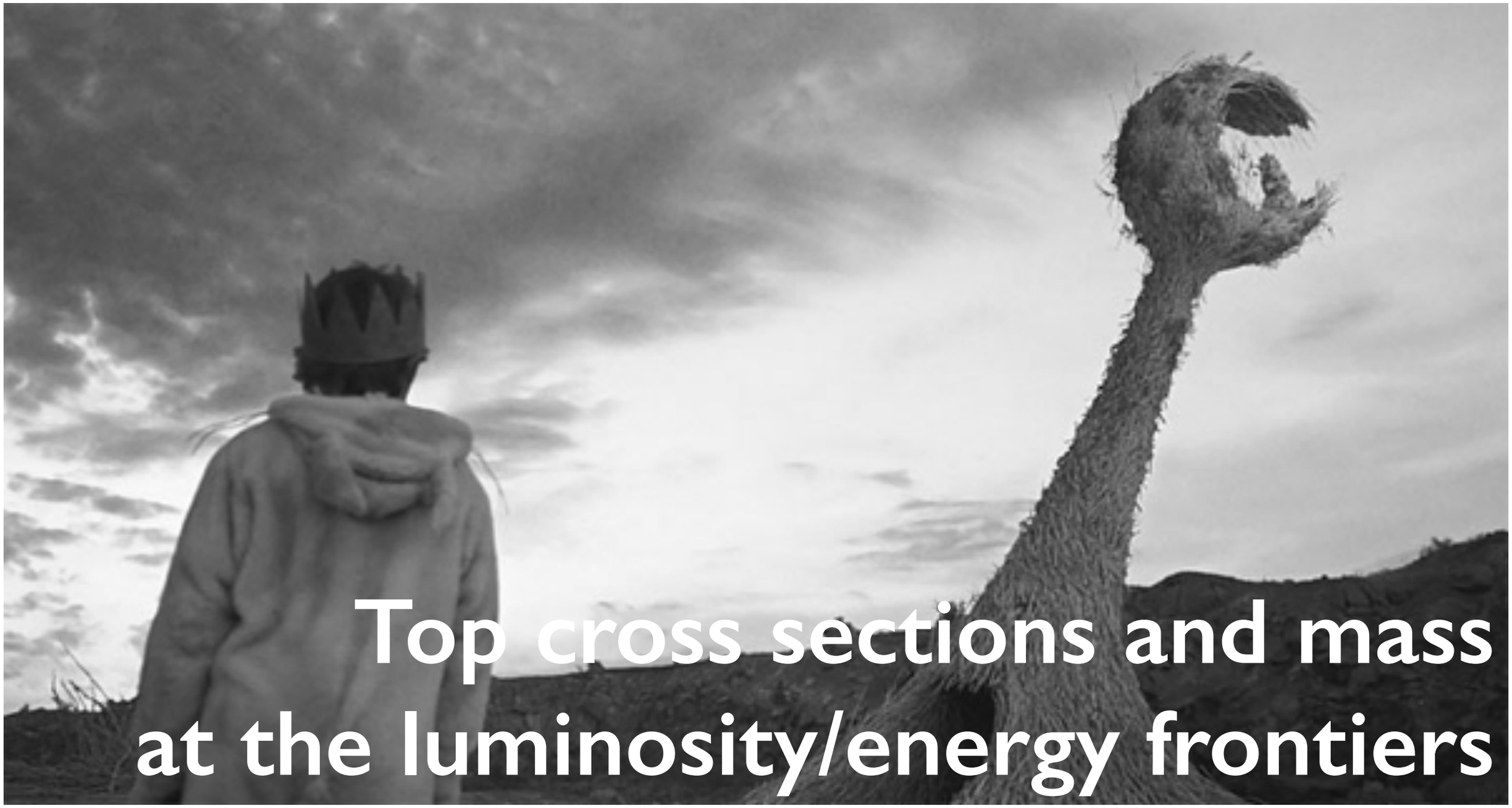


(c) Warner Bros. Pictures

Top cross sections and mass at the luminosity/energy frontiers

P. Ferreira da Silva (CERN)

on behalf of the ATLAS, CMS and LHCb collaborations

Workshop on the physics of HL-LHC and perspectives at HE-LHC

1st November 2017

Foreword - personal view

- **A HLHE-LHC YR is a unique opportunity to set generic strategies for future top analyses**
  - the YRs from the LHCHXSWG are a good example of this practice
- **For what follows, no need for other than fixed-order calculations/generator level studies**
  - **(m_t, α_S, PDFs) + search for new physics** (benchmarks, EFTs) = **compelling motivations**
    in the first case would be good to quantify the target precision needed for real impact (e.g. on ggH)
  - choose a couple of **benchmark measurements**: e.g. M(tt), $p_T(t)$, $y_{t\text{-}ch}(t)$, A_c, etc.
    - identify dominant **systematics** and forecast their **evolution**
    - special attention to **ratios**: quantify impact of HE-LHC/HL-LHC or HL-LHC/Run I type of scenarios
    - complementarity and **combination** of ATLAS / CMS / LHCb
- **Need input from theory and experiment**

⇒ a task force within the LHCtopWG is the natural place to align the required inputs

Outlook

Cross-sections state of the art and current challenges

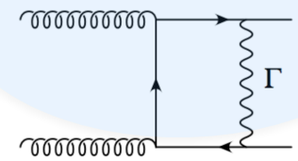
probing new physics beyond the systematics barrier

Top mass en route to a legacy LHC measurement

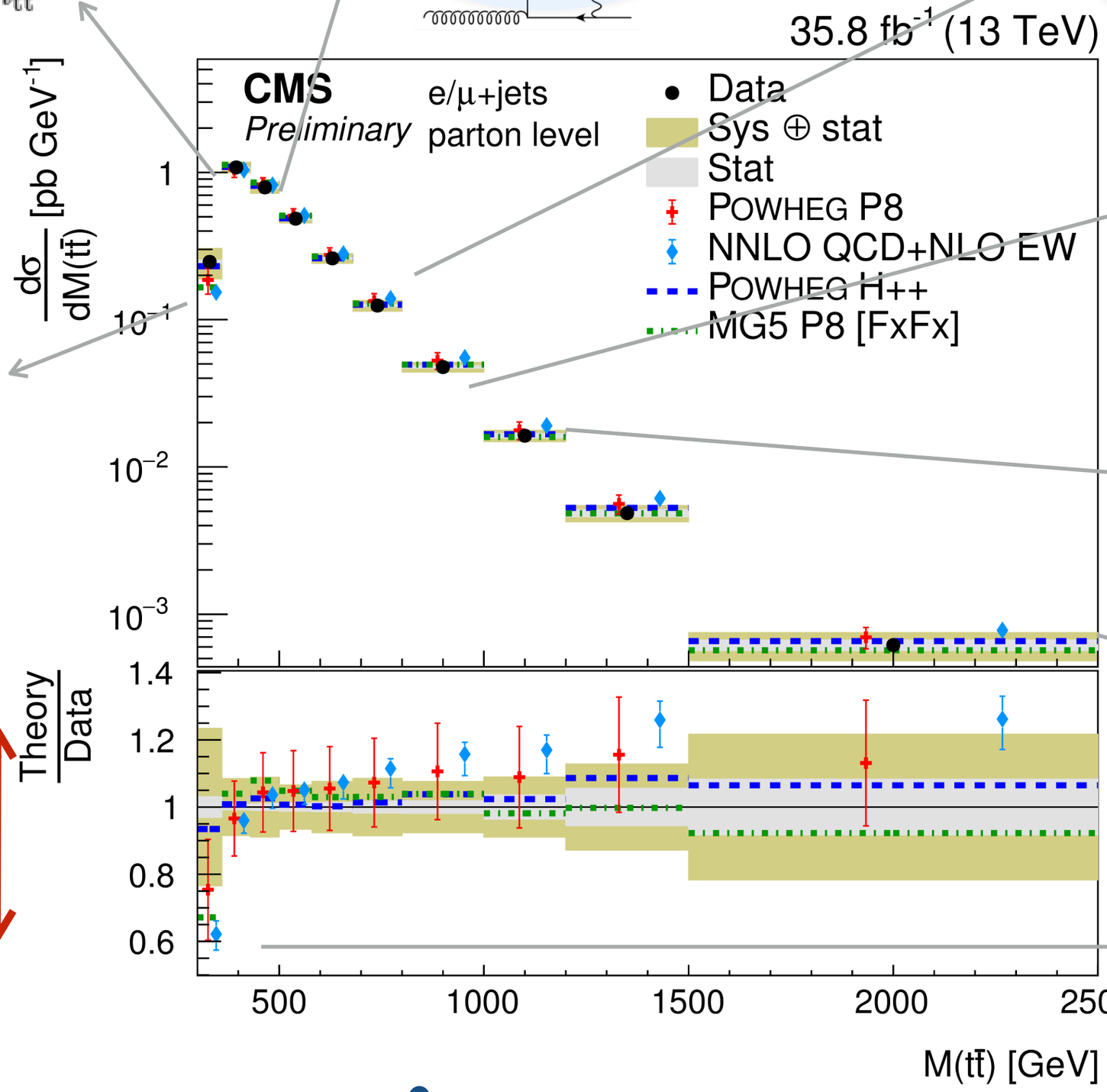
Pole mass scan
JHEP 0901:047,2009

$$\frac{\Delta m_t}{m_t} \sim 1.2 \frac{\Delta m_{t\bar{t}}}{m_{t\bar{t}}}$$

Sensitivity to EW corrections (Z,γ,H)
PRD 91, 014020 (2015)



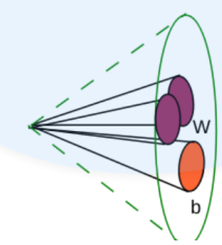
Elusive signs of new physics
PRD 90, 014008 (2014)
10.1007/JHEP01(2015)092



Bump hunting
H→tt, Z'→tt

Near threshold QCD production modes
JHEP 1009:034,2010

Entering the boosted regime



PDFs, α_S at high x

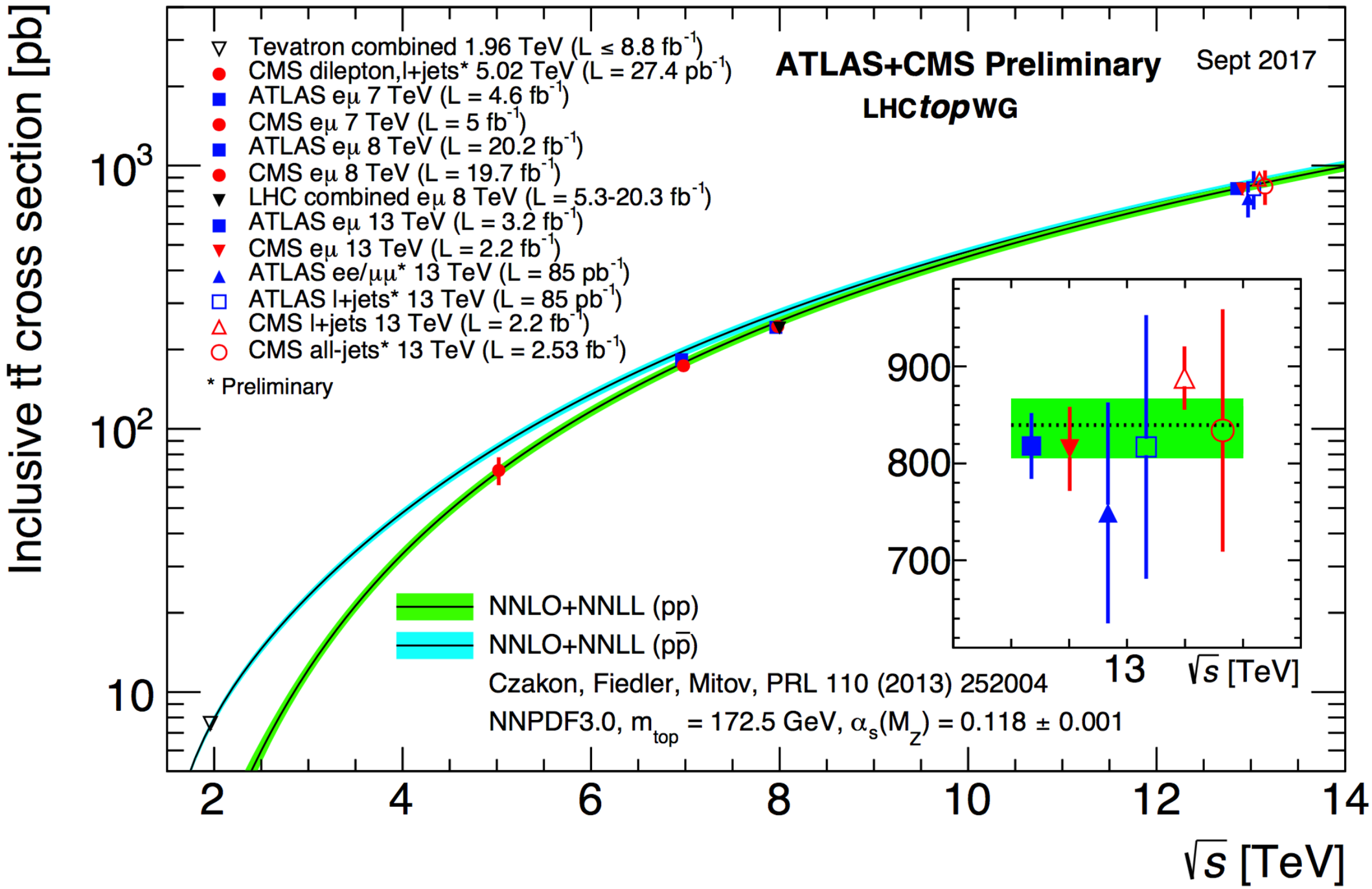
many ???
large δ_{syst}

Top mass running?

$$m_t = m_t(\mu)$$

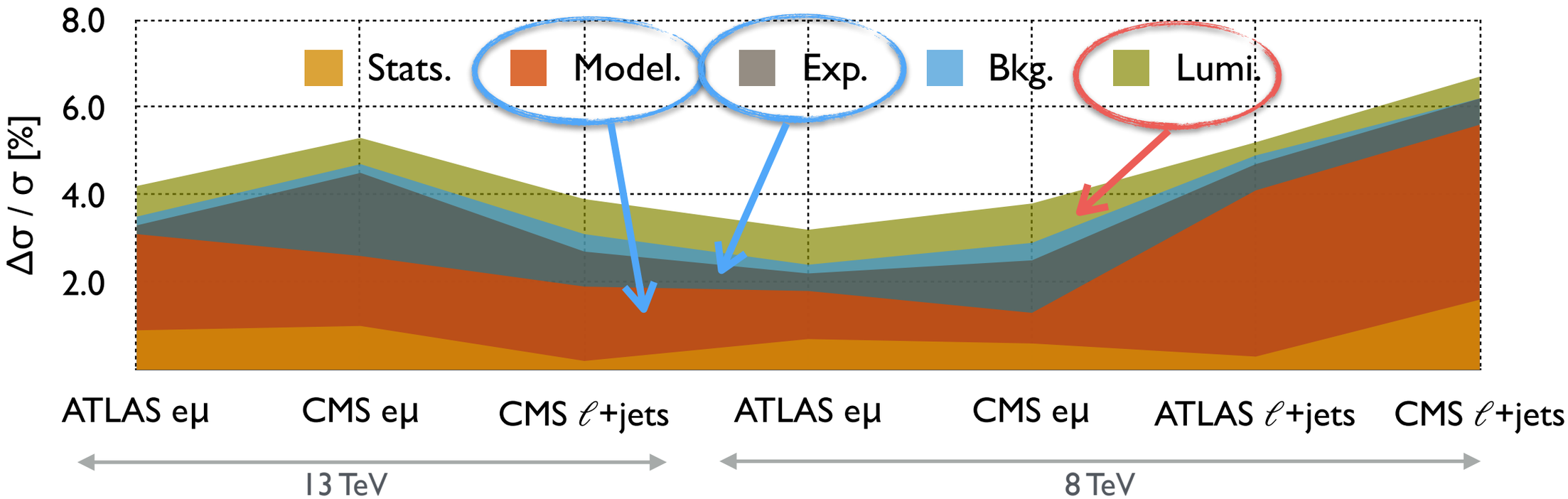
Cross-sections

Top pair cross sections



- **Several measurements have been performed at 4 pp centre-of-mass energies**
  - overall good agreement with NNLO+NNLL QCD prediction, $\frac{\delta\sigma_{th}}{\sigma_{th}} \sim \frac{\delta\sigma_{exp}}{\sigma_{exp}}$

Main uncertainties



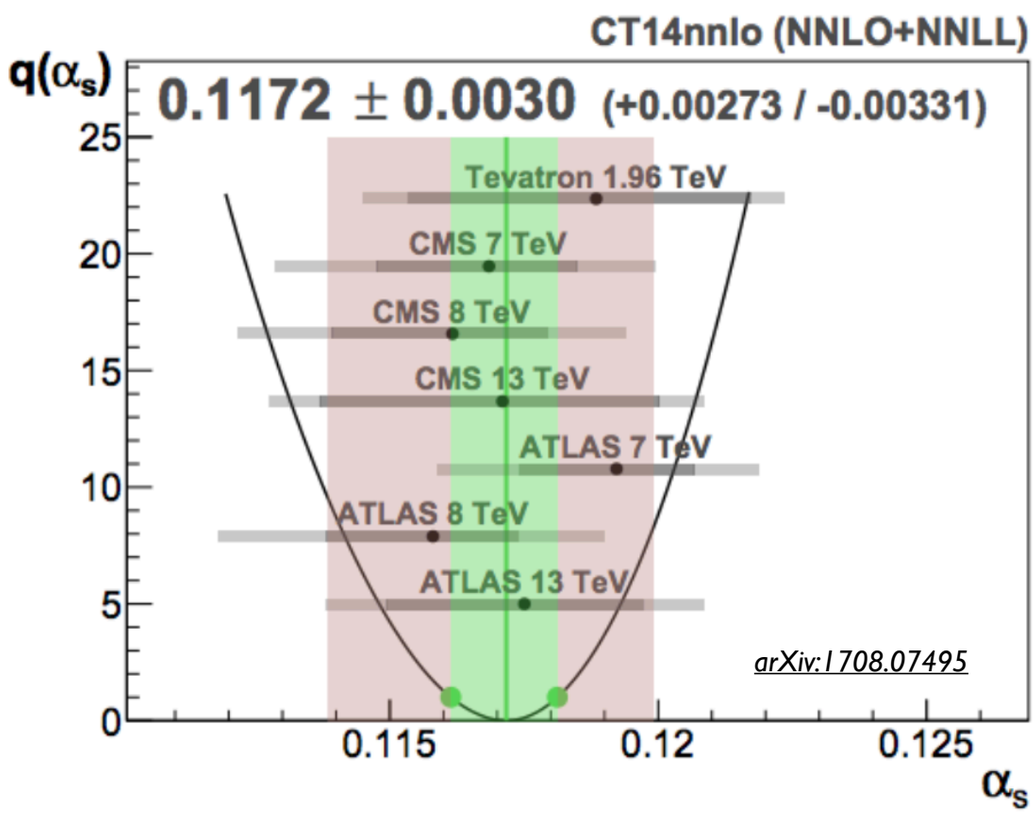
- **Modelling uncertainties non-negligible despite widespread use of NLO MC at 13 TeV**
  - impact of parton shower related uncertainties is non-negligible (main MC is Powheg)
  - partially reducible with ancillary measurements and in-situ profiling
- **Trigger/selection efficiency uncertainties**
  - still potential for improving, but challenging to maintain inclusive triggers with low thresholds
- **Integrated luminosity**
  - uncertainties limited by x-y correlations and length scale determination in VdM scans
  - LHCb has shown capability of achieving 1.2% unc. in luminosity with beam imaging (see backup)

