Observation of top-quark pair production in proton-lead collisions in ATLAS

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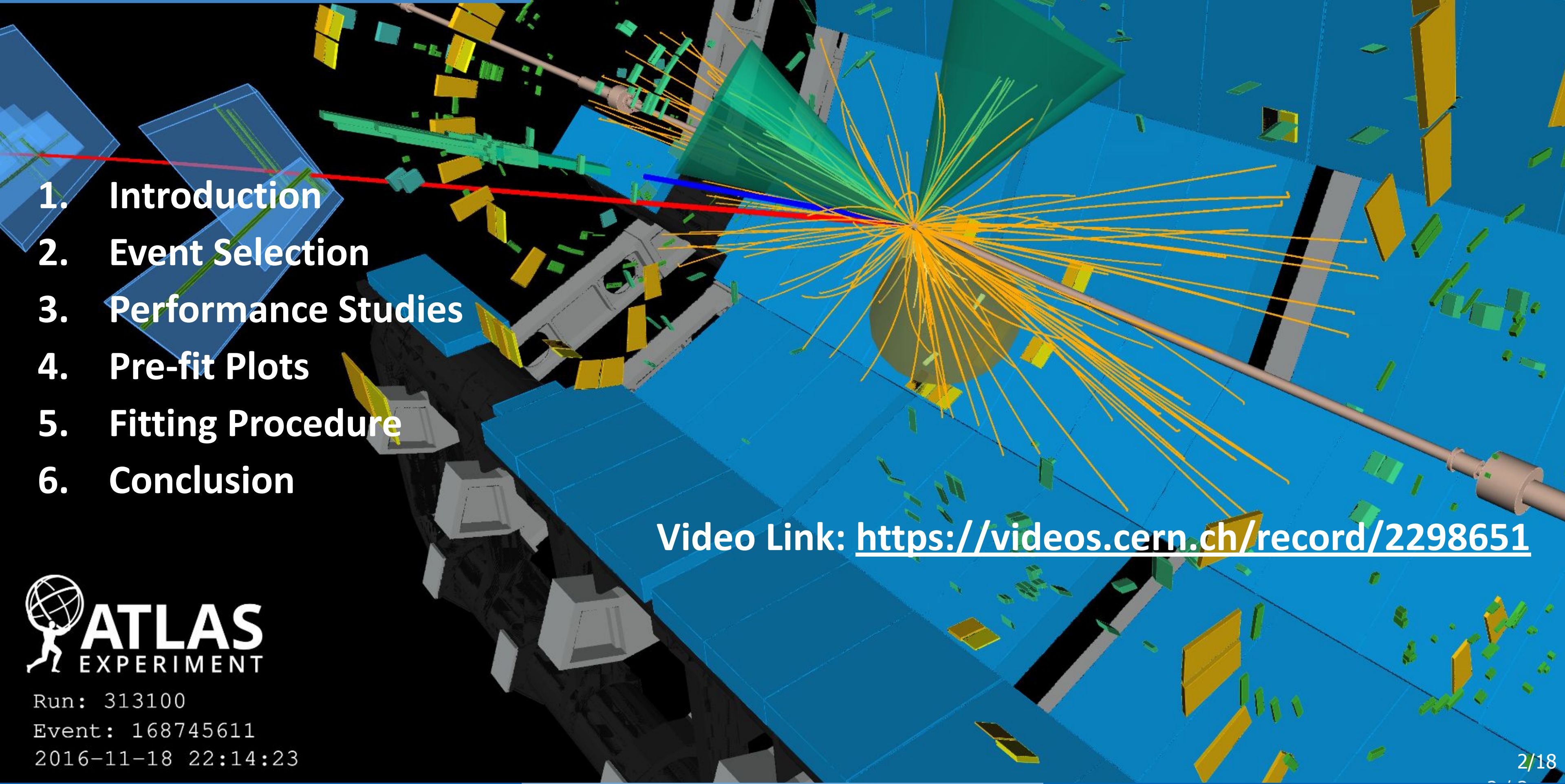
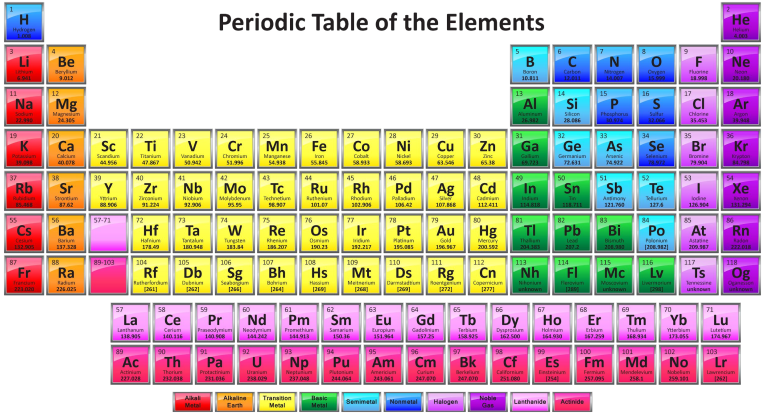
Outline

