Recent experimental results on top and heavy-flavor production

QCD@LHC 2024

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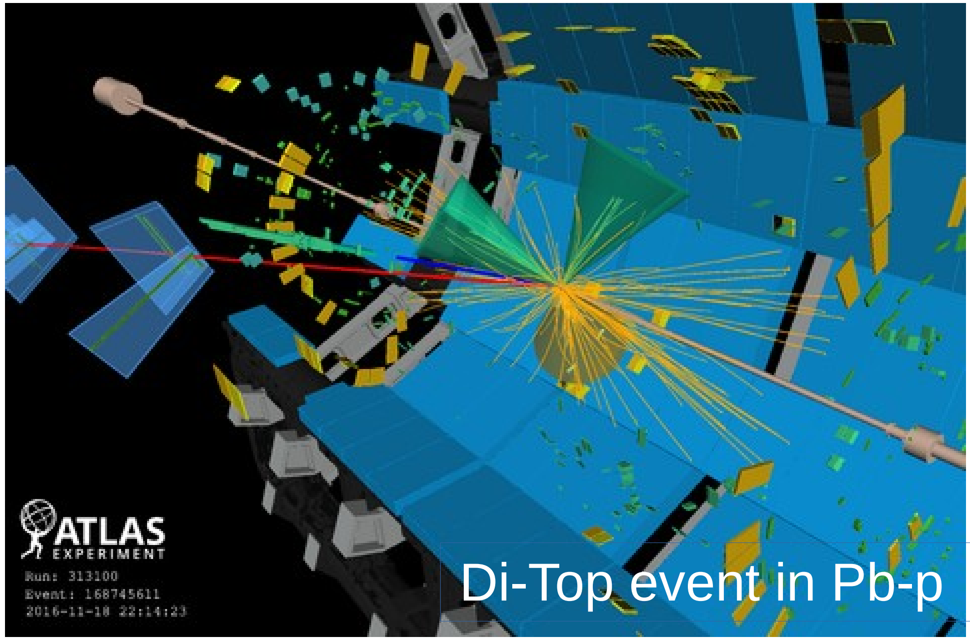
October, 9th 2024

On behalf of the Atlas, CMS and LHCb collaboration

Heavy flavor production at LHC



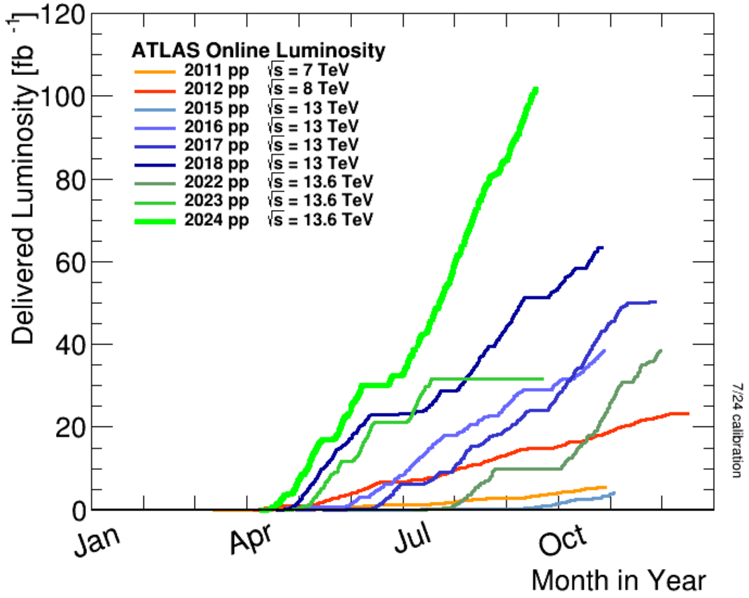
Di-Top event in Pb-p

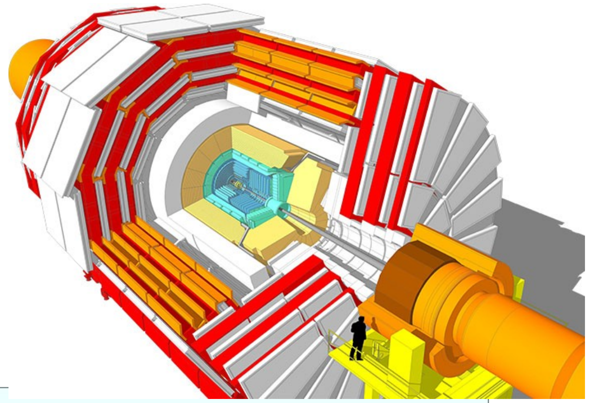
- **Heavy flavor production ($t\bar{t}$, $b\bar{b}$, $c\bar{c}$)** with/without associated particles ($t\bar{t}b\bar{b}$, $t\bar{t}Z$, $b\bar{b}c\bar{c}$, $Wb\bar{b}$…)
  is crucial to understand:
  - Background for new physics signatures
    - Signatures involving b-jets, multi-leptons, Missing energy …
  - Measurement of fundamental SM parameters (top and W mass)

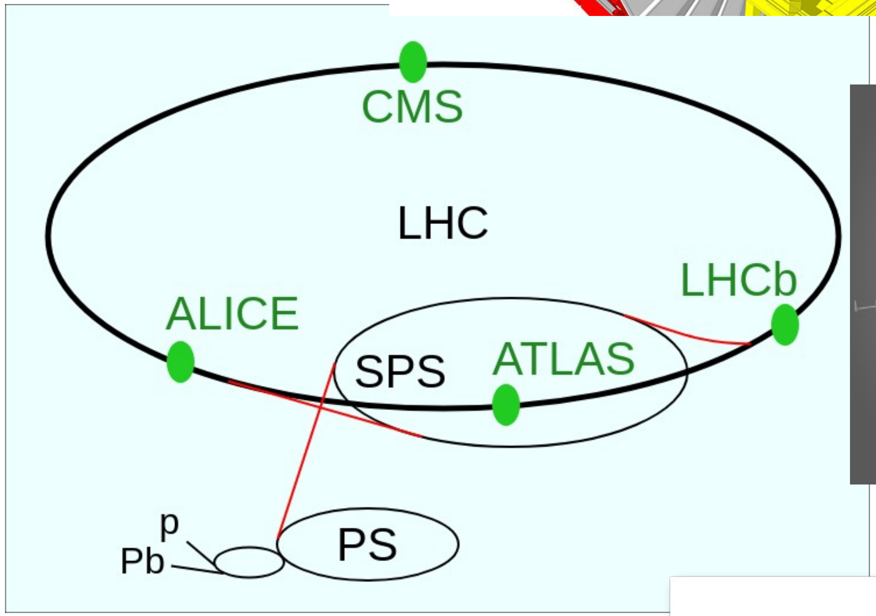
- **Need very accurate QCD prediction and understanding**:
  - Precise prediction for signal and backgrounds
  - Multi scale problem
  - Development and tuning for state of the art MC simulations (massive quark treatment, variable flavor scheme, matched/merged MC for high jet multiplicity, off shell top)

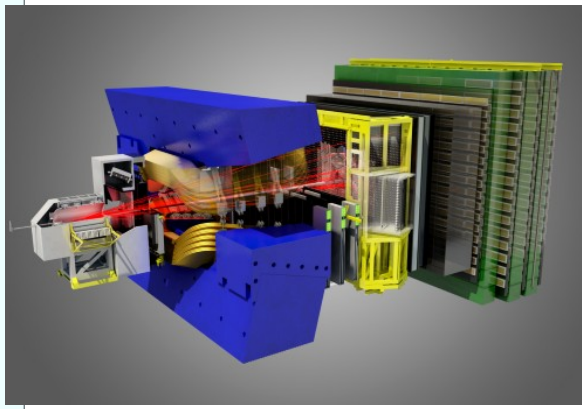
Experiments

- **13 Years of successful data** taking at the LHC covering many energies:

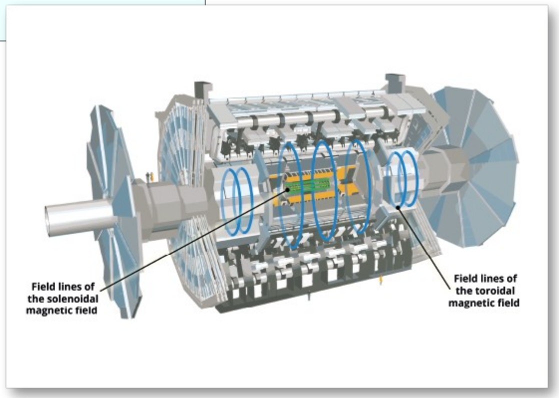








- **Multipurpose detectors:**
  - Atlas and CMS
- **Dedicated experiment for heavy flavor physics:**
  - LHCb

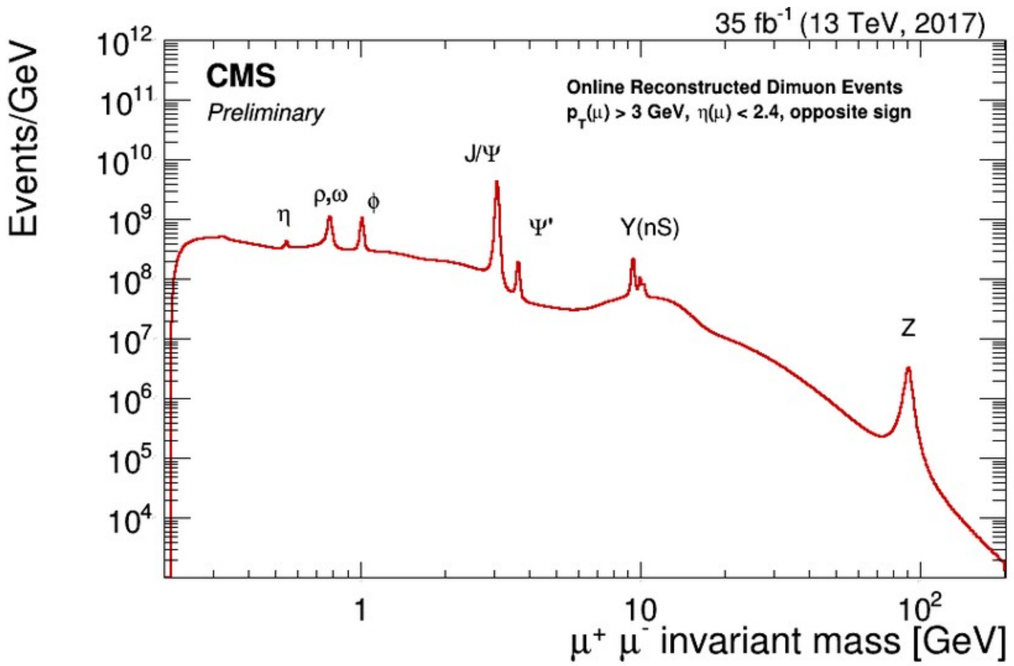


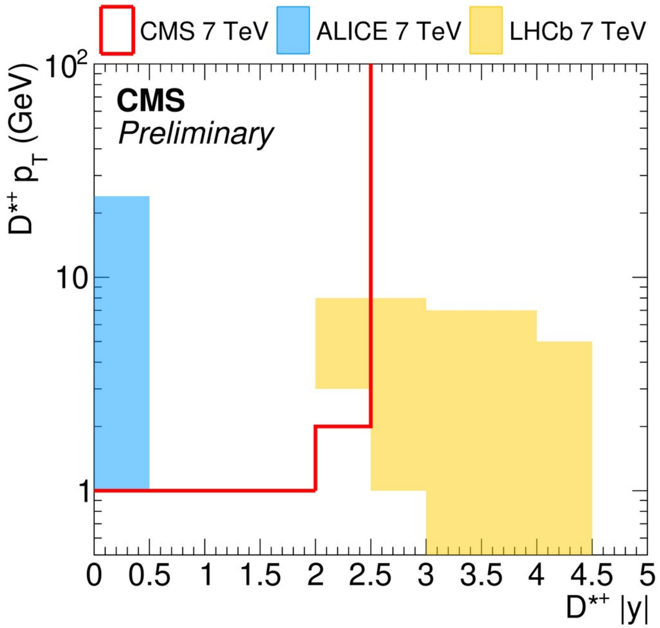
Datasets

- **LHC is a top factory:**
  - Atlas/CMS mostly using unprescaled **single lepton triggers**, fully efficient for **lepton p_T >25 GeV**
  - Millions of top candidates recorded by them
  - **Jet-p_T > 25/30 GeV and b-jet tagging**

- **b/c physics mostly rely on (prescaled) di-lepton triggers:**
  - Atlas/CMS: most data taken at very high pile up (up to 60 events/bx), limitations at low p_T
  - LHCb: dedicated for HF running at moderate inst. luminosity

- **Complementary in angular acceptance of Atlas/CMS and LHCb:**
  - Multipurpose detector are efficient for $|\eta| < 2.4\text{-}2.5$
  - LHCb is efficient in forward direction $2.0 < |\eta| < 4.5$