$\sigma_{t\bar{t}}$ and fundamental parameters

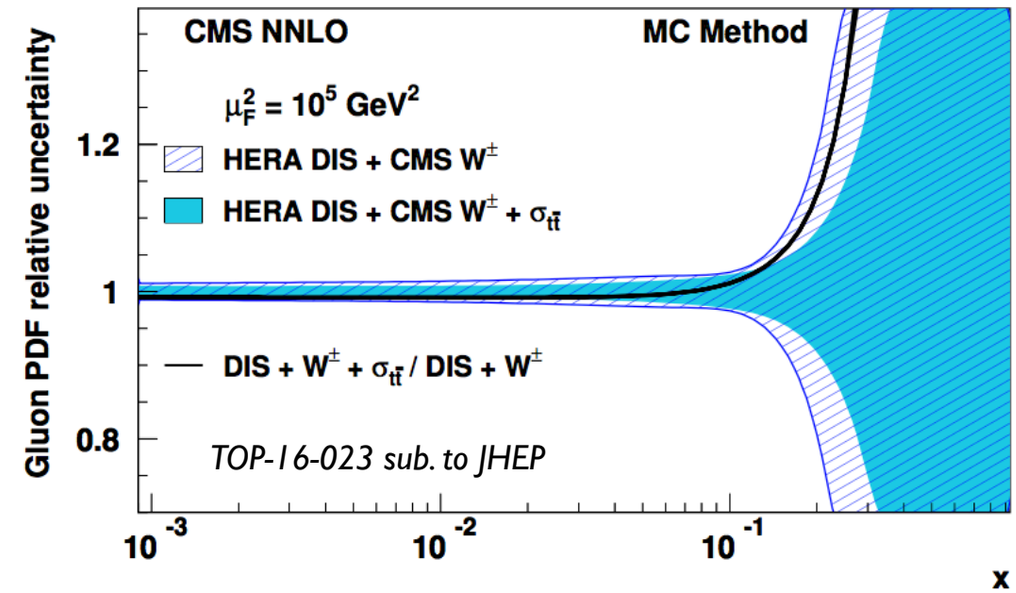
- **Individual extraction of m_t or α_S** (or PDFs)
  - crucial to minimise dependence of acceptance on parameter being extracted
  - extrapolation uncertainties dominated by the impact of the QCD scale choice

⇒ tendency to prefer dilepton final states which can be triggered with looser requirements

α_S extracted with ≅2.6% unc. ▼



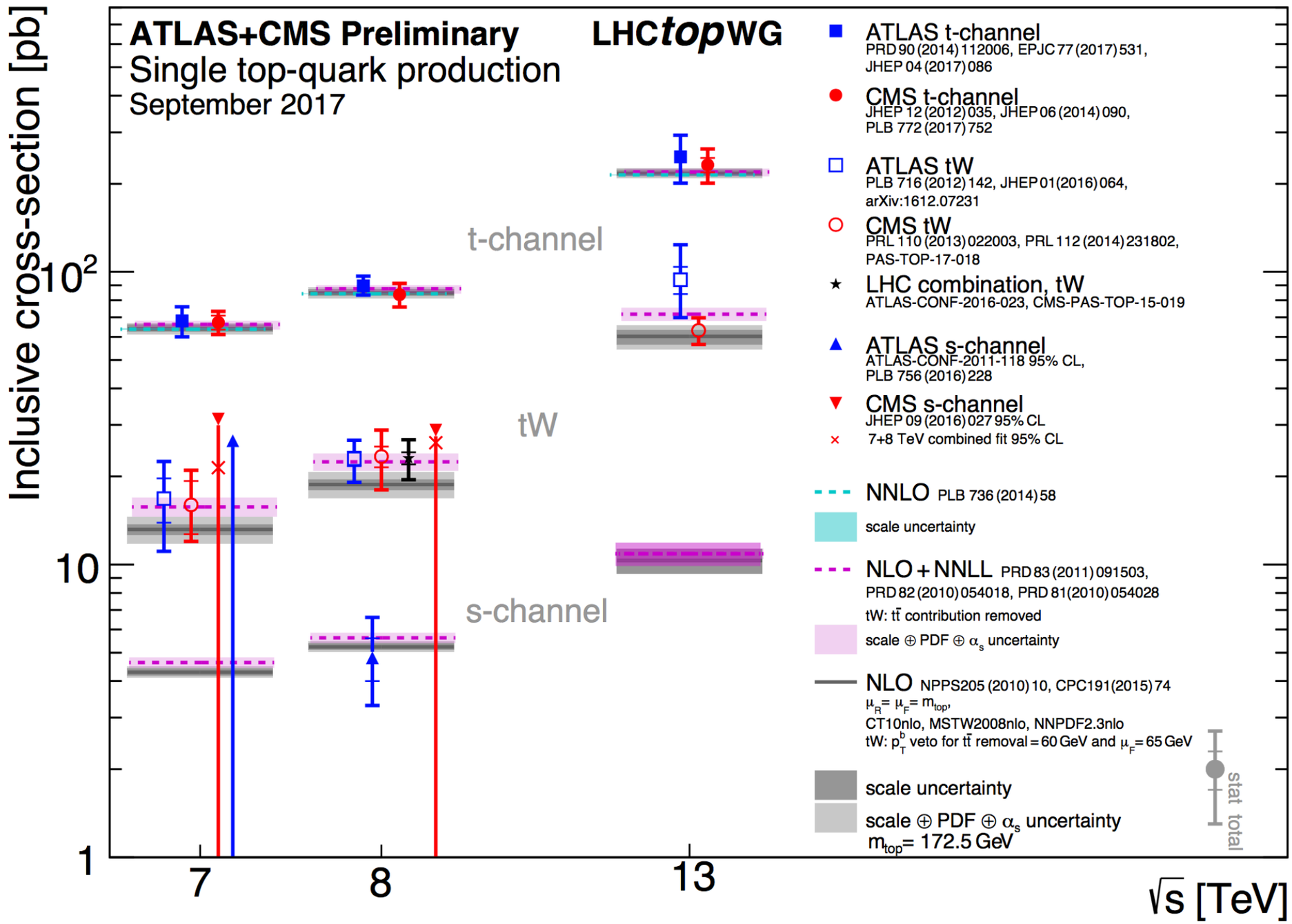
Impact gluon PDFs at high (μ_f,x) ▼



Experiment	$\sqrt{s}$	m_t [GeV]	PDF
ATLAS eμ	7+8	$172.9^{+2.5}_{-2.6}$	PDF4LHC 1
CMS eμ	7+8	$174.3^{+2.1}_{-2.2}$	CT14
CMS ℓ+jets	13	170.6 ± 2.7	CT14

Pole mass extracted with ≅1.5% unc ▶

Electroweak production of top quarks



- **Production through EWK vertices in agreement with predictions at different $s^{1/2}$**
  - $\frac{\delta\sigma_{th}}{\sigma_{th}} < \frac{\delta\sigma_{exp}}{\sigma_{exp}}$: background, experimental uncertainties typically higher than in tt case

$\sigma_{t+\bar{t}}$ impact on V_{tb} and main uncertainties

- **Extraction of V_{tb} from signal strength**

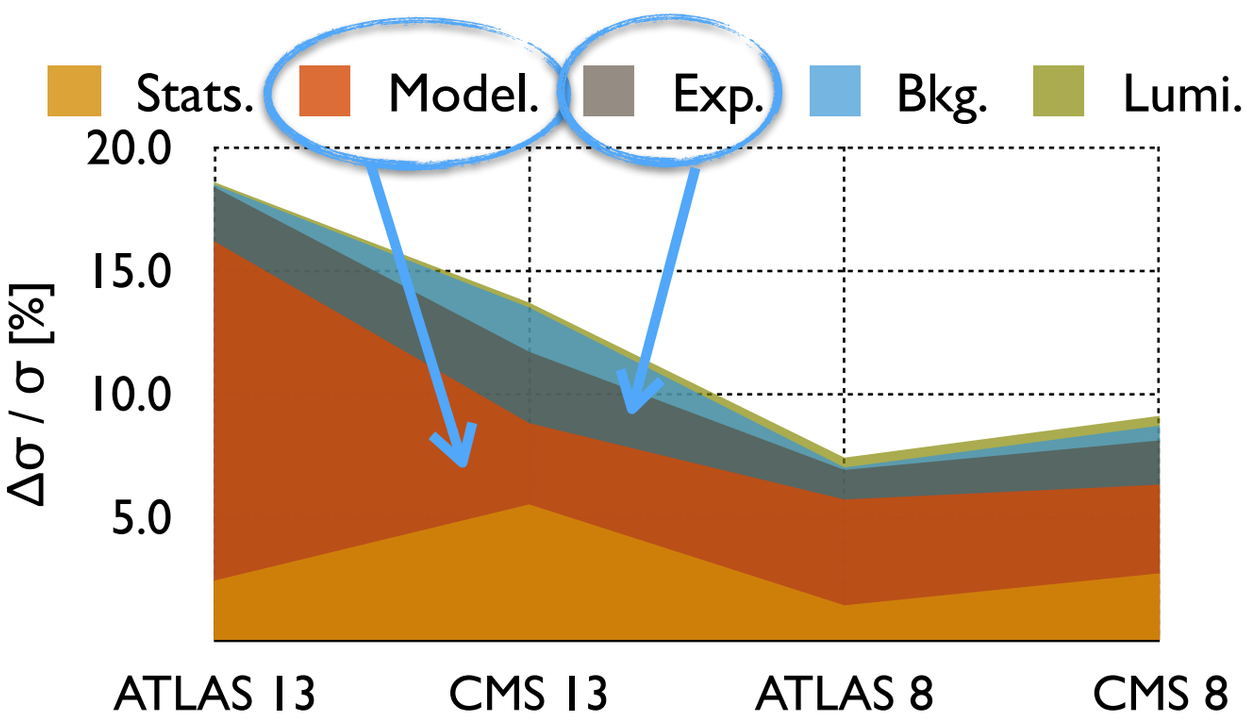
$$\frac{\delta V_{tb}}{V_{tb}} = \frac{1}{2}\left(\frac{\delta\sigma_{th}}{\sigma_{th}} \oplus \frac{\delta\sigma_{exp}}{\sigma_{exp}}\right)$$

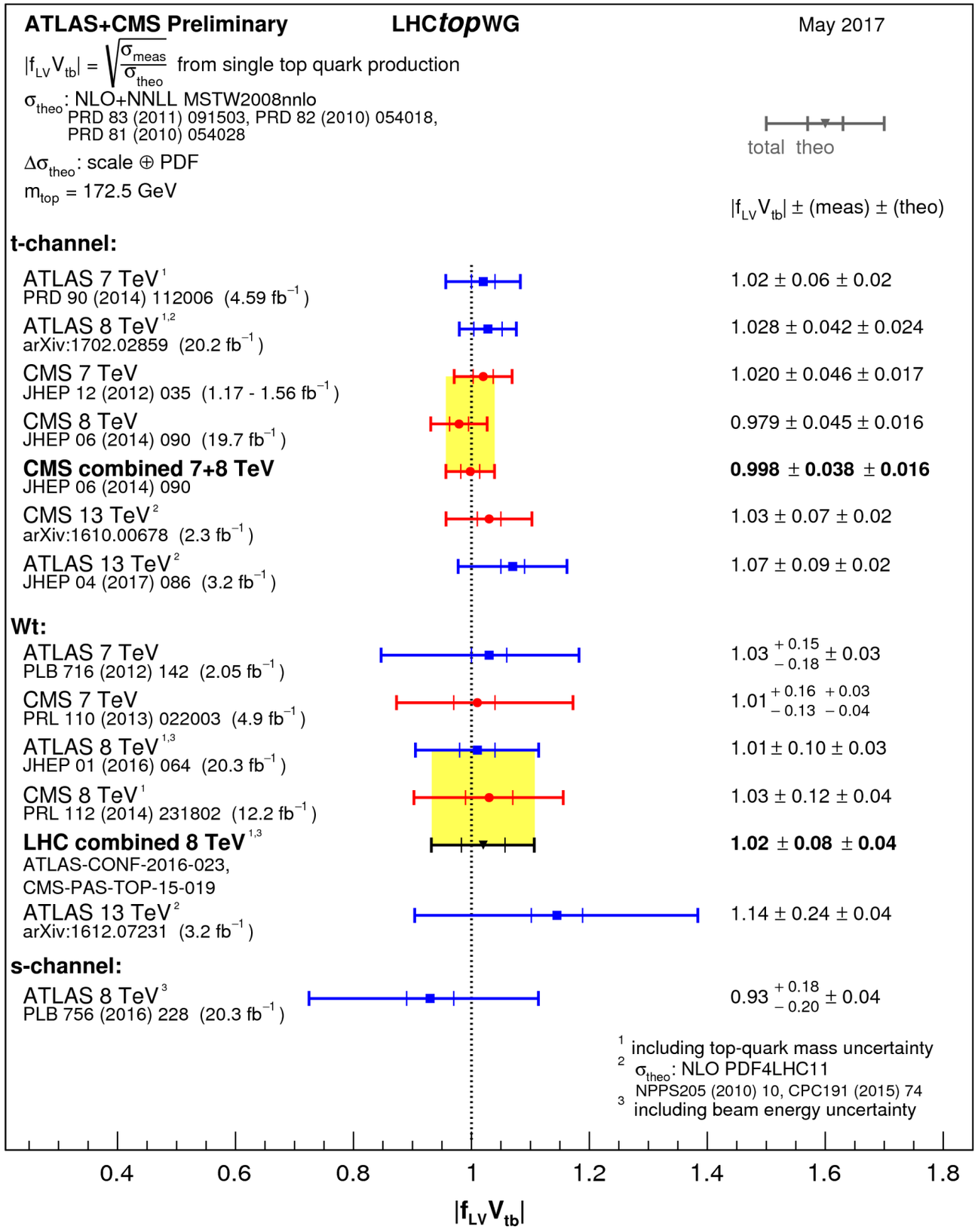
+0.9/-0.3%

~7-13%

NNLO QCD
arXiv:1404.7116

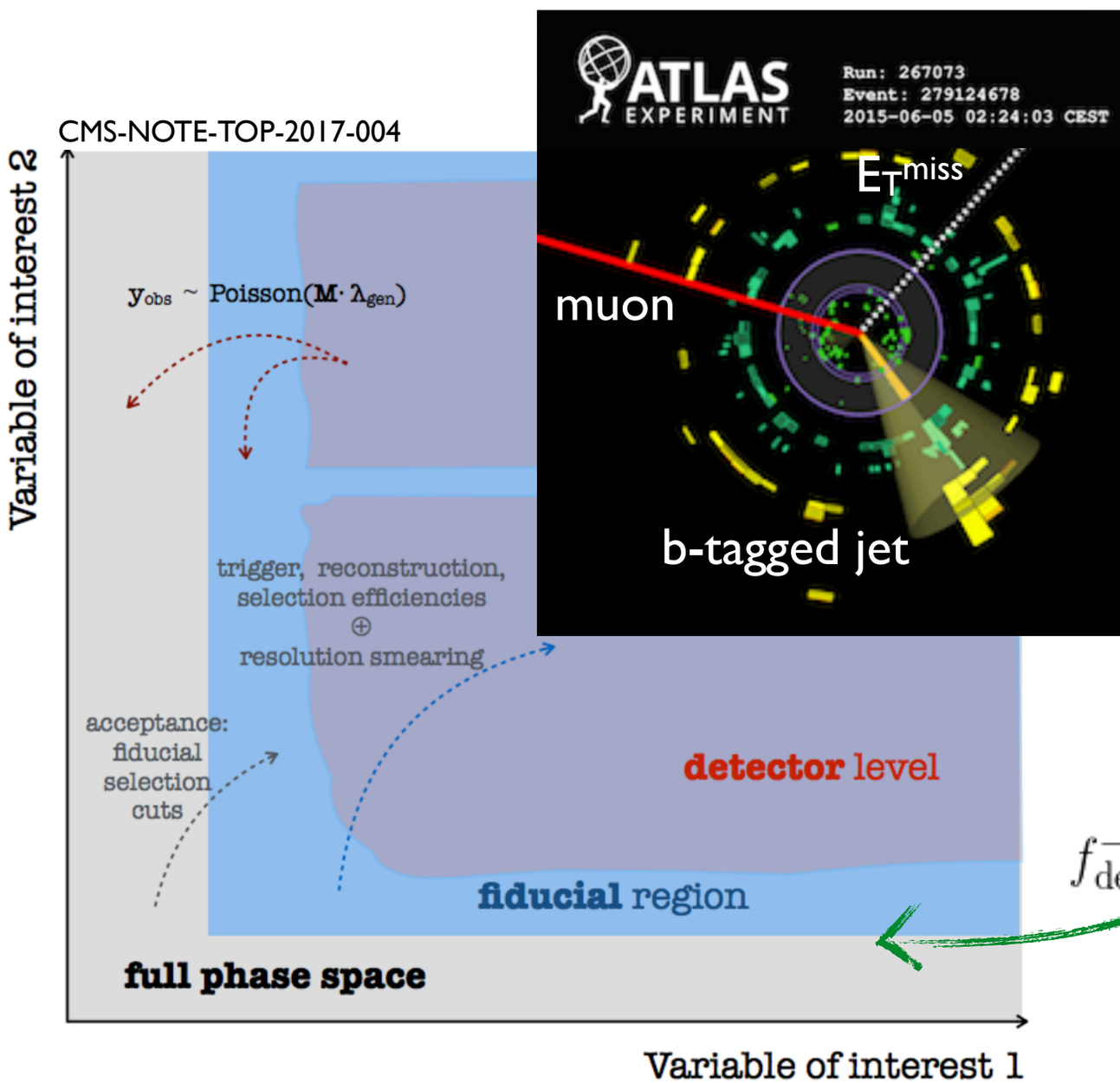
Experiment	$\sqrt{s}$	σ_t [pb]
ATLAS	8	$89.6^{+7.1}_{-6.3}$
CMS	8	83.6 ± 7.7
ATLAS	13	247 ± 46
CMS	13	238 ± 32





