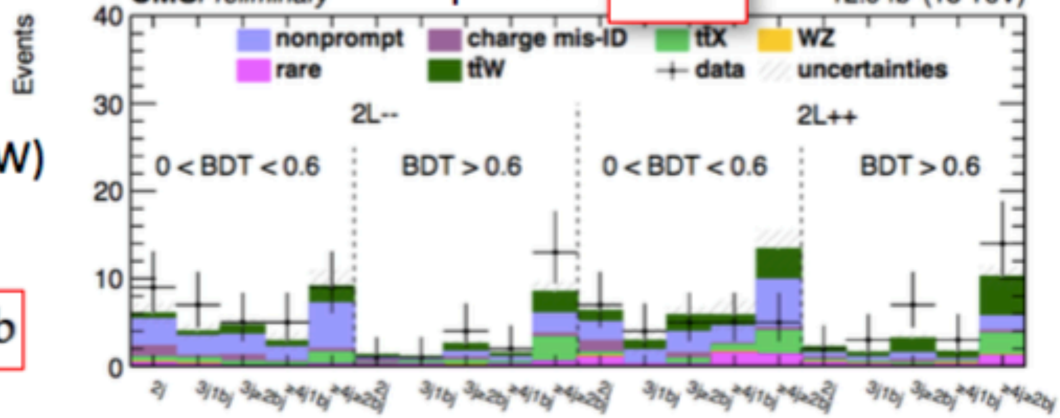
Select event with 2 SameSign leptons(TTW) or 3 or 4 leptons (TTZ)

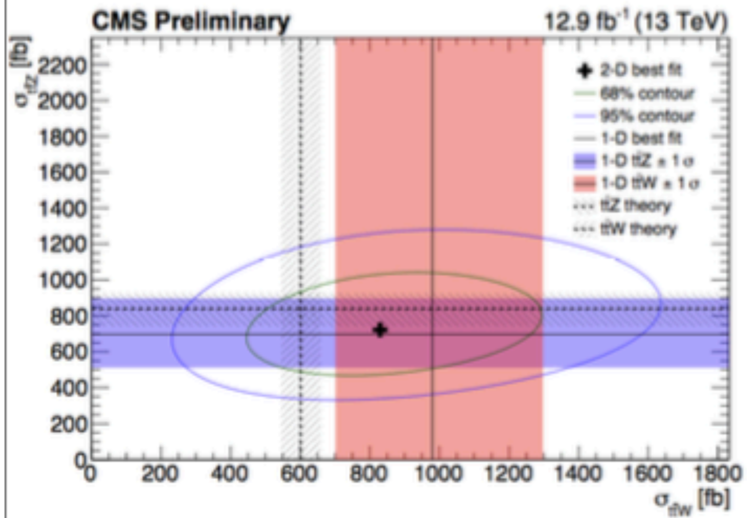
$$\sigma(t\bar{t}Z) = 0.70^{+0.16}_{-0.15}(\text{stat.})^{+0.14}_{-0.12}(\text{sys.})\,\text{pb}$$

$$\sigma(t\bar{t}W) = 0.98\,^{+0.23}_{-0.22}(\text{stat.})\,^{+0.22}_{-0.18}(\text{sys.})\,\text{pb}$$

2 leptons

ttW

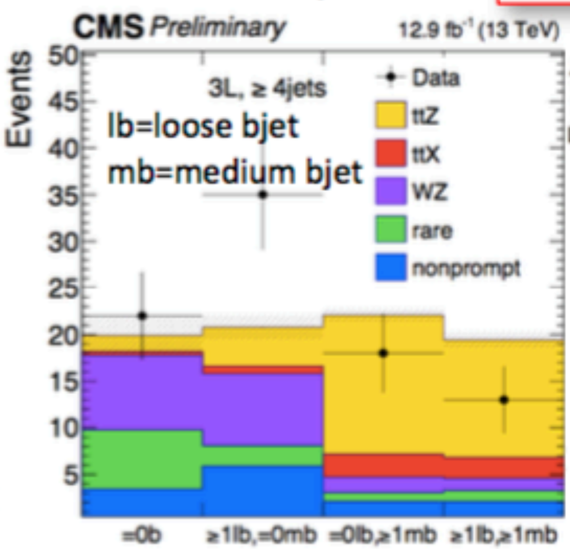


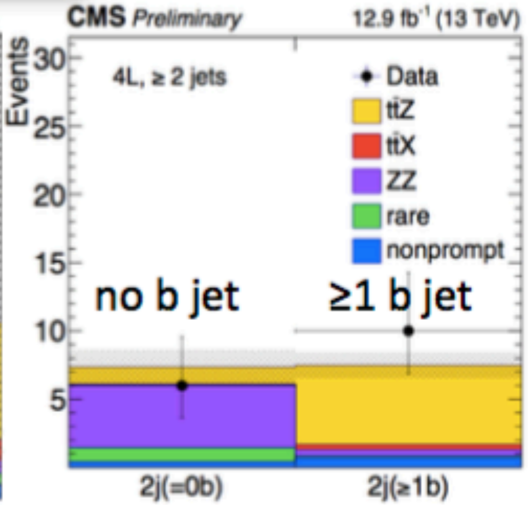


3 leptons

ttZ

4 leptons



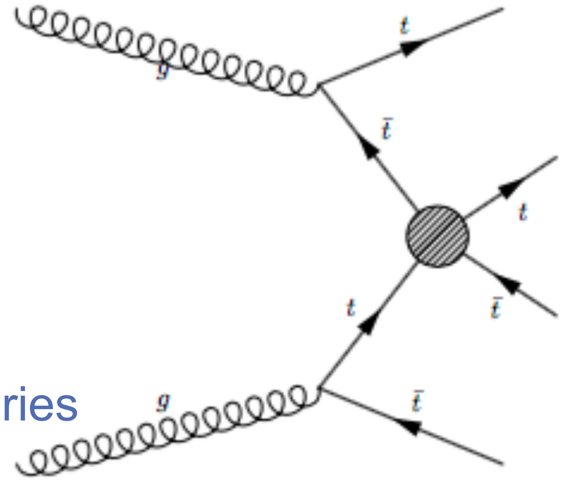


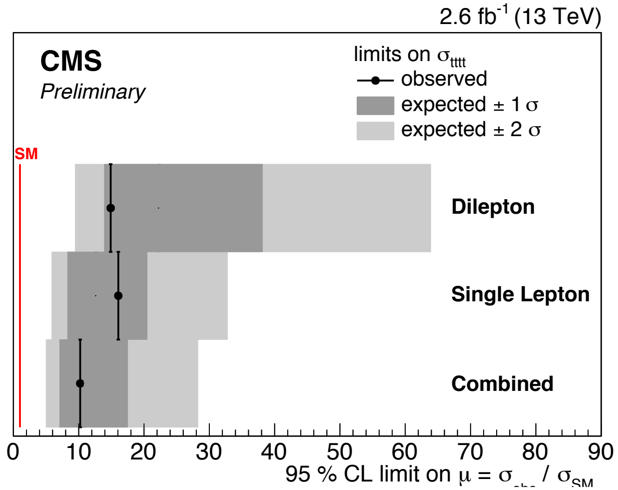
tttt

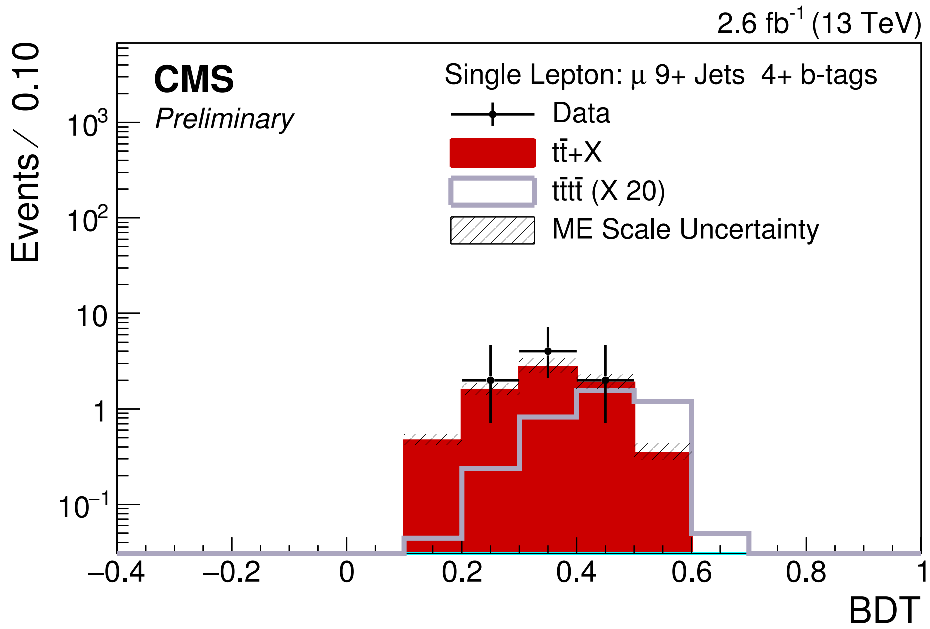
CMS-TOP-16-016

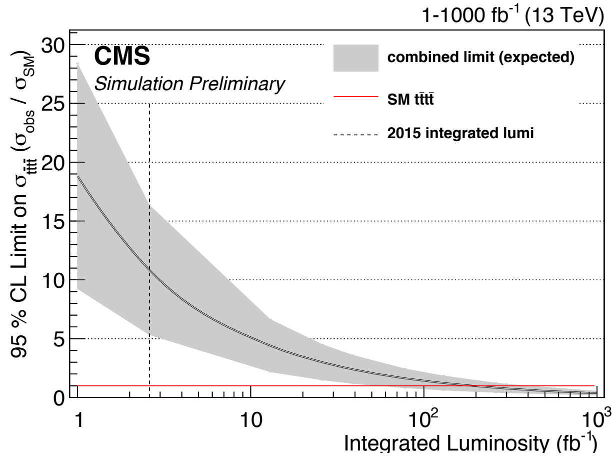
Search for SM four top production

- Extremely rare SM process $\sigma_{tttt} \sim 9$ fb
- Sensitive to new physics
- Combining single- and dilepton channels
- Fit to multivariate discriminator in (b)jet categories







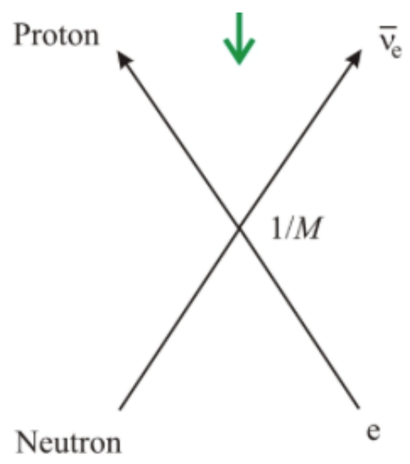


- **Obs. (exp.) limits 10 (11) x SM σ_{tttt}**
  - **Sensitivity limited by statistics**
  - **Factor of 2 increase in sensitivity wrt 8 TeV**

THE EFFECTIVE FIELD THEORY APPROACH - an *agnostic* approach to finding new physics in the top quark sector

- Precision top quark observables are sensitive to new physics.
- If new physics scale Λ is very large wrt to LHC scale new physics manifest as virtual effects only.
    - In this case, an effective field theory is a sufficient description

Nothing new -
Recall the classic effective Fermi theory of Beta decay.



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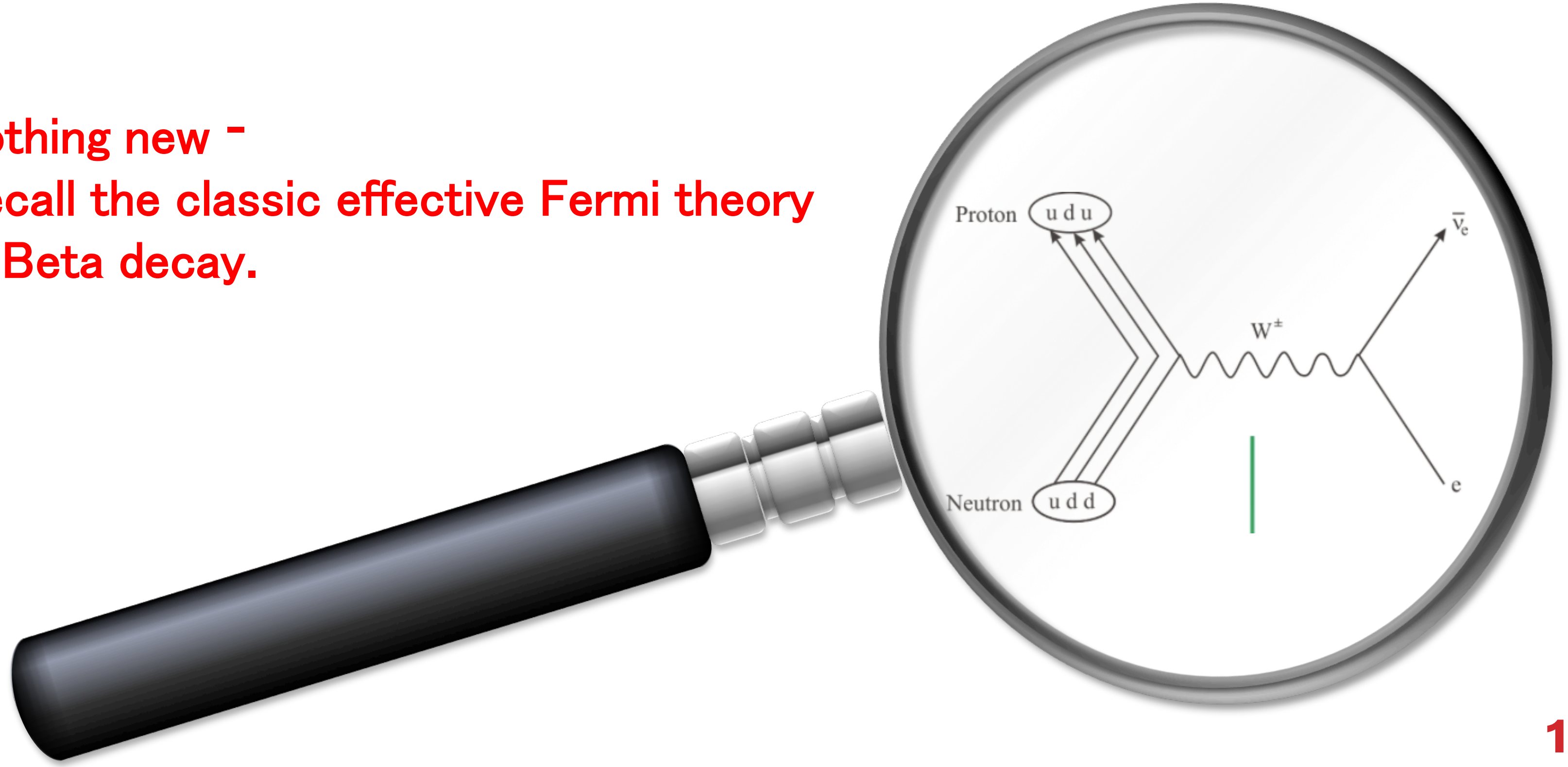


EFT PARADIGM IN THE TOP SECTOR
- SMEFT

- The Standard Model Effective Field Theory (SMEFT) is a model-independent approach to SM deviations.

$$\mathcal{L}_{\mathrm{Eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4}) \qquad \Lambda = \text{NP scale}$$

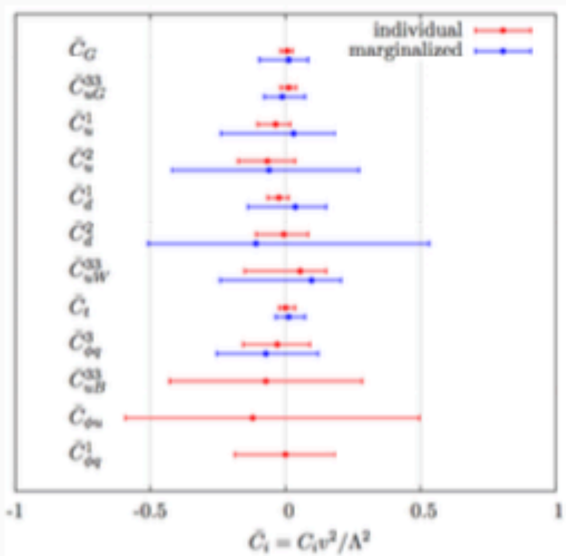
- In the top quark sector, deviations from the SM are parametrized by adding top-quark operators, e.g. for *tbW*:

$$O_{\varphi Q}^{(3)} = i(\varphi^\dagger D_\mu \tau^I \varphi)(\bar{Q}\tau^I \gamma^\mu Q) \qquad O_{\varphi\varphi} = i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu b)$$

$$O_{tW} = (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu} \qquad O_{bW} = (\bar{Q}\sigma^{\mu\nu}\tau^I b)\varphi W^I_{\mu\nu}$$

- Global fit can be performed with SMEFT by including all available measurements.

Top fit: LHC8+Tevatron [A. Buckley et al.]



EFT PARADIGM IN THE TOP SECTOR - SMEFT

- Electroweak operators:
  - For testing $tbW/ttZ/tt\gamma$ couplings.
  - Key processes: single top, $pp \to t\bar{t} + V$, and $e^+e^- \to t\bar{t}$.

[CZ] [Bylund, Maltoni, Tsinikos, Vryonidou, CZ]

for ttZ see also: [R. Rontsch and M. Schulze] [R. Rontsch and M. Schulze]

- Top-Higgs operators:
  - For testing $ttH/gtt(gttH)/ggH$ couplings.
  - Key processes: $pp \to t\bar{t}$, $pp \to t\bar{t} + H$, and loop-induced $gg \to H, Hj, HZ, HH, \cdots$

[D. Franzosi and CZ] [Maltoni, Vryonidou, CZ]

- FCNC operators:
  - For testing $qtg/qtZ/qt\gamma/qtH$ couplings.
  - Key processes: $q + g \to t$, $q + g \to t + Z/\gamma/H$, and $e^+e^- \to tj$

[Degrande, Maltoni, Wang, CZ] [Durieux, Maltoni, CZ]

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LATEST PROGRESS – EFT @ NLO

- SM Effective Field Theory in the top sector promoted to NLO in QCD with parton shower. Relevant processes automated with MadGraph5_aMC@NLO and can be directly used in experimental analyses.