Content

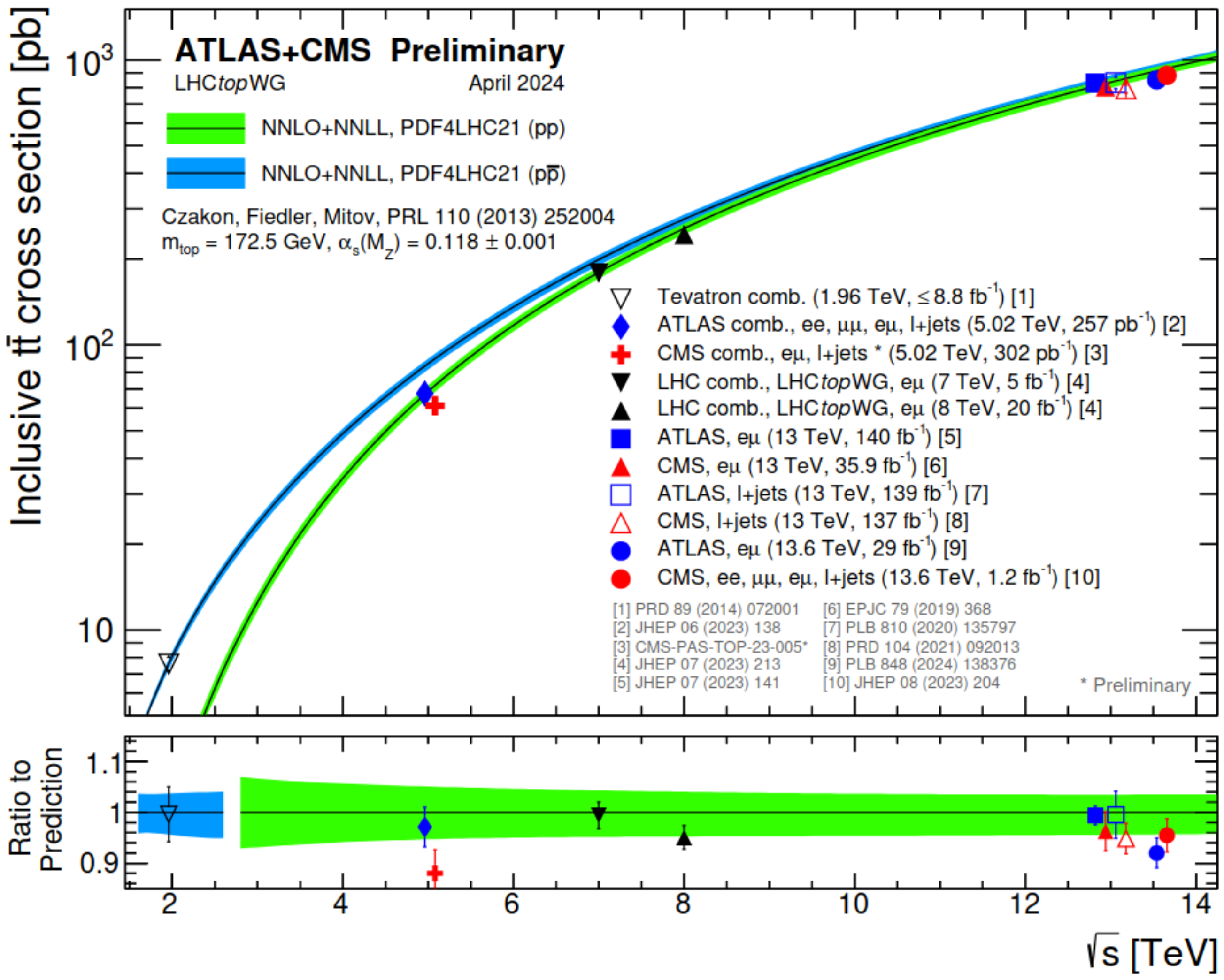
- **(di-)top production**
  - Inclusive Production
  - tt+jets
  - tt+b/c jets
  - tt+V
  - tt+MET

- **HF (bottom and charm) production**
  - J/psi and Y production
  - D* production
  - Y+J/psi and J/psi+J/psi

Top production

Top pair cross section

- **Measurements cover a huge range in center of mass energy:** top cross section rise by factor 100 vs Tevatron
- **Comparison with NNLO+NNLL theory prediction:**
  - Data agree with calculation inside theory error
  - Single best data result [5] has 2.5 times smaller error than theory
- CMS and Atlas have 13.6 TeV results → next page
- Most recent:
  - CMS@5 TeV (CMS-PAS-TOP-23-005)
  - Atlas Pb-p @8.16 TeV (TOPQ-2023-32)
- Complementary in η range:
  - LHCb (JHEP 08 (2018) 174)



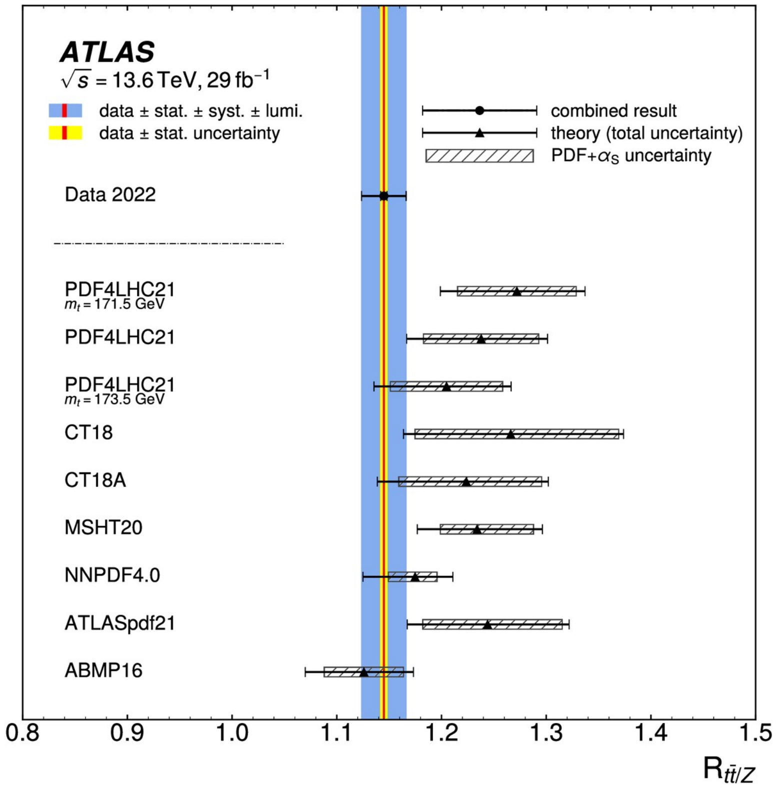
Top pair cross section @13.6 TeV

- **Cross section increases by 12% vs 13 TeV**
- **Atlas results @ 13.6 TeV using di-lepton events:**
  - In-situ calibration of the b-jets
  - Results dominated by systematic and luminosity error (2.4%) (Atlas [9]):

$$\sigma_{t\bar{t}} = 850 \pm 3(\text{stat.}) \pm 18(\text{syst.}) \pm 20(\text{lumi.})\ \text{pb.}$$

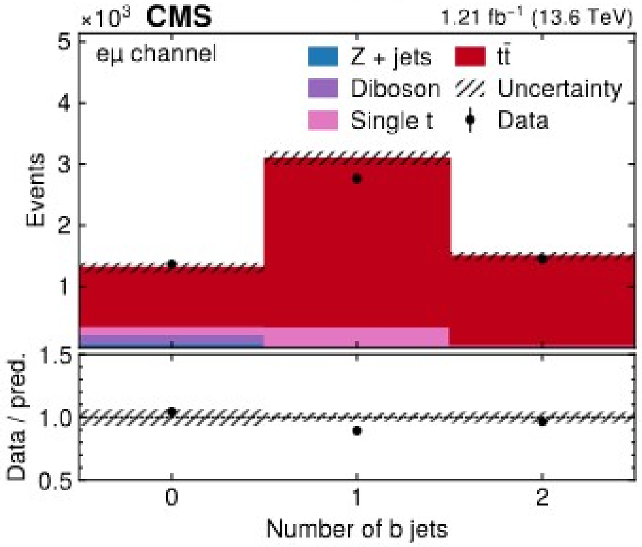
  - Use ratio vs Z cross section to eliminate luminosity error:

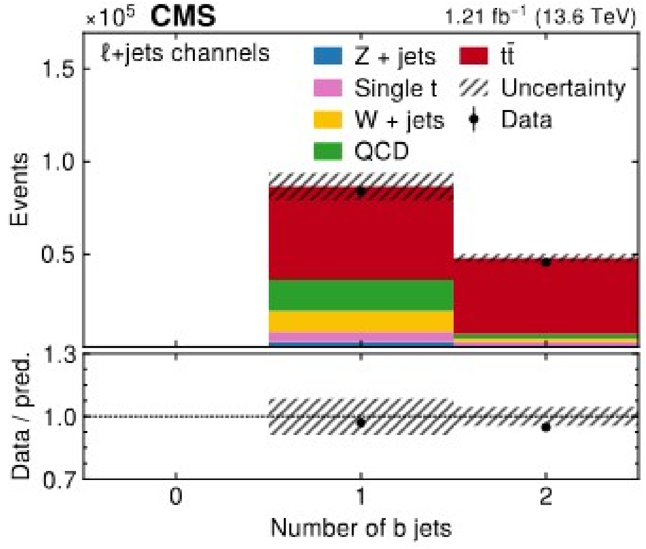
$$R_{t\bar{t}/Z} = 1.145 \pm 0.003(\text{stat.}) \pm 0.021(\text{syst.}) \pm 0.002(\text{lumi.})$$



- **CMS @ 13.6 TeV [10] di-lepton and lepton+jets**

$$\sigma_{t\bar{t}} = 881 \pm 23\,(\text{stat+syst}) \pm 20\,(\text{lumi})\ \text{pb.}$$

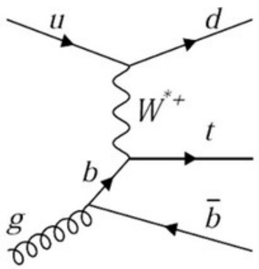


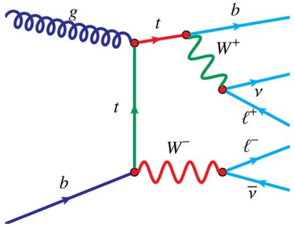


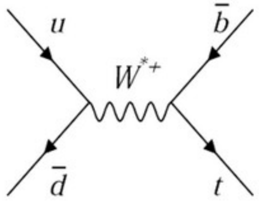
- Di-top measurement has already a decent understanding of experimental systematics
  - Still a factor 2 bigger then final 13 TeV
  - Luminosity is a limiting factor

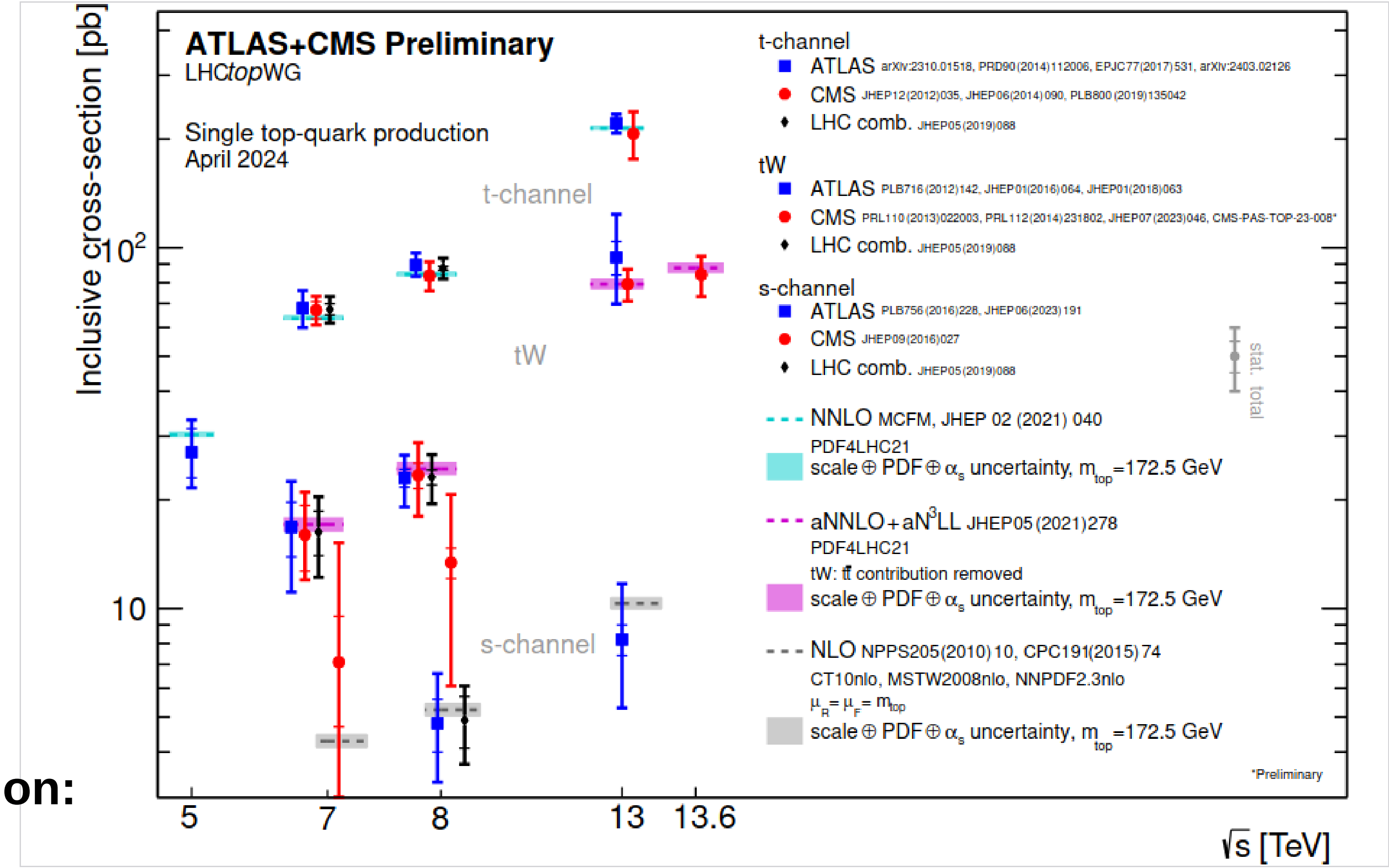
Single Top cross section

- Cross section for
  - **T-channel**
    ~ 5% precision
  - **Wt-production**
    ~10% precision
  - **S-channel**
    ~25% precision