Differential top cross sections

- **Maximise the sensitivity to m_t, α_S, PDFs, pQCD predictions and new physics**
  - final state products used to reconstruct top quark candidates, global event properties
  - comparison to theory needs to "un-smear" data for reconstruction, parton shower effects

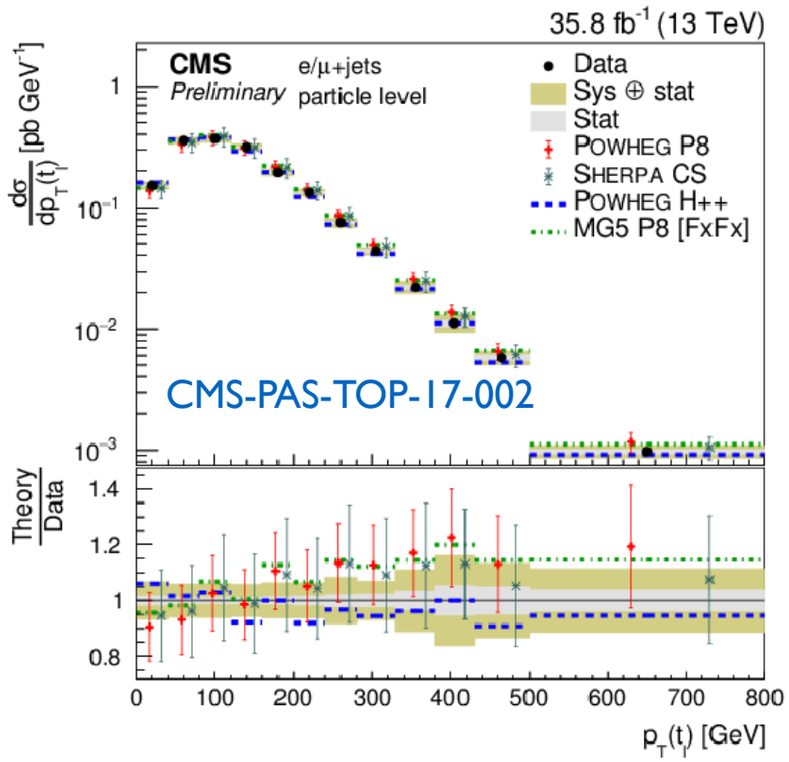


- **Theory-safe definitions when possible**
  - particle level top from stable final states
  - mimic reconstruction techniques as in data
  - minimise dependency on parton shower
  - find implementation in RIVET routines
  - direct comparison to NLO+PS (eagerly waiting for particle level NNLO)

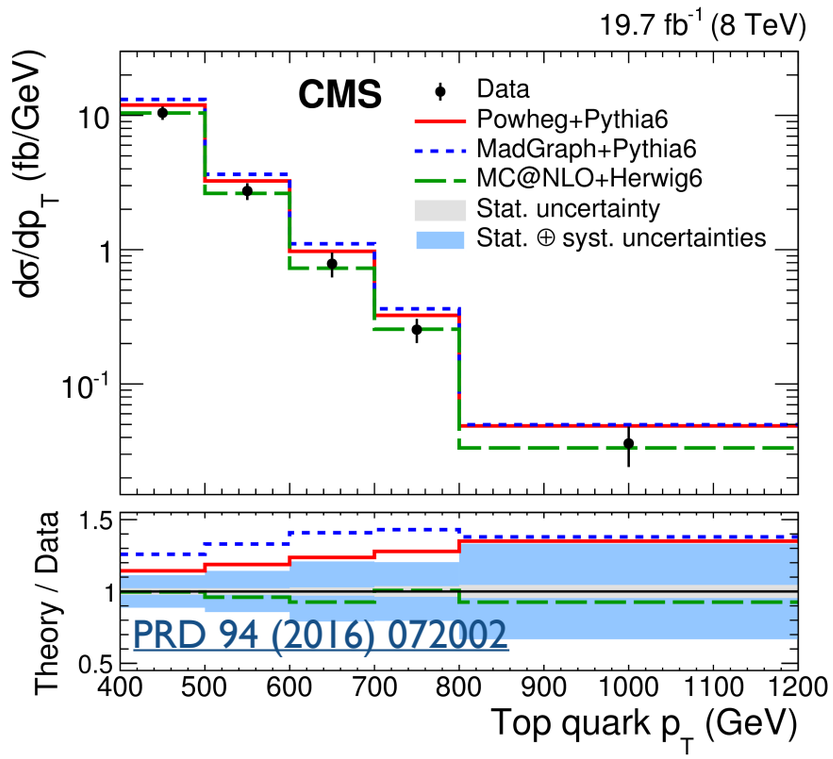
$$f^{-1}_{\text{detector}}\left(p_i, i \in [\text{leptons}, \text{jets}, \text{E}_\text{T}^\text{miss}]\right)$$

$d\sigma_{t(t)}/dX$ status (illustrative examples)

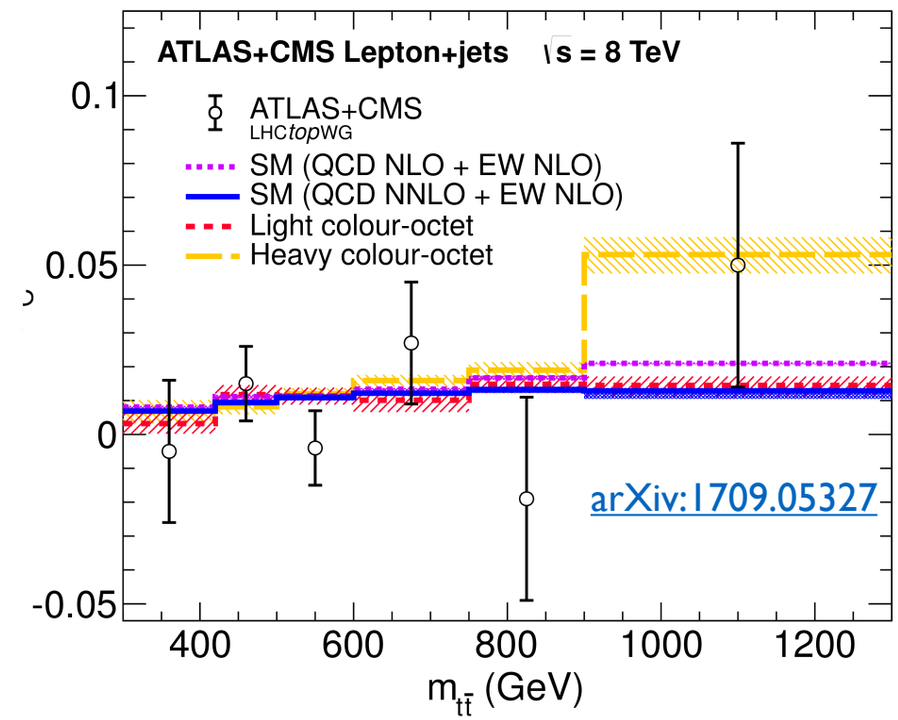
Resolved tt: ≧1D



Bosted tt

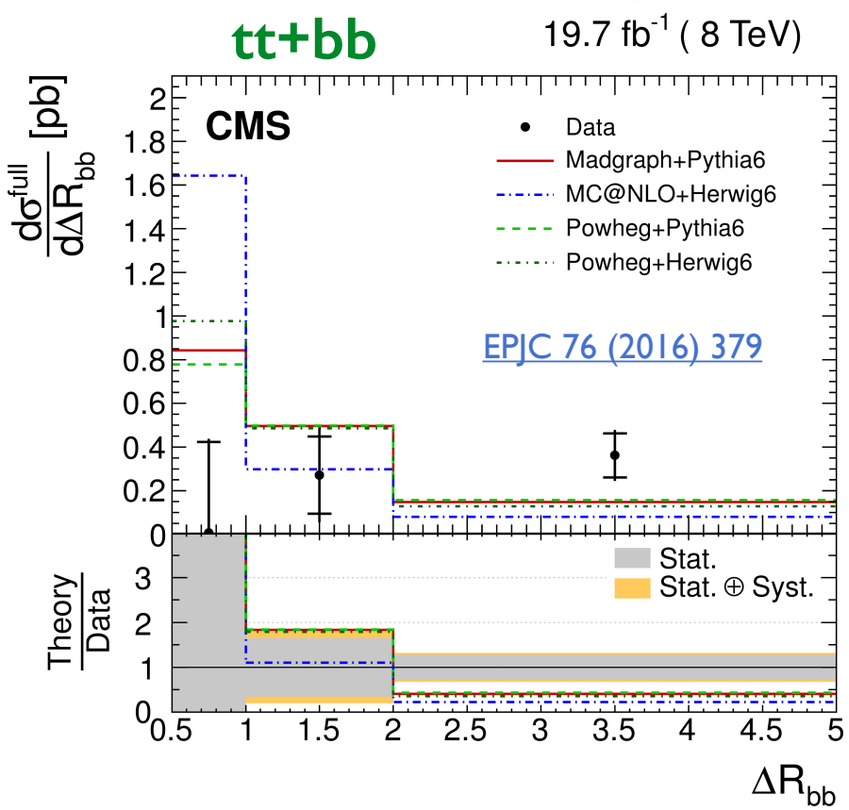


First LHC combination: A_c!

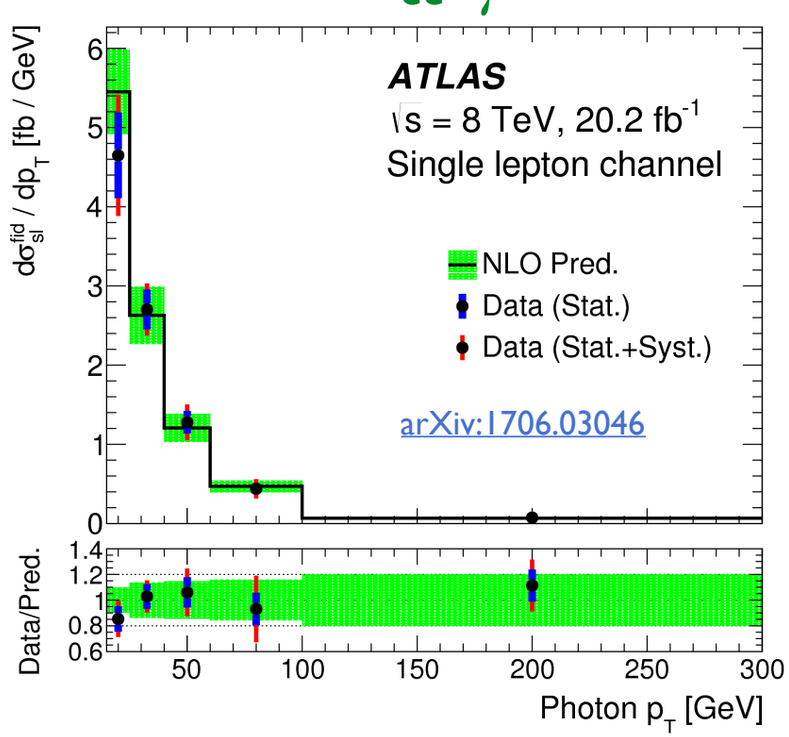


Associated productions

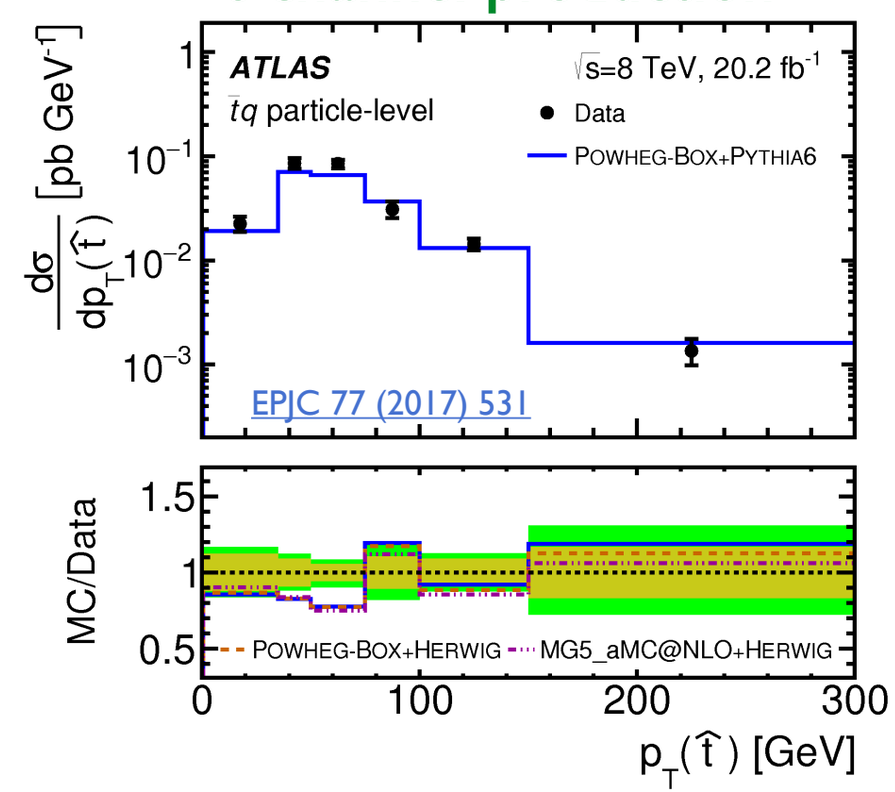
tt+bb



tt+γ



t-channel production



$d\sigma_{t(t)}/dX$ status (illustrative examples)

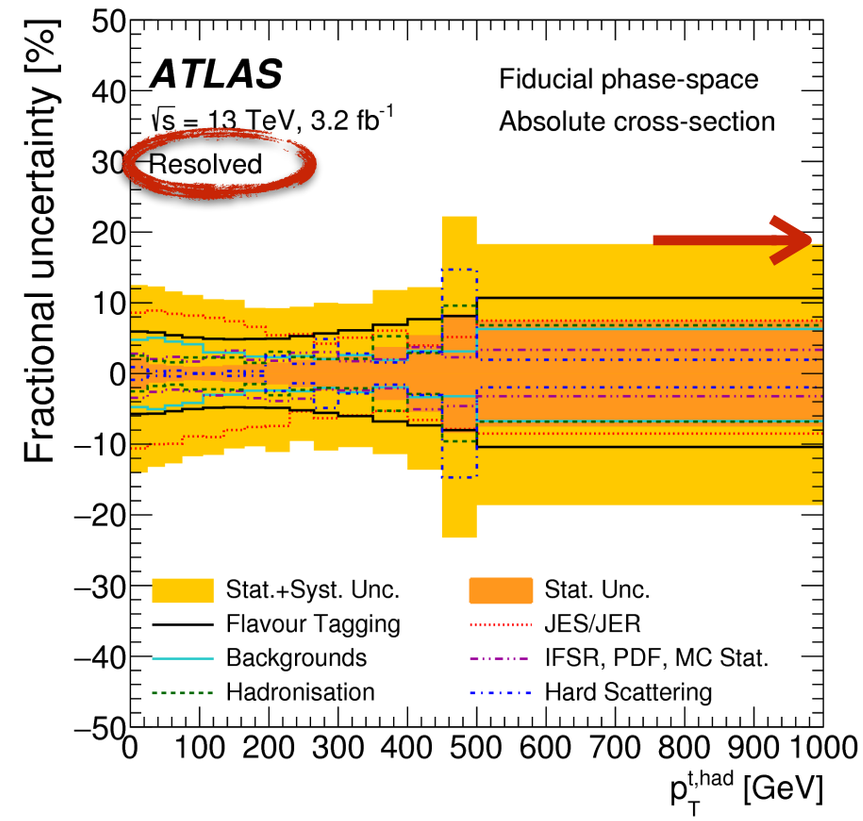
- **General observation: rates/shapes well reproduced at NLO QCD within uncertainties**
  - largest discrepancy in top p_T in tt events

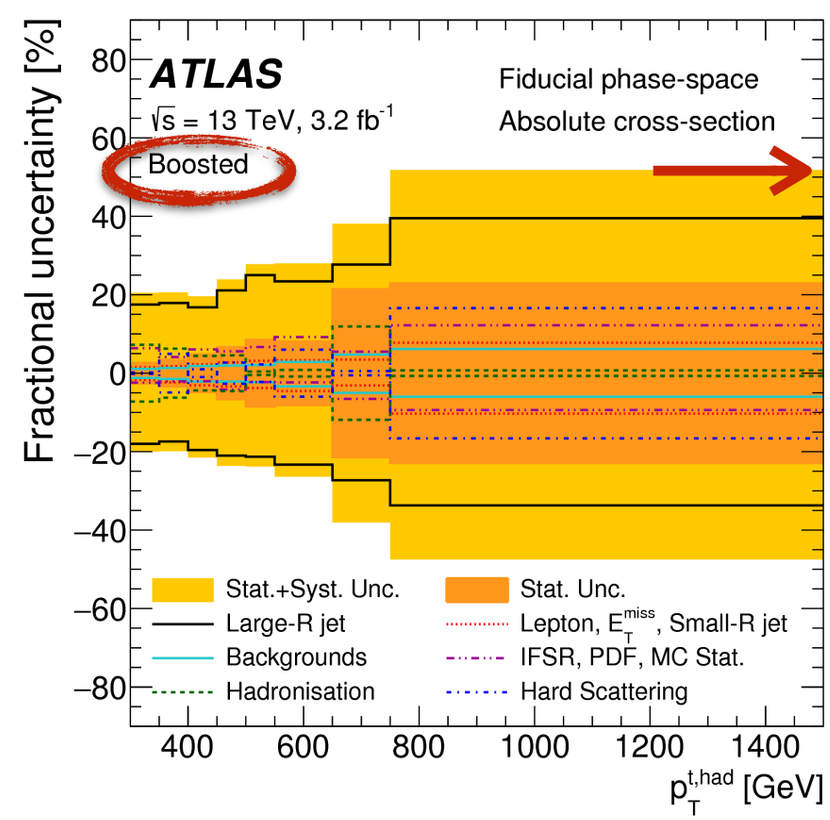
    NNLO QCDxNLO EW and alternative recoiling schemes at NLO+PS in better agreement with data
  - start to profit from large statistics to unfold in several dimensions simultaneously
- **First ATLAS+CMS A_C combination in agreement with state-of-the art predictions**
- **t-channel probing kinematics and polarisation-related variables**
- **Recent progresses in starting to probe rarer processes (so far Run I)**
  - will benefit from higher integrated luminosity and energies to improve statistical uncertainty
  - associated productions : playground for searches but also for improved y_t measurements