Status:

- Three classes of operators are now available
  - Top-EW
  - Higgs-top
  - Top-FCNC

LATEST PROGRESS – EFT @ NLO

$pp \to t\bar{t}$: O_{tG}

Top chromo-dipole moment O_{tG} in $t\bar{t}$ production:

- Cross sections

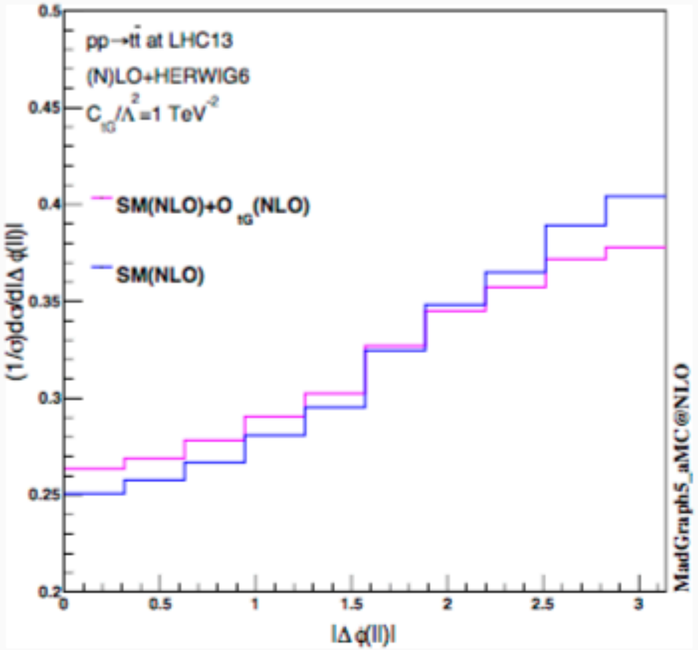
O_{tG} cross sections ($C_{tG}/\Lambda^2 = 1/\text{TeV}^2$)

β_1	LO [pb TeV^2]	NLO [pb TeV^2]	K factor
Tevatron	$1.61^{+0.66\ (+41\%)}_{-0.43\ (-27\%)}$	$1.810^{+0.073\ (+4.05\%)}_{-0.197\ (-10.88\%)}$	1.12
LHC8	$50.7^{+17.3\ (+34\%)}_{-12.4\ (-25\%)}$	$72.62^{+9.26\ (+12.7\%)}_{-10.53\ (-14.5\%)}$	1.43
LHC13	$161.6^{+48.0\ (+29.7\%)}_{-36.2\ (-22.4\%)}$	$239.5^{+29.0\ (+12.1\%)}_{-31.8\ (-13.3\%)}$	1.48
LHC14	$191.3^{+55.6\ (+29.0\%)}_{-42.2\ (-22.0\%)}$	$283.0^{+33.6\ (+11.9\%)}_{-36.9\ (-13.1\%)}$	1.48

Limits on C_{tG}/Λ^2

	LO [TeV^{-2}]	NLO [TeV^{-2}]
Tevatron	[-0.33, 0.75]	[-0.32, 0.73]
LHC8	[-0.56, 0.41]	[-0.42, 0.30]
LHC14	[-0.56, 0.61]	[-0.39, 0.43]

Decayed top: spin correlation



- Distributions
  E.g. $A_{FB} = 0.095 + C_{tG} \times 0.021(\text{TeV}/\Lambda)^2$
- Spin correlation taken into account by MADSPIN.

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- Future plans: four-fermion operators, CP-odd operators, complex mass scheme, dynamic EFT scale, ...

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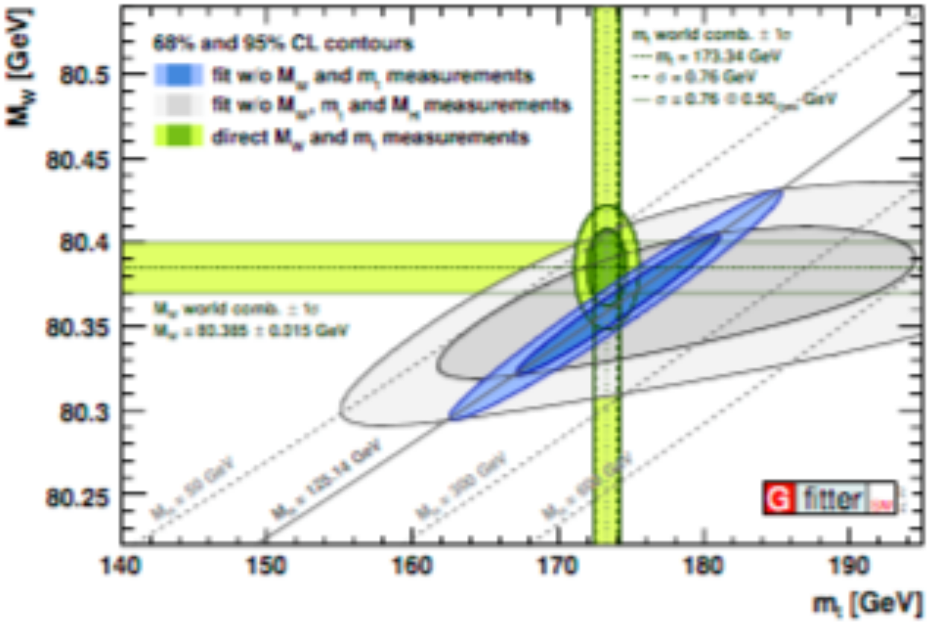
TOP QUARK MASS CALIBRATION FOR MONTE-CARLO EVENT GENERATORS (M.PREISSER)

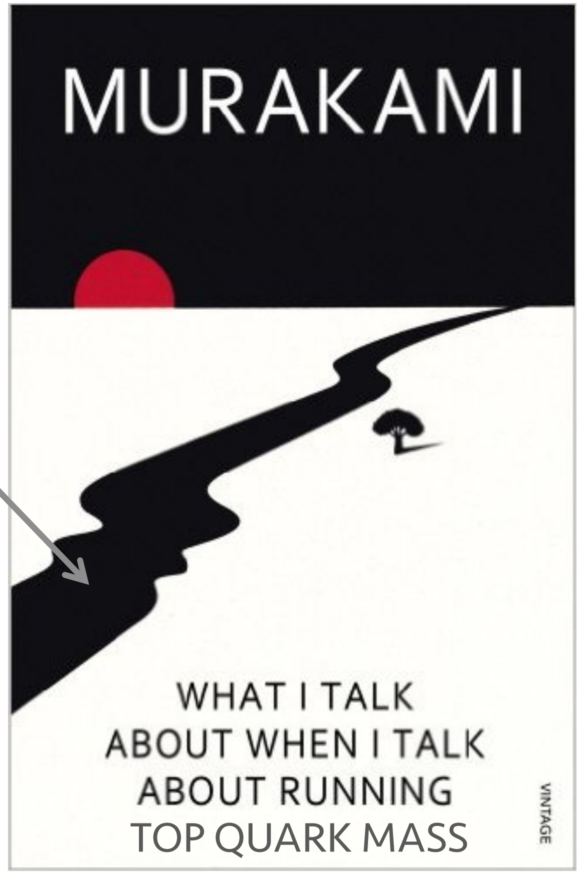
Persistent question in determination of top mass:
“What do really measure when we measure M_t”

TOP QUARK MASS CALIBRATION FOR MONTE-CARLO EVENT GENERATORS (M.PREISSER)

- Persistent question in top physics:
  "What do really measure when we measure M_t?"
- The top quark's ultra short lifetime means standard measurements extract M_t from kinematic reconstruction of decay
- Not trivial to interpret this M_t as a fundamental parameter of the SM

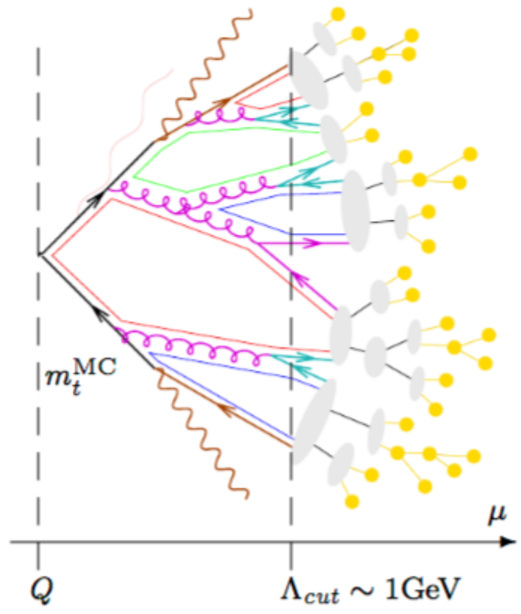


OR



TOP QUARK MASS CALIBRATION FOR MONTE-CARLO EVENT GENERATORS (M.PREISSER)

- Persistent question in top physics:
  "What do really measure when we measure M_t?"
  - The top quark's ultra short lifetime means standard measurements extract M_t from kinematic reconstruction of decay
  - Not trivial to interpret this M_t as a fundamental parameter of the SM
  - Need to convert Mt to a less model-dependent *short-distance* mass scheme, e.g. MSR,$\overline{\text{MS}}$



[original picture D. Zeppenfeld]

TOP QUARK MASS CALIBRATION FOR MONTE-CARLO EVENT GENERATORS (M.PREISSER)

- **Strategy:** compare quark mass-sensitive hadron level QCD calculations with sample data from some MC
  - look into observables with strong kinematic mass sensitivity
  - get accurate hadron level QCD predictions ($\geq$NLO/NLL) with full control over quark mass scheme dependence
  - fit QCD masses to different values of m_t^{MC} $\rightarrow$ for now we use PYTHIA

$$\boxed{m_t^{\mathrm{MC}} = m_t^{\mathrm{MSR}}(R \simeq 1\mathrm{GeV}) + \Delta_{\mathrm{t,MC}}^{\mathrm{MSR}}(\mathrm{R} \simeq 1\mathrm{GeV})}$$

$$\boxed{m_t^{\mathrm{MC}} = m_t^{\mathrm{pole}} + \Delta_{t,\mathrm{MC}}^{\mathrm{pole}}} \qquad \Delta_{t,\mathrm{MC}} \simeq \mathcal{O}(1\mathrm{GeV})$$

Uncertainties we address in our e^+e^- study

- ▷ perturbative uncertainty
- ▷ scale uncertainties
- ▷ electroweak effects
- ▷ strong coupling α_s
- ▷ non-perturbative parameters

Additional pp systematics

- ▷ PS + UE
- ▷ color reconnection
- ▷ intrinsic uncertainty

TOP QUARK MASS CALIBRATION FOR MONTE-CARLO EVENT GENERATORS (M.PREISSER)

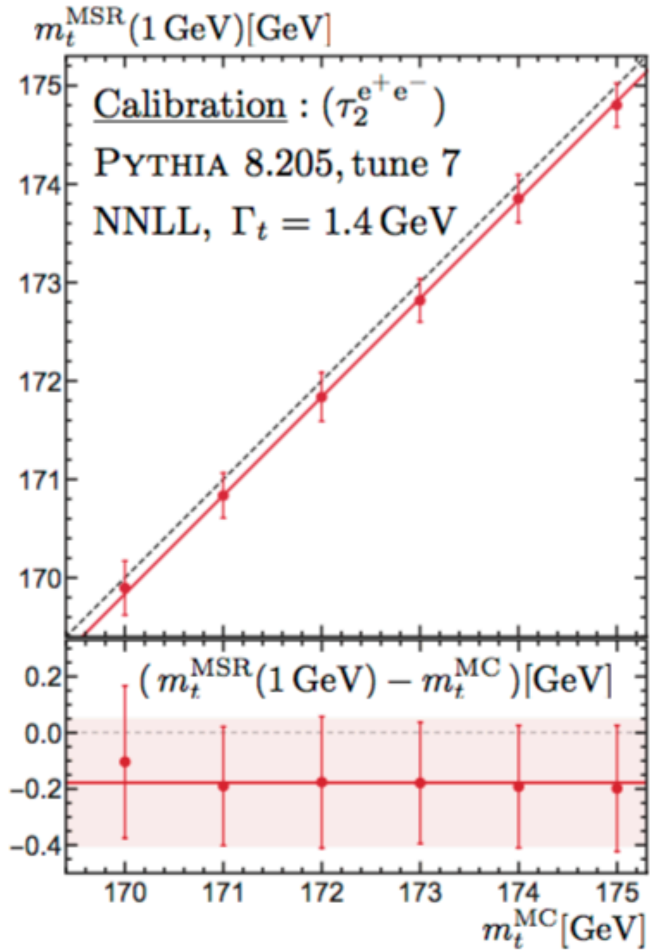
Final Results

- All investigated MC top mass values show consistent picture
- MC top quark mass is indeed closely related to MSR mass

  within uncertainties:
  $m_t^{\mathrm{MC}} \simeq m_t^{\mathrm{MSR}}(1\mathrm{GeV})$

$m_t^{\mathrm{MC}} = 173\,\mathrm{GeV}\ \ (\tau_2^{e^+e^-})$

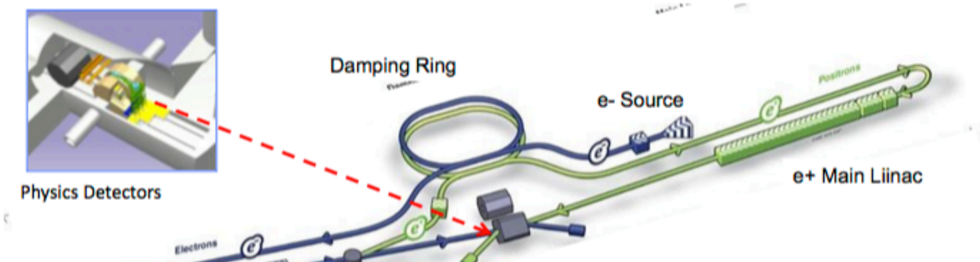
mass	order	central	perturb.	incompatibility	total
$m_{t,1\,\mathrm{GeV}}^{\mathrm{MSR}}$	NLL	172.80	0.26	0.14	0.29
$m_{t,1\,\mathrm{GeV}}^{\mathrm{MSR}}$	$\mathrm{N^2LL}$	172.82	0.19	0.11	0.22
m_t^{pole}	NLL	172.10	0.34	0.16	0.38
m_t^{pole}	$\mathrm{N^2LL}$	172.43	0.18	0.22	0.28

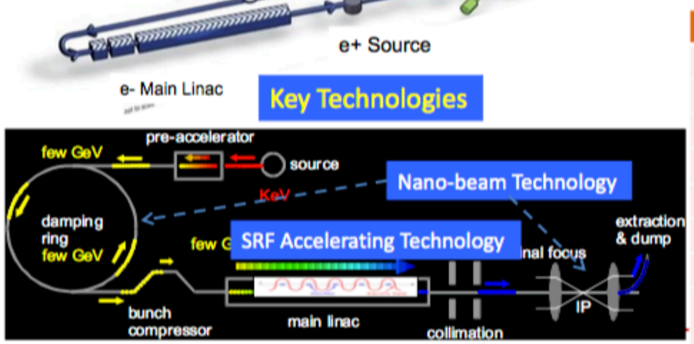


For now just e+e- investigated…

FUTURE FACILITIES - ILC

- 500 GeV linear e+e- collider primarily for extremely precise Higgs physics





Item	Parameters
C.M. Energy	500 GeV
Length	31 km
Luminosity	1.8 x10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA
Beam size (y) at FF	5.9 nm
SRF Cavity G. Q_0	31.5 MV/m Q_0 = 1x10^{10}

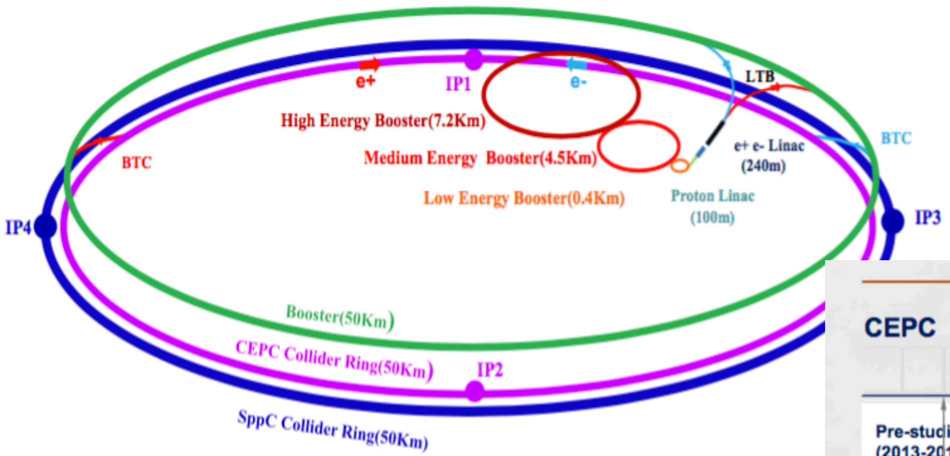
- International Linear Collider (ILC) being prepared for an energy frontier e+e- collider at C.E. 500 GeV, extendable to 1 TeV.
- Nano-Beam and SRF technologies advanced particularly well integrated at ATF, and at European XFEL.
- The ILC key accelerator technologies being ready for the project realization.

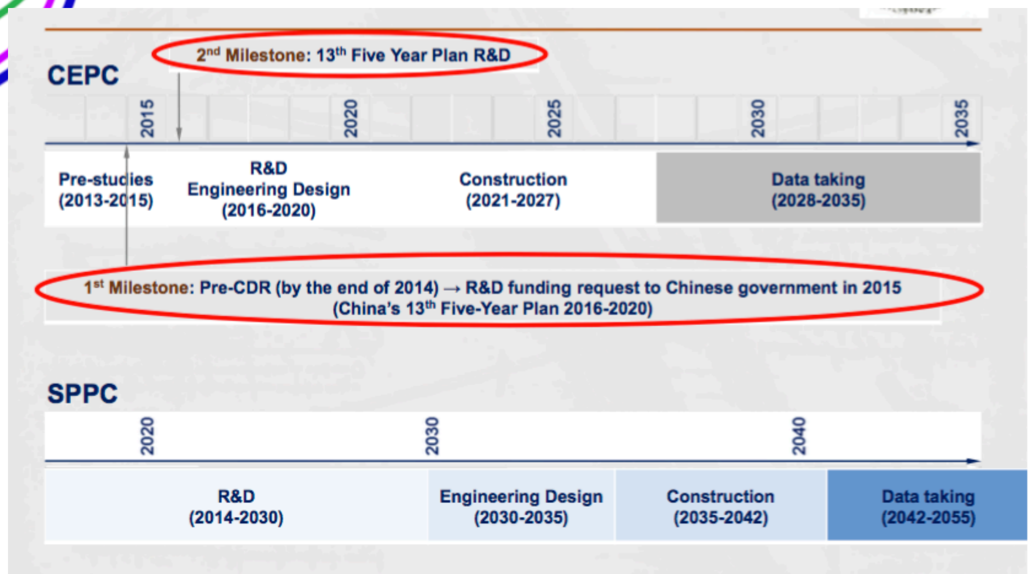
Nice synergy with XFEL at DESY

FUTURE HEP FACILITIES

FUTURE FACILITES

- CEPC-SPPC
  - Ambitious Chinese project for an initial 240 GeV e+e- and subsequent 70 TeV pp colliders in the same 50k circular tunnel.
  - Initially a Higgs,Z factory for precision, then an all-out discovery machine
  - http://cepc.ihep.ac.cn/preCDR/volume.html





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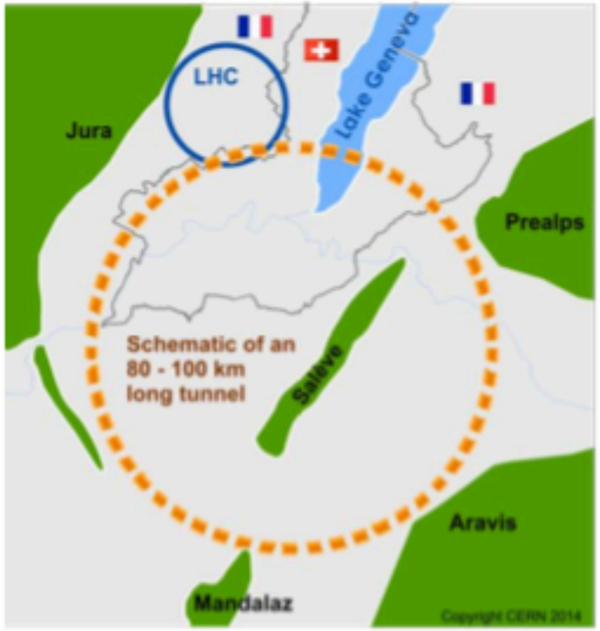
An aggressive timeline is envisaged…