- **Comparison with theory prediction:**
  - Data agree with calculation
  - Different situation than di-top: results are mostly limited by experimental errors (jet reconstruction and understanding of b-tagging) and modeling uncertainties (acceptance)

tt + jets

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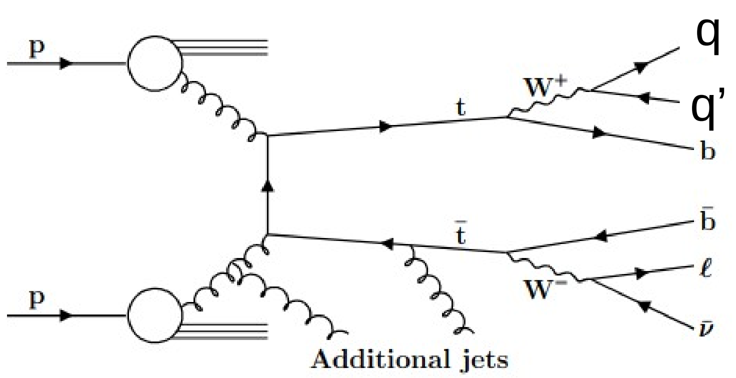
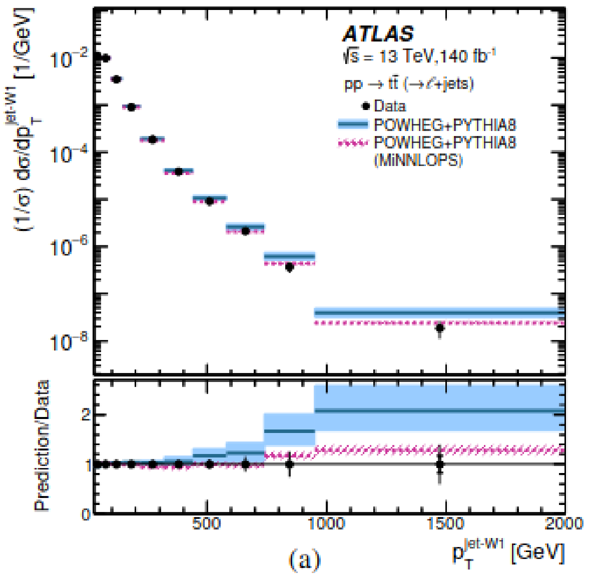
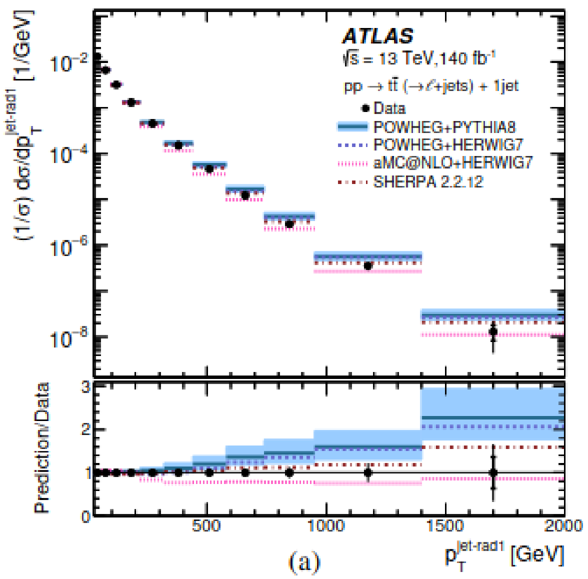


- **Lepton+jet final state analysis (Atlas) in bins of N_{jet}**
- **jets are associated** to tops or identified as radiation jet using **pseudo-top algorithm**:
  - Two highest p_T b-jets are **top b-jets**
  - The two additional jets most consistent with a W-boson are **W-jets** (jet-W1 and jet-W2)
  - **Additional jets** (jet-rad1, jet-rad2) for N_{jet} > 4 bins
  - Neutrinos can be reconstructed up to a ambiguity
- **Jet based observables** (p_T, Y; m, ΔY and $\Delta\phi$ of two jets)
  - Measured normalized and compared to NNLO+NNLL cross section

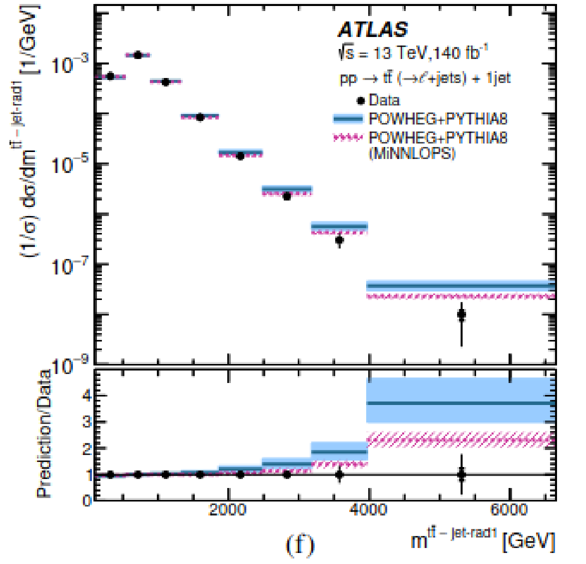
tt incl.



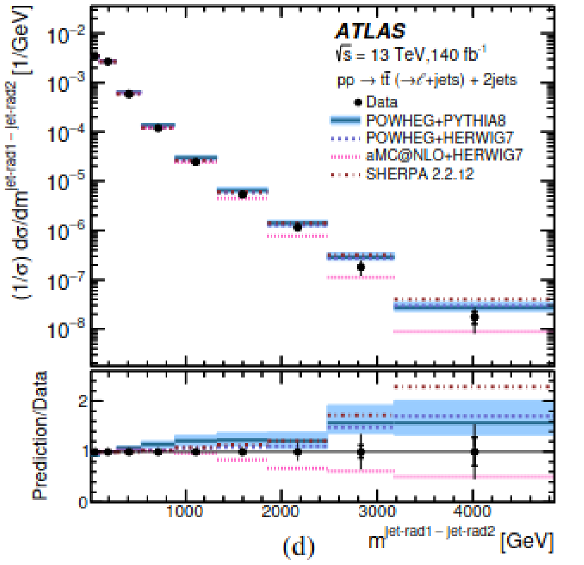
tt+1jet



tt + 1jet

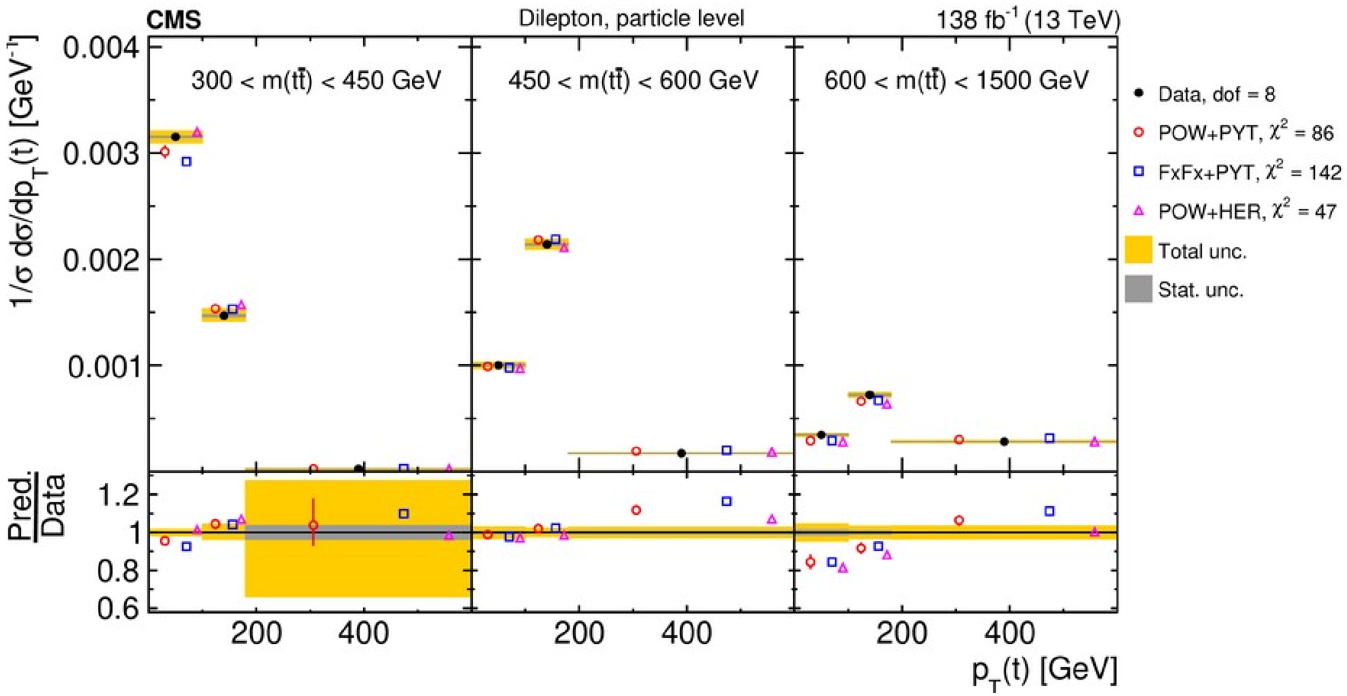


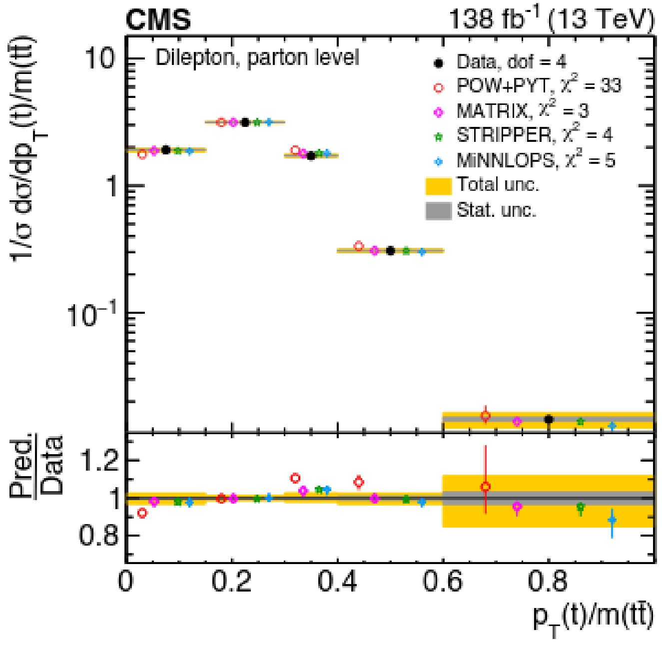
tt + 2jet



tt+jets up to 3-dimensional

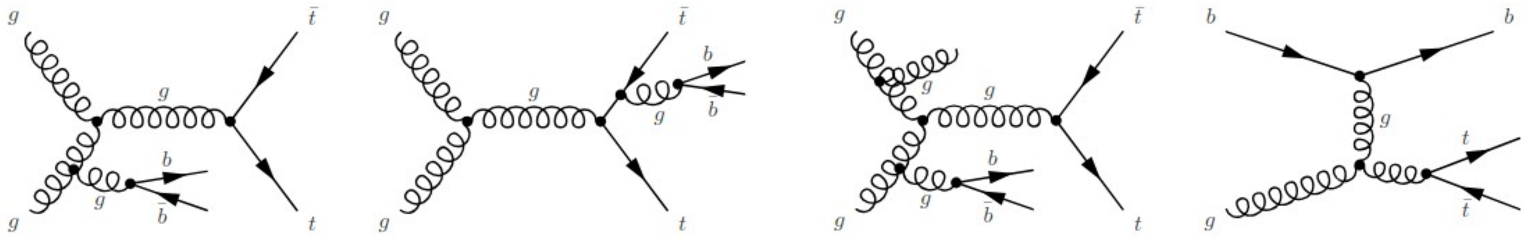
- **Di-lepton selection (CMS)**:
  - Full di-top reconstruction; neutrinos are reconstructed using kinematic constrains, top and W mass and smearing technique
- **Observables:**
  - Direction and p_T of the tops and di-top systems are shown
  - New variables to describe the dynamics of the events: $p_T(t)/m(t\bar{t})$, $p_T(t\bar{t})/m(t\bar{t})$
  - Up to three dimensional distributions (differential in three variables)
- **Comparison of data** with
  - different **generator setups**
    - Powheg with Pythia8/Herwig
    - aMC@NLO + up to 2 add. partons using FxFx matching/merging
  - different **theory predictions** @NNLO:
    - Matrix, Stripper, MiNNLOPS