Typical dominant uncertainties in $d\sigma_{t(t)}/dX$

- **Using as an example $p_T(t)$ measurement in ℓ+jets**
- **Experimental uncertainties are significant at 13 TeV**
  - in this case jet energy scale related and b-tagging uncertainties
  - more data: calibrations and scale factors expected to improve
- **Total modelling uncertainties are however comparable**
  - model assumptions intrinsic to unfolding procedure
    e.g. correcting for events in which at least one ISR jet was used
  - can partially improve with better understanding of MCs
  - but statistical analysis also needs to improve (next slide)
- **Relative cross sections (shape only)**
  - uncertainty reduced around mode of the distributions (2-5%)
  - however it is still as large as 12-40% in the tails of $p_T(t)$
  - and information on the total rate is lost …

arXiv:1708.00727

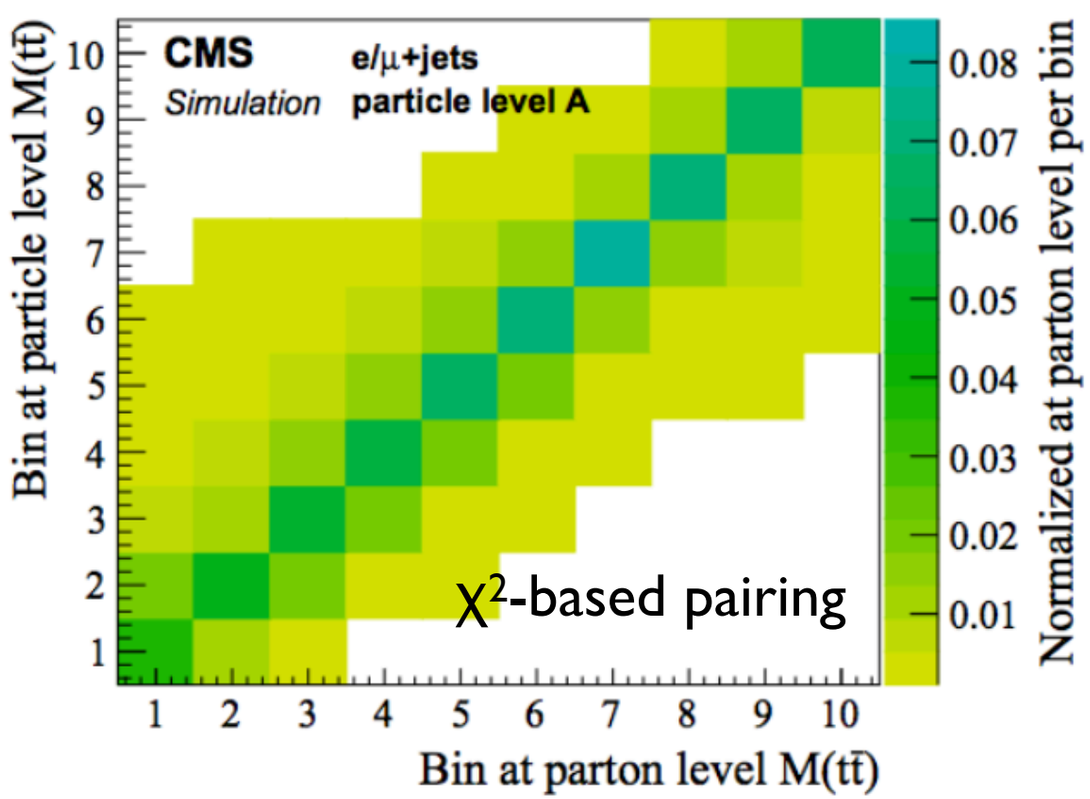


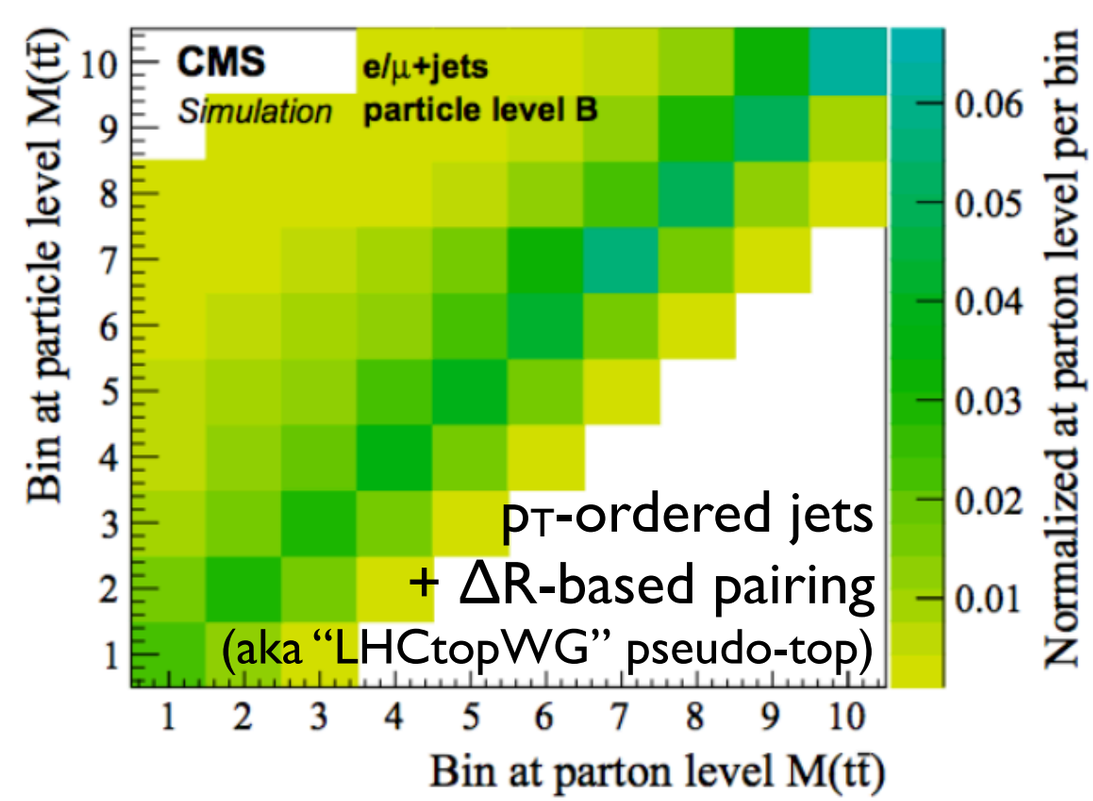


Challenges for $d\sigma_{t(t)}/dX$

- **Binning and correlations** (typically 40-70% between neighbouring bins)
  - resolution-limited : need high purity/stability matrices for stable numerical inversion
  - higher stats doesn't imply finer binning/smaller correlations keeping same reconstruction
  - include profiling of systematic uncertainties in unfolding? forward folding? ML-based regression?
- **Monte-Carlo driven corrections**
  - statistics in some corners of the phase space is a limiting factor (in particular with neg. weights)
  - data is corrected by simulations available at the time of the analysis
  - particle level definitions allow to factorise better detector effects from model effects
  - reconstruction algorithm: optimise for particle level to follow as close as possible parton level

CMS-NOTE-TOP-2017-004





Looking beyond the systematics wall

- With no striking signs of new physics, we're looking for subtle effects

Looking beyond the systematics wall

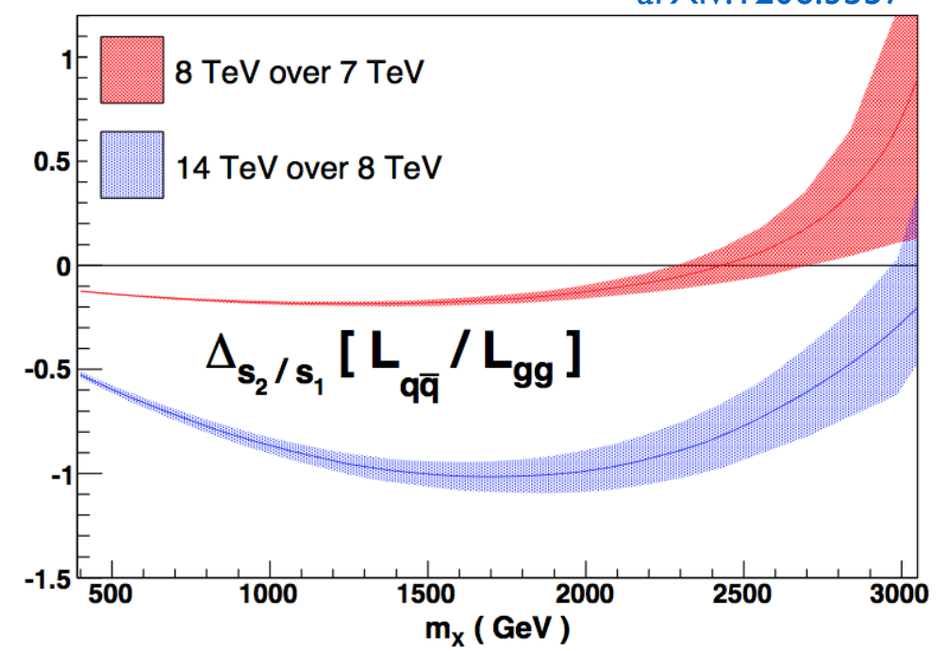
- **With no striking signs of new physics, we're looking for subtle effects**
- **If BSM evolution as function of energy is different from SM take $\sigma(E_1)/\sigma(E_2)$**
  - simplified approach to common fit to two $s^{1/2}$, expect significant cancellation of uncertainties
  - profit from data and expand ratios differentially

$$R^X_{E_1/E_2} \sim \frac{\sigma_X^{\rm SM}(E_1)}{\sigma_X^{\rm SM}(E_2)} \times \left\{ 1 + \frac{\sigma_X^{\rm BSM}(E_1)}{\sigma_X^{\rm SM}(E_1)} \, \Delta_{E_1/E_2} \left[\frac{\sigma_X^{\rm BSM}}{\sigma_X^{\rm SM}} \right] \right\}$$

HL-LHC or Run2 ratios to Run 1 will provide longer leverage arm with respect to theory uncertainties

usually a double ratio of parton luminosities at different $s^{1/2}$

arXiv:1206.3557



Looking beyond the systematics wall

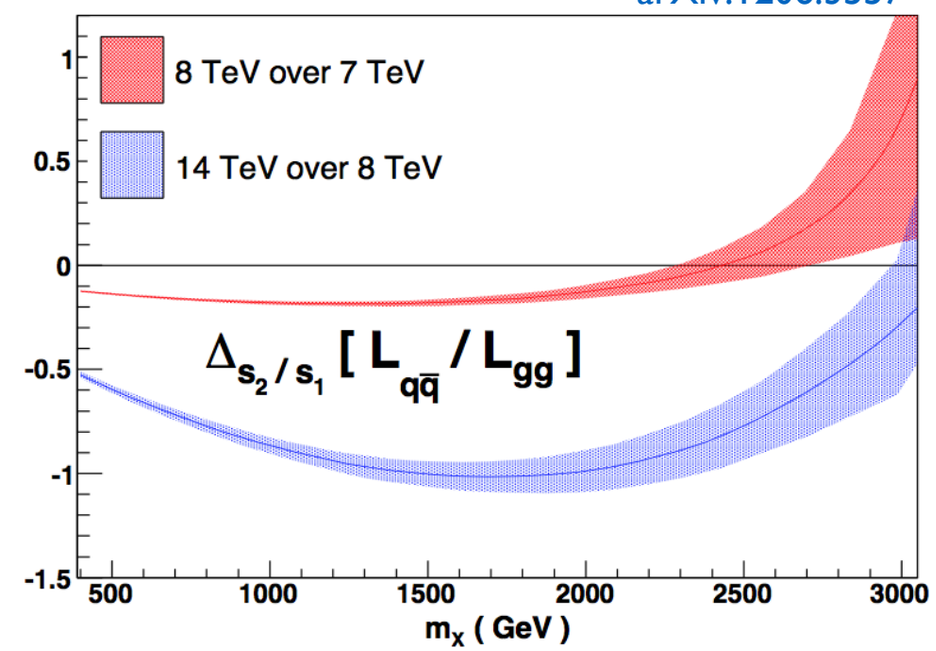
- **With no striking signs of new physics, we're looking for subtle effects**
- **If BSM evolution as function of energy is different from SM take $\sigma(E_1)/\sigma(E_2)$**
  - simplified approach to common fit to two $s^{1/2}$, expect significant cancellation of uncertainties
  - profit from data and expand ratios differentially

$$R^X_{E_1/E_2} \sim \frac{\sigma_X^{\rm SM}(E_1)}{\sigma_X^{\rm SM}(E_2)} \times \left\{ 1 + \frac{\sigma_X^{\rm BSM}(E_1)}{\sigma_X^{\rm SM}(E_1)} \, \Delta_{E_1/E_2} \left[\frac{\sigma_X^{\rm BSM}}{\sigma_X^{\rm SM}} \right] \right\}$$

HL-LHC or Run2 ratios to Run 1 will provide longer leverage arm with respect to theory uncertainties

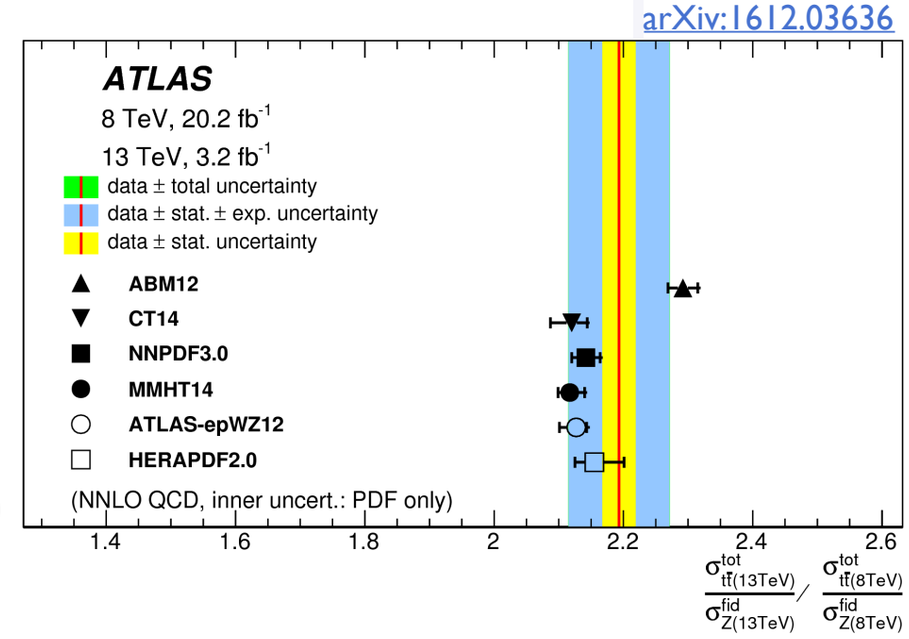
usually a double ratio of parton luminosities at different $s^{1/2}$

arXiv:1206.3557



- **No need to restrict inclusive ratios to a single process**
  - further reduce experimental uncertainties (e.g. efficiencies)
  - e.g. theory uncertainties on W, Z ~3-4% at NNLO
  - optimisation of the fiducial regions, common selection strategies
  - apply to associated productions with top quarks (γ,Z,W,H,bb,4t)