- **Pre-CDR completed**
  - **No show-stoppers**
  - **Technical challenges identified ➔ R&D issues**
  - **Preliminary cost estimate**
- **R&D issues identified and funding request underway**
  - **Seed money from IHEP available: 12 M RMB/3 years**
  - **MOST: ~ 80 M RMB / 5yr, 36M RMB has been proved in June 2016**
  - **Onters topical issue funds from NSFC, CAS and the Science and Technoogy Bureau of Beijing Municipal: ~9M RMB**
  - **Working towards CDR, Accelerator by 2016 and Detector by 2017**
  - **A working machine on paper solving the problems left by Pre-CDR**
- **Site selections**
- **Internationalization & organization**

FUTURE FACILITIES – FCC-ee

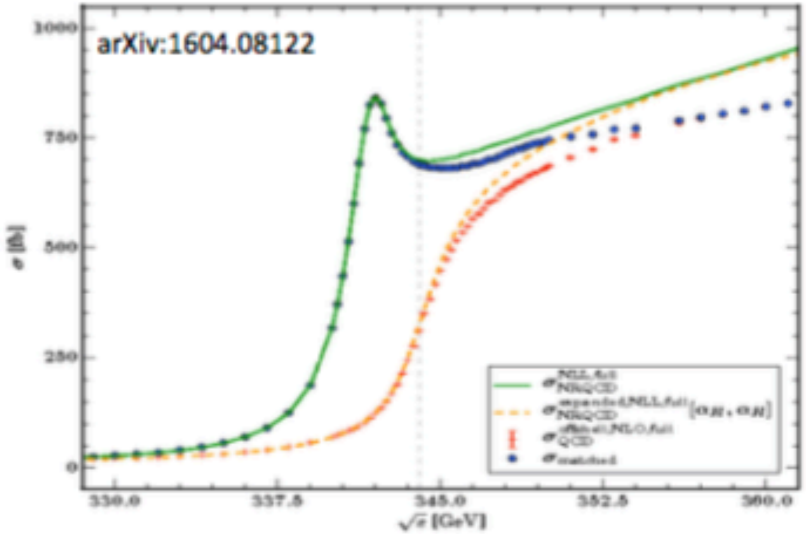
- High-luminosity **ee circular collider** proposed in new 80-100 km tunnel near CERN
- **Flexible** centre-of-mass-energy from **90 to 400 GeV**
- Schedule (and physics) **complementary** and in synergy with FCC-hh (pp @ 100 TeV)

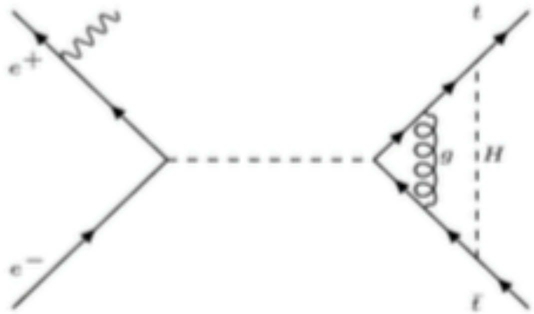


- Explore energy scales to at **least10 TeV**
  - With precision measurements, 20-50 fold improvement on many SM parameters such as
    - m_Z m_W m_{top} $\sin^2\theta_W^{eff}$ R_B, α_{QED} α_S, top and Higgs couplings
- Potential to directly or indirectly **discover** BSM physics
    - Understand BSM through quantum effects in loops
    - DM as invisible decay of H as Higgs factory
    - FCNC in Z and ttbar, flavour physics

FUTURE FACILITIES – FCC-ee

merit of m_{top} threshold scan





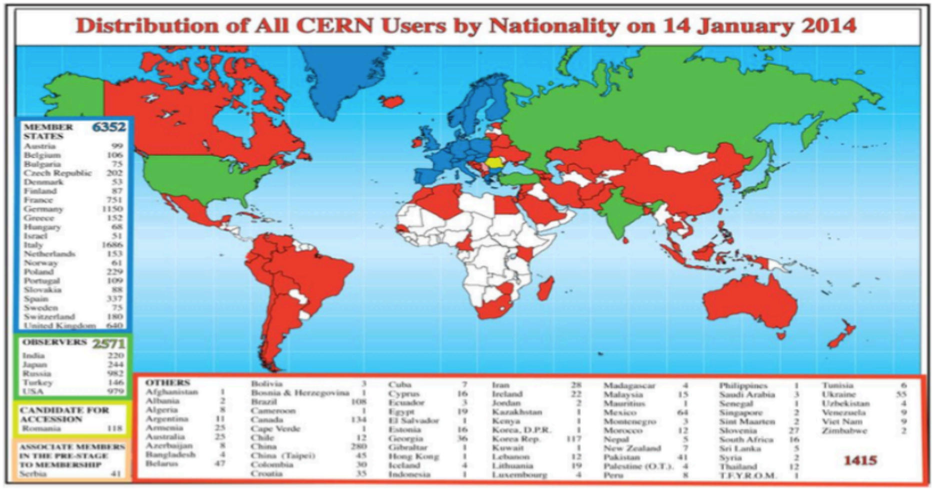
At lepton colliders, measurement of photons from ISR can be used to scan cross section vs centre-of-mass

- FCC-ee will measure α_s with unprecedented precision at Z pole and WW threshold
- Cross section shape depends strongly on top quark mass and width, α_s and Y_t
- Top mass and width can be measured directly with an accurate top cross section threshold scan
  - Improved α_s drastically improves correlations m_t, Γ_t and Y_t

DIVERSITY + INCLUSION

- First ever ICHEP session on this topic
- Interesting, stimulation talks with a great variety of topics
- Staggering statistics on the underrepresentation of minorities in physics, especially from PhD level onwards…
- Many programs at national and experiment level to address this.

About 0.5% of CERN users are African Nationals



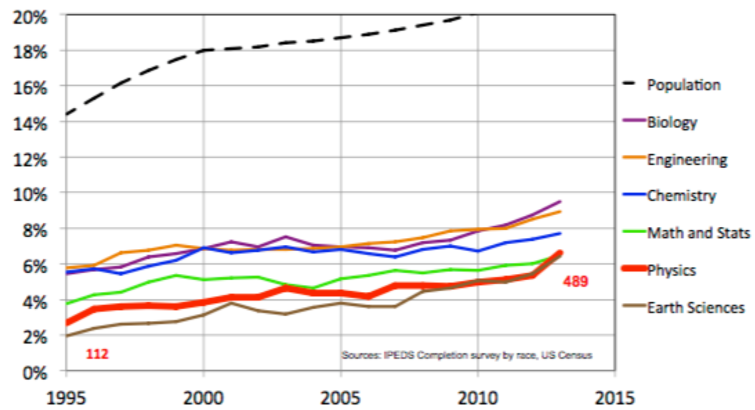
Fri 05/08 | Sat 06/08 | All days

Print | PDF | Full screen | Detailed view | Filter

Introductory Remarks	Zeblon Vilakazi	Huron	09:00 - 09:05
Ground Rules and Guidelines	Brian Nord	Huron	09:05 - 09:08
Project Juno: Advancing Gender Equality In Physics Careers In Higher Education In The UK	Marcella Bona	Huron	09:08 - 09:10
A New US-CERN Summer Program on ATLAS Experiment of LHC at CERN for California State University System	Yongsheng Gao et al.		
The early career, gender, and diversity actions within the LHCb Collaboration	Barbara Sciascia et al.	Huron	09:12 - 09:14
Composition of the ATLAS Collaboration	Joleen Pater et al.	Huron	09:14 - 09:26
Creating Inclusive Work Environments -- to break culture-cloning	Tuva Ora Herenui Richert	Huron	09:26 - 09:38
Increasing diversity in science	Maria Isabel Pedraza Morales	Huron	09:38 - 09:50
Benefits of diverse and interdisciplinary co-creation for HEP - a showcase	Daniel Dobos	Huron	09:50 - 10:02
Bridge Programs as an approach to improving diversity in physics	Brian Beckford	Huron	10:02 - 10:14
Panel Discussion	Inclusivity in our work environments	Huron	10:14 - 10:50
Session of International Outreach and Capacity Development	Ketevi Adikle Assamagan	Huron	11:10 - 11:22
Promoting Women in Physics in South Africa	Kate Shaw et al.	Huron	11:22 - 11:34
The early career, gender, and diversity actions within the LHCb Collaboration	Jonas Rademacker et al.	Huron	11:34 - 11:46
The Masterclass of particle physics and scientific careers from the point of view of male and female students	Sandra Leone		
The Davis-Bacall Scholars Program	Margaret Norris	Huron	11:57 - 12:08
Pre-College Science and Engineering for Inner-City Middle School Students	Kevin Pitts et al.	Huron	12:08 - 12:19
The Cevale2ve case	Arturo Sanchez	Huron	12:19 - 12:30
Panel Discussion	Providing access to science	Huron	12:30 - 13:00

DIVERSITY + INCLUSION

- APS Bridge program underway to equalise the numbers of black and hispanic students at Bachelor and PhD levels



Americans who earned physics doctorates in the US from 1973-2012

	Women	Men
White	2,488	22,172
Asian	625	2,480
Hispanic	106	615
Black	66	354
Native American	6	47

Bridge Programs in Physics

Bridge Program -

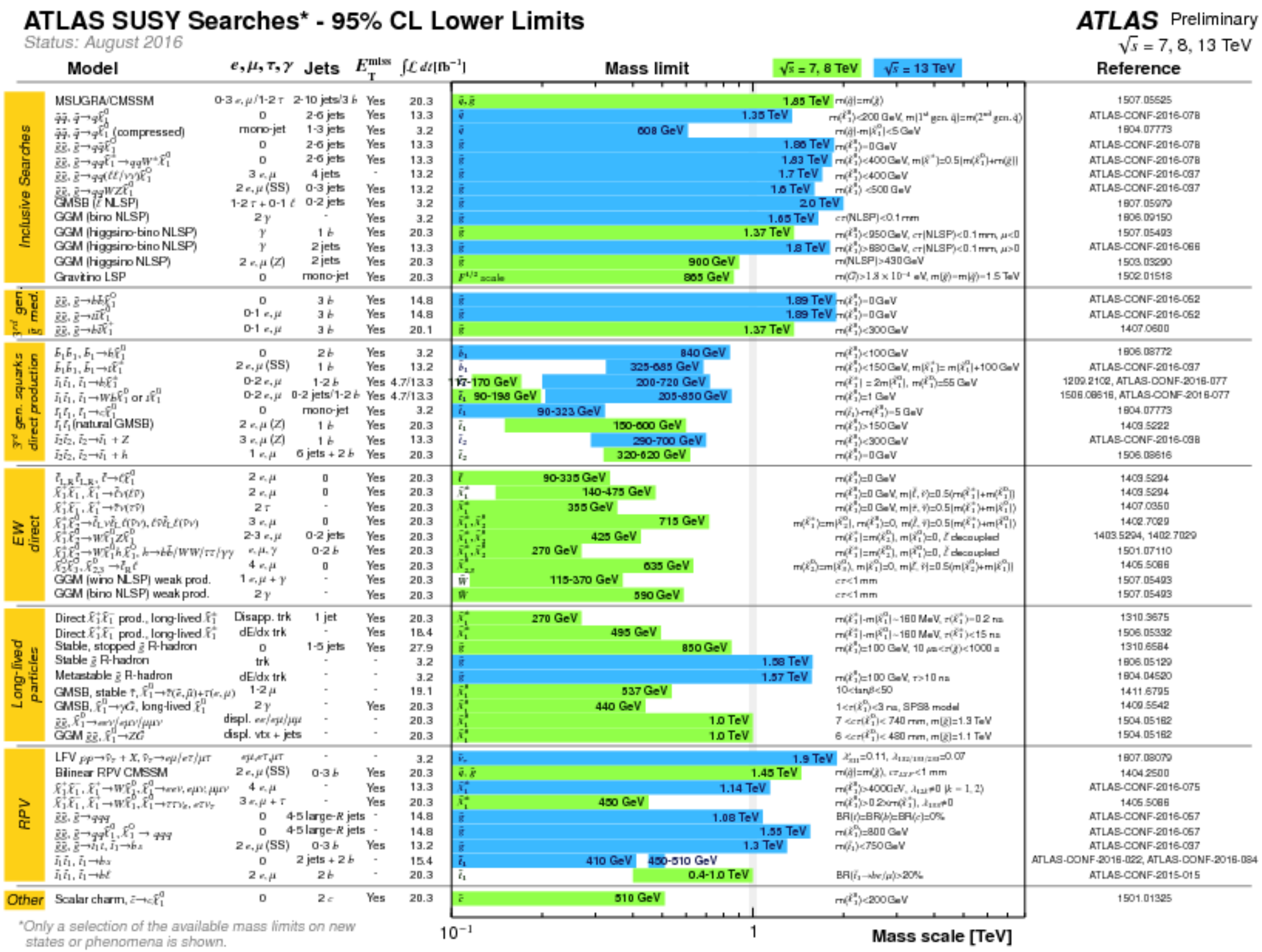
- An approach to addressing the underrepresentation of some groups in physics
- Aim to provide opportunities for students to be successful that may not have had such chances by traditional means

APS Bridge Program - National effort to increase the number of PhD earned by underrepresented students in physics.

SUMMARY

- ICHEP 2016 was a unique gathering of the HEP community
  - Excitement due to enormous dataset was palpable.
  - Disappointment due to null result mitigated by the realisation that this enormous dataset set is still only ~1%
- Yet at least one (somewhat) surprising, beautiful result –
  - CP violation in the baryon sector
- Null results stimulated the imaginations of phenomenologists
  - Top-phillic Z'
  - EFT @ NLO
- Exciting plans for future colliders becoming more concrete
  - CEPC-SppS, ILC, FCC