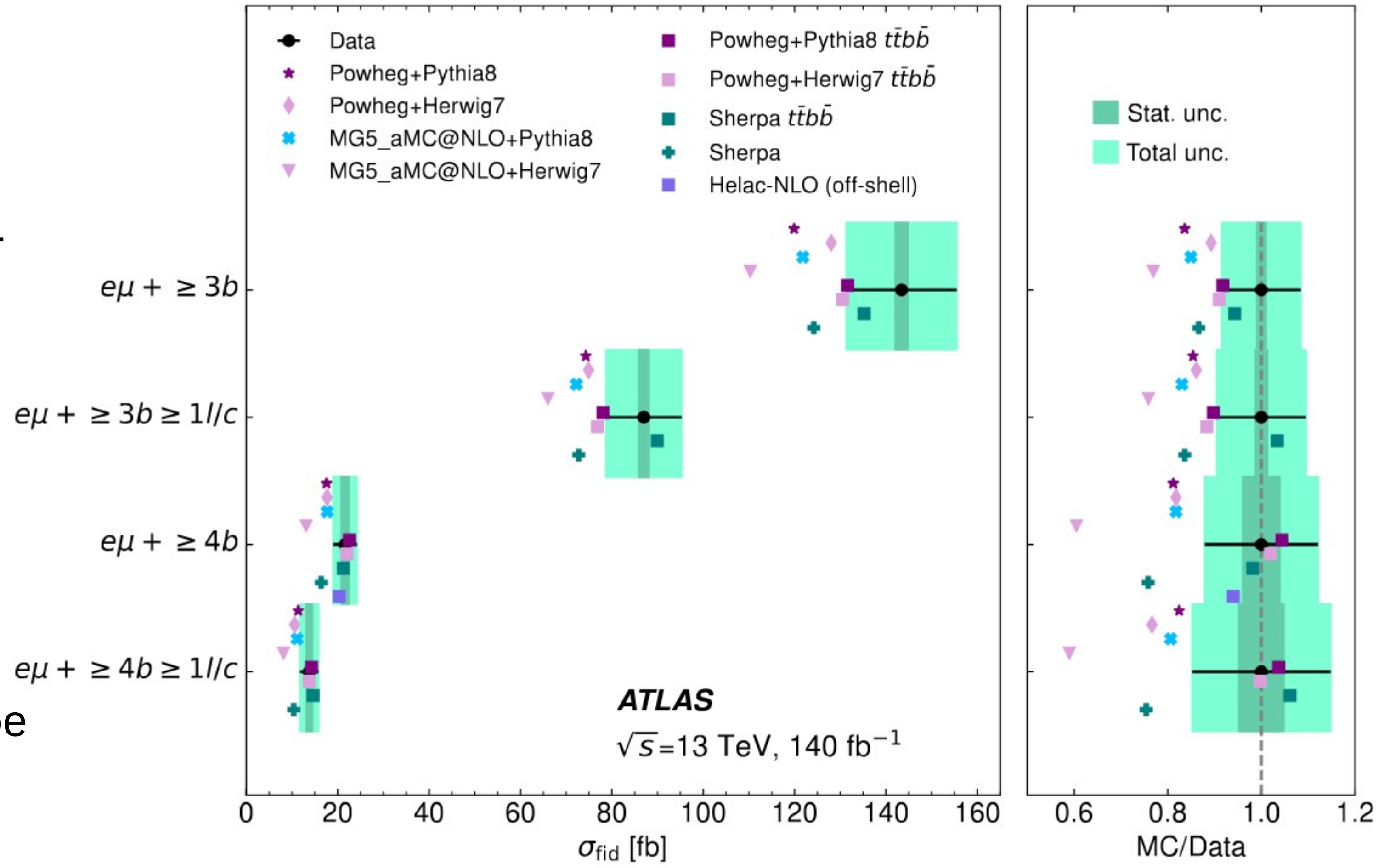


$t\bar{t}+b\bar{b}$

arXiv:2407.13473



- **Atlas $t\bar{t}+b\bar{b}$ using full 13 TeV dataset:**
  - di-lepton channel
  - corrected to particle level
  - showing **absolute cross sections** and **normalized differential distribution** to disentangle normalization and shape
  - To reduce generator related systematics from HF sample composition: fit of flavor components in MC to the data using the distribution of b-tags



- **Comparison to** different 4- and 5-flavor generators/calculations:
  - **5-f generators** general underestimate number of additional b-jets
  - **4-f $t\bar{t}b\bar{b}$ generators/calculation** describe (mostly) ≥4-jet distributions better, but have similar problem for ≥3jets

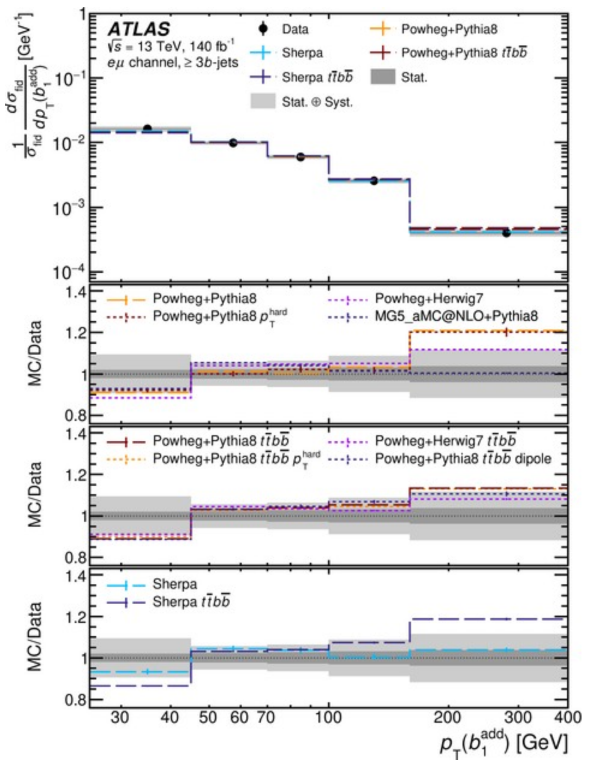
$t\bar{t}+b\bar{b}$

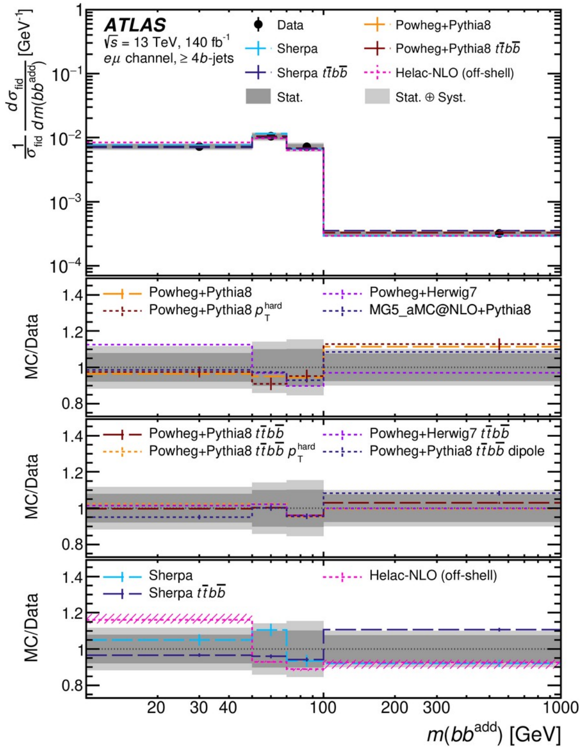
- **Measured distributions for ≥3jets** dominated by systematics, p_T of additional b-jets is too hard in Powheg and 4-flavor-generators, better in 5-flavor aMC@NLO and sherpa

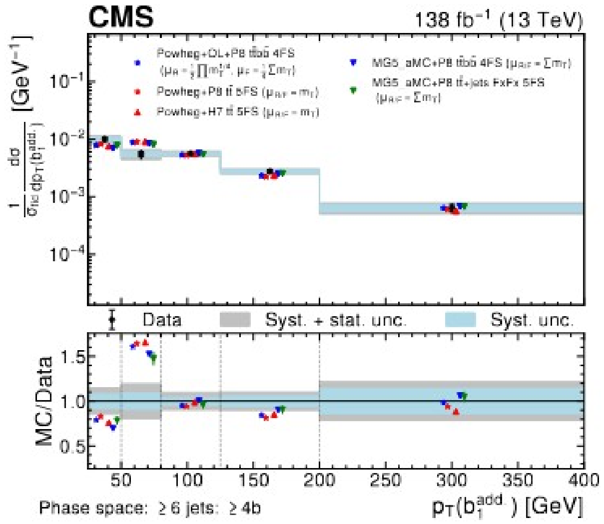
- **Distributions for ≥4jets** similar limited by statistics and systematics: generators/calculations show agreement inside errors with different trends

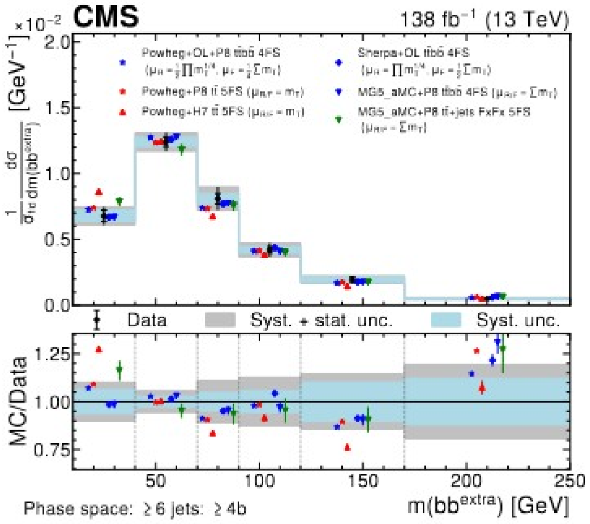
- **Similar tendencies** are seen in older **CMS publication in lepton+jet channel** (b-jets are corrected to similar phase space):
  arXiv:2309.14442
  - **New generator setups/comparisons are available,** sherpa in variable flavor schema:

    arXiv:2402.15497



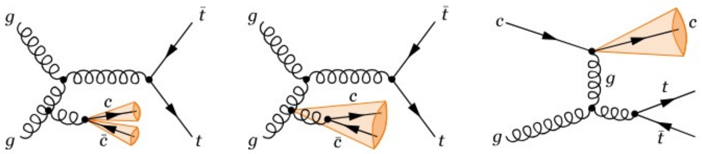




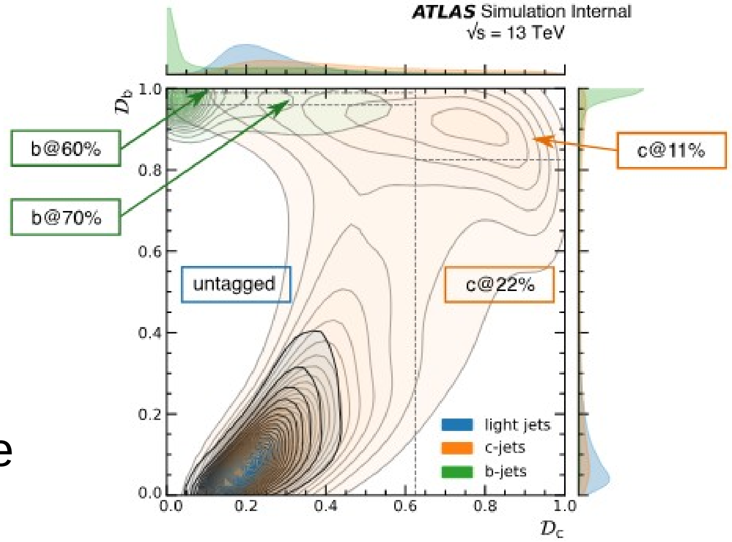


$t\bar{t}+c(\bar{c})$

arXiv:2409.11305



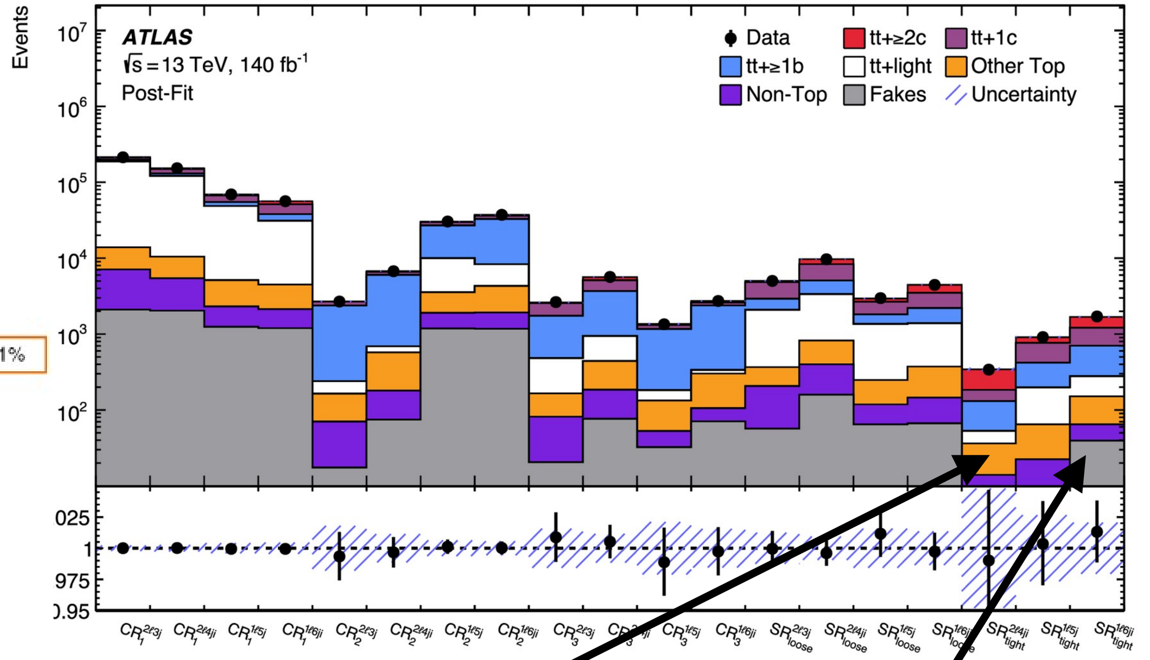
- New Atlas result
- **c-tagging is much more challenging than b-tagging**
  - Using multiple working points in two dimensional plane of "b-ness" D_b and "c-ness" D_c to separate b-jets and light-jets

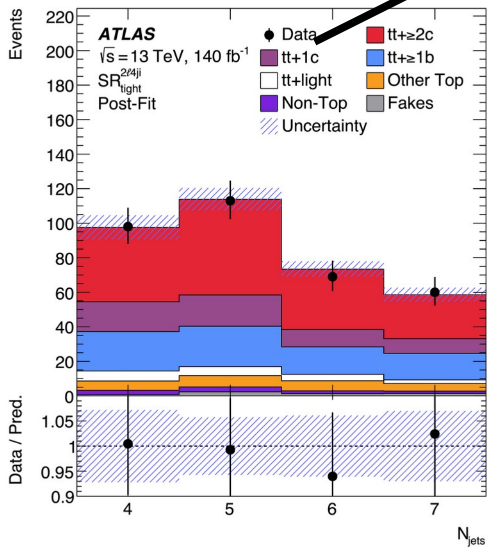


- Result using 2-lepton and lepton+jet channel
- Multiple control and signal region to control different background distributions
- Maximum likelihood fit using all systematics as nuisance parameters:

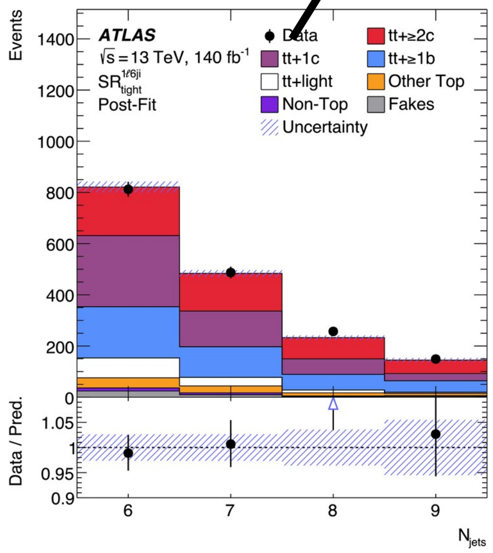
$$\sigma^{\mathrm{fid}}(t\bar{t} + \geq 2c) = 1.28\,^{+0.16}_{-0.10}\,(\mathrm{stat})\,^{+0.21}_{-0.22}\,(\mathrm{syst})\ \mathrm{pb} = 1.28\,^{+0.27}_{-0.24}\ \mathrm{pb},$$

$$\sigma^{\mathrm{fid}}(t\bar{t} + 1c) = 6.4\,^{+0.5}_{-0.4}\,(\mathrm{stat}) \pm 0.8\,(\mathrm{syst})\ \mathrm{pb} = 6.4\,^{+1.0}_{-0.9}\ \mathrm{pb}.$$





2 Leptons/4+ jets

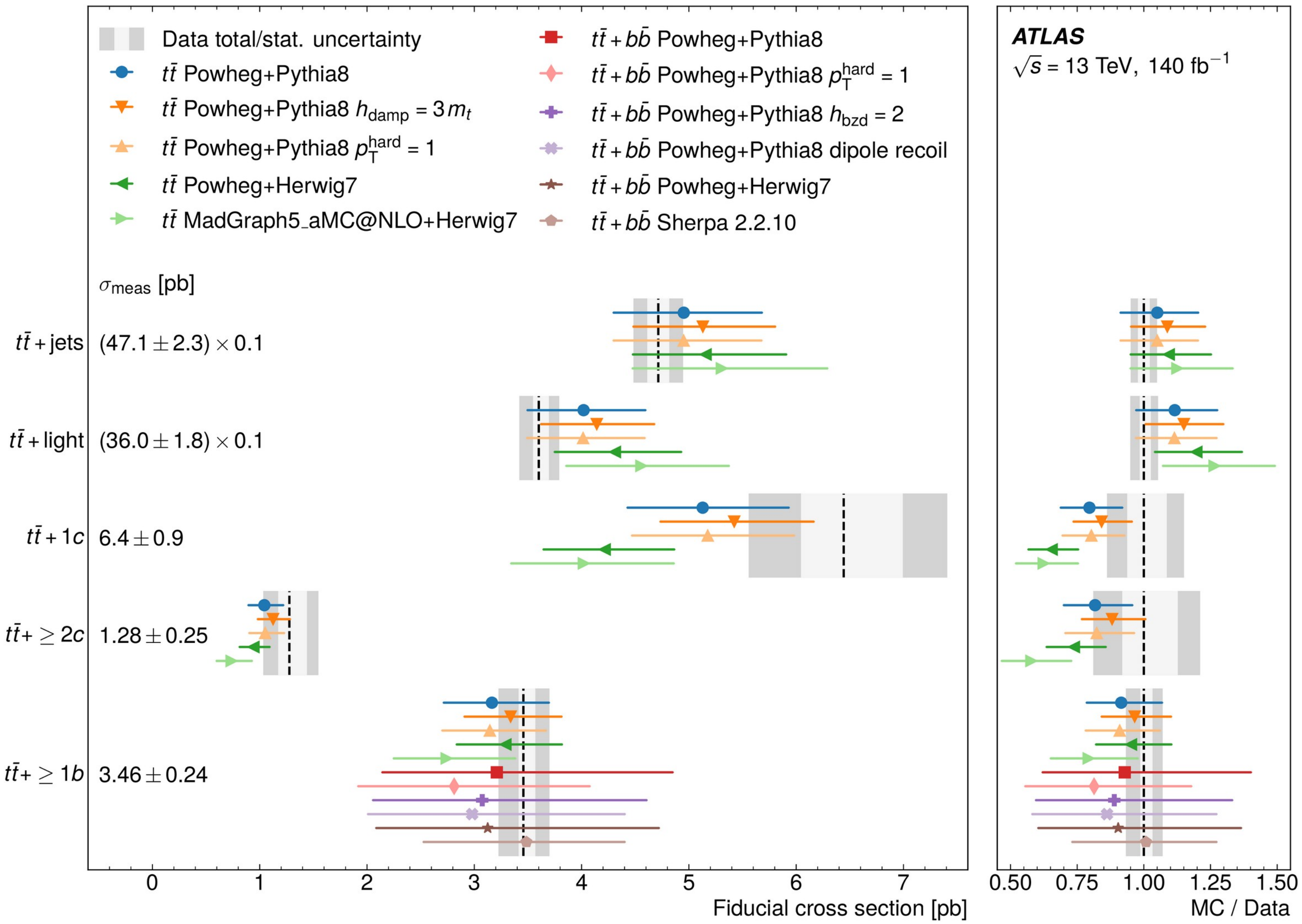


1 Lepton/6+ jets

$t\bar{t}+c\bar{c}$

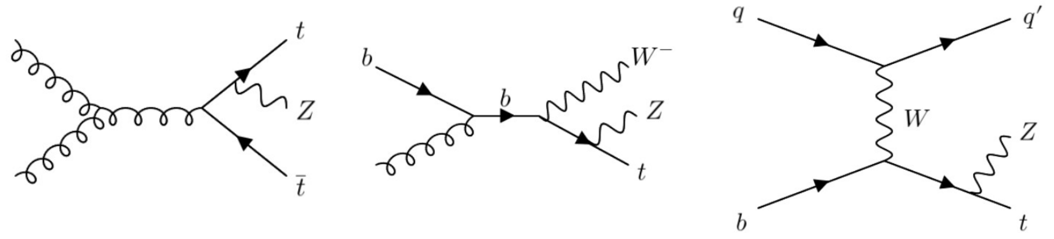
- **Comparison to various 4 flavor and 5 flavor generator setups** for the 4 measured fractions (b, c, $c\bar{c}$, light) in the profile likelihood fit:

  - **b-jet rate** is underestimated in generators except Sherpa 5F **consistent with the $t\bar{t}b\bar{b}$ analysis**
  - **c and 2c rate is underestimated by ~ 25%**
    - Herwig7 lower then Pythia8
    - Some dependency on the Pythia8 setup

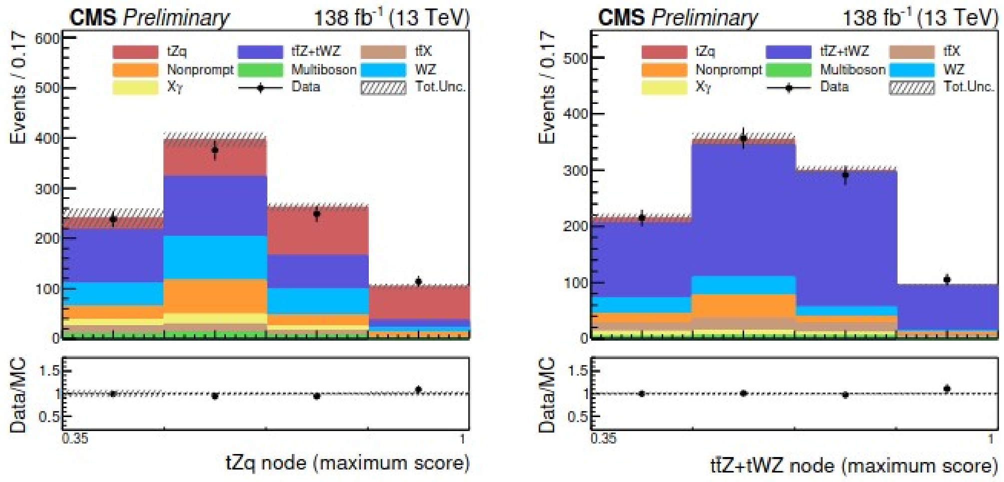


Top+Weak Bosons

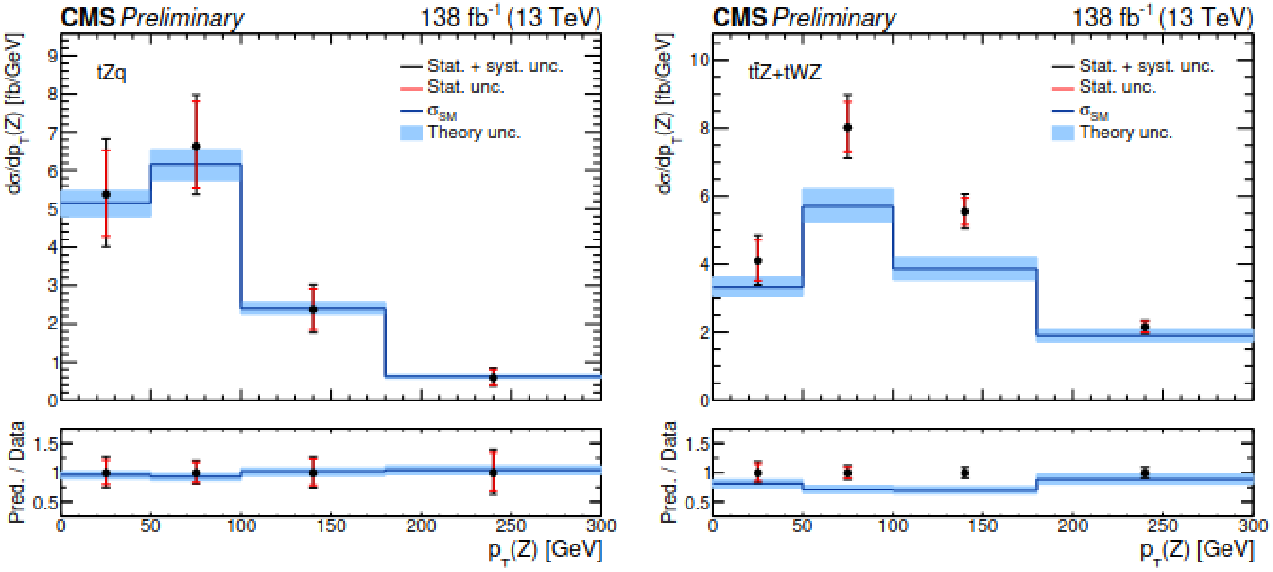
- 3 lepton final state, two consistent with a Z boson, selection are used to select tt/Wt+Z and tZ events

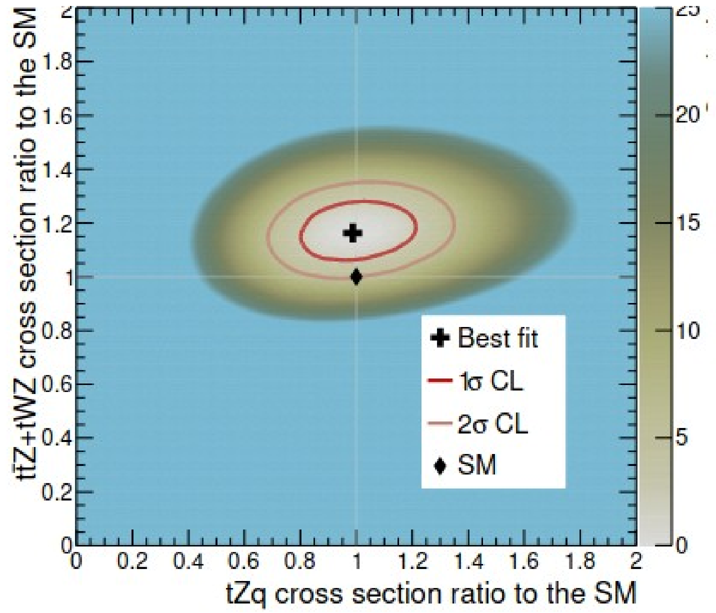


- Simultaneous likelihood fit on:
  - **DNN with 26 inputs** require 3 leptons and a b-jet



  - **Additional input:**
    - N b-jet distribution for 4 selected leptons
    - N_{jet} for no b-jet(WZ background) enrich



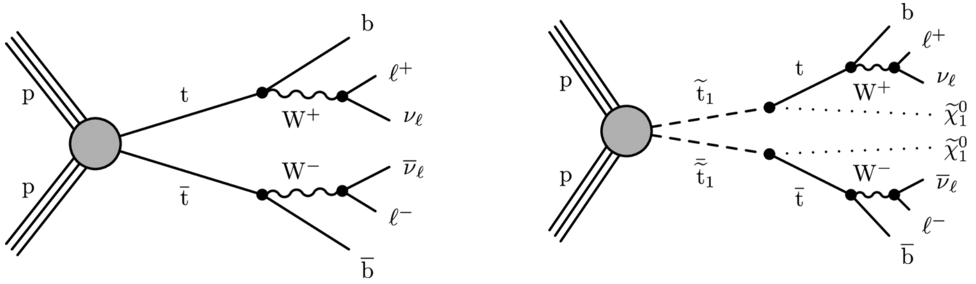


$$\sigma(t\bar{t}Z + tWZ) = 1.14 \pm 0.05\ (\text{stat}) \pm 0.04(\ \text{syst})\ \text{pb},$$
$$\sigma(tZq) = 0.81 \pm 0.07\ (\text{stat}) \pm 0.06\ (\text{syst})\ \text{pb}.$$