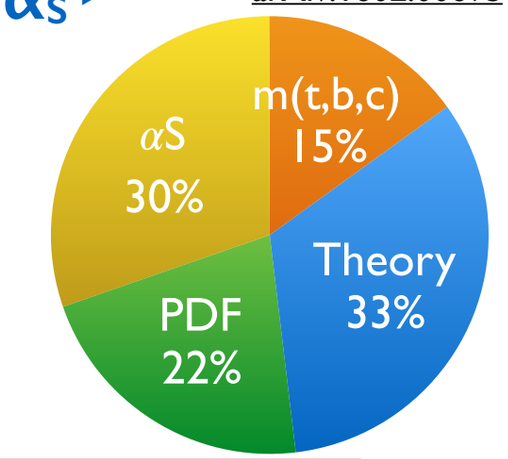
arXiv:1612.03636

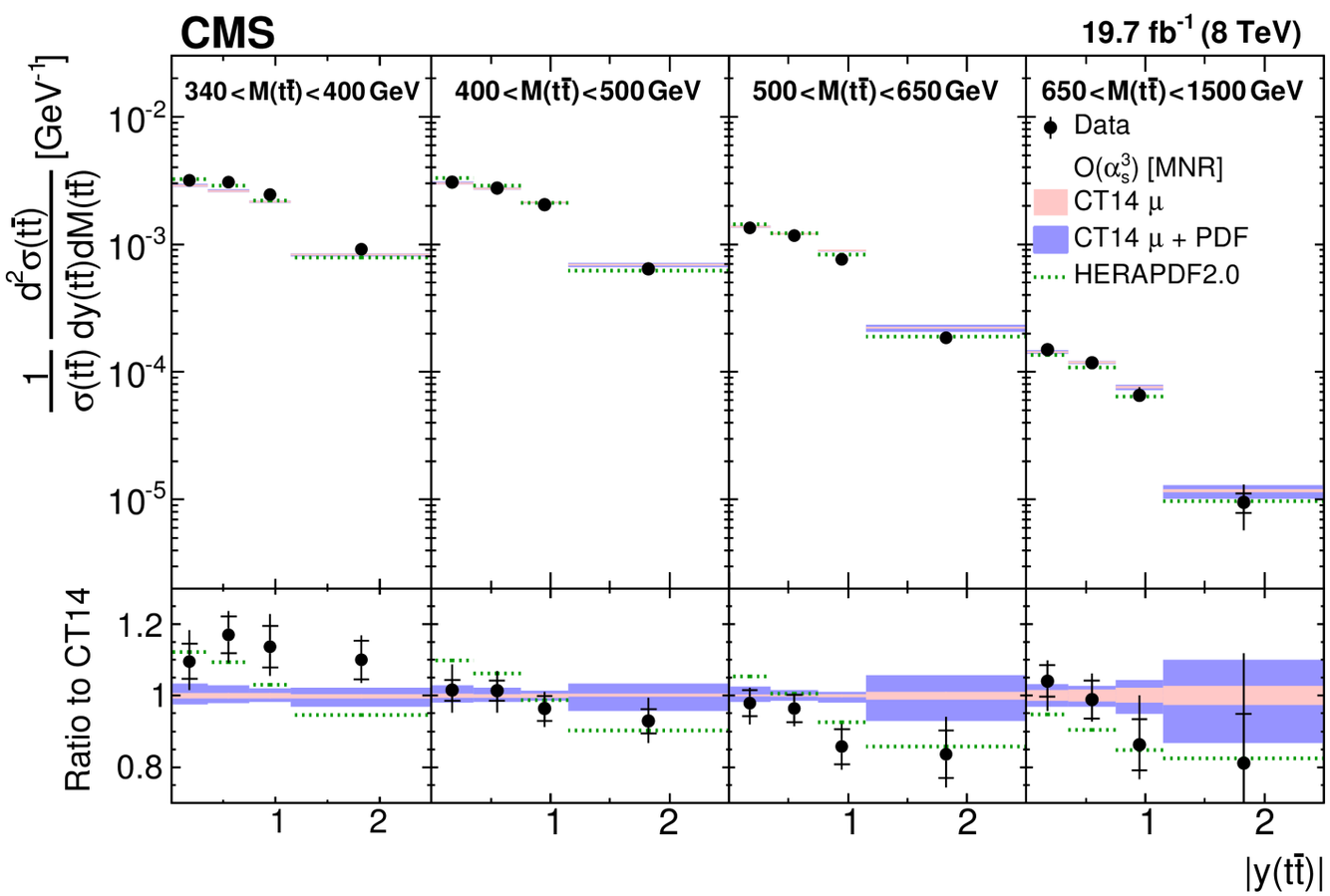


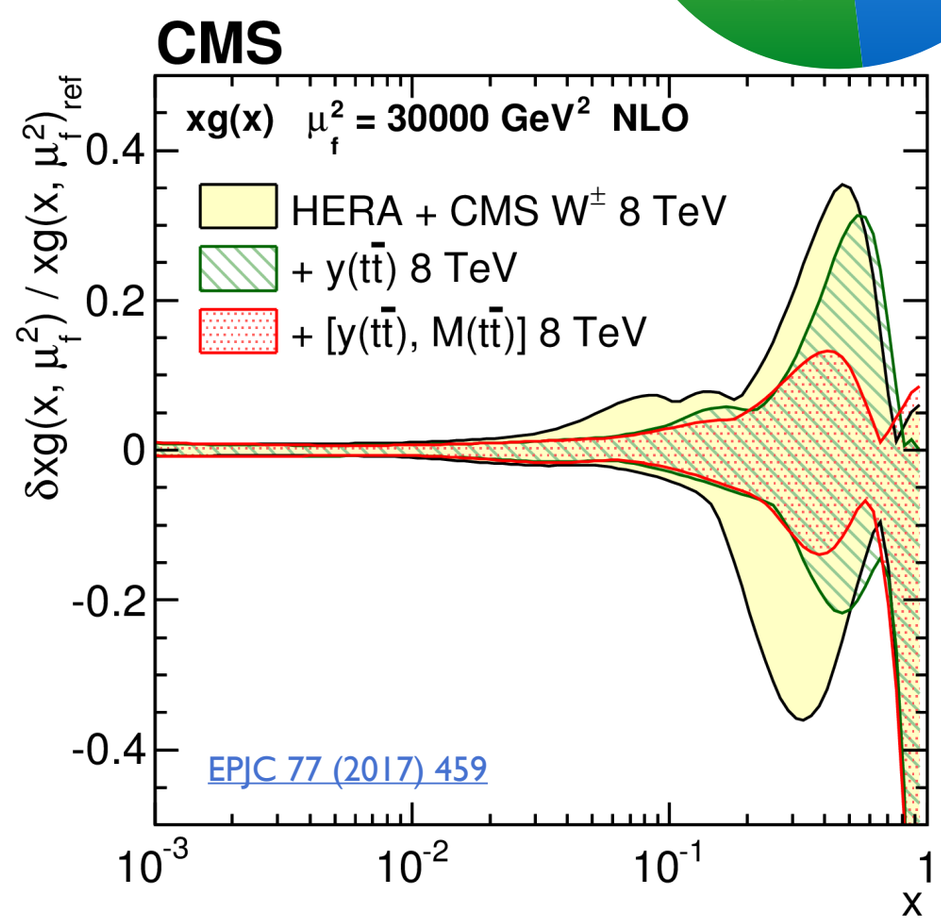
Top quark and PDFs I

- **How far can we push to reduce uncertainties on ggH from PDFs and α_S**
- **Significant impact on PDFs at high x from scanning M(tt) and y(tt)**
  - statistical uncertainties still relevant (higher rapidities and masses)

σ(gg→H) at N³LO
arXiv:1602.00695







- **Charge asymmetry in single top production**
  - interesting to explore differential with higher statistics for q-PDF

Top quark and PDFs II

- **Usage of forward region expected to play an important role at HL-LHC**
  - LHCb and extended tracker coverage in ATLAS/CMS can probe further qX-enhanced regions
  - unique case for charge asymmetries and resonant productions (see more in F. Deliot's talk)

$$x_i = \frac{m_T^2}{\sqrt{\hat{s}}}\left(e^{\pm y_t} + e^{\pm y_{\bar{t}}}\right)$$

ATLAS/CMS probed so far small Δy

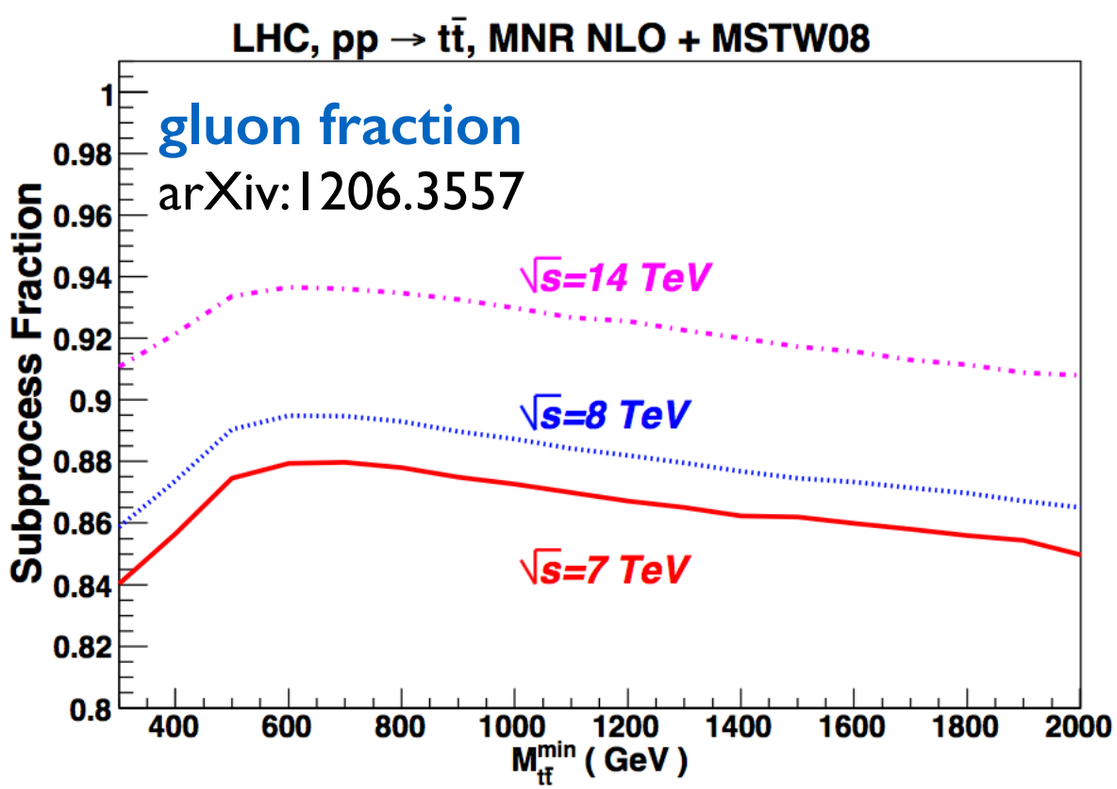
$x_1 \sim x_2$ (typically ~0.05)

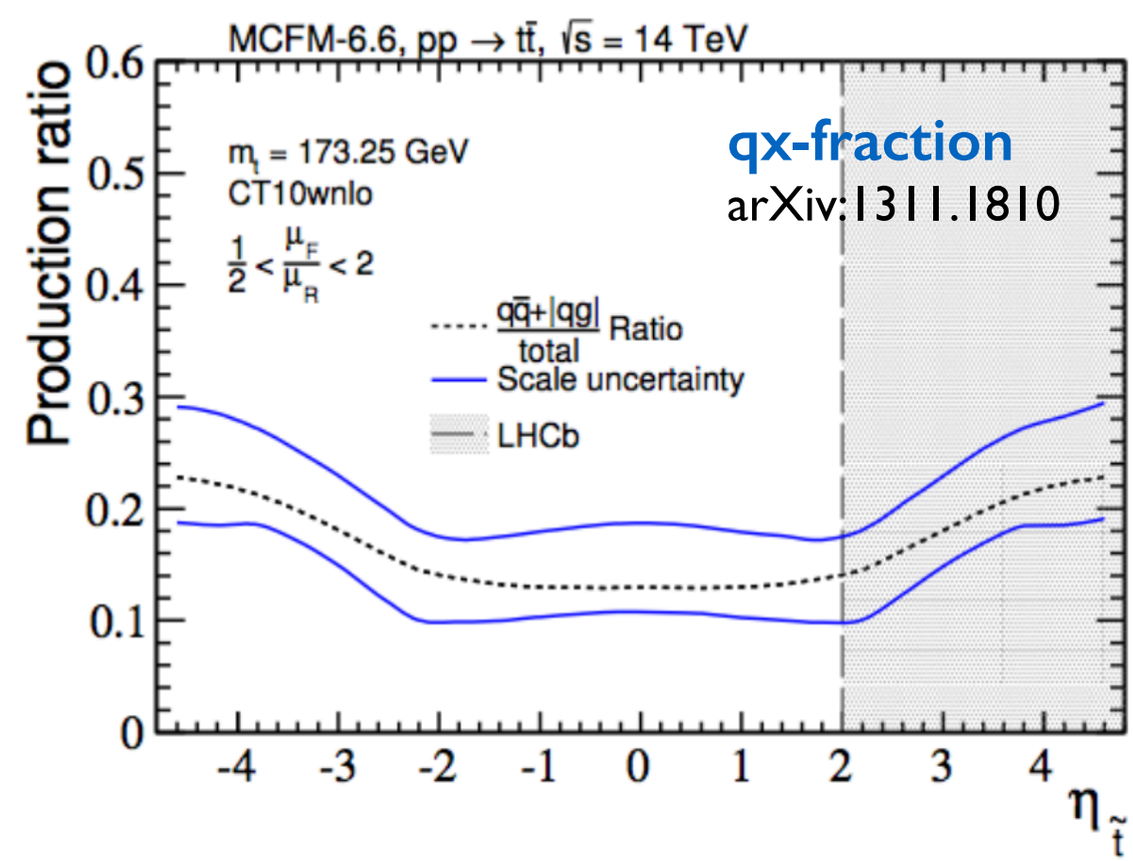
⇒ still g-dominated at high M_{tt} from $\hat{\sigma}_{gg}^{t-ch} \propto \frac{\log(M_{t\bar{t}}^2)}{M_{t\bar{t}}^2}$

LHCb can probe large Δy

$x_1 > x_2$ enhances valence quark contribution

⇒ slight enhancement of qq/qg

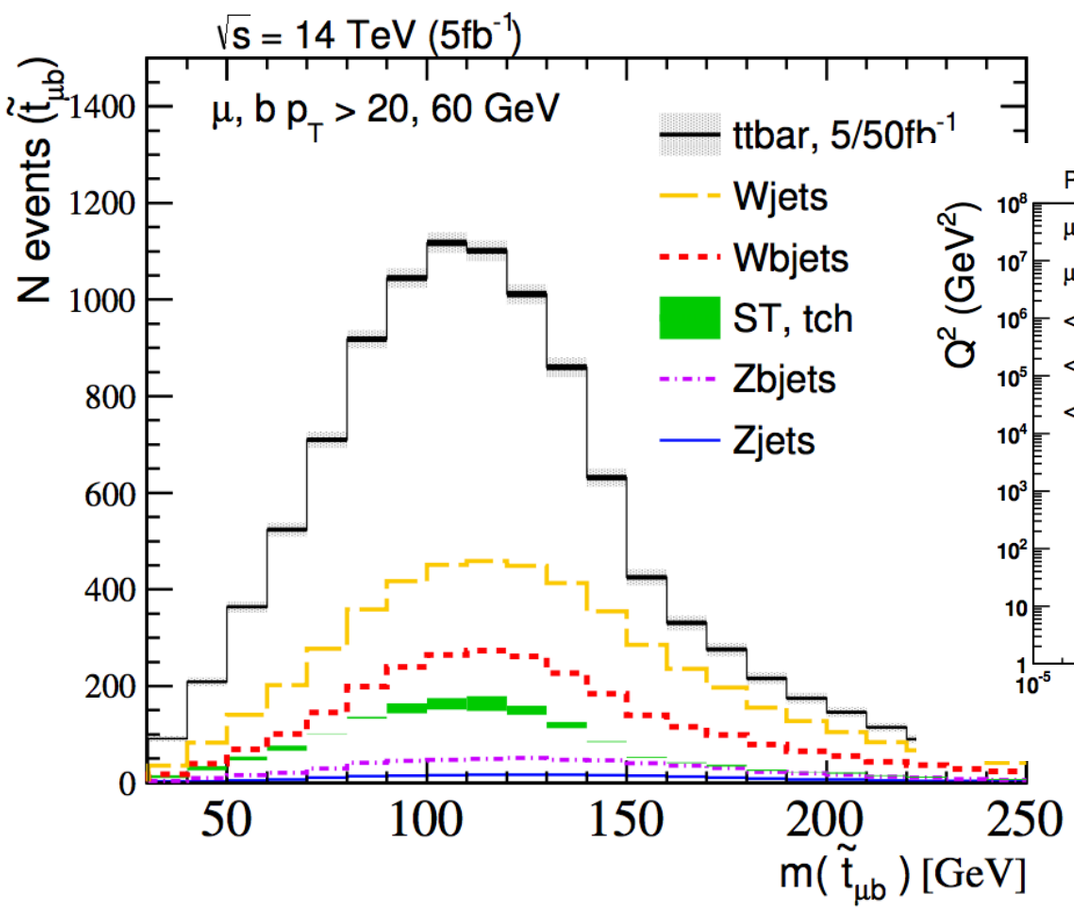




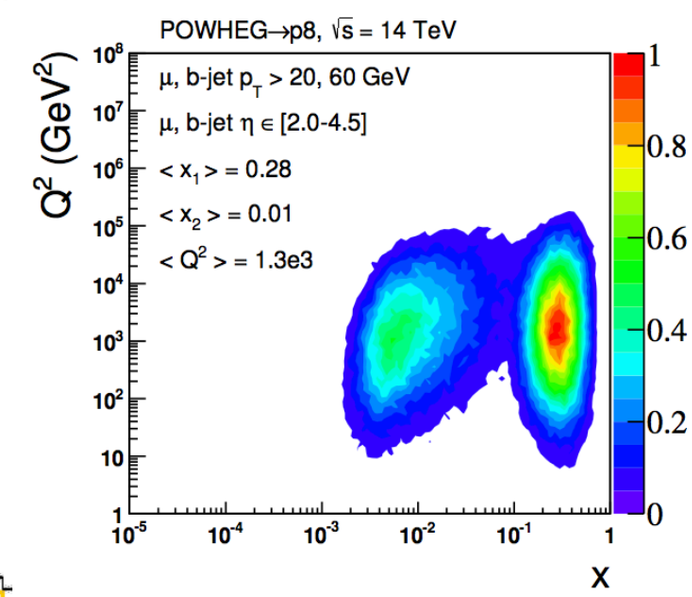
Top in the forward region

- **LHCb complements "blind" regions of ATLAS/CMS for new physics in t asymmetries**
  - e.g. t-channel/u-channel exchange of light mediator [arXiv:1103.3747]
- **Expect significant increase in statistics wrt to early observation of top in forward region**
  - assuming current performances: ε_μ~90% ε_e~70% and ε_b~65% for ε_q~0.5%

Final state	Run 2 (5/fb)	Upgrade (300/fb)
ℓb	11k	680k
ℓbj	6k	360k
ℓbb	1.4k	90k
ℓbbj	0.8k	50k
$\ell\ell$	2k	120k
$\ell\ell$b	0.8k	50k