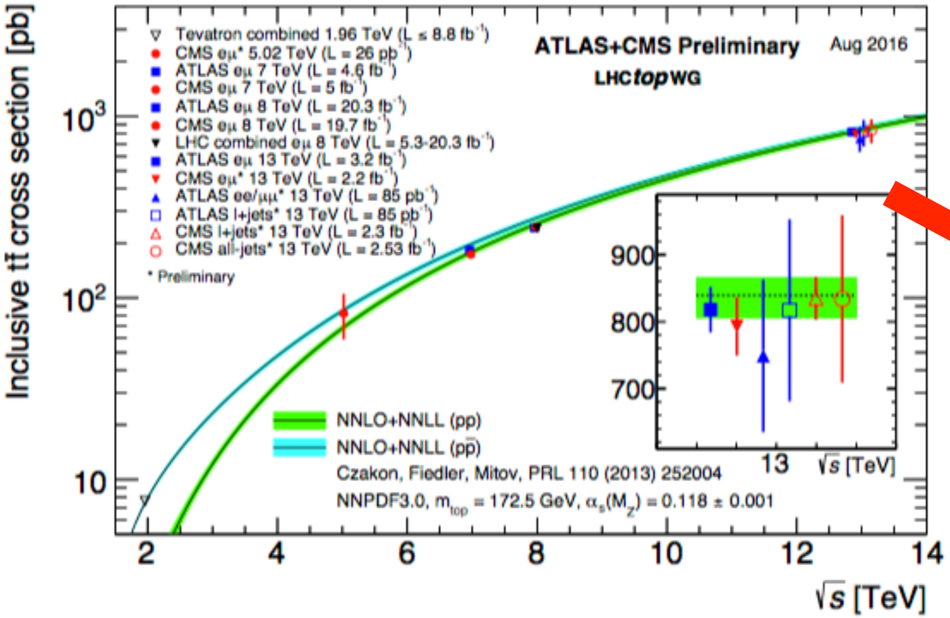
SEARCHES FOR SUPERSYMMETRY

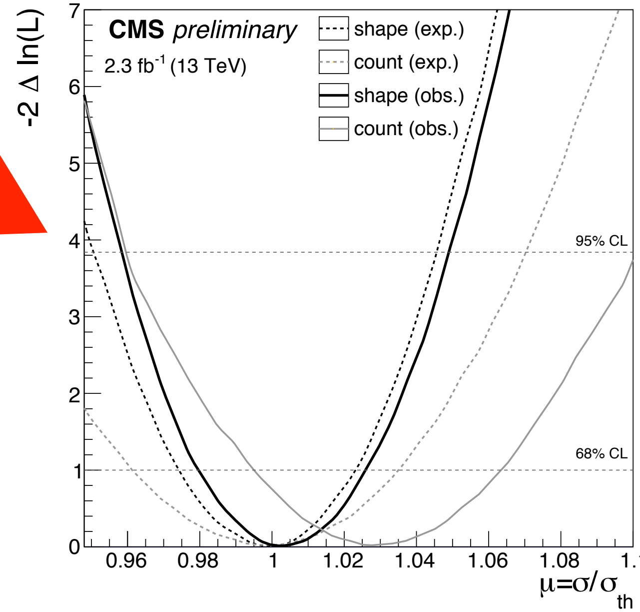


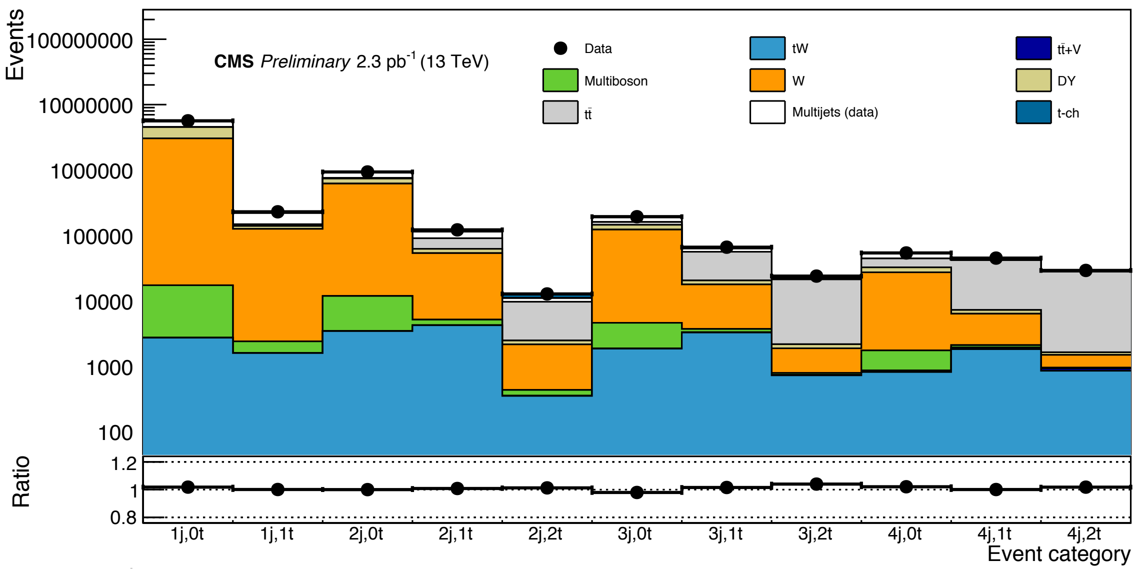
This plot says it all…

TOP QUARK PHYSICS

- **Inclusive ttbar cross section**



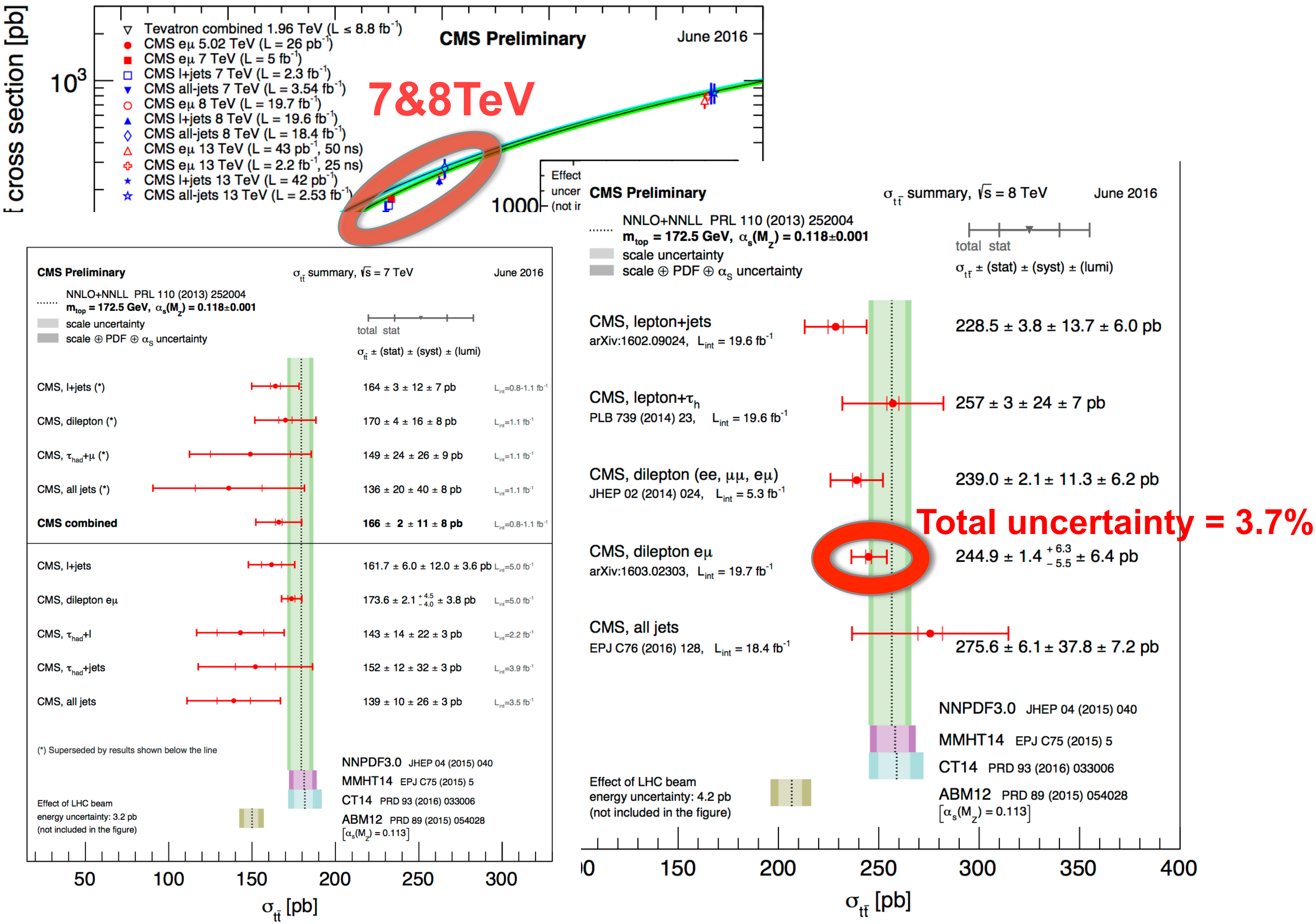




- Total uncertainty **3.9 %**

- Most precise **13 TeV** CMS measurement so far

Incl. σ_{tt} measurements



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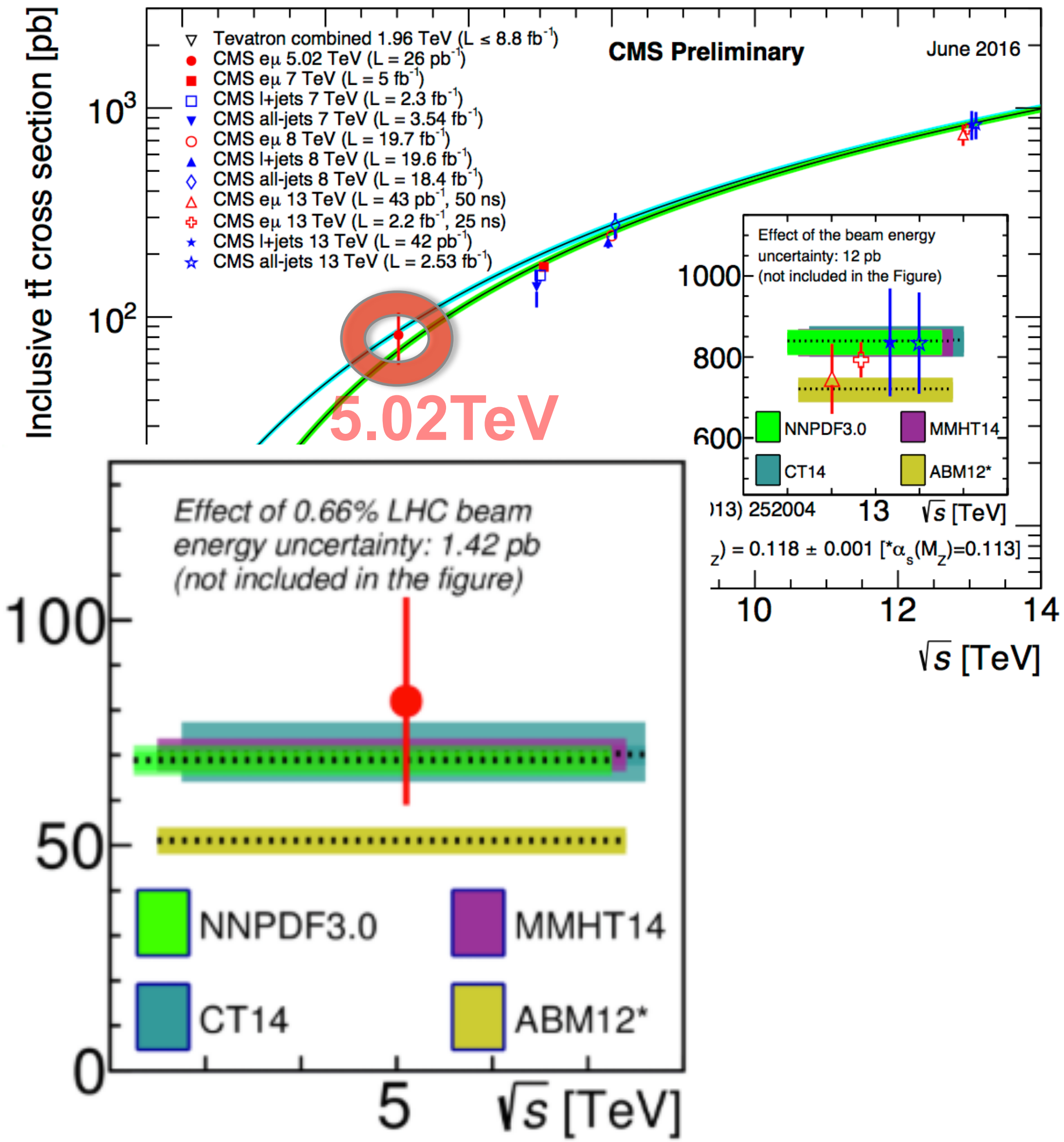

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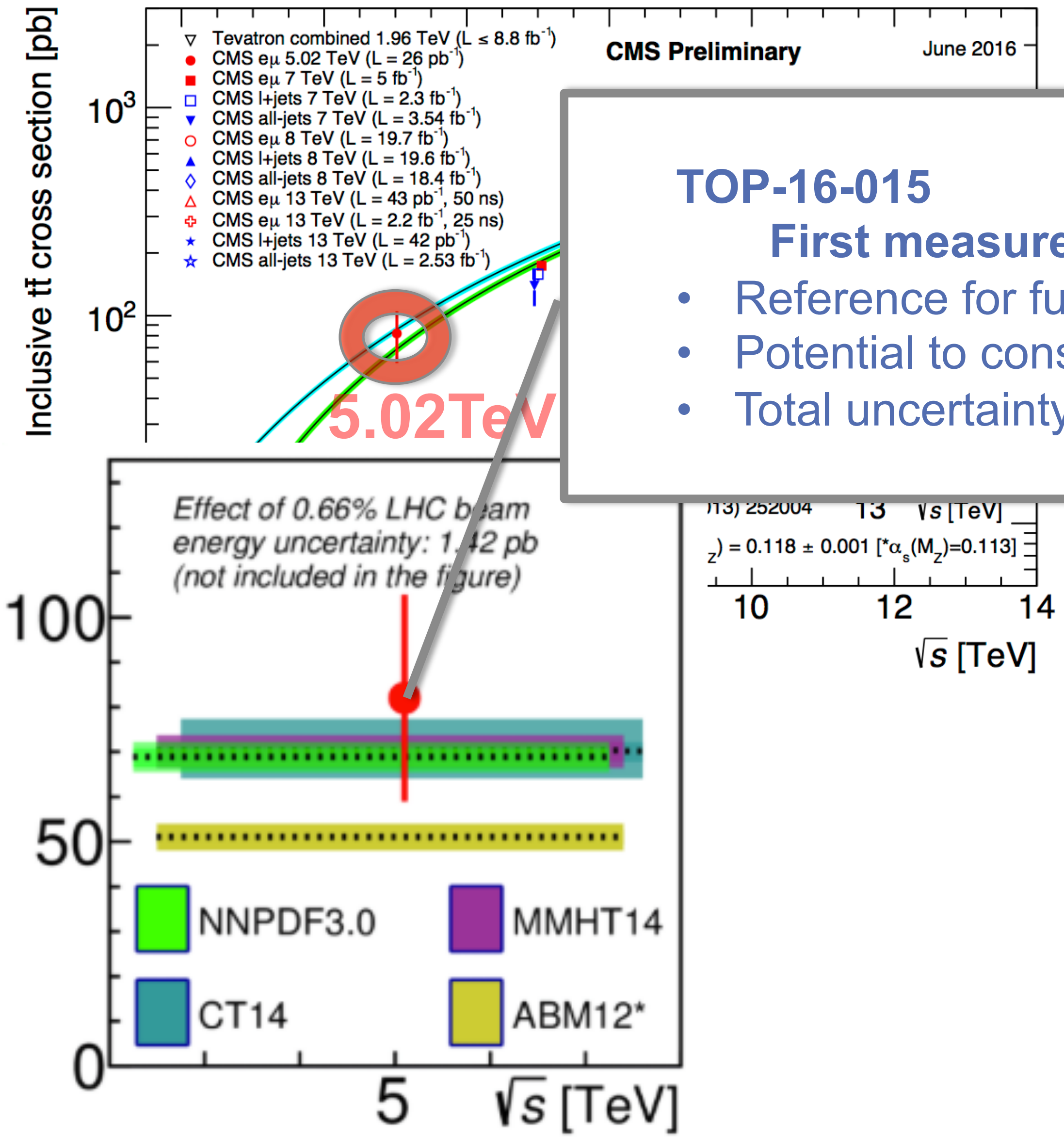
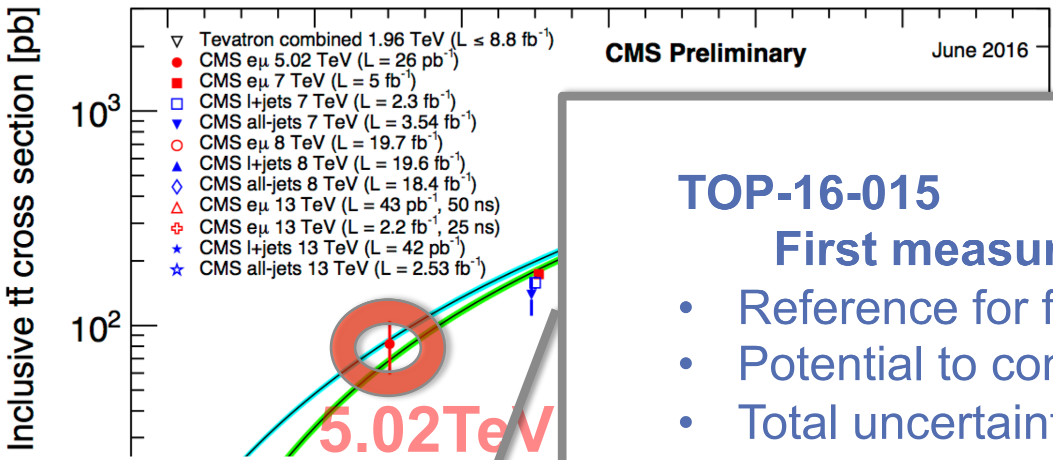


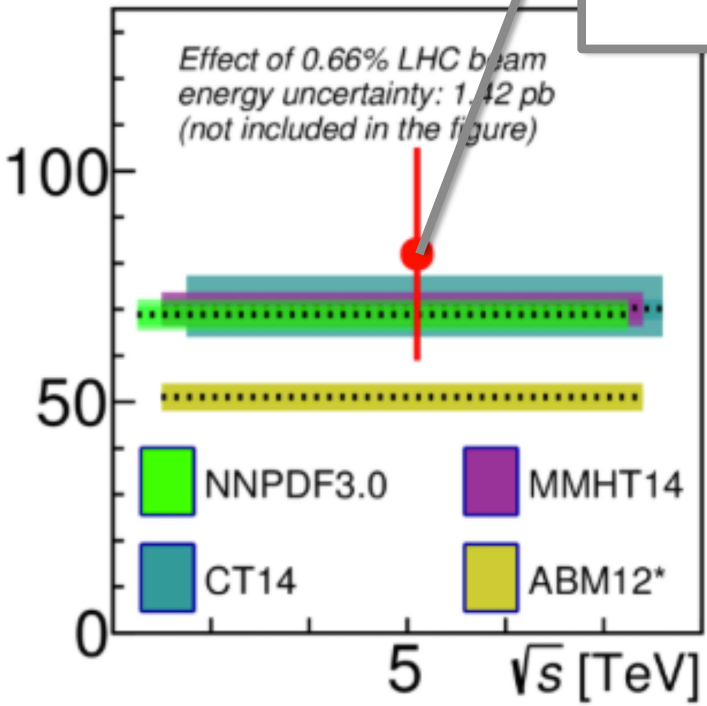
TOP-16-015

First measurement at this energy!

- Reference for future measurement with heavy ions.
- Potential to constrain high-x gluon PDF
- Total uncertainty ~25% (statistics dominate)

Incl. σ_{tt} measurements





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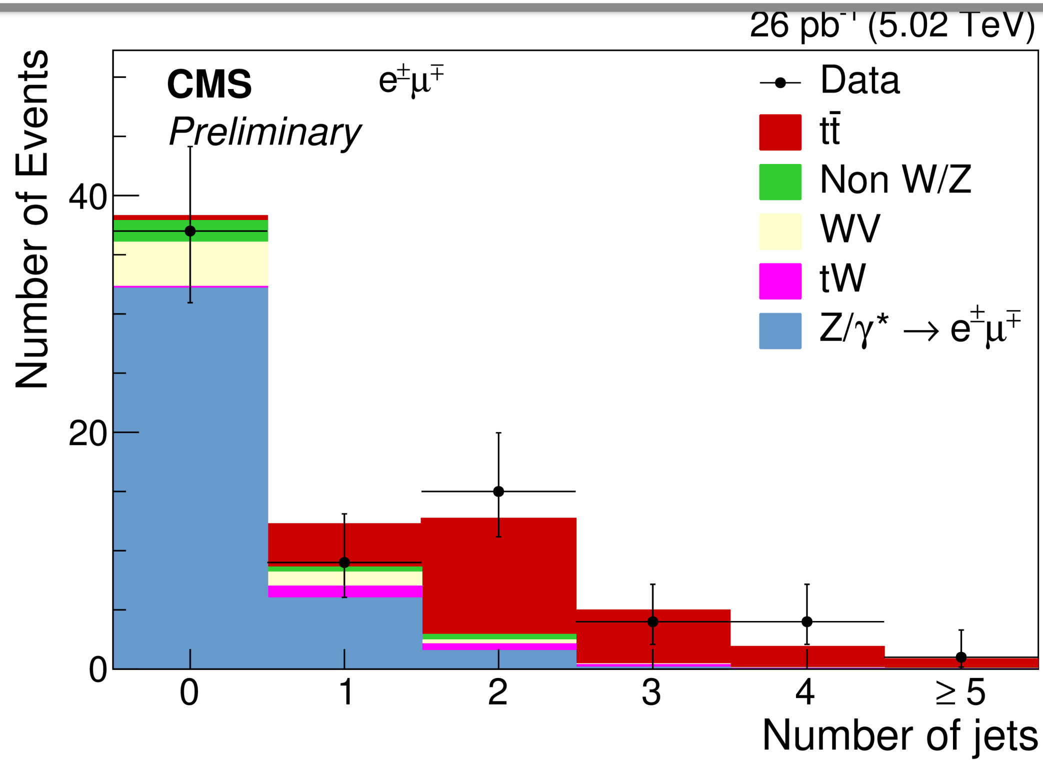
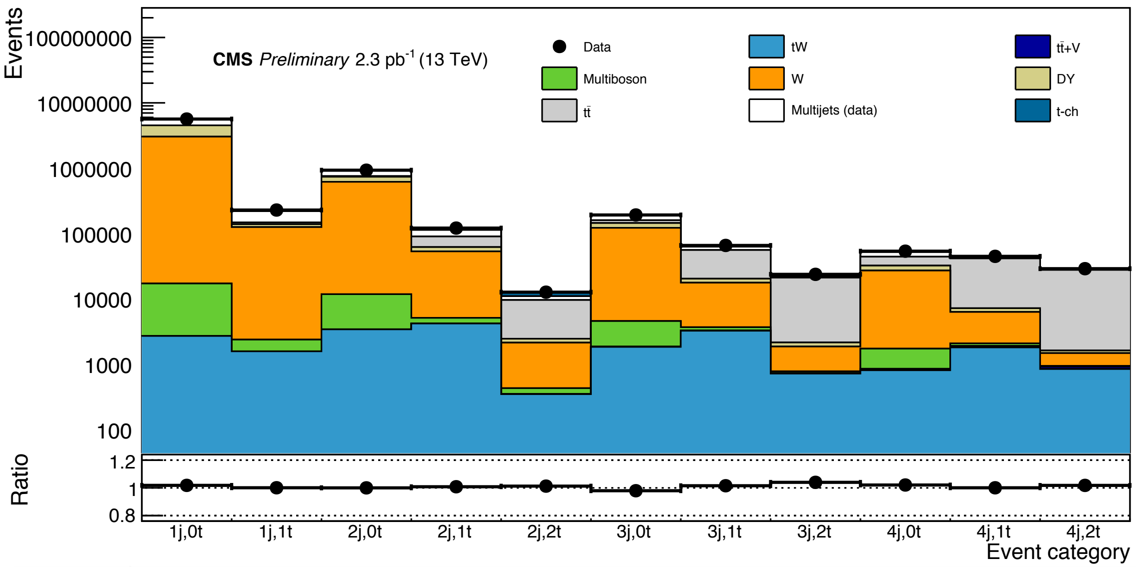