CMS-PAS-TOP-24-001

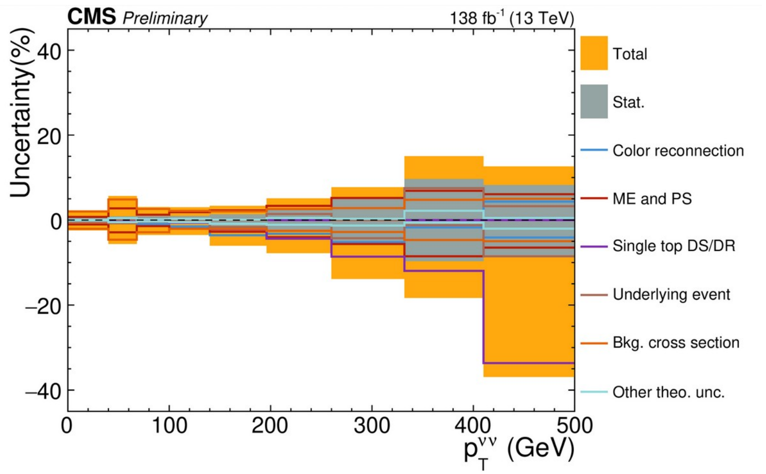
MET in di-top events

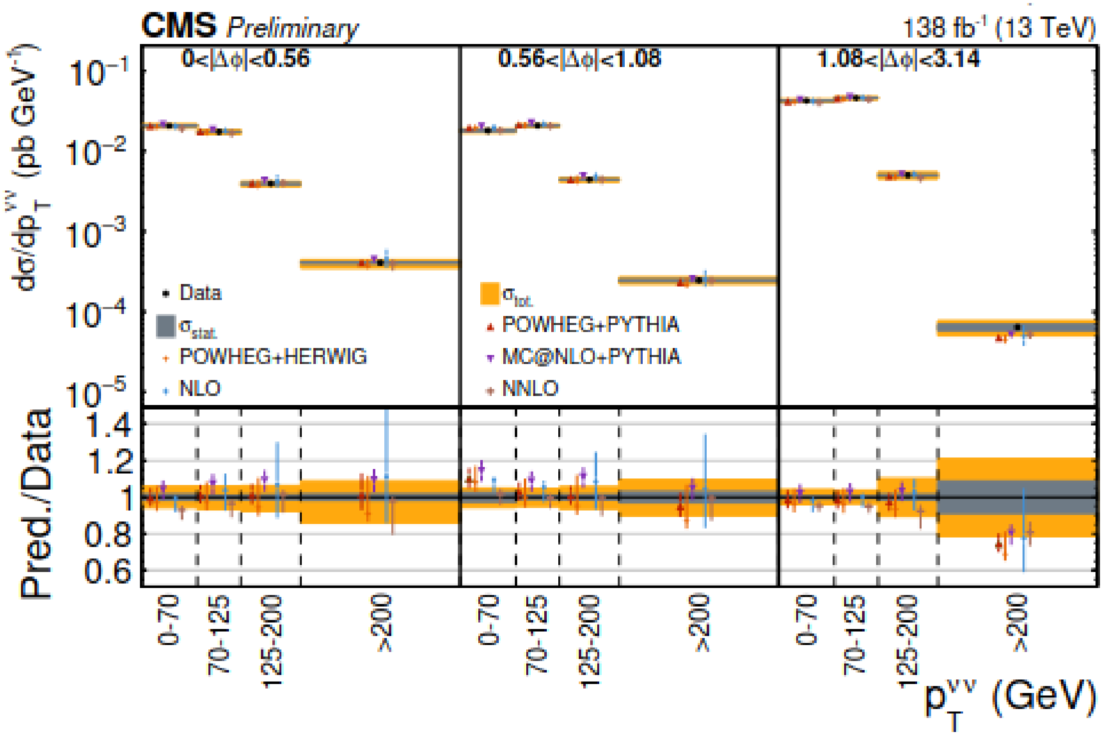
- Description of **events with high MET in top** is **important for many searches:**



- **Very sensitive on the description of** off-shell top events and **Wt:** diagram subtraction (default) vs diagram removal is a significant systematics at very high MET

- **CMS analysis shows double differential distribution** of the p_T of the di-neutrino system and its minimal angle to the leptons
  - Agreement of data with generators/calculation reasonable in most areas
  - Large MET at large angle not that well described





Charm and beauty production

Υ-Production (LHCb)

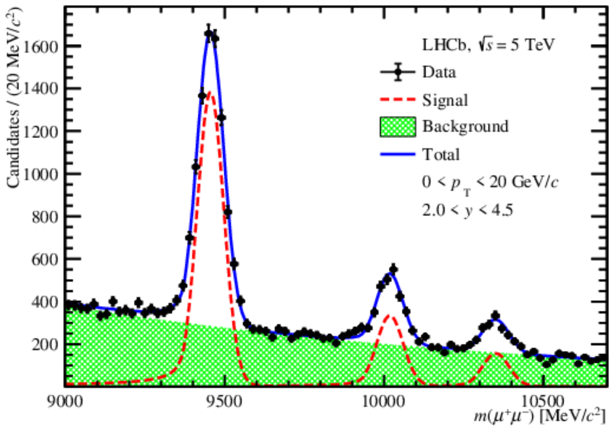
JHEP 07 (2023) 069

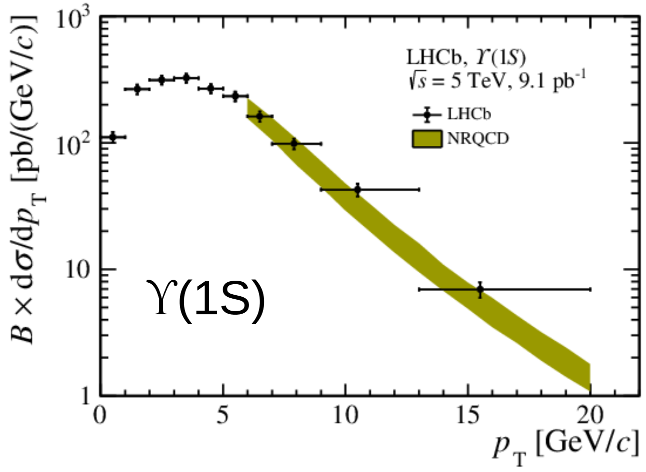
- **Result from LHCb** using small dataset taken at 5 TeV to compare to HI results
  - **Cross section extracted** using mass distribution fitted with a crystal ball function and

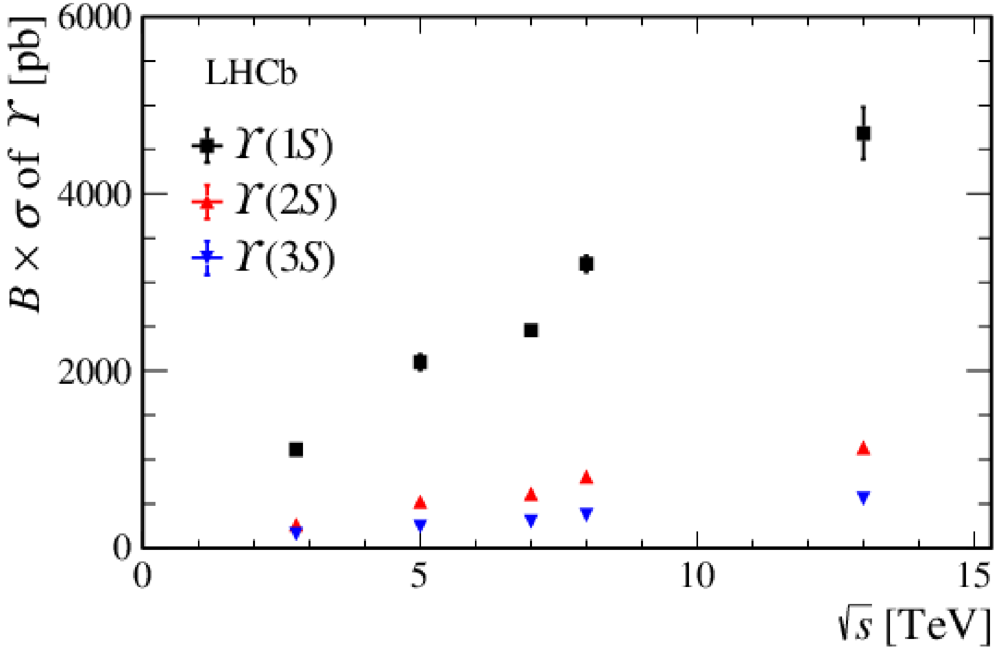
$$\sigma(\Upsilon(1S)) \times \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) = 2101 \pm 33 \pm 83\,\text{pb}$$
$$\sigma(\Upsilon(2S)) \times \mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-) = 526 \pm 20 \pm 21\,\text{pb}$$
$$\sigma(\Upsilon(3S)) \times \mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-) = 242 \pm 16 \pm 10\,\text{pb}$$

  - **Differential distributions** in p_T and y are shown for Υ(1S), Υ(2S), Υ3(S)
    Υ(1S) **compared to NRQCD**

- **Comparison of Υ production cross section** at different LHC center of mass energies: now have results **at all pp ECM**







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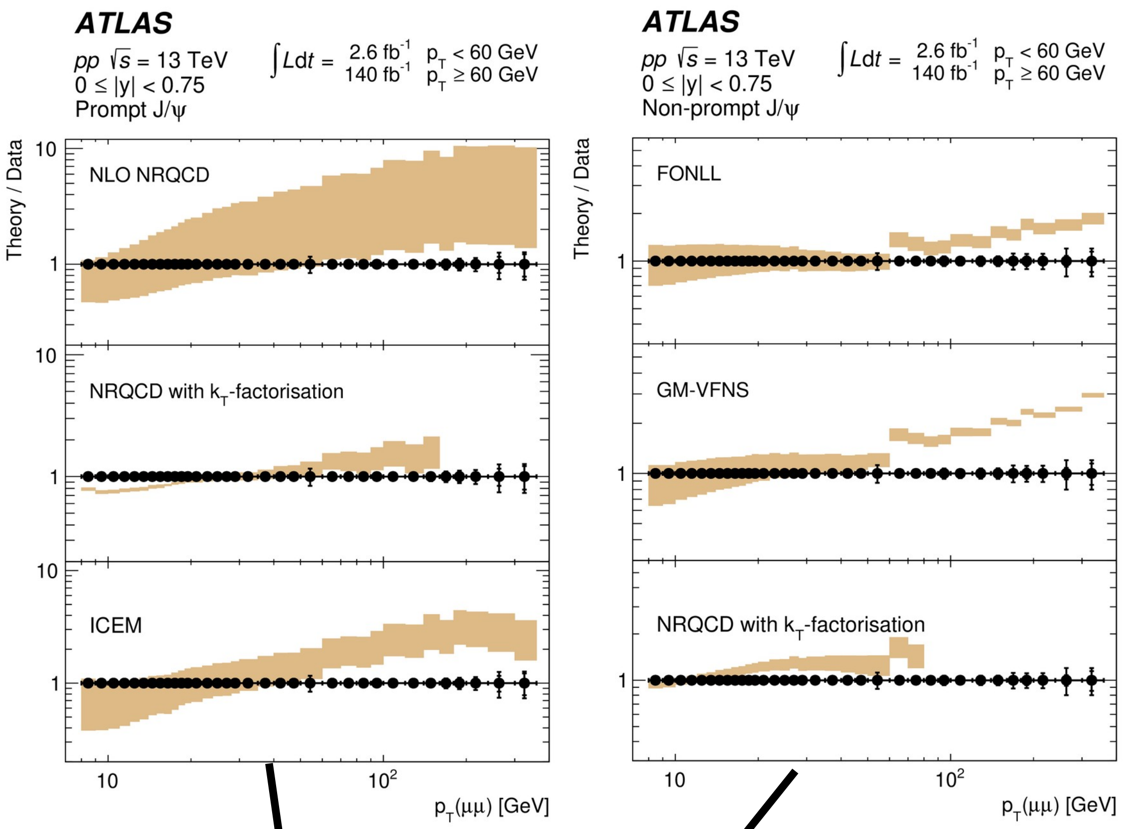
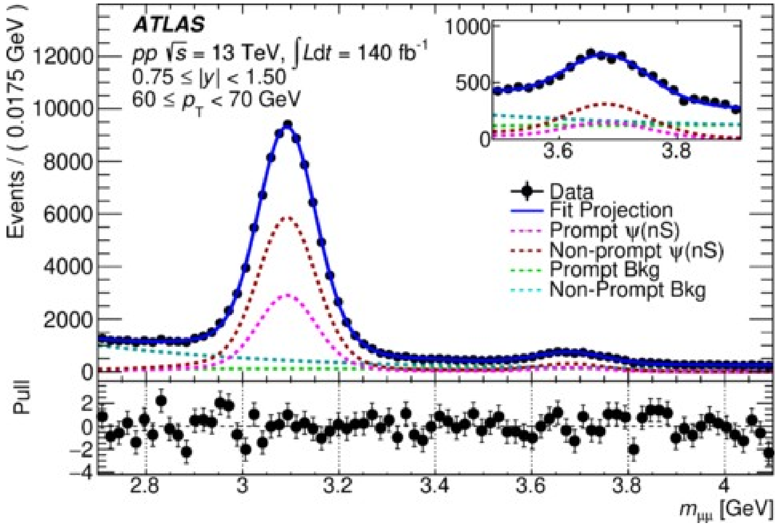
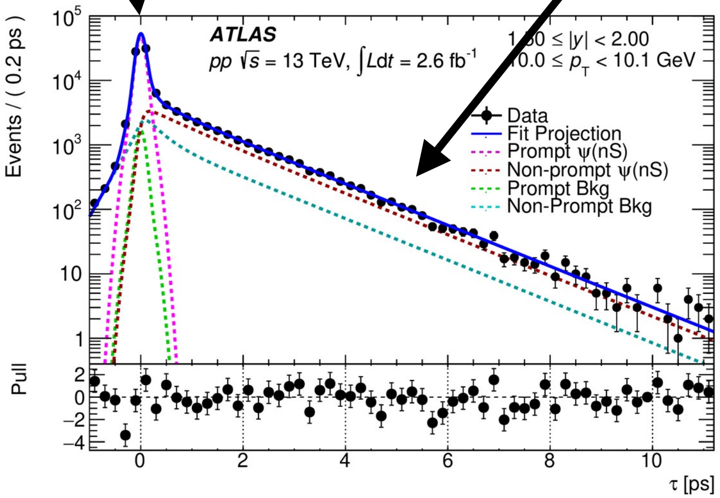
J/ψ and ψ(2S) production (Atlas)