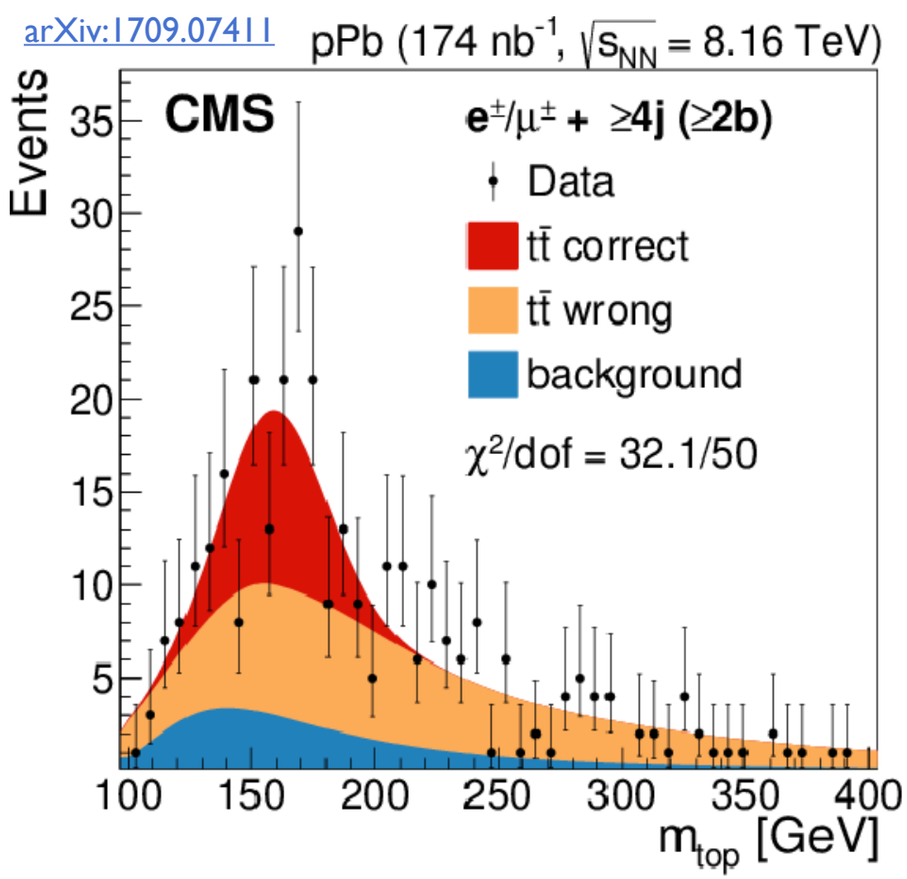
arXiv:1311.1810

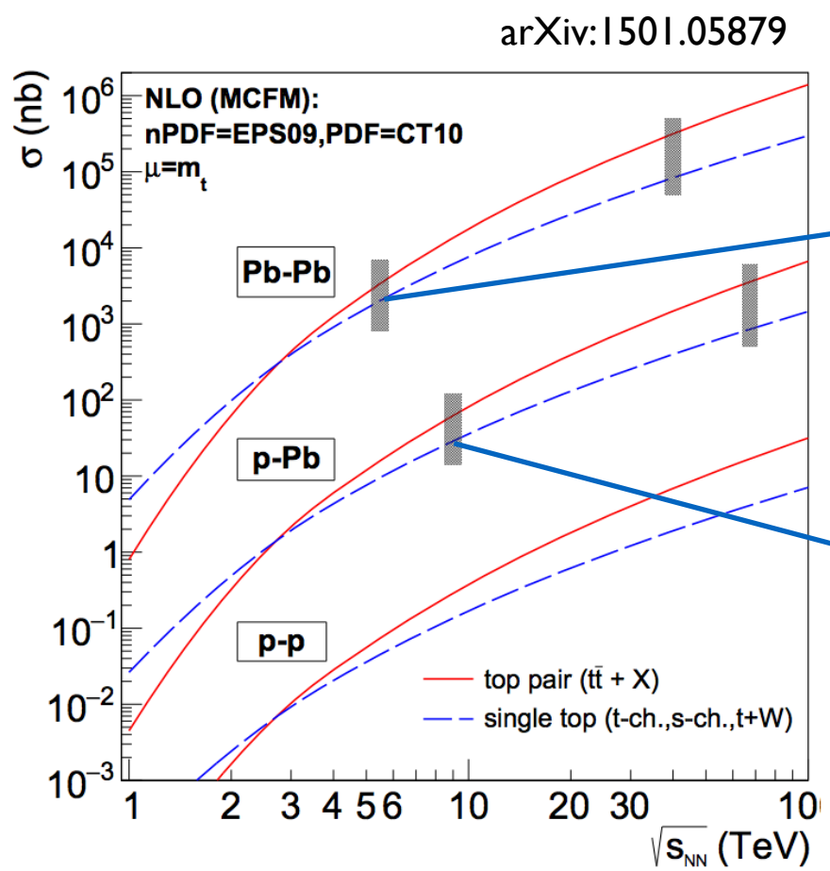


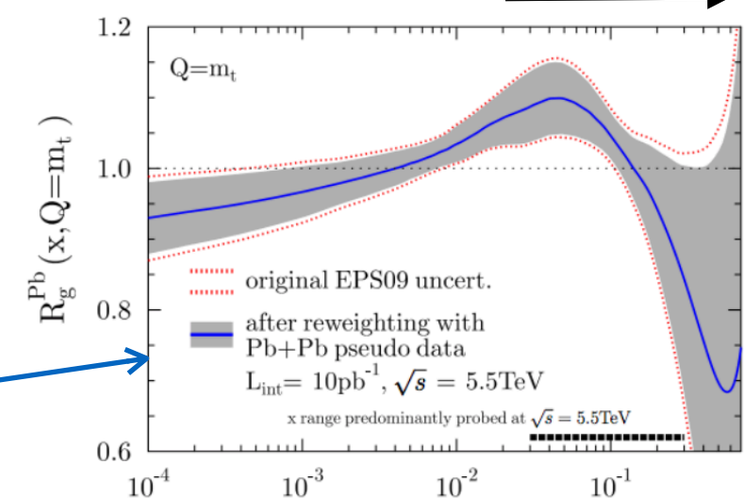
Top as a probe in heavy ions

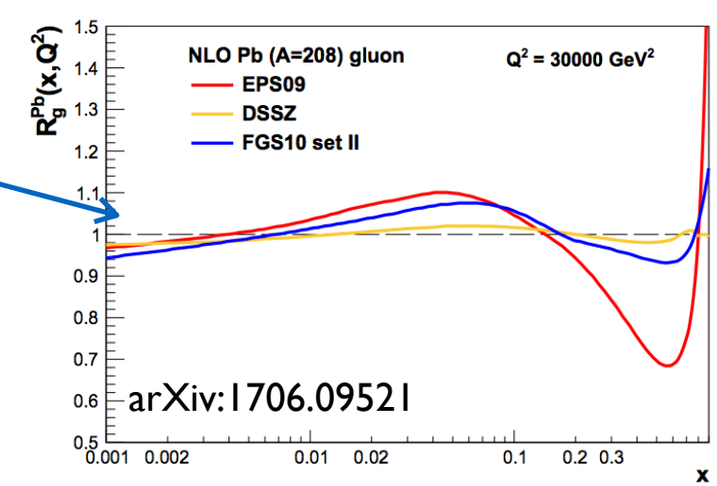
- **Recently established for the first time in pPb collisions at 8.16 TeV!**
- **Expect O(10 nb^{-1}) of PbPb at HL-LHC at $\sqrt{s_{NN}}$=5.5 TeV**
  - ~900 dilepton events after typical pp selection cuts
  - impact on nPDFs at uncharted x ▶
  - unique to probe QGP with EWK-decaying free quark
- **Also, a clear case for higher luminosity pPb runs**

potential to probe unexplored anti-shadowing and EMC regions







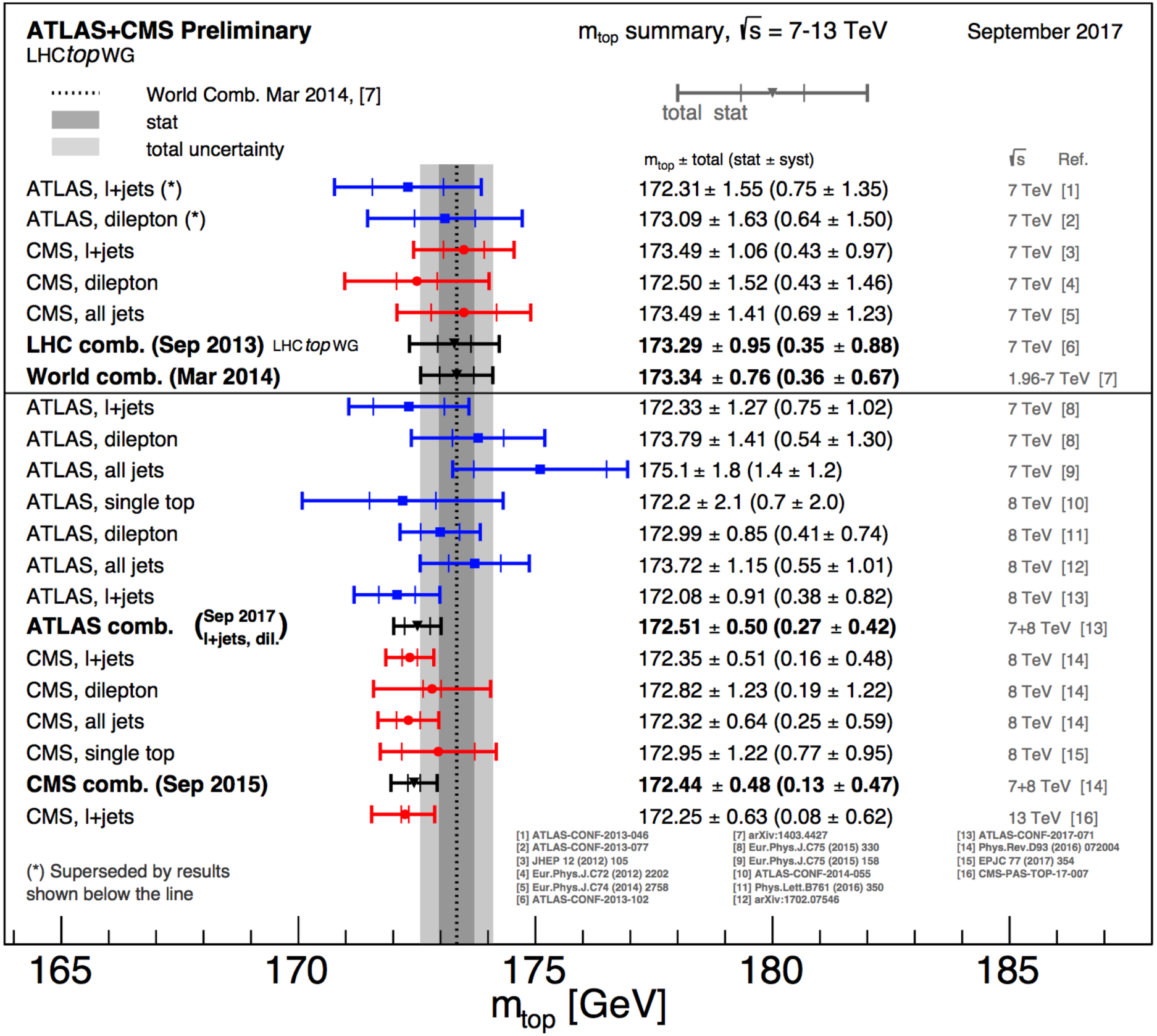


***t*-QUARK MASS**	
t-Quark Mass (Direct Measurements)	173.1 ± 0.6 GeV (S = 1.6)
t-Quark Mass from Cross-Section Measurements	160^{+5}_{-4} GeV
t-Quark Pole Mass from Cross-Section Measurements	173.5 ± 1.1 GeV
$m_t - m_{\bar{t}}$	-0.2 ± 0.5 GeV (S = 1.1)
t-quark DECAY WIDTH	$1.41^{+0.19}_{-0.15}$ GeV (S = 1.4)

unification in sight?

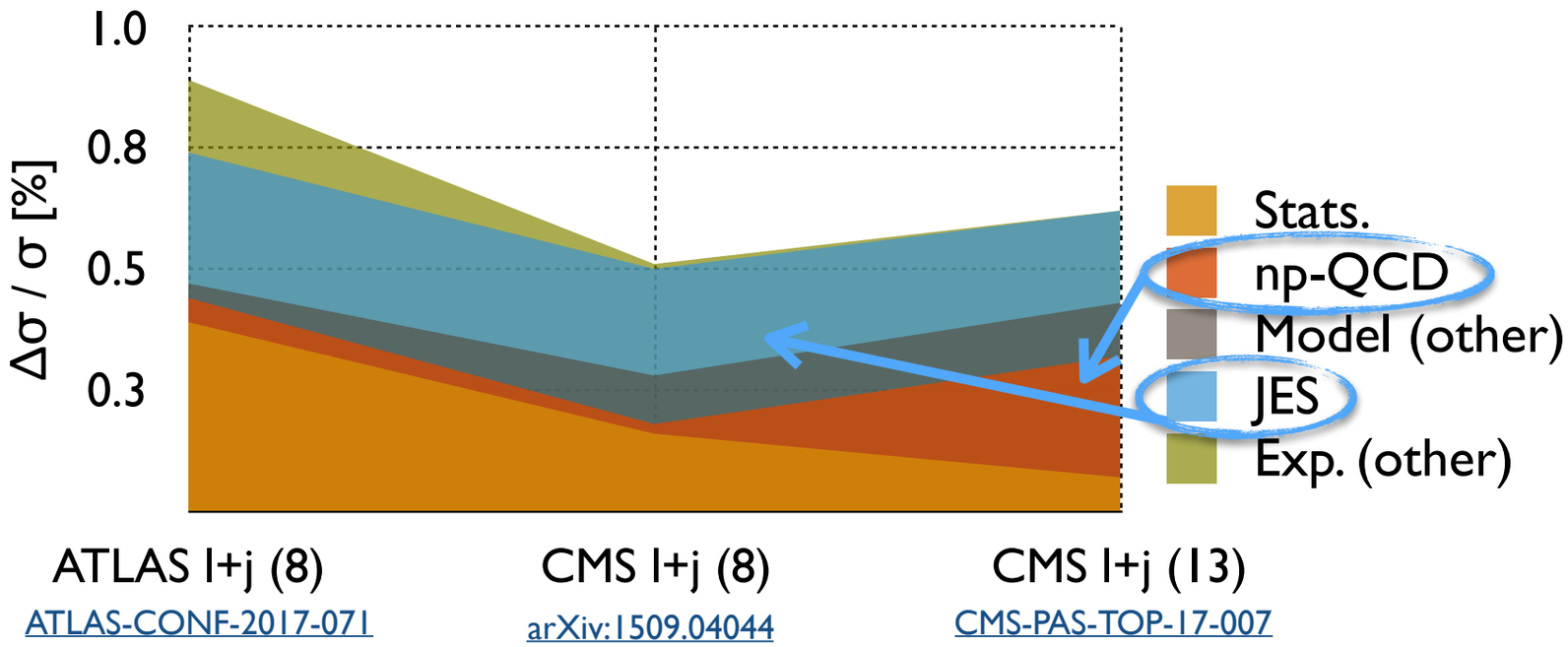
Top mass

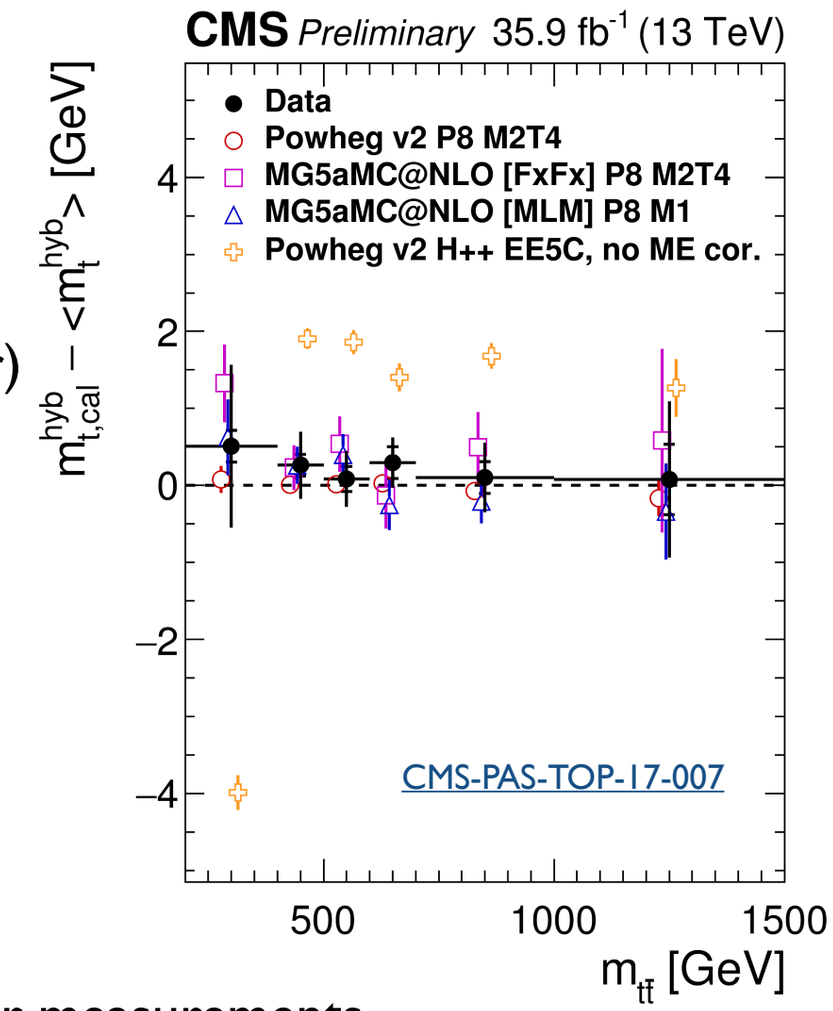
Direct top mass measurements at the LHC



- Expected to lead in precision
- Achieved <0.3% uncertainty
- Good agreement between LHC experiments
- Good agreement with alternative techniques where $\delta m_t/m_t$=0.4% (CMS-PAS-TOP-15-012)
- Ultimately limited by Λ_{QCD} ambiguities