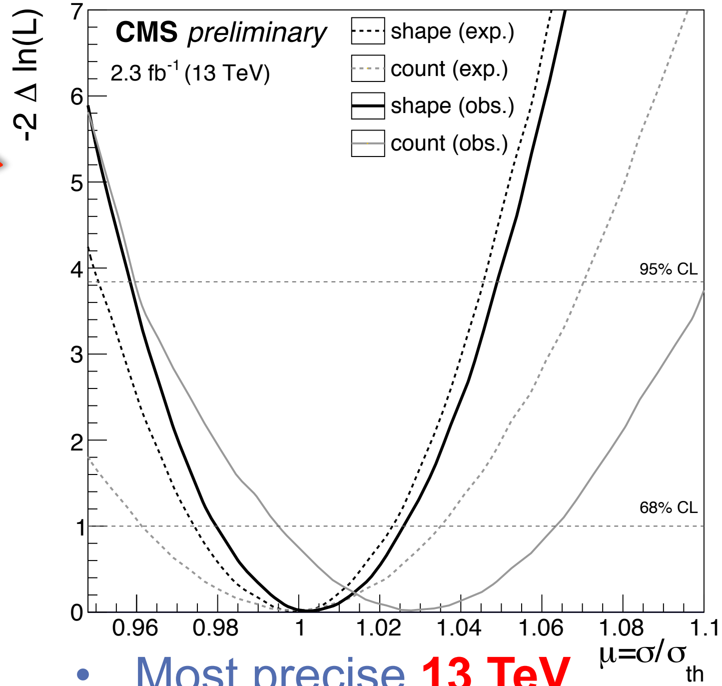
Incl. σ_{tt} measurements

NEW

TOP-16-006 – e/μ +jets channel at 13 TeV

- Shape fit in 44 lepton charge (b) jet multiplicity categories.
- In-situ constraints on systematics
- Total uncertainty ~ **3.9%**

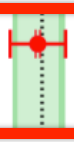




- Most precise **13 TeV** CMS measurement so far
- Largest uncertainties:
  - W+jets bkg. modelling
  - Luminosity
- Extraction of M_{top} (pole)

  $m_t = 172.3^{+2.7}_{-2.3}$ GeV

CMS, l+jets *
CMS-PAS TOP-16-006
L_{int} = 2.3 fb^{-1}, 25 ns

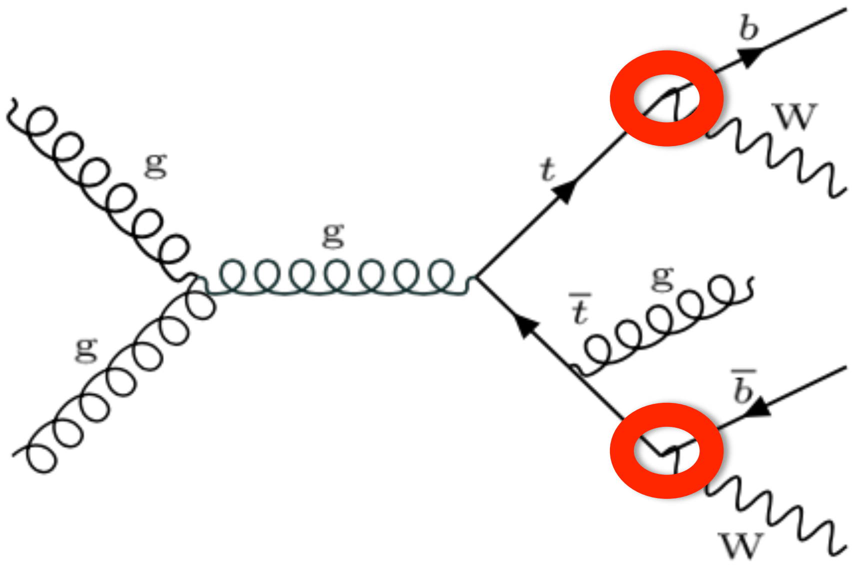


835 ± 3 ± 23 ± 23 pb

See talk from E. Bouvier on M_{top} extraction

measuring σ_{tt} differentially

Top quark definitions

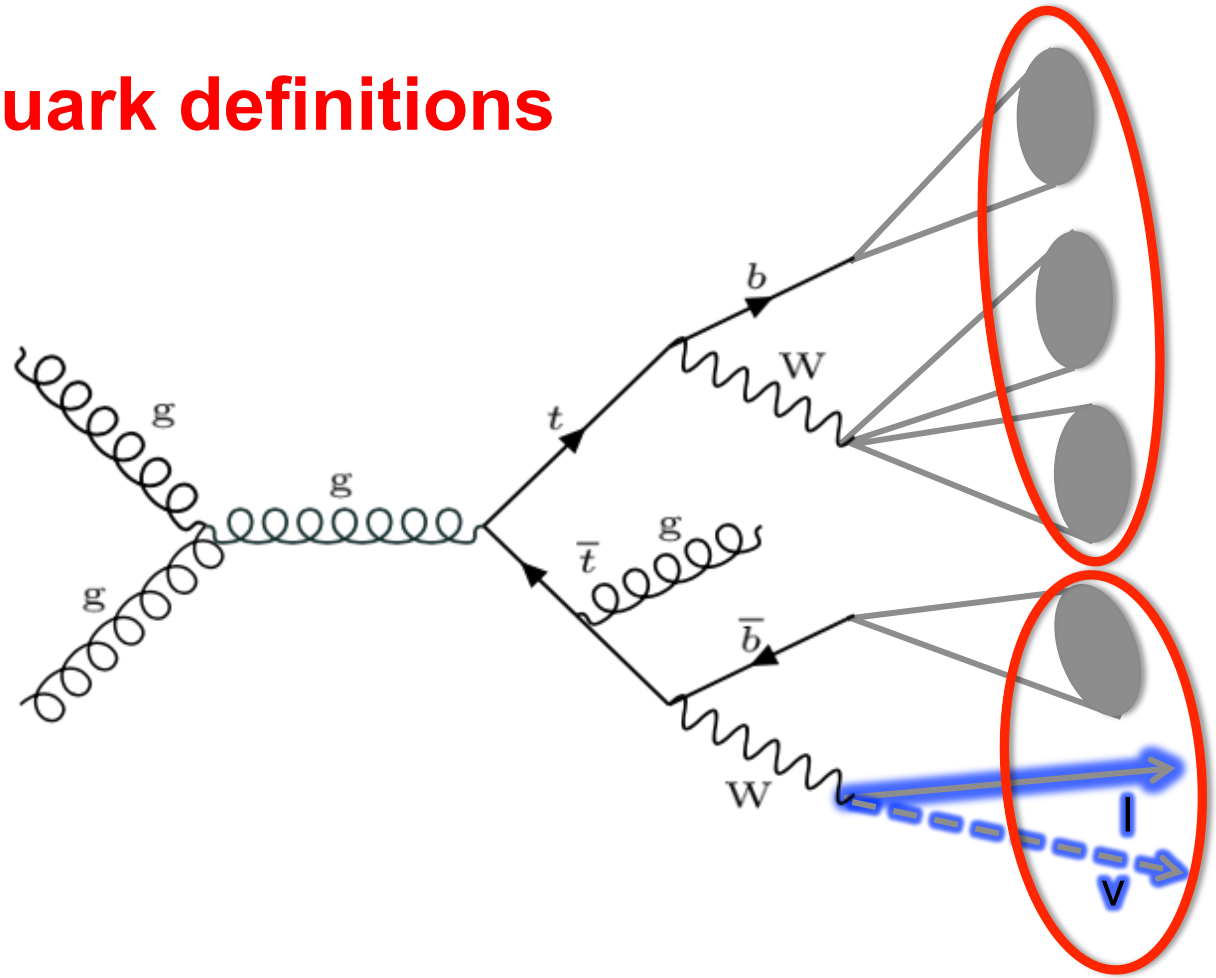


Parton-level:

top quark after radiation but before decay

measuring σ_{tt} differentially

Top quark definitions



Particle-level:

top quark proxy reconstructed from decay products after hadronisation

differential σ_{tt}

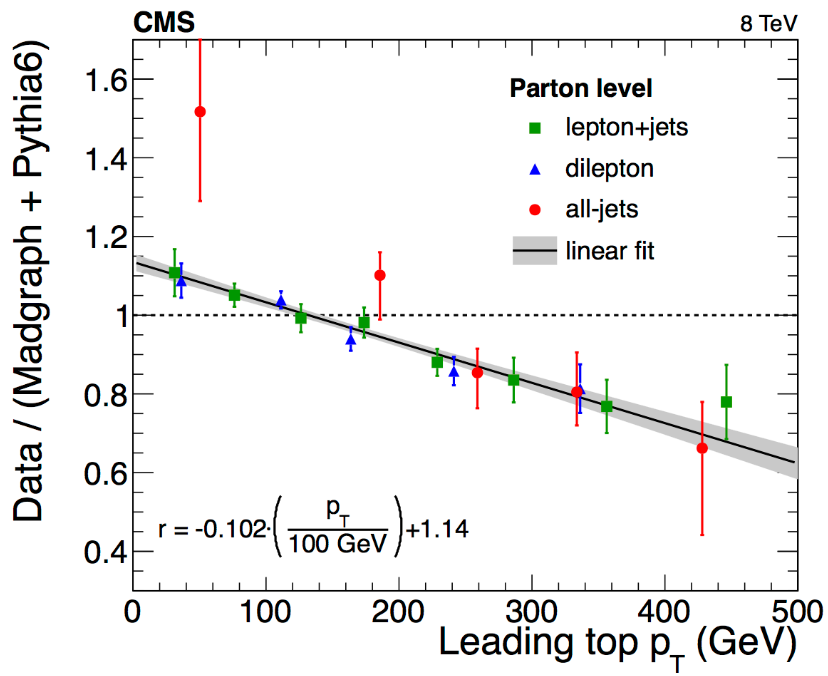
TOP-14-018, TOP-12-028, TOP-15-011
(arXiv:1509.06076, arXiv:1505.04480)

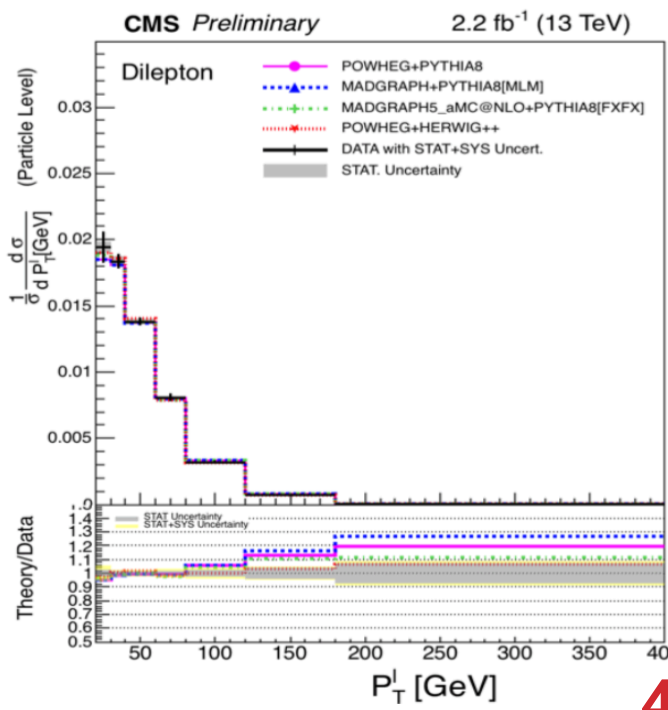
- Differential cross sections at **8 TeV**
  - Comparisons to NLO MC generators and N^{N}LO QCD predictions
  - **Miss-modelling of top Pt spectrum observed in all decay channels.**

NEW

TOP-16-007

- Differential cross sections in the eμ channel at particle-level at **13 TeV**
  - Miss-modelling of top Pt spectrum re-confirmed at particle-level
  - Similar results at 13 TeV parton-level (TOP-16-008, TOP-16-011)





differential σ_{tt}

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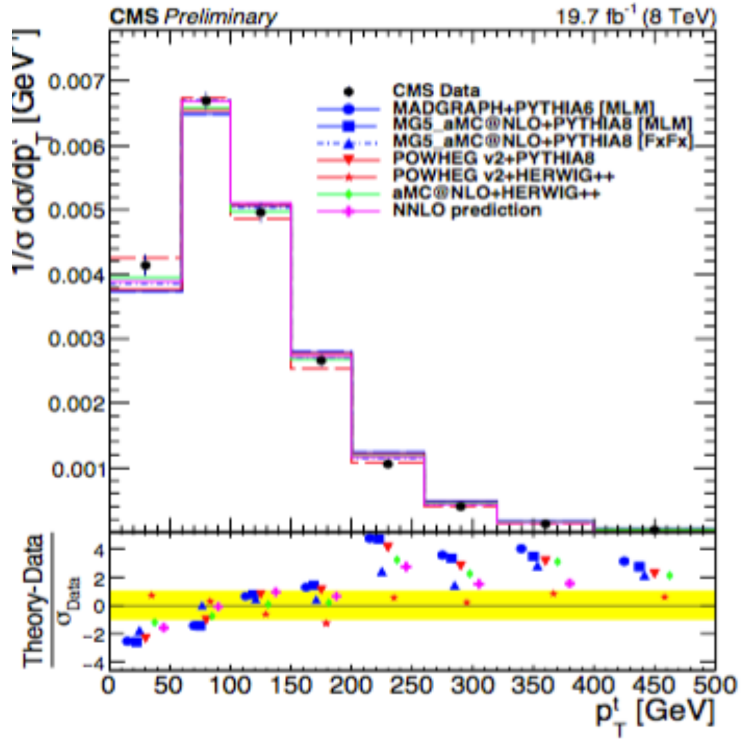
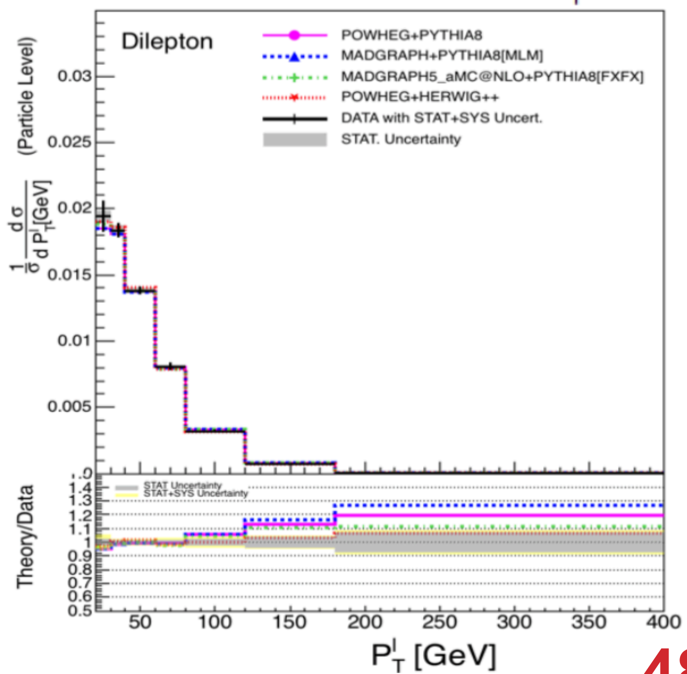
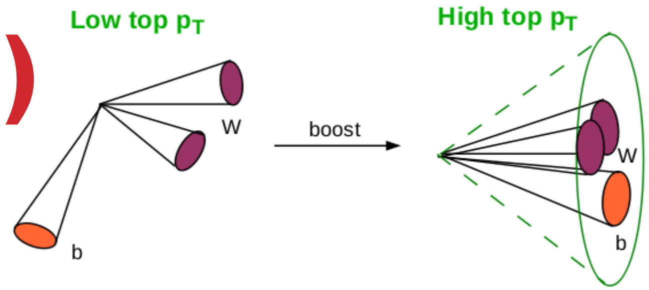




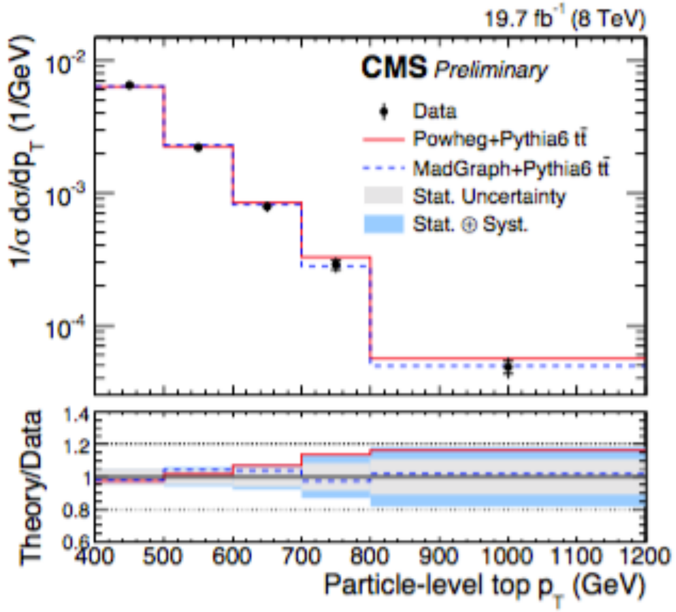
differential σ_{tt} (boosted)



Boosted **reconstruction**

-> hadronic top decay reconstructed in one jet

-> jet substructure techniques used to ***tag*** tops



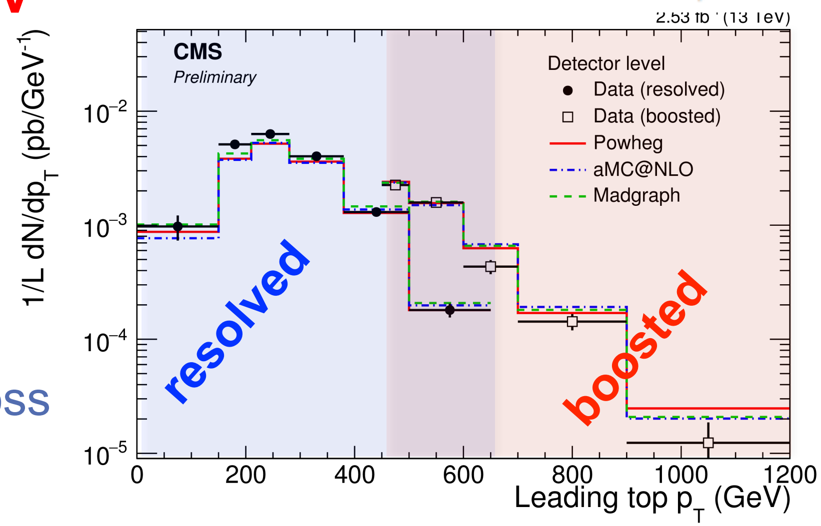
TOP-14-012 (arXiv:1605.00116)

- Parton and particle level at **8 TeV**
  - P_t >400 GeV
  - Pt mis-modelling observed again

TOP-16-013

Boosted **&** resolved reconstruction at **13 TeV**

- top P_t measured from **0 -> 1.2 TeV** at parton and detector levels
- compared to MC generator predictions
- P_t in data softer than MC prediction across spectrum