- **Measurement of J/ψ + ψ(2S) in bins of p_T (8-320 GeV)** and |y|<2
  - Different datasets/triggers for low p_T (di-muon trigger) and high p_T (single muon trigger)
  - Very high p_T range is covered
  - **Results for prompt (charm production) and non-prompt (bottom decay chains)** are presented and compared with theory



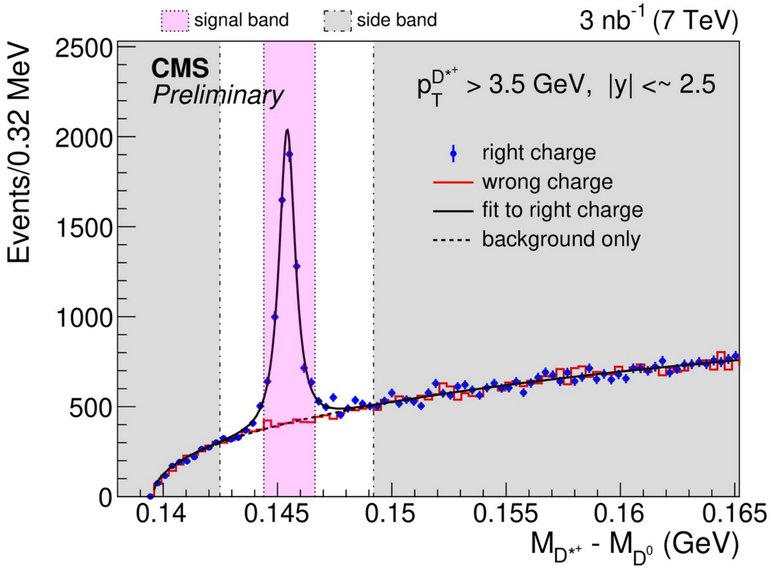


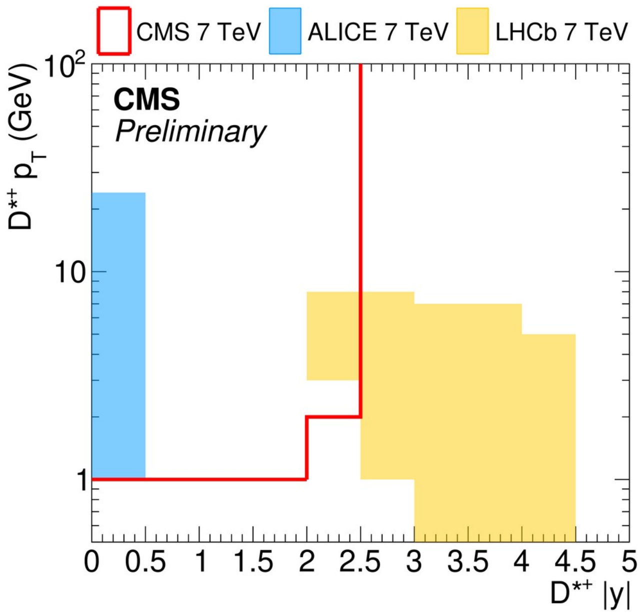


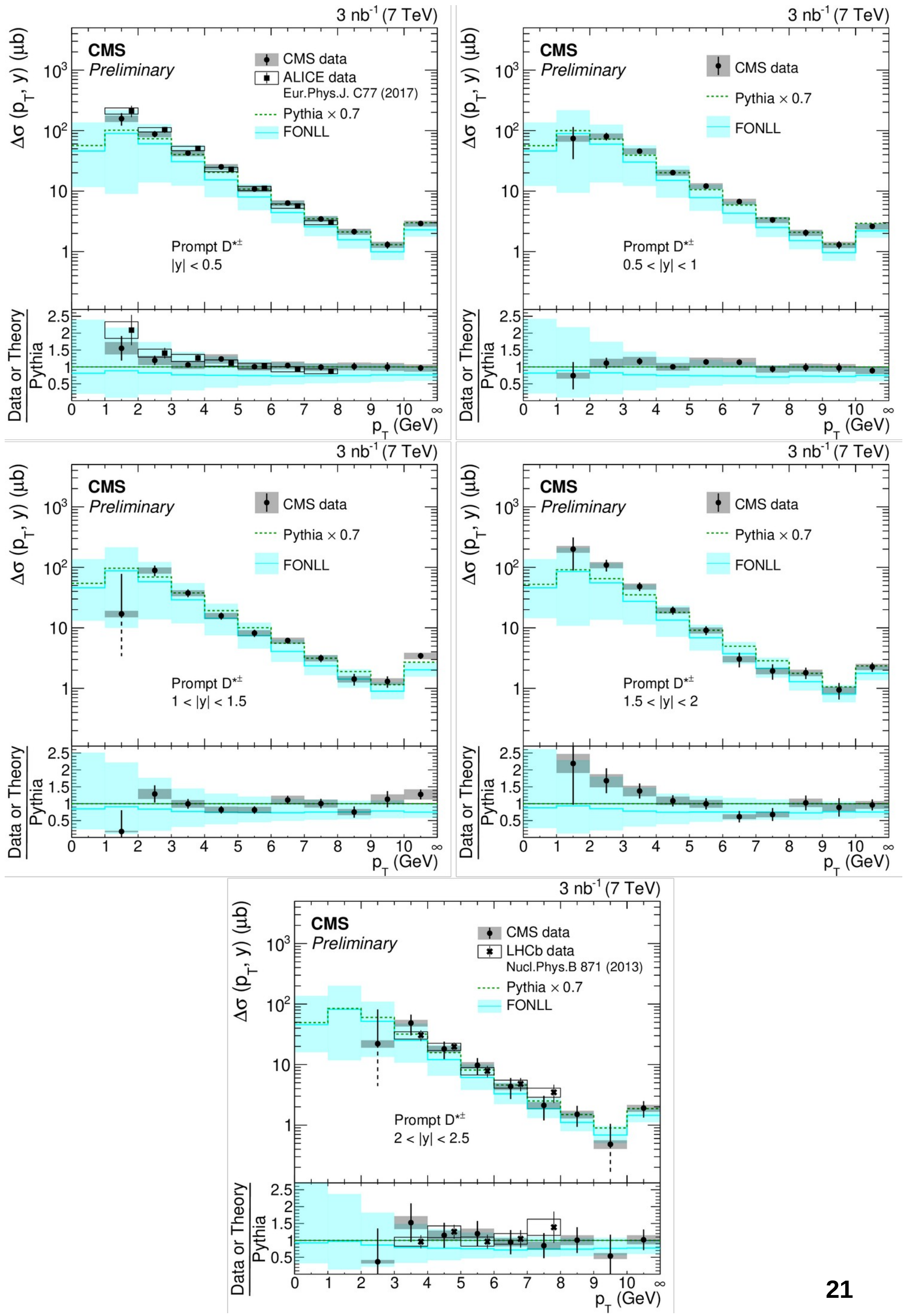
CMS-PAS-BPH-22-007

$D^{*+} \rightarrow (K^{\pm}\pi^{\pm})\pi_s^{\pm}$ (CMS, 7TeV)

- **7 TeV result using data sample taken at very low μ (~2)**
  - 50% minimum bias trigger
  - 50% events where an other interaction triggered the event
  - Only small contribution of beauty decays (~5-10%)
- **Nice consistency with LHCb/ALICE measurement inside overlapping region** of mostly orthogonal phase space







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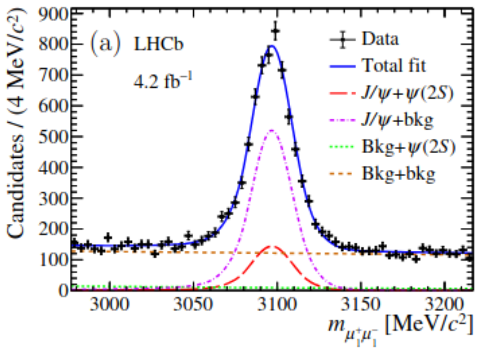
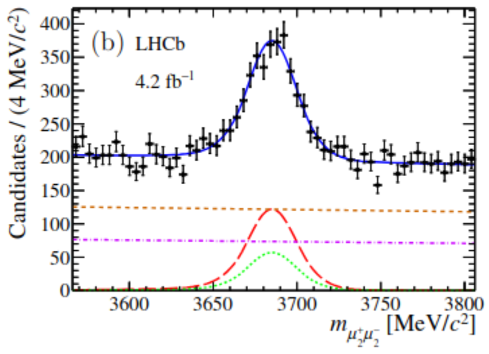
J/ψ+ψ(2S) (LHCb)

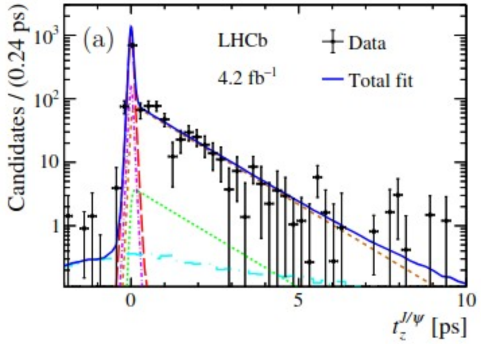
- **Measurement of correlated production at 13 TeV**
  - Two mesons can be produced directly from charm (prompt) or from B-decay (non-prompt), has to be subtracted
  - Prompt production for p_T <14.5 GeV and 2<y<4.5

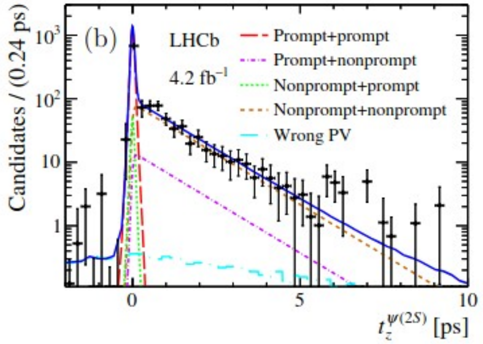
$$\sigma_{J/\psi\text{-}\psi(2S)} = 4.5 \pm 0.7\ (\text{stat}) \pm 0.3\ (\text{syst})\ \text{nb}$$

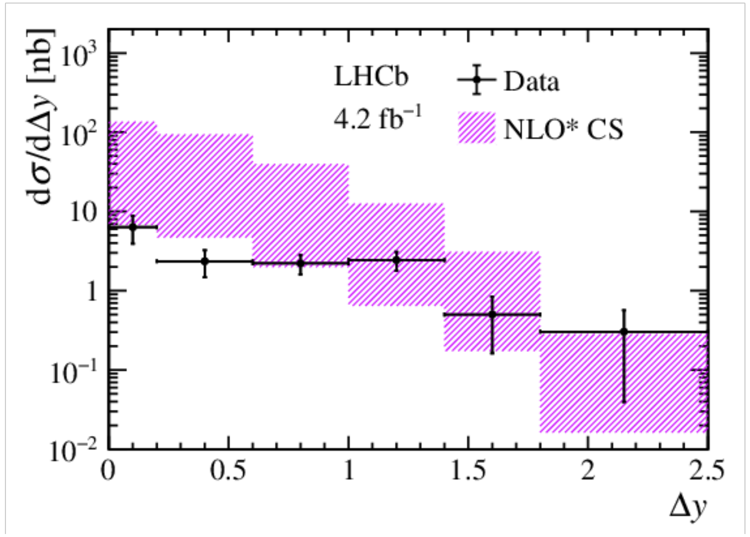
  - Kinematic of the system is compared to theory