Dominant uncertainties in m_t

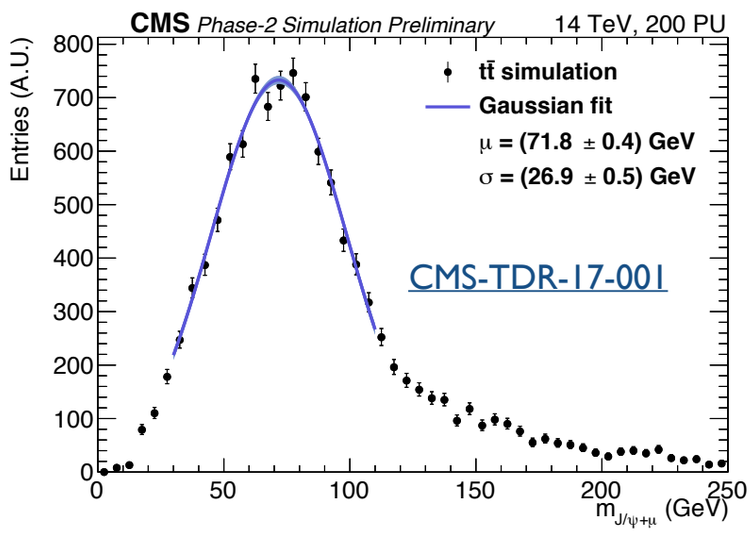


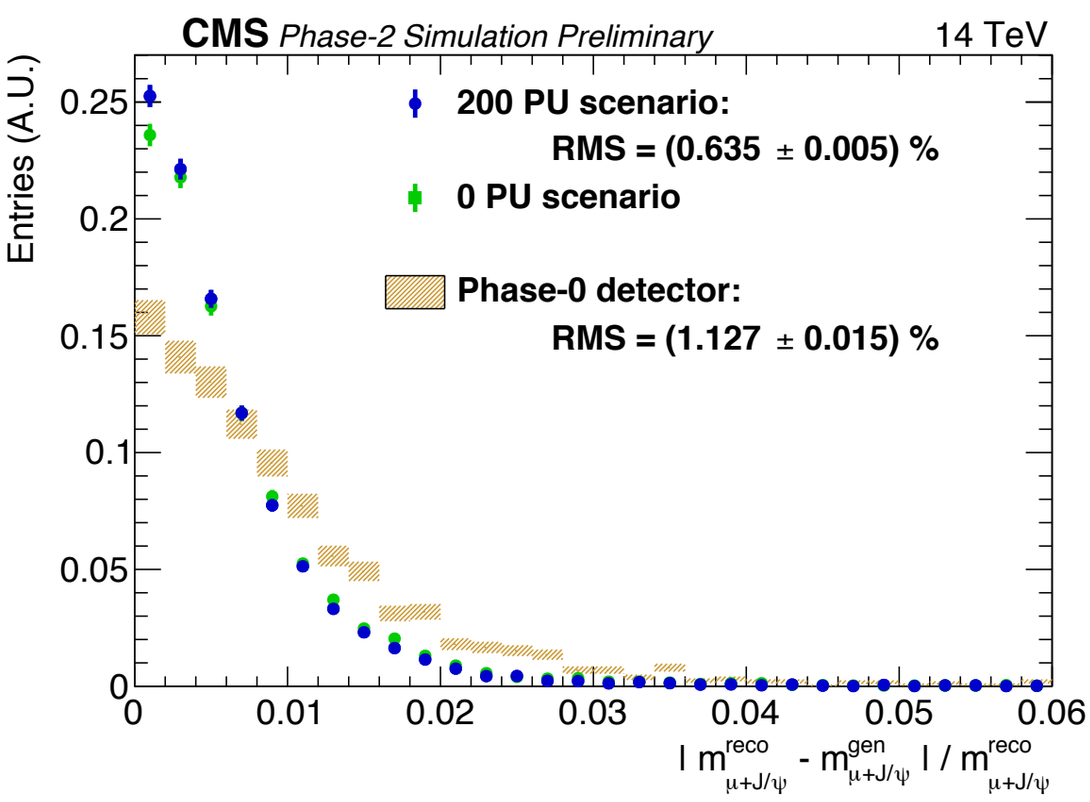


- **Using as example single most precise channel**
  - expected to remain the leading one at higher statistics
  - combinations will benefit from different correlations with other measurements
- **Jet energy scale: 3D-fit will probably leverage most of the current unc. on bJES**
  - benefit from integrated jet id with jet energy scale: heavy-flavour, q/g and PU discrimination
- **Non-perturbative effects: moving from CR on/off to new models does increase unc.**
  - differential measurements with profiling will be the next step
    "easy" to exclude extreme models, profit from statistics to constraint in-situ subtle ones

Rise of alternative methods

- **Tracks-only measurements evade the dependency on the JES**
  - M(ℓ,J/Ψ) and related variations: more prone to b-fragmentation ⇒ *constrain in-situ with charmed/bottom mesons*

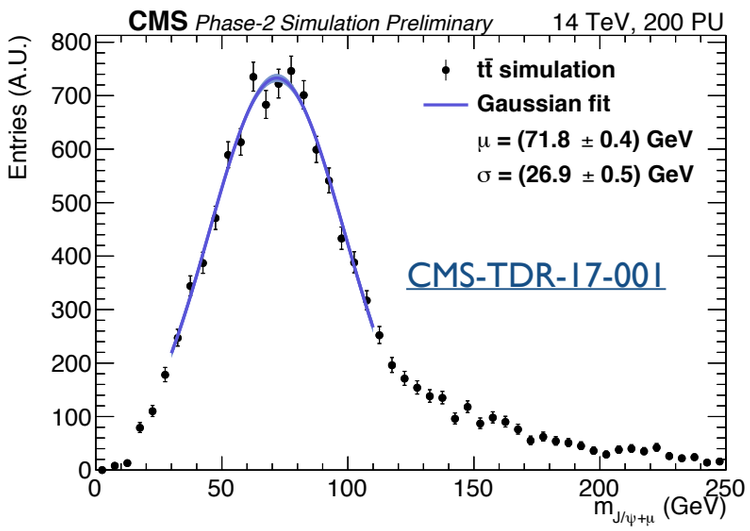


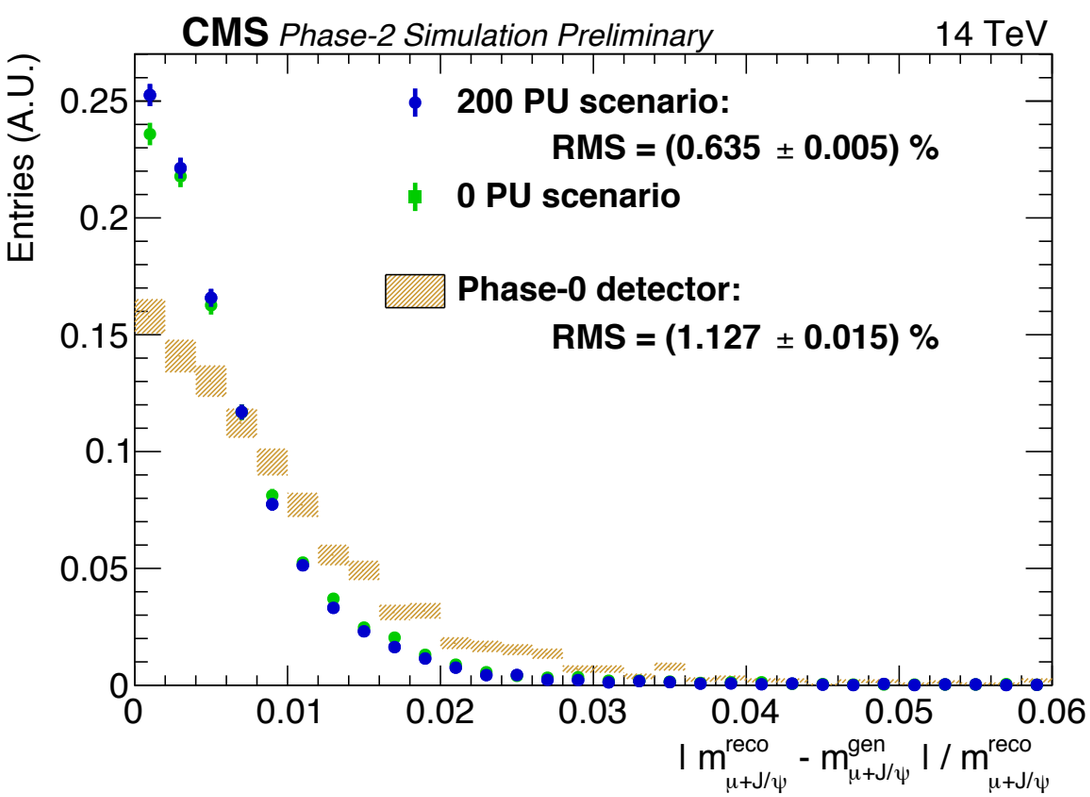


Rise of alternative methods

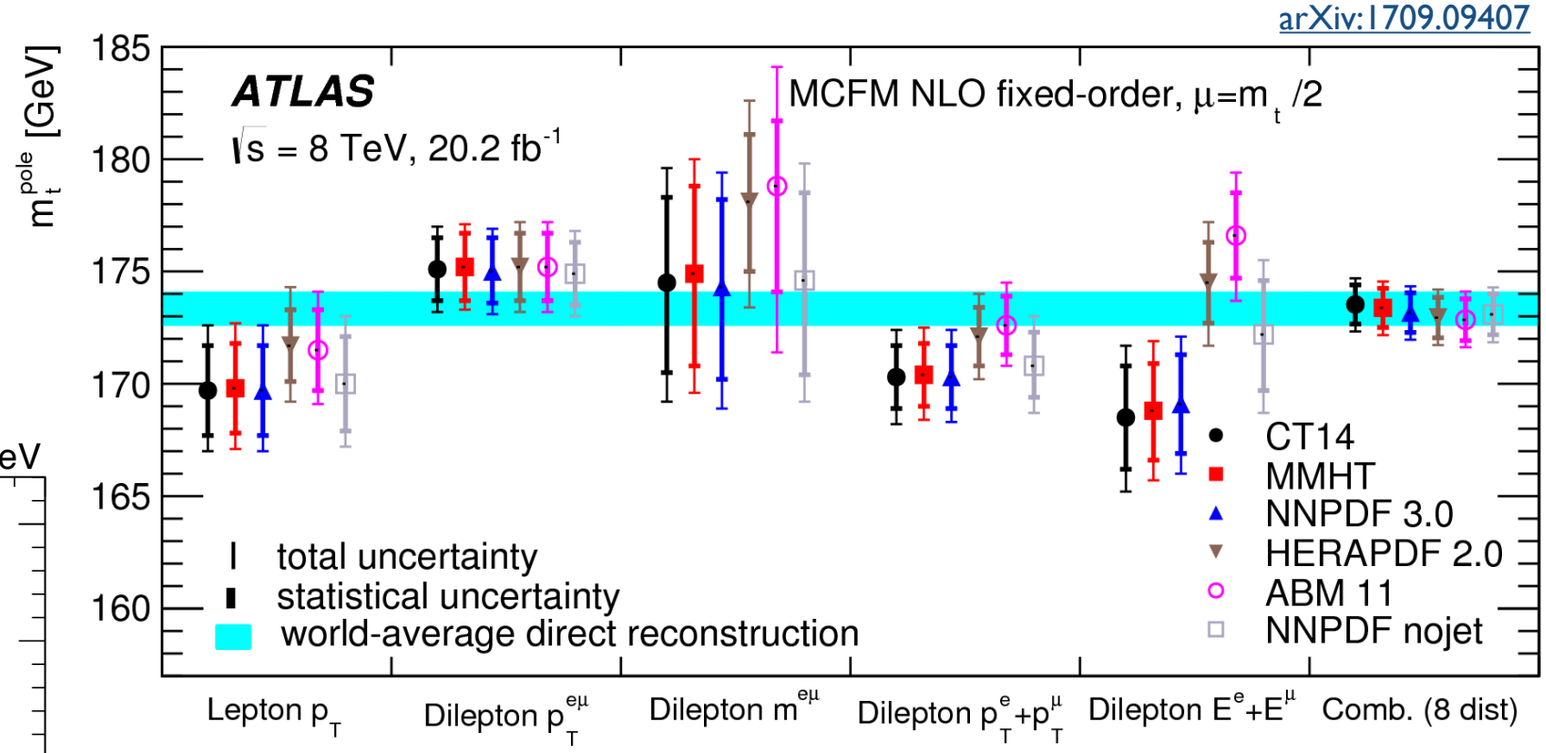
- **Tracks-only measurements evade the dependency on the JES**
  - M(ℓ,J/Ψ) and related variations: more prone to b-fragmentation ⇒ *constrain in-situ with charmed/bottom mesons*
  - dilepton kinematics: rely on excellent lepton calibrations ⇒ *benefit from NNLO at particle level for m_t^{pole}*

    normalised: no lumi, eff. uncertainties!





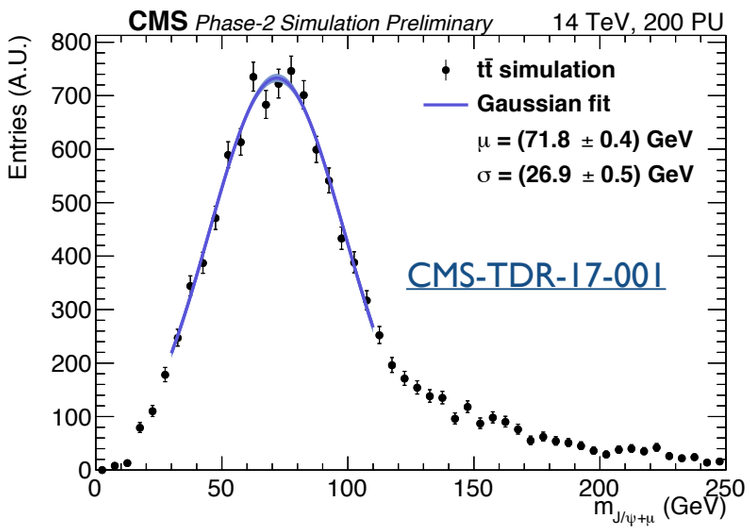
arXiv:1709.09407

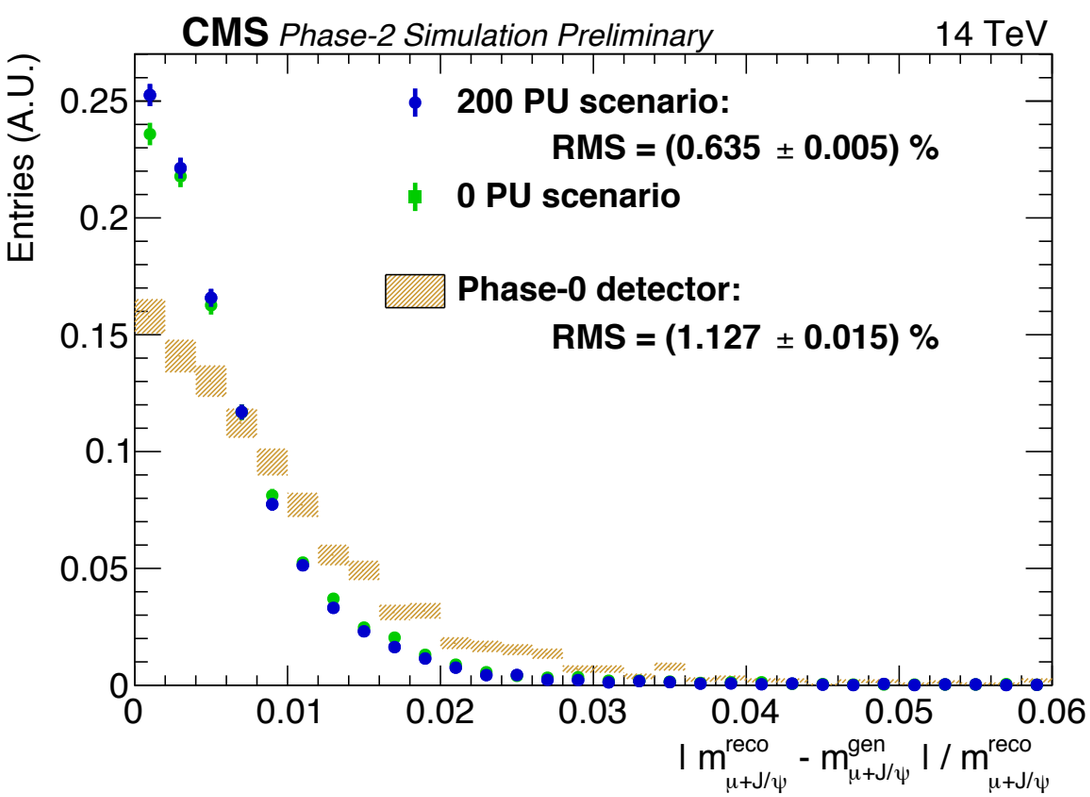


Rise of alternative methods

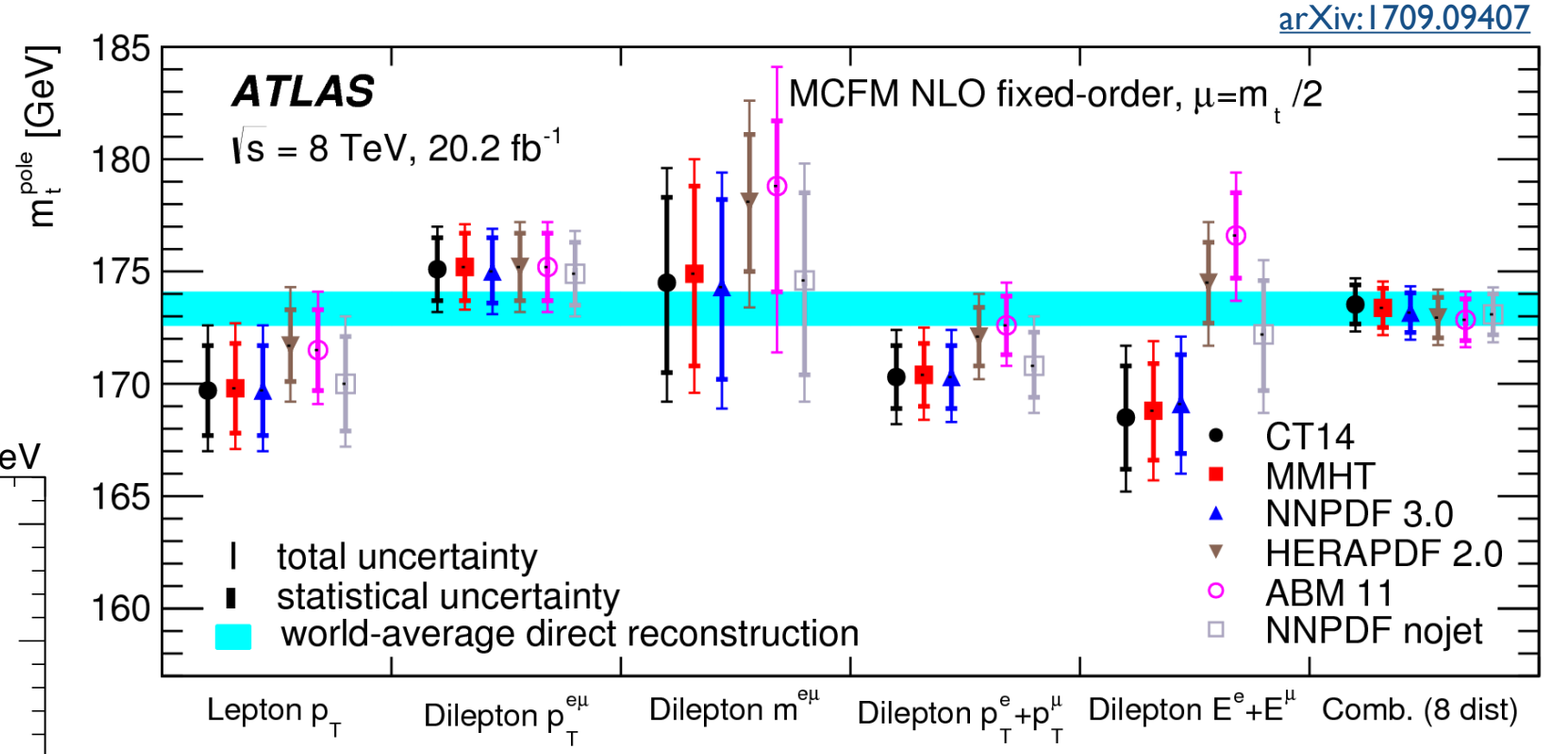
- **Tracks-only measurements evade the dependency on the JES**
  - M(ℓ,J/Ψ) and related variations: more prone to b-fragmentation ⇒ *constrain in-situ with charmed/bottom mesons*
  - dilepton kinematics: rely on excellent lepton calibrations ⇒ *benefit from NNLO at particle level for m_t^{pole}*

    normalised: no lumi, eff. uncertainties!