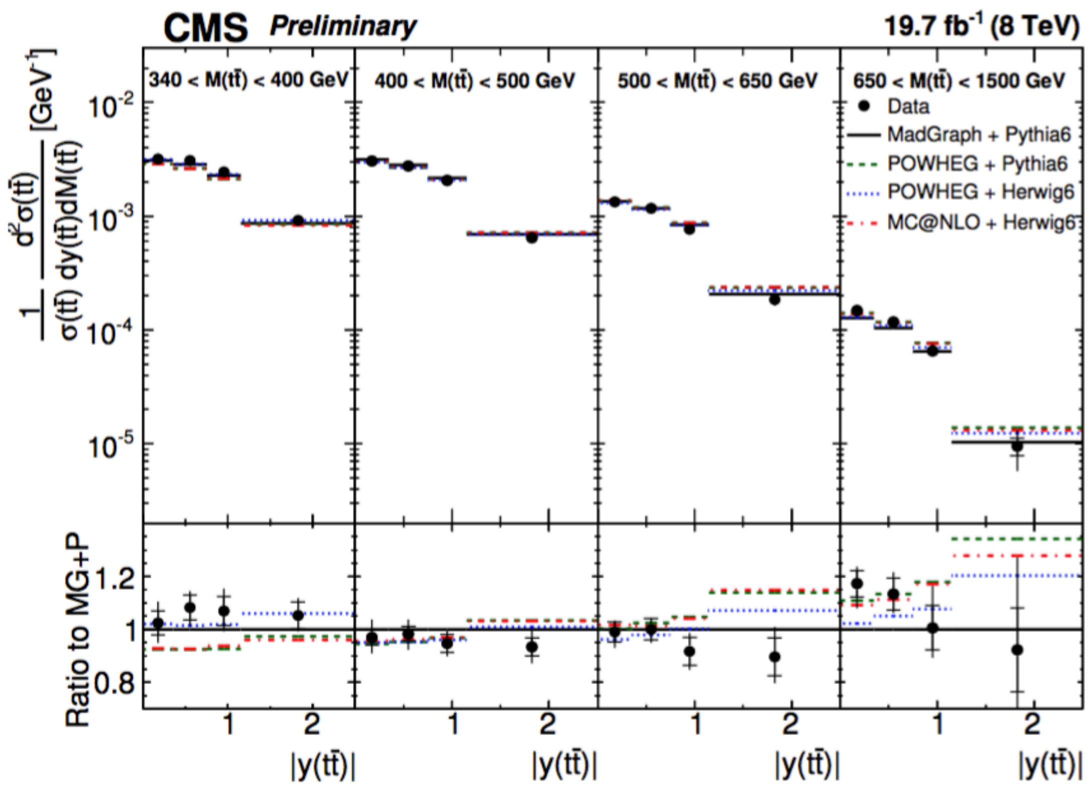
differential σ_{tt}

NEW

[TOP-14-013]()

Double-differential tt cross sections at 8 TeV

- first measurement of this type at the LHC
- bin tt events in two variables e.g., $Pt_{top} - y_{top}$, $M_{tt} - y_{tt}$
- $M_{tt} - y_{tt}$ especially sensitive to PDFs
- 2D distributions provide stronger PDFs constraints than 1D



differential σ_{tt}

NEW

TOP-14-013

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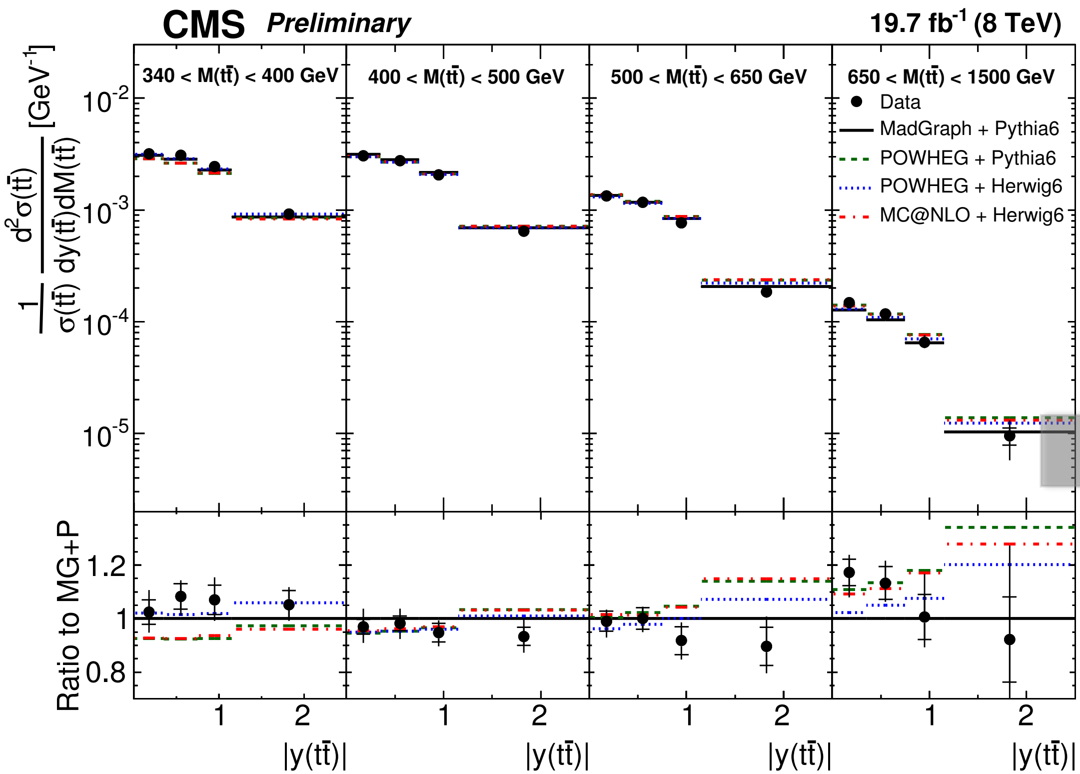
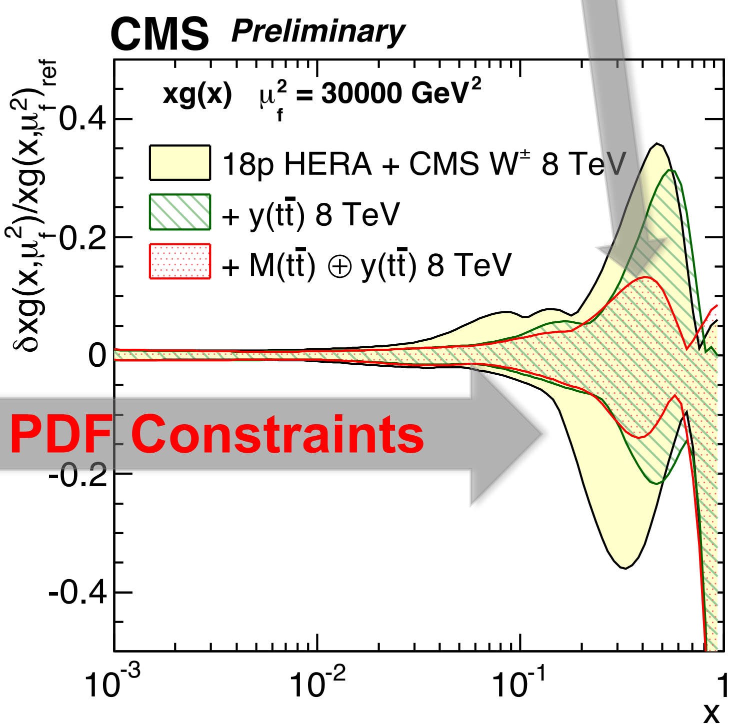
Significant reduction of uncertainty at high-x



PDF Constraints



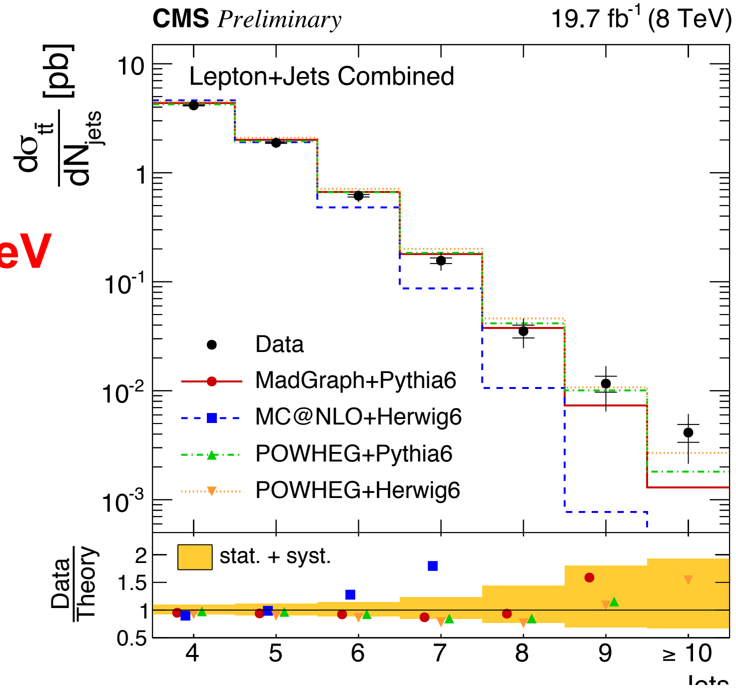
tt+jets, tt+bb

NEW

TOP-15-006, TOP-15-011

- Measurement of tt+jets, tt+jj cross sections at **8TeV**
- Jet multiplicity well modelled by most generators
- tt+jj cross section in agreement with prediction (*JHEP* **07 (2014) 135**)

Category	$d\sigma/dN_{jets}$ [pb]	Stat.	Exp.	Theor.	Total
$t\bar{t} \to \ell + 4$ jets	4.15	1.0%	6.2%	5.3%	8.6%
$t\bar{t} \to \ell + 5$ jets	1.88	1.3%	7.4%	7.0%	10.6%
$t\bar{t} \to \ell + 6$ jets	0.615	2.6%	8.7%	8.5%	12.7%
$t\bar{t} \to \ell + 7$ jets	0.156	5.9%	13.6%	11.7%	19.1%
$t\bar{t} \to \ell + 8$ jets	0.0352	13.4%	19.1%	19.3%	30.4%
$t\bar{t} \to \ell + 9$ jets	0.0116	16.7%	24.3%	33.3%	44.6%
$t\bar{t} \to \ell + \geq 10$ jets	0.00413	18.7%	27.9%	34.6%	48.3%

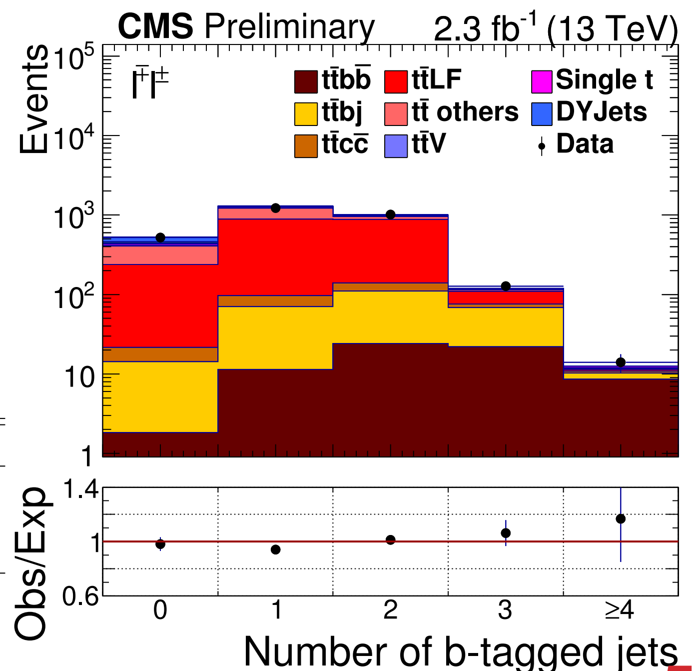


TOP-16-010

NEW

- tt+bb, tt+jj at particle level in visible region at **13TeV**
- Probes QCD, constrains bkd for tt +Higgs
- Results consistent with POWHEG MC prediction

Phase Space	$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$\sigma_{t\bar{t}jj}$ [pb]	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
Measurement			
Visible	$0.085 \pm 0.012 \pm 0.029$	$3.5 \pm 0.1 \pm 0.7$	$0.024 \pm 0.003 \pm 0.007$
Full	$3.9 \pm 0.6 \pm 1.3$	$176 \pm 5 \pm 33$	$0.022 \pm 0.003 \pm 0.006$
Simulation (POWHEG)			
Visible	0.070 ± 0.009	5.1 ± 0.5	0.014 ± 0.001
Full	3.2 ± 0.4	257 ± 26	0.012 ± 0.001



tt+jets, tt+bb

NEW

TOP-15-006, **TOP-15-011**

- Measurement of tt+jets, tt+jj cross sections at **8TeV**
- Jet multiplicity well modelled by most generators
- tt+jj cross section in agreement with prediction (*JHEP* 07 (2014) 135)

Category	$d\sigma/dN_{jets}$ [pb]	Stat.	Exp.	Theor.	Total
$t\bar{t} \to \ell + 4$ jets	4.15	1.0%	6.2%	5.3%	8.6%
$t\bar{t} \to \ell + 5$ jets	1.88	1.3%	7.4%	7.0%	10.6%
$t\bar{t} \to \ell + 6$ jets	0.615	2.6%	8.7%	8.5%	12.7%
$t\bar{t} \to \ell + 7$ jets	0.156	5.9%	13.6%	11.7%	19.1%
$t\bar{t} \to \ell + 8$ jets	0.0352	13.4%	19.1%	19.3%	30.4%
$t\bar{t} \to \ell + 9$ jets	0.0116	16.7%	24.3%	33.3%	44.6%
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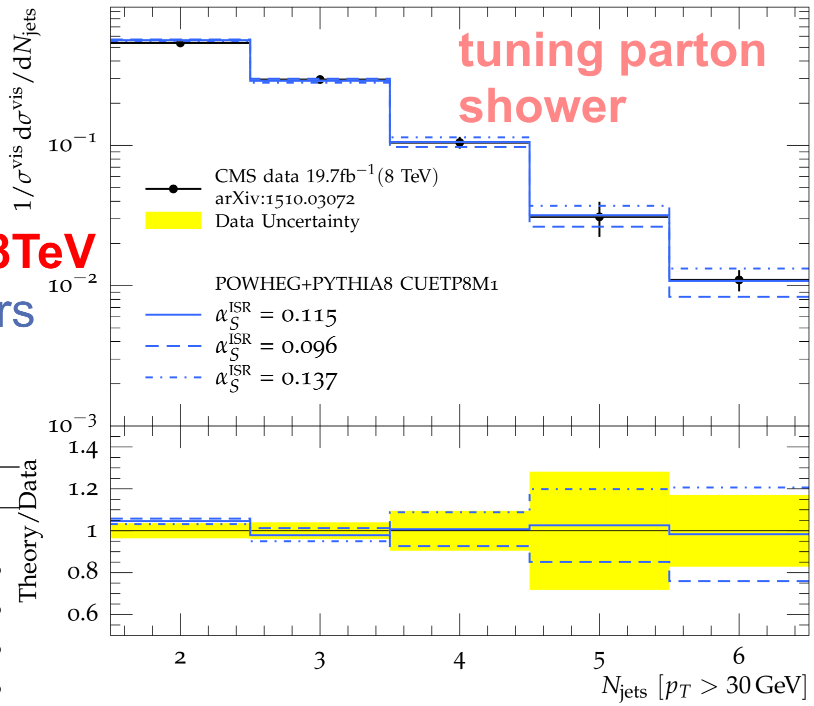

TOP-16-010

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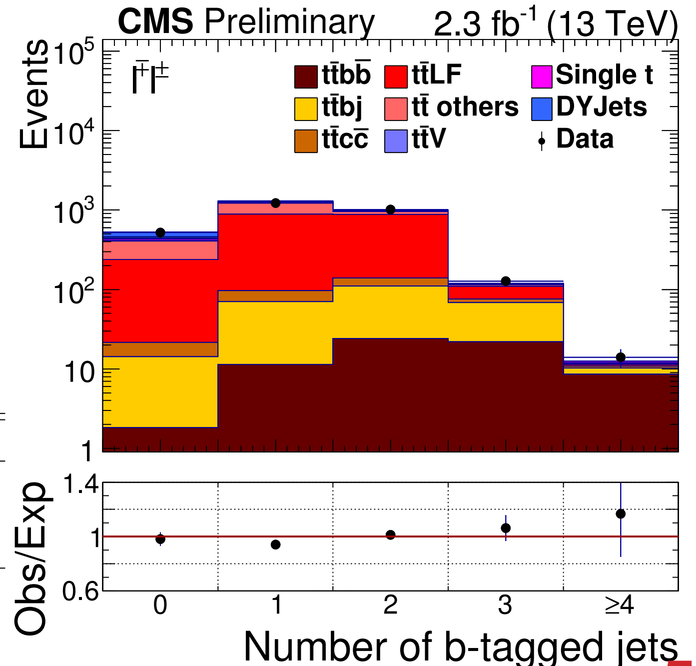


tttt

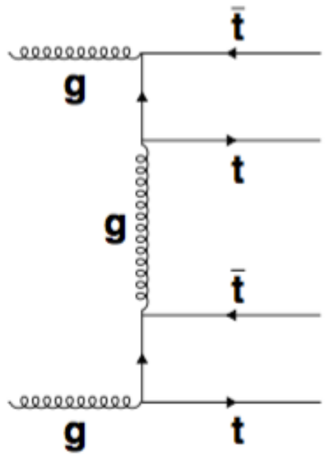
TOP-16-016 –

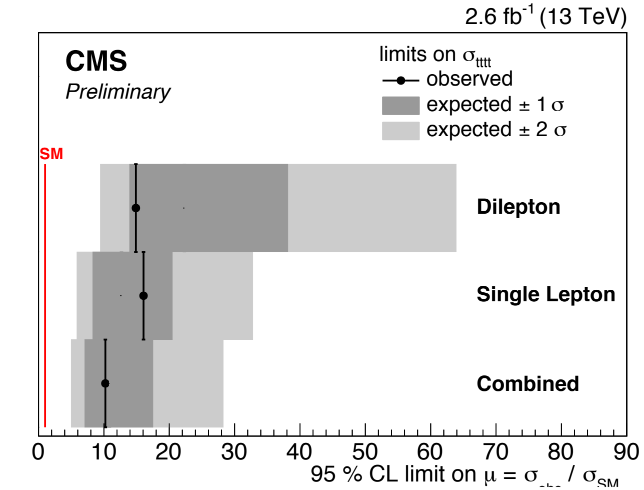
Search for SM four top production

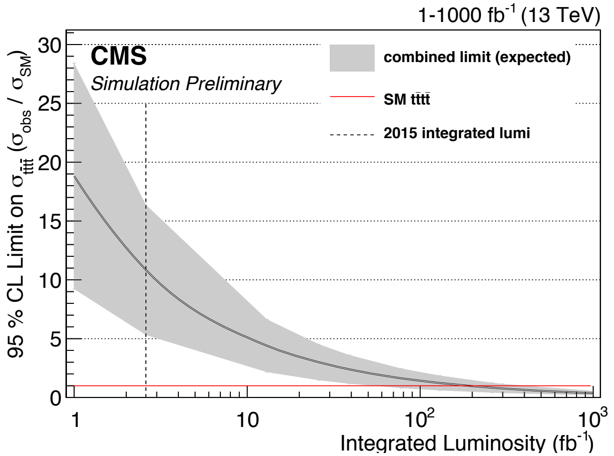
- Extremely rare SM process $\sigma_{tttt} \sim 9$ fb
- Sensitive to new physics
- Combining single- and dilepton channels
- Fit to multivariate discriminator in (b)jet categories