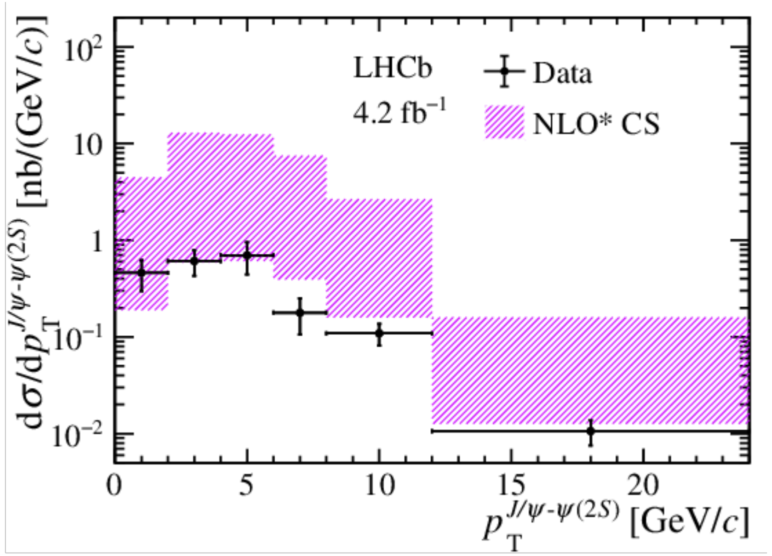


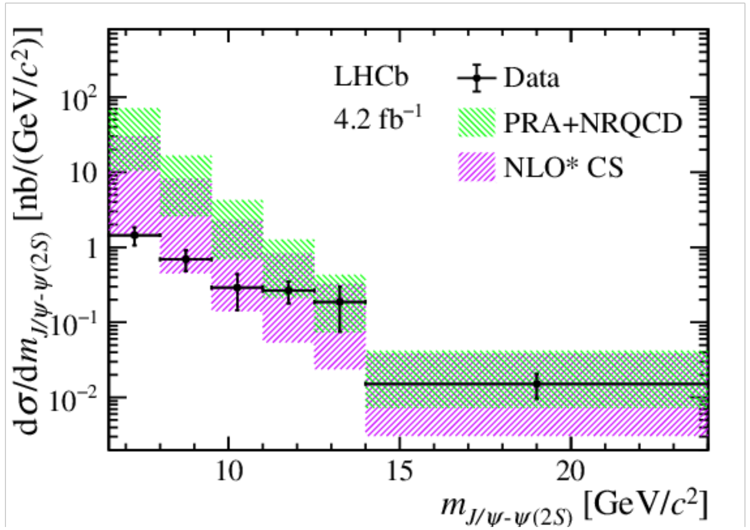












arXiv:2305.15580

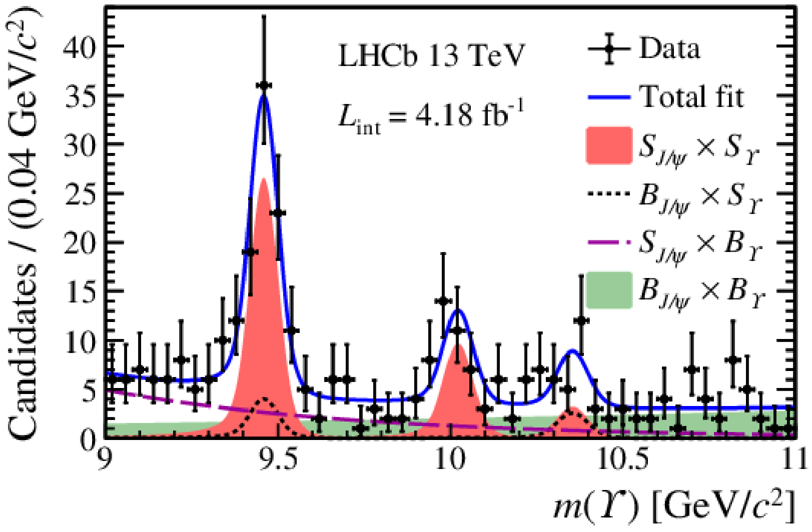
ϒ(1S,2S)+J/ψ production (LHCb)

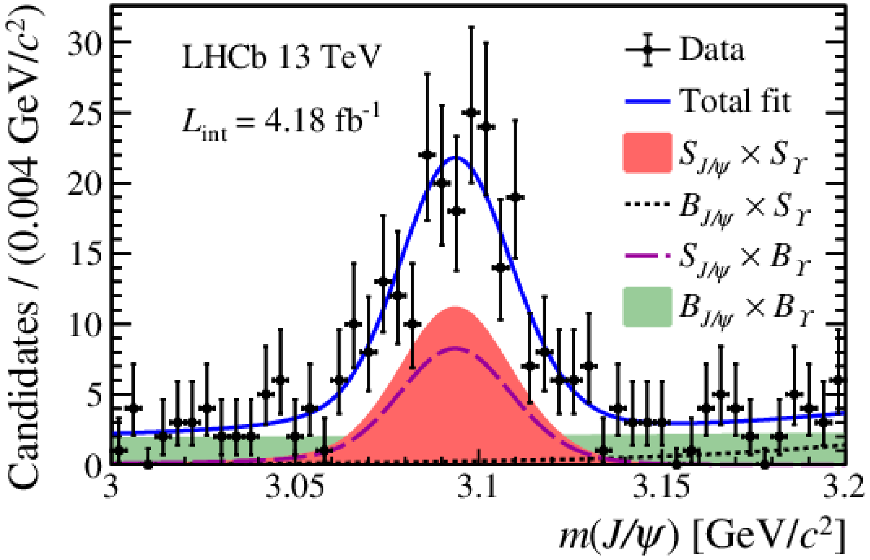
- **Correlated production at 13 TeV:**
  - Events are selected by cut in the two dimensional mass plane (→ projections shown)
  - Dataset 76 ϒ(1S)+J/ψ and 30 ϒ(2S)+J/ψ events
  - Cross sections estimated and correlation between the mesons are studied

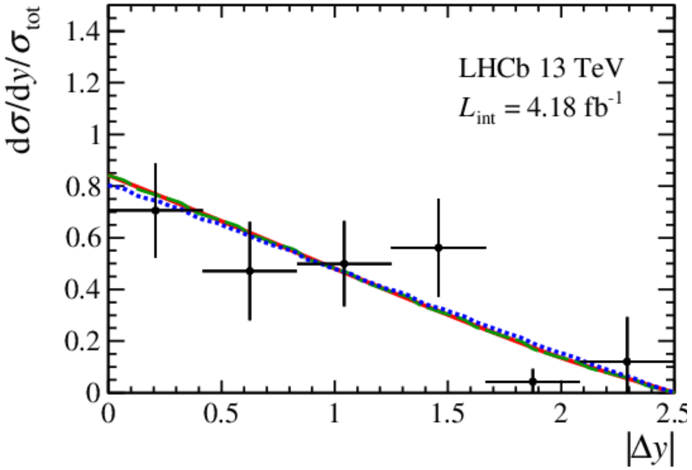
$$\sigma(J/\psi\text{–}\Upsilon(1S)) = 133 \pm 22 \pm 7 \pm 3\,\text{pb},$$

$$\sigma(J/\psi\text{–}\Upsilon(2S)) = 76 \pm 21 \pm 4 \pm 7\,\text{pb},$$

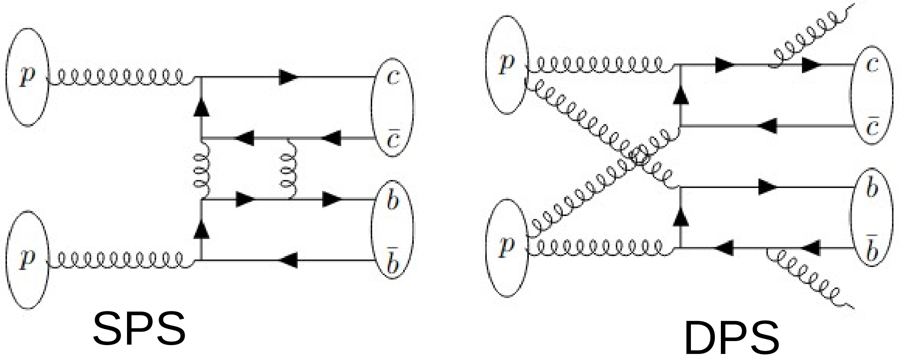
$$\frac{\mathcal{B}_{\Upsilon(2S)\to\mu^+\mu^-} \times \sigma(J/\psi\text{–}\Upsilon(2S))}{\mathcal{B}_{\Upsilon(1S)\to\mu^+\mu^-} \times \sigma(J/\psi\text{–}\Upsilon(1S))} = 0.442 \pm 0.143 \pm 0.004,$$







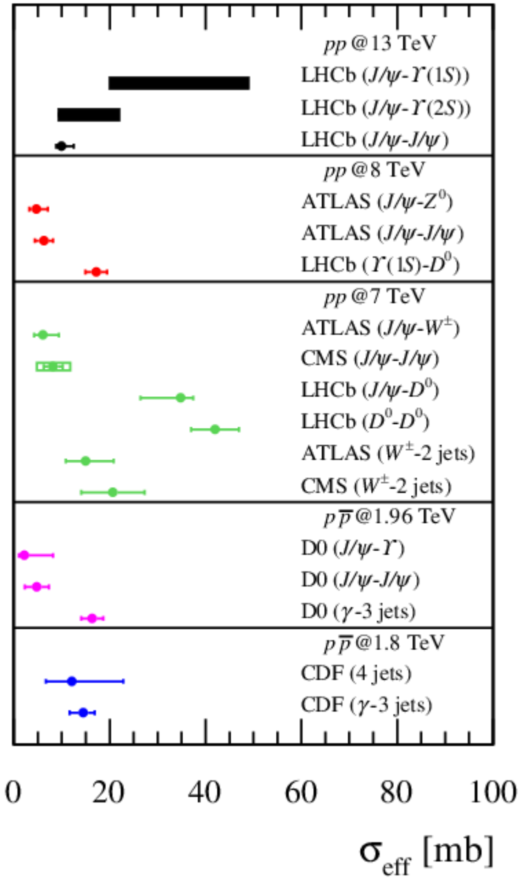
correlated production of $b\bar{b}/c\bar{c}$ and $c\bar{c}$



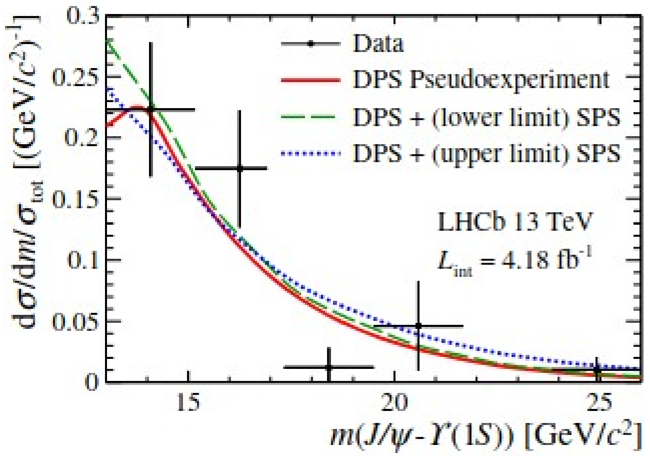
- **Two $b\bar{b}/c\bar{c}$ mesons can be produced in** single parton scattering **SPS** or double parton scattering **DPS**
- **DPS process probes the distributions and correlations between partons in proton:**

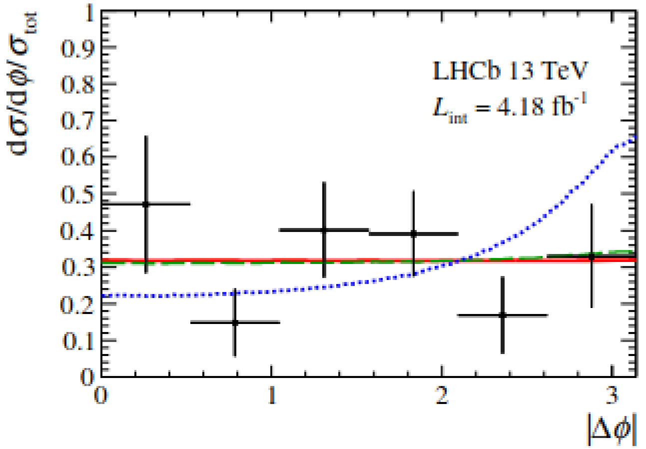
$$\sigma_{\mathrm{DPS}}(J/\psi\text{–}\Upsilon) = \frac{\sigma(J/\psi) \times \sigma(\Upsilon)}{\sigma_{\mathrm{eff}}}$$

σ_{eff} **universal** assuming two partons are uncorrelated and transversal and longitudinal part of the **PDF factorize**



- **To test if hypothesis** is valid three **pseudo samples** are compared with data, but all 3 agree inside errors

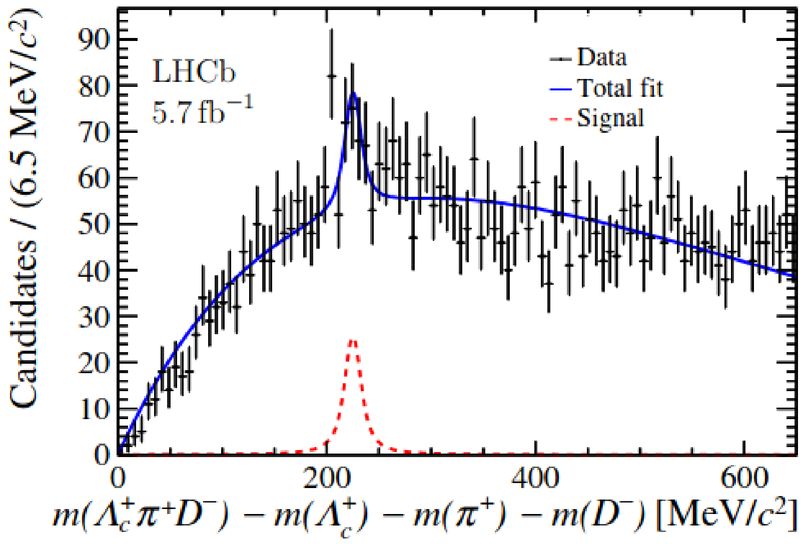




Summary

- **LHC has collected huge datasets at diverse center of mass energies**
  - Inclusive cross sections:
    - Impressive agreement with Standard Model over a large range of center of mass energies

- **Differential result of (associated) HF production shown:**
  - $t\bar{t}b\bar{b}$, $t\bar{t}c\bar{c}$, $t\bar{t}$+jets, $b\bar{b}c\bar{c}$, $c\bar{c}c\bar{c}$
  - **Tendency to multidimensional differential distributions**
    - Important to understand the dynamic in a QCD environment
  - $t\bar{t}+c\bar{c}$ and $t\bar{t}$+c determined separately in one measurement first time
  - **Correlated $b\bar{b}c\bar{c}$ and $c\bar{c}c\bar{c}$ production** give a insign in the production mechanism **(MPI)**
- Could not cover all analysis, e.g. Pentaquarks in charm final states @ LHCb



arXiv.org:2404.07131