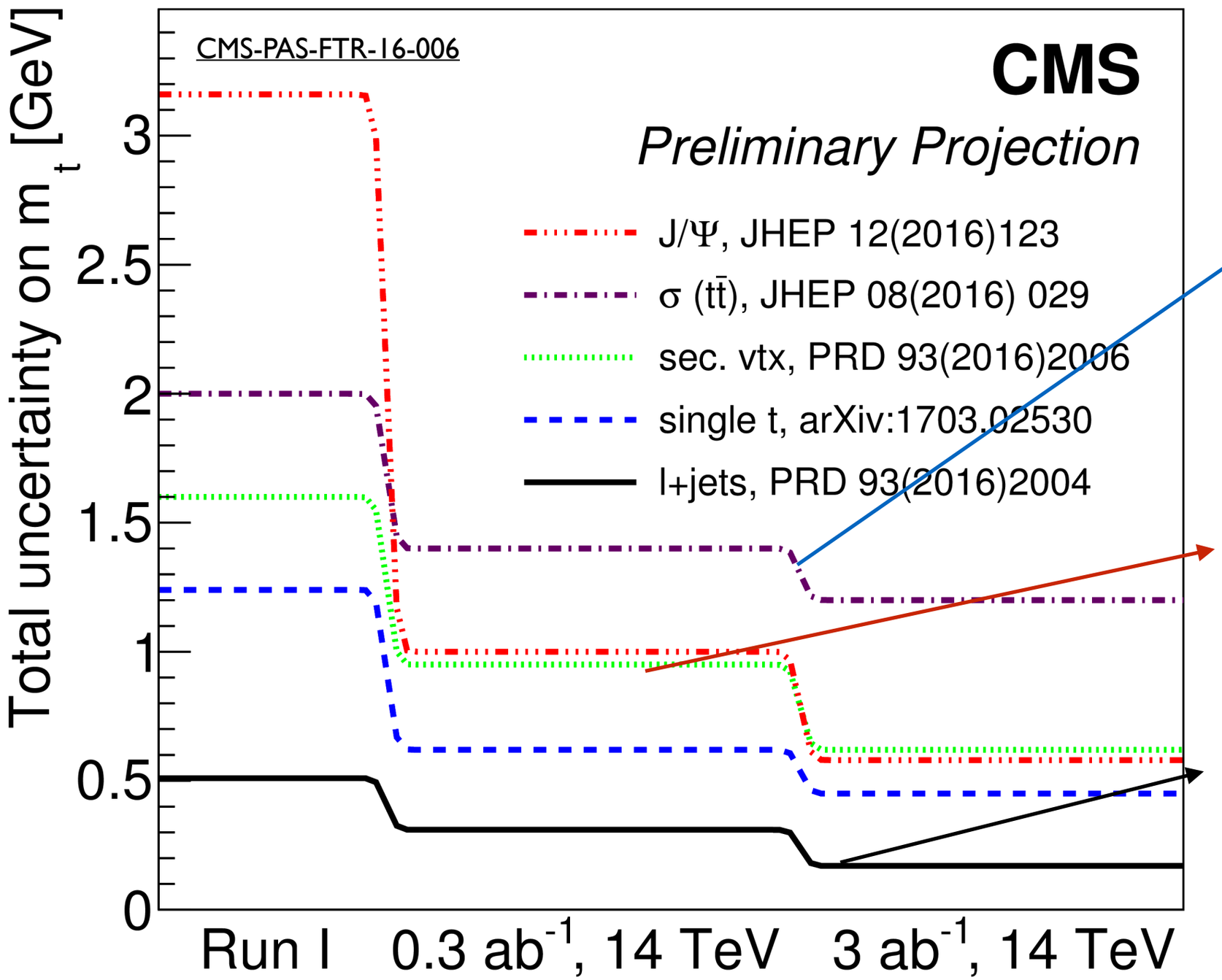


arXiv:1709.09407



- **Two-fold goal for alternative methods**
  - complement systematics ⇒ gain in final combination
  - confirm/calibrate direct m_t measurements to m_t^{pole}

Projections



from σ(tt)

- improved PDFs, and α_S
- no acceptance slope
- no beam energy unc.
- $m_t^{MC}=m_t^{pole}$

from tracks

- in-situ b-fragmentation
- improved top p_T description

from "classic" methods

- 3D fit: mt, JSF, bJSF
- npQCD, from in-situ and ancillary measurements

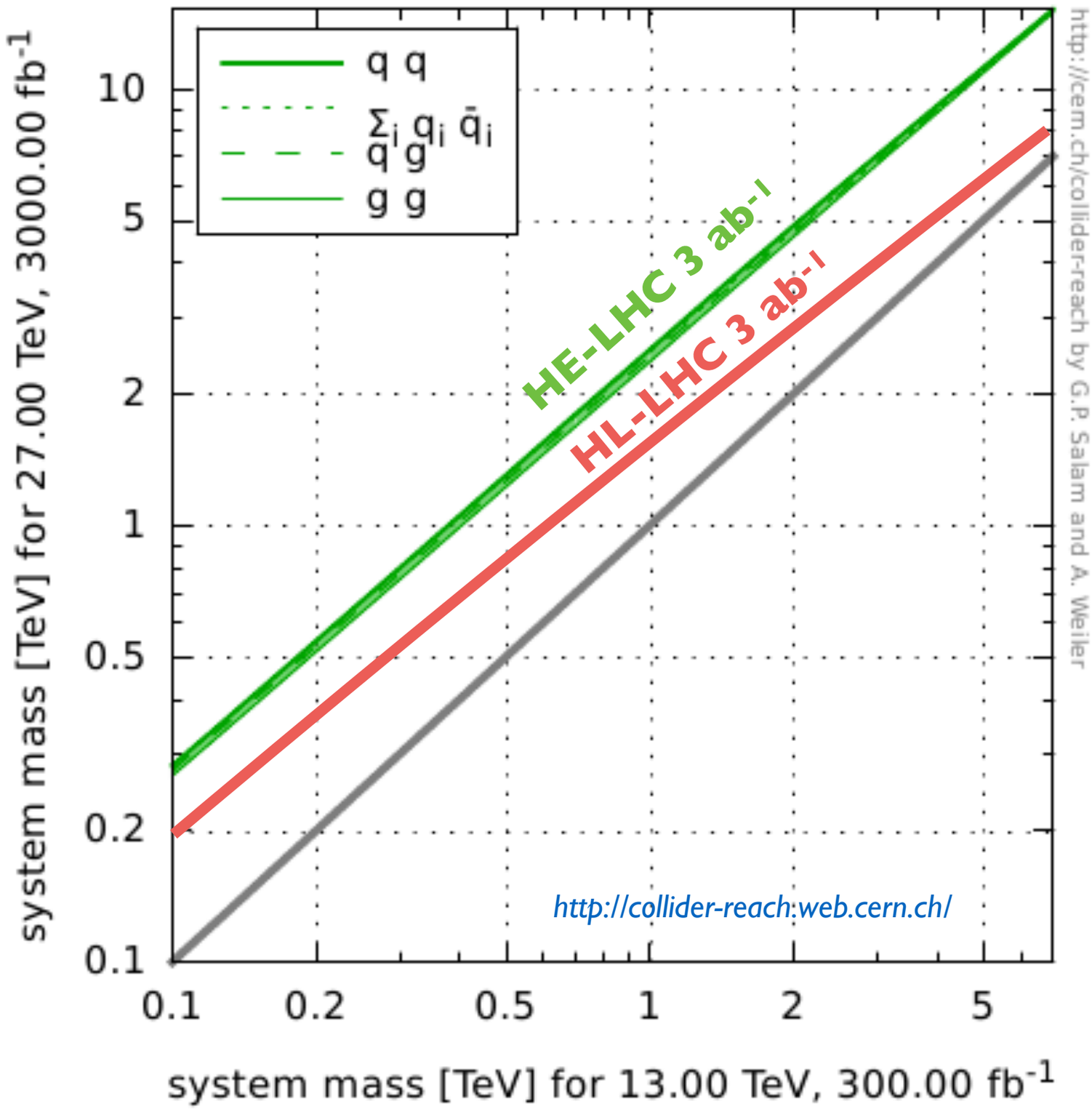
Summary

Summary

- **We are still at the surface of probing the top quark**
  - long term programme for top physics at the LHC needs to cope with the systematics
  - in-situ constraints and ancillary measurements expected to improve modelling
  - design measurements such that particle level definition follows closely the parton level
  - long leverage arm in energy to Run I has unique potential to probe BSM using ratios
    (any gain from a high lumi run at 7 TeV in the future?)
  - complementarity between ATLAS/CMS and LHCb to probe asymmetries in forward region
  - top in heavy ions is just starting: possibility to study much more at the HL-LHC
- **The case for the top quark mass - is unification in sight after LHC?**
  - experiments have reached an excellent precision with Run I data
  - prospects to attain Λ_{QCD} by the end of HL-LHC are not unrealistic
  - programme needs to be complemented with alternative techniques:
    make the bridge or confirm direct measurements as pole mass measurements

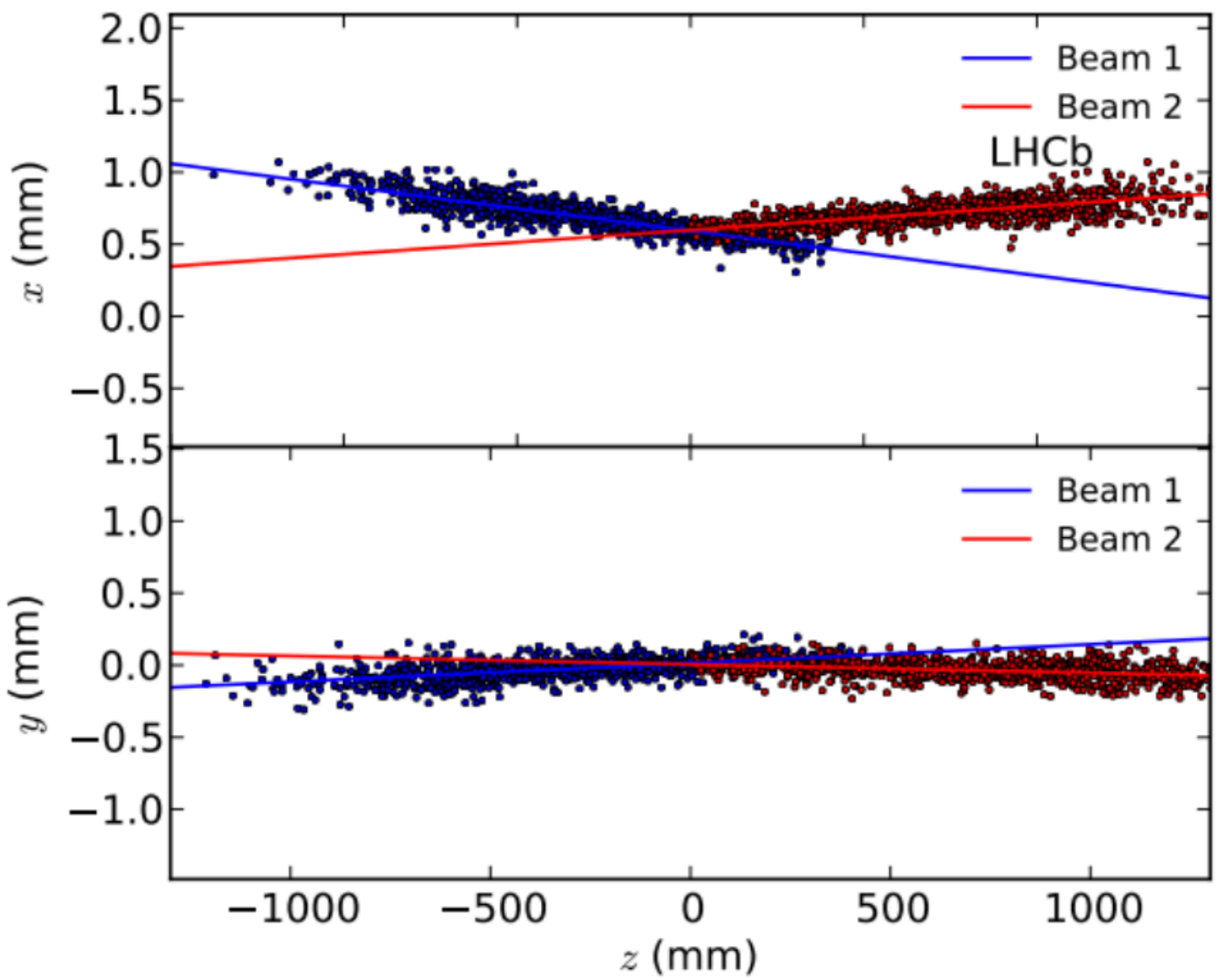
Backup

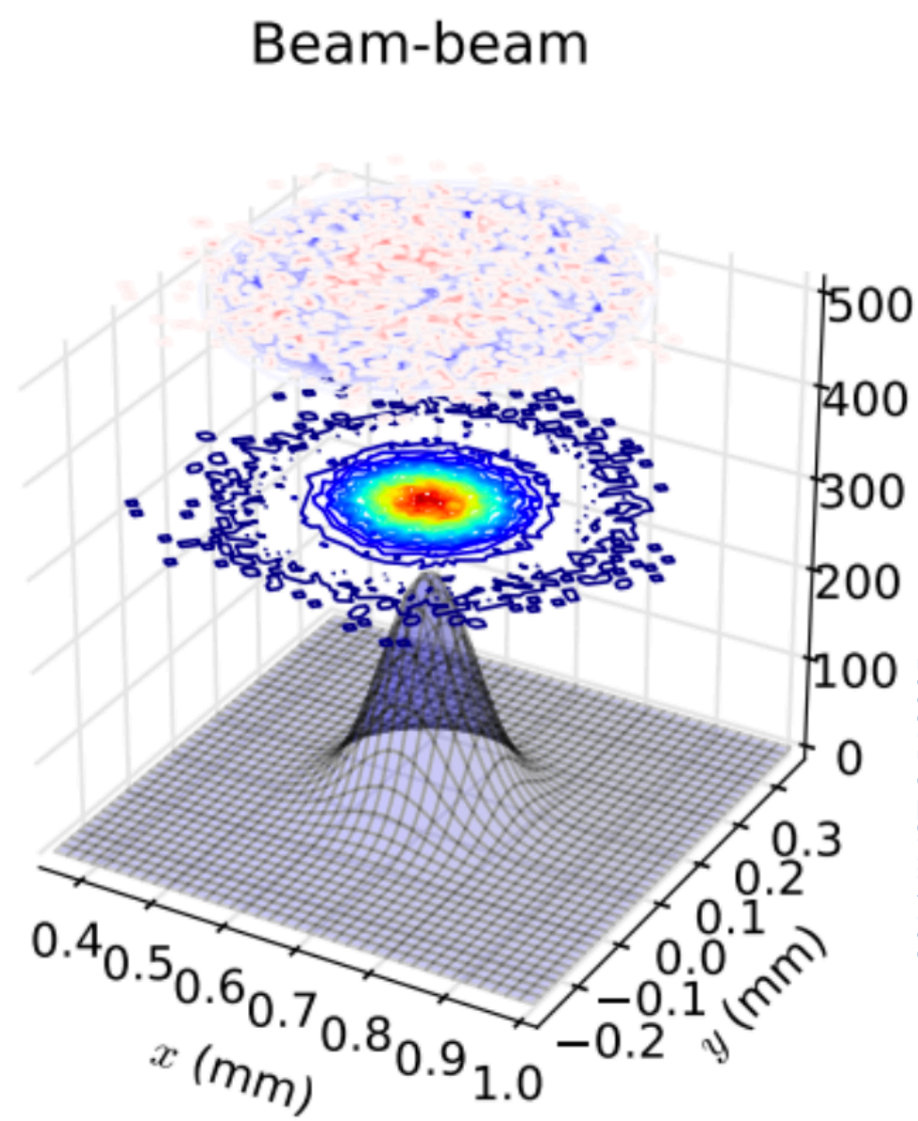
Mass reach of HLHE-LHC for 3ab^{-1}



Reducing x-y dependencies in the luminosity calibration

- **LHCb tracking system is able to measure the beams overlap integral very accurately**
  - direct measurement of the beam profile without need for displacement - complements VdM scan
  - x-y dependency is measured in situ, minimising potential bias in the VdM scan
  - after combination $\frac{\delta\sigma}{\sigma}|_{\text{LHCb 8 TeV}} = 1.2\%$





2014 JINST 9 P12005