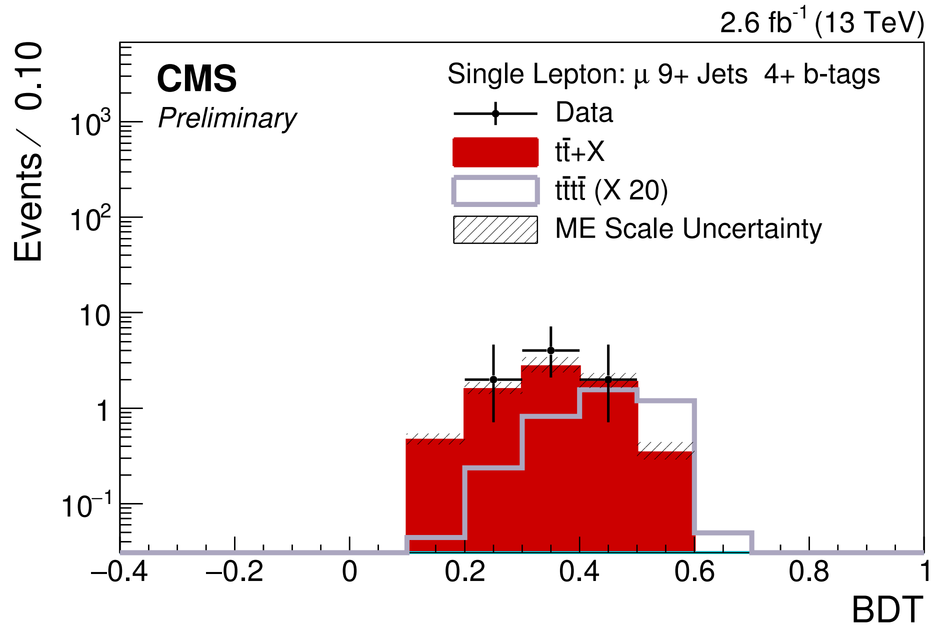
NEW

SM









- **Obs. (exp.) limits 10 (11) x SM σ_{tttt}**
  - **Sensitivity limited by statistics**
  - **Factor of 2 increase in sensitivity wrt 8 TeV results**

tttt

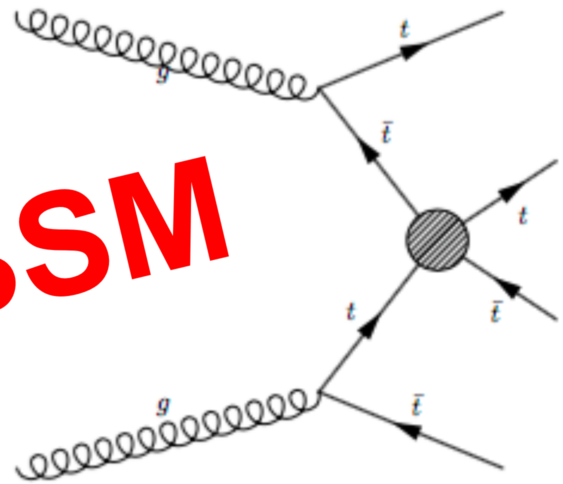
TOP-16-016 –

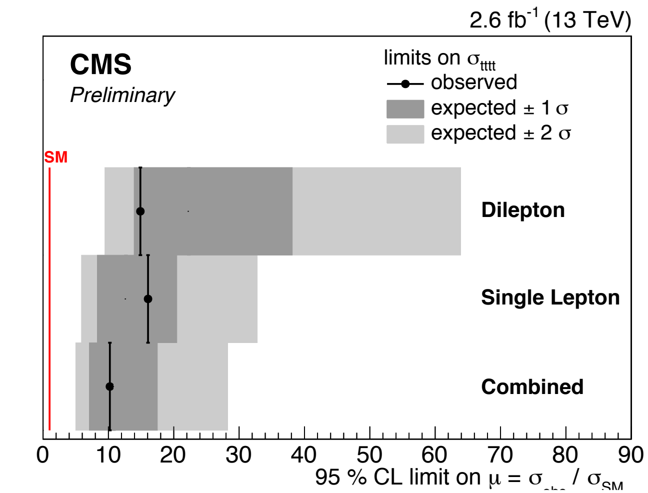
Search for SM four top production

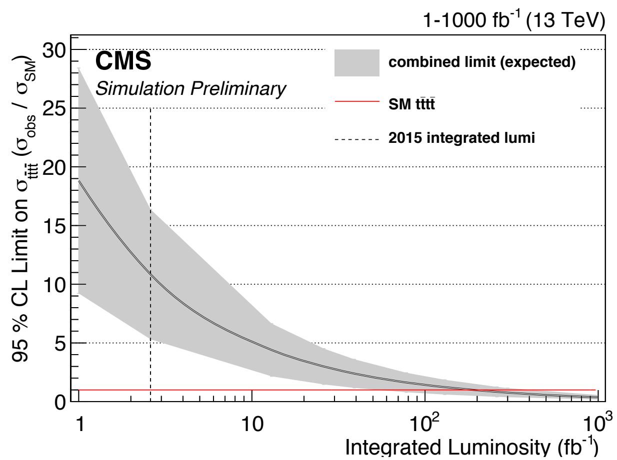
- Extremely rare SM process $\sigma_{tttt} \sim 9$ fb
- Sensitive to new physics
- Combining single- and dilepton channels
- Fit to multivariate discriminator in (b)jet categories

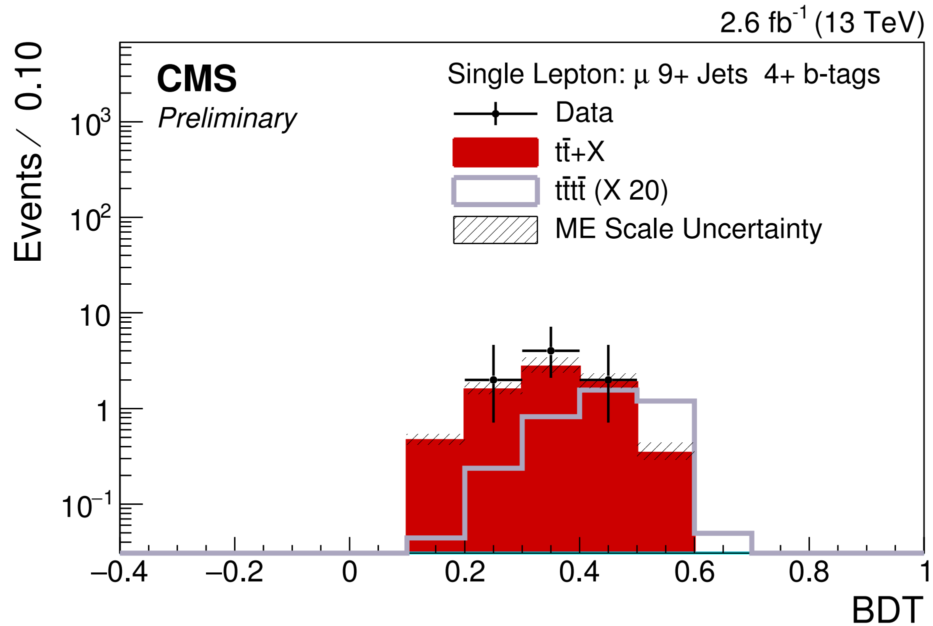
NEW

BSM









- **Obs. (exp.) limits 10 (11) x SM σ_{tttt}**
  - **Sensitivity limited by statistics**
  - **Factor of 2 increase in sensitivity wrt 8 TeV results**

CONCLUSIONS AND OUTLOOK

Broad range of tt cross section measurements from CMS:

- **Incl. tt - results consistent with SM**
  - Constraints on light stops, PDFs and m_t
- **1D differential - top Pt spectrum mis-modelled**
  - NNLO predictions describe the data better
- **2D differential - deeper probe of modelling**
  - 2D measurements constrain PDFs at high-x
- **tt+jets,tt+bb - particle-level measurements**
  - tune MC prediction and constrain ttbb background for ttH
- **tttt - combined search in single and dilepton channels**
  - **world’s tightest limit on SM tttt production**

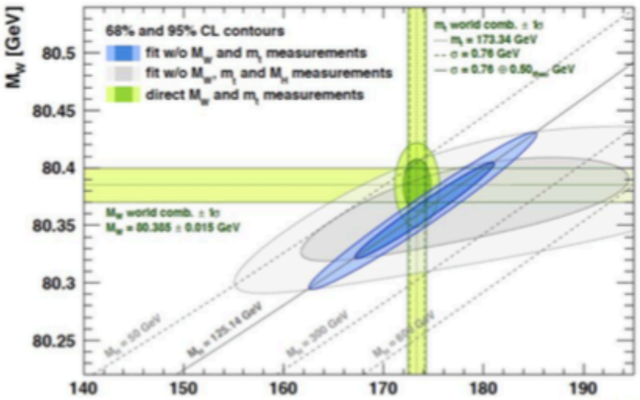
BACKUP

TOP QUARK PHYSICS

Testing the Standard Model

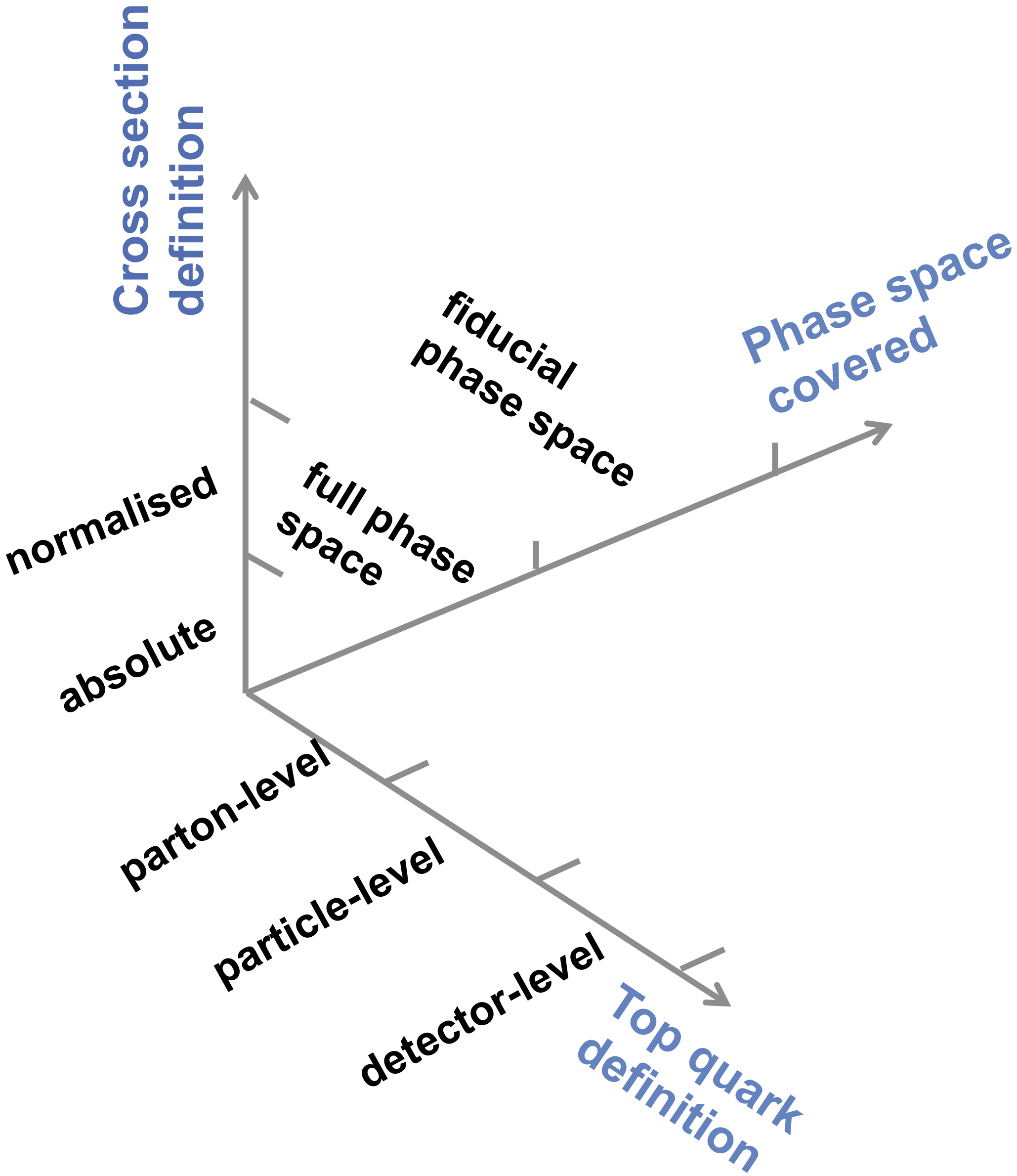
- Unprecedented levels of precision in measurements of σ_{tt} and M_t

Self-consistency of the SM

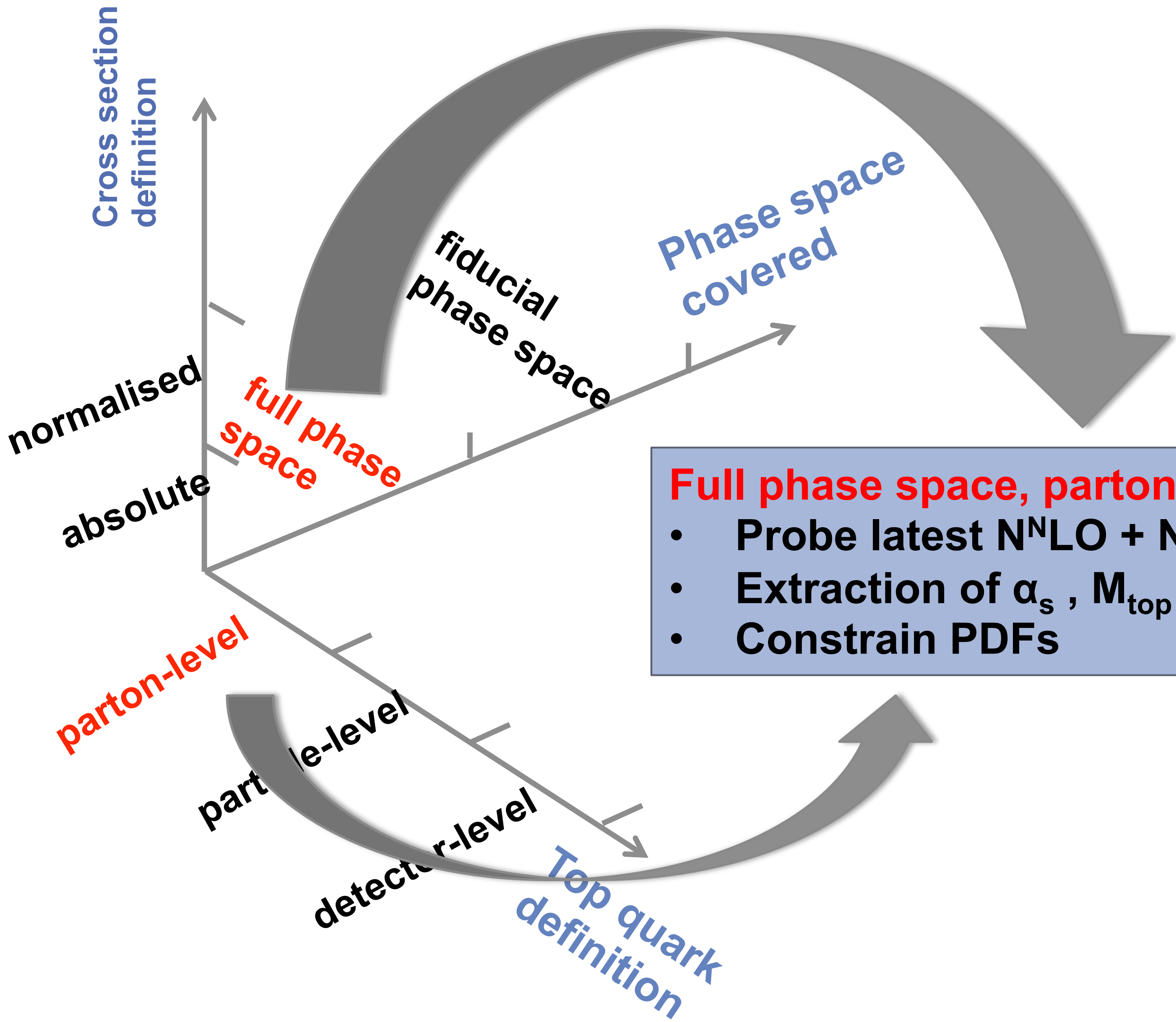


Baak *et al* 2014

DIFFERENTIAL MEASUREMENTS



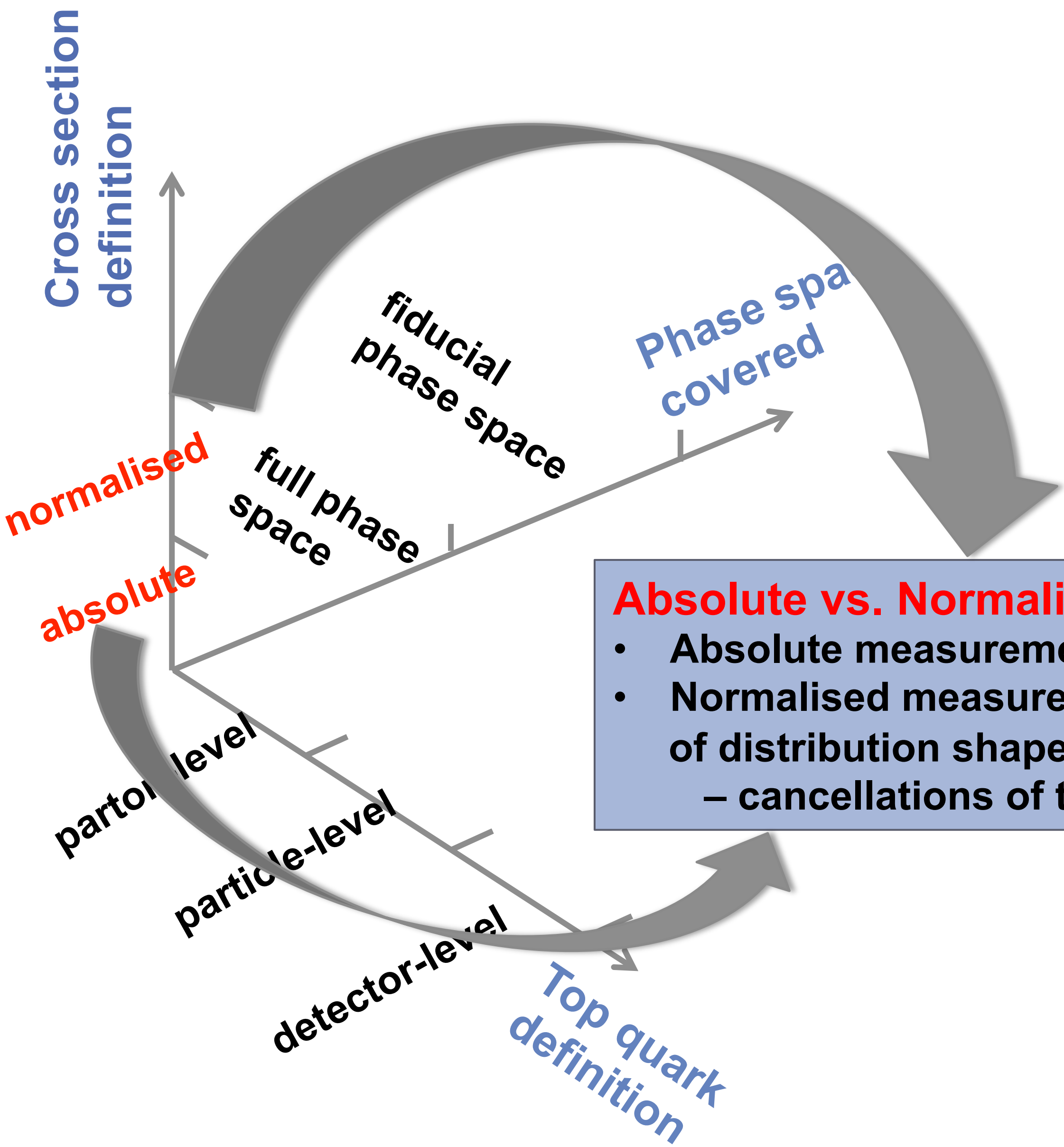
DIFFERENTIAL MEASUREMENTS



Full phase space, parton-level measurements

- Probe latest $N^NLO + N^NLL$ pQCD
- Extraction of α_s , M_{top}
- Constrain PDFs

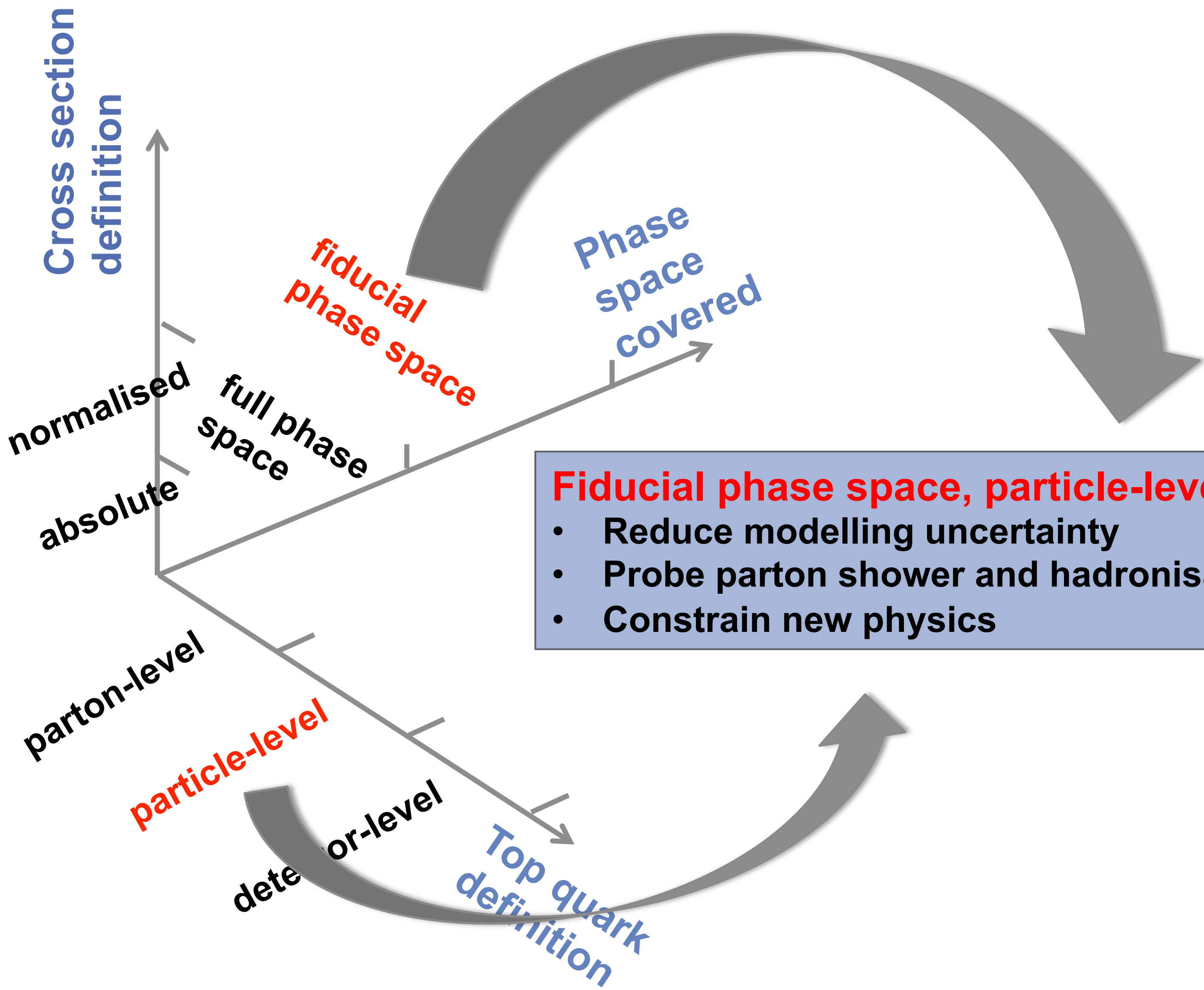
DIFFERENTIAL MEASUREMENTS



Absolute vs. Normalised measurements

- Absolute measurements reveal maximal information
- Normalised measurements allow more precise probes of distribution shapes
  - – cancellations of th. and exp. uncertainties

DIFFERENTIAL MEASUREMENTS

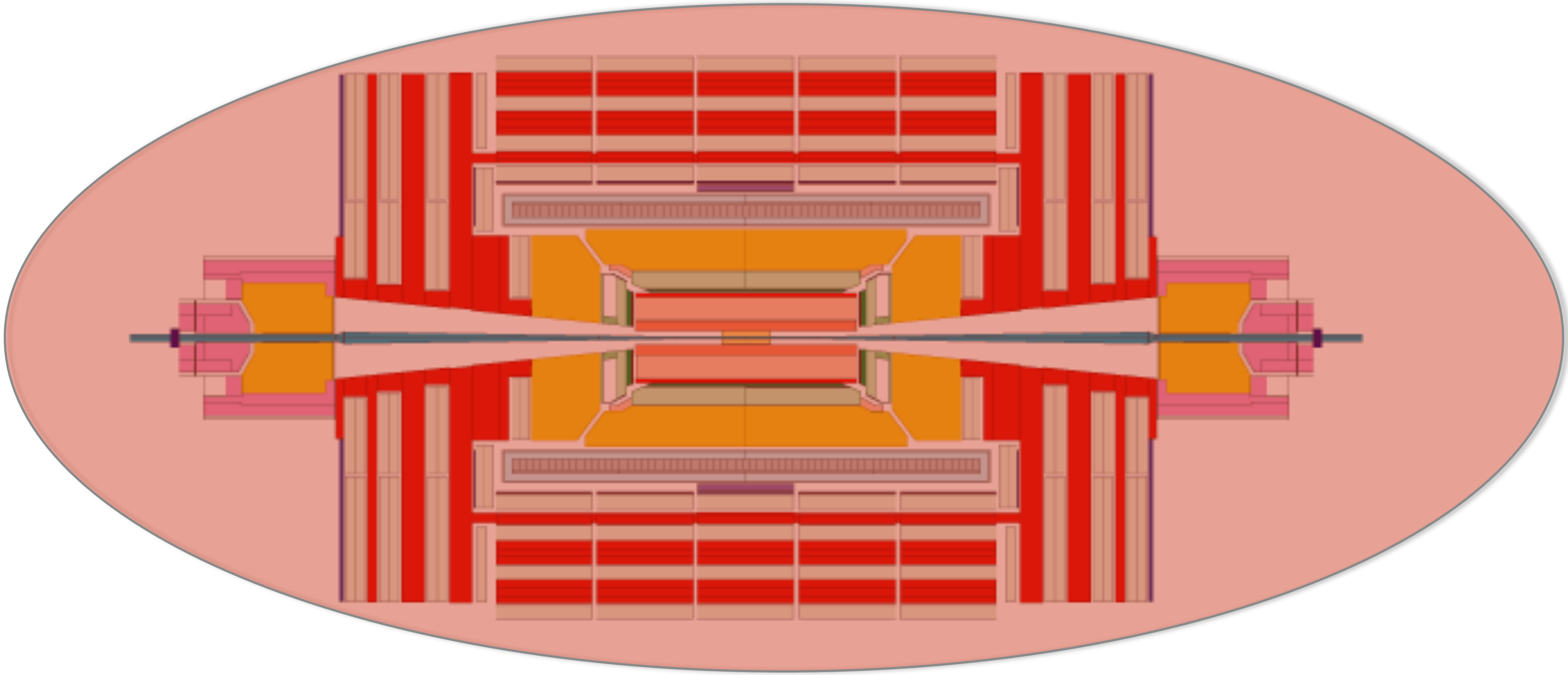


Fiducial phase space, particle-level measurements

- Reduce modelling uncertainty
- Probe parton shower and hadronisation models
- Constrain new physics

measuring tt differentially

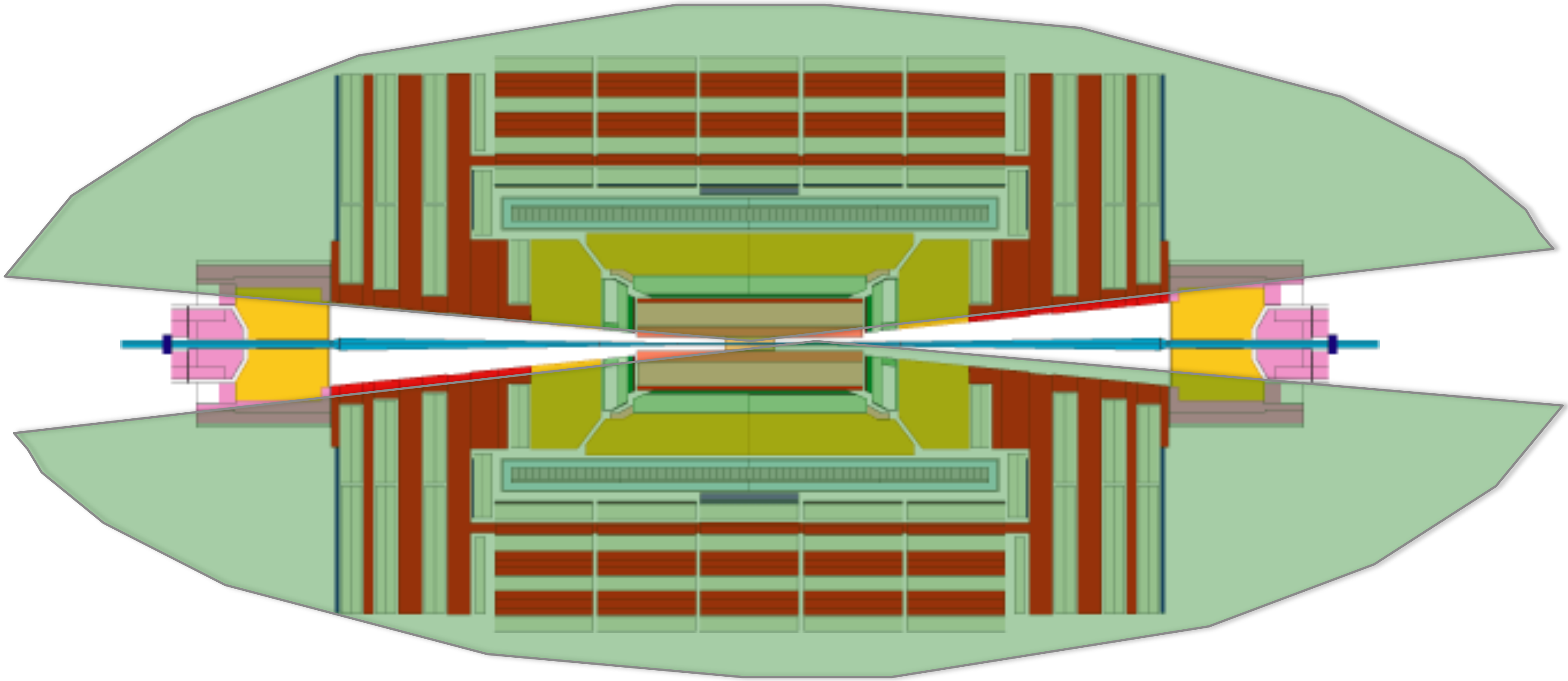
Top quark definitions



Full phase space:
Covers all possible tt kinematics.

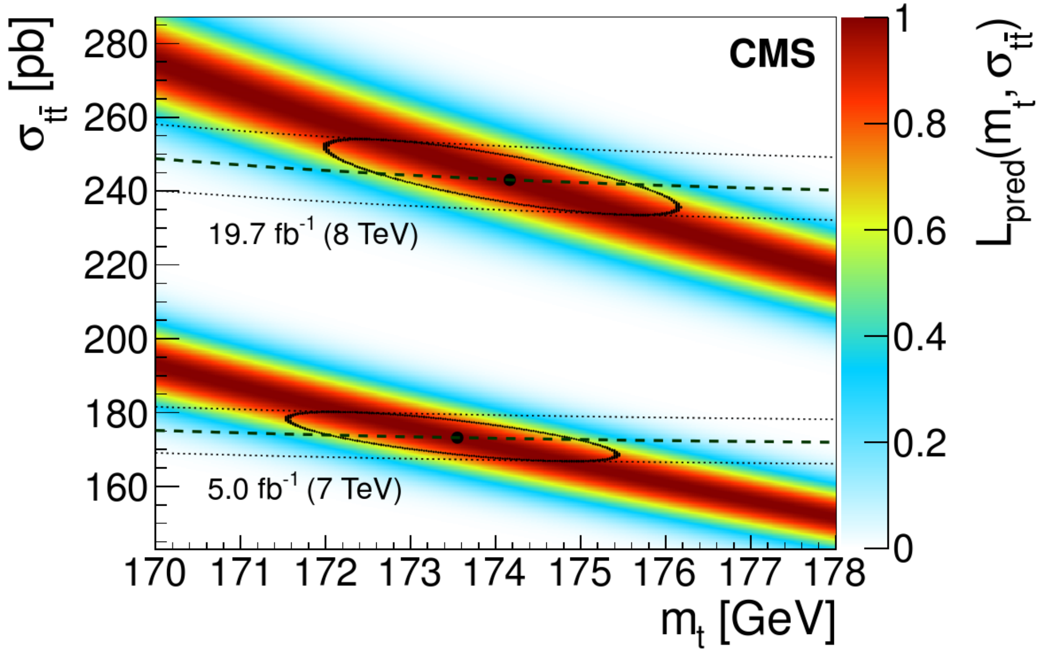
measuring tt differentially

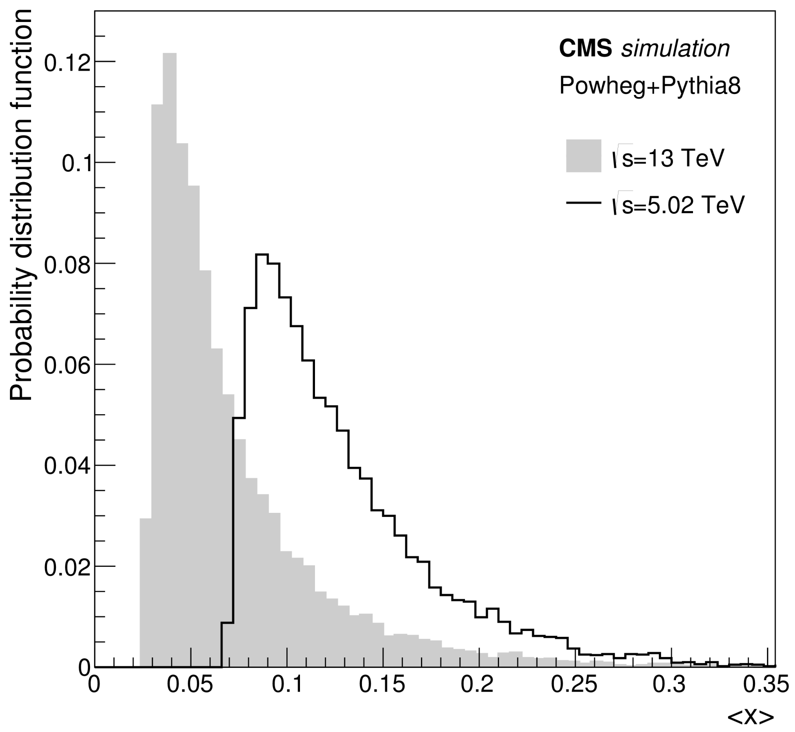
Top quark definitions



Visible phase space:
Kinematic region accessed by CMS detector

TOP-13-004

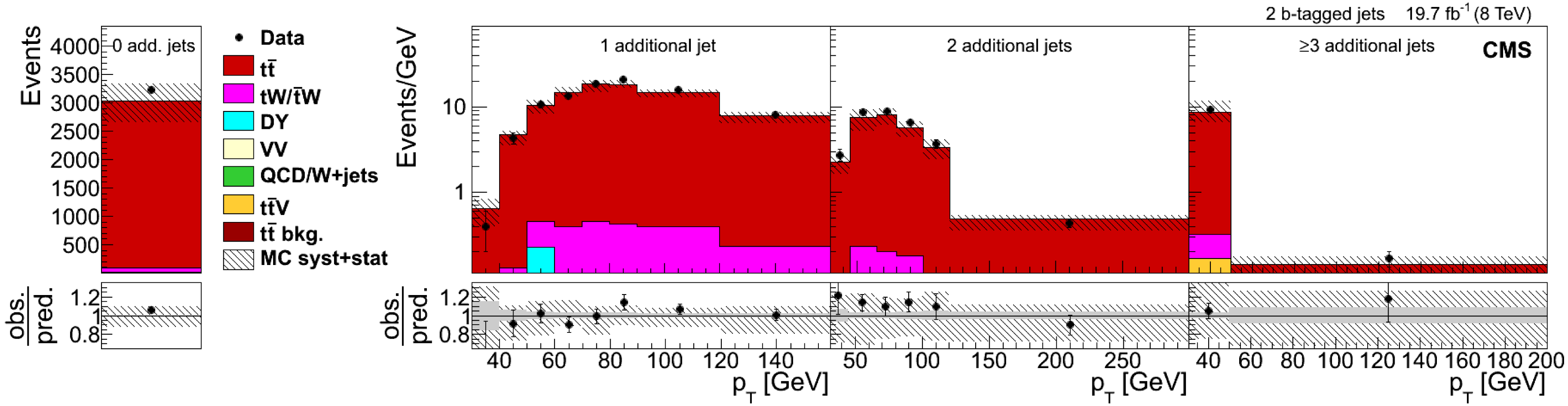


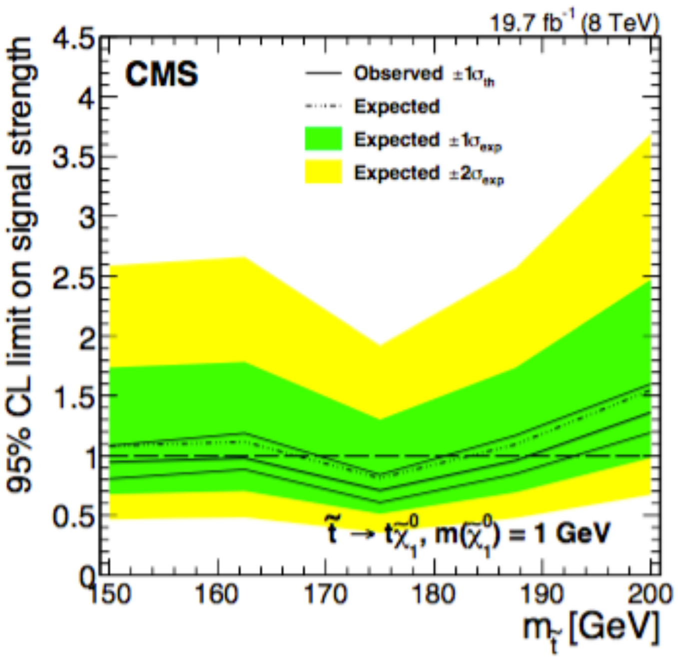


TOP-16-015

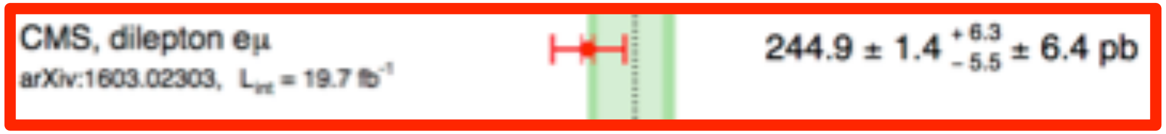
Incl. σ_{tt} measurements

TOP-13-004 –
tt cross sections in the eμ channel at 7 and 8 TeV





- Fit to Jet Pt in b and non-b jet categories



- **Total uncertainty ~ 3.7%**
- Extraction of M_{top} (pole) = **$173.8^{+1.7}_{-1.8}$ GeV**
- Limits on light stops