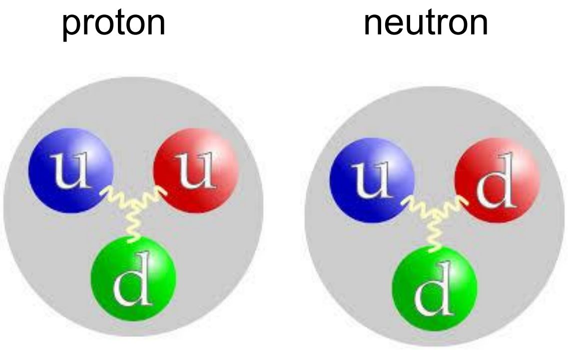
1. Introduction
2. Event Selection
3. Performance Studies
4. Pre-fit Plots
5. Fitting Procedure
6. Conclusion

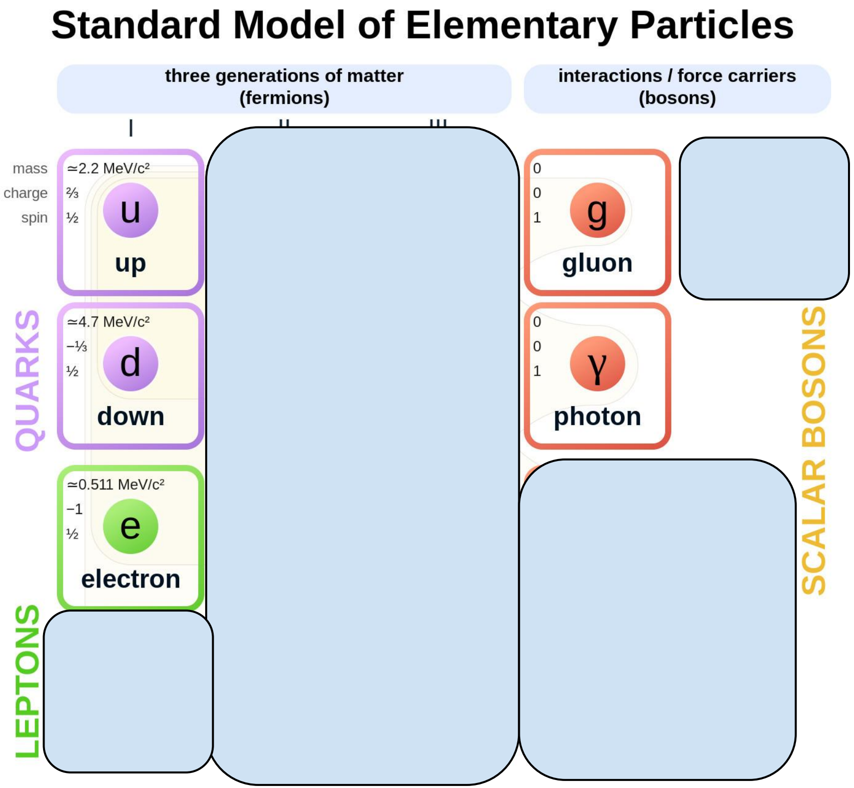
Video Link: https://videos.cern.ch/record/2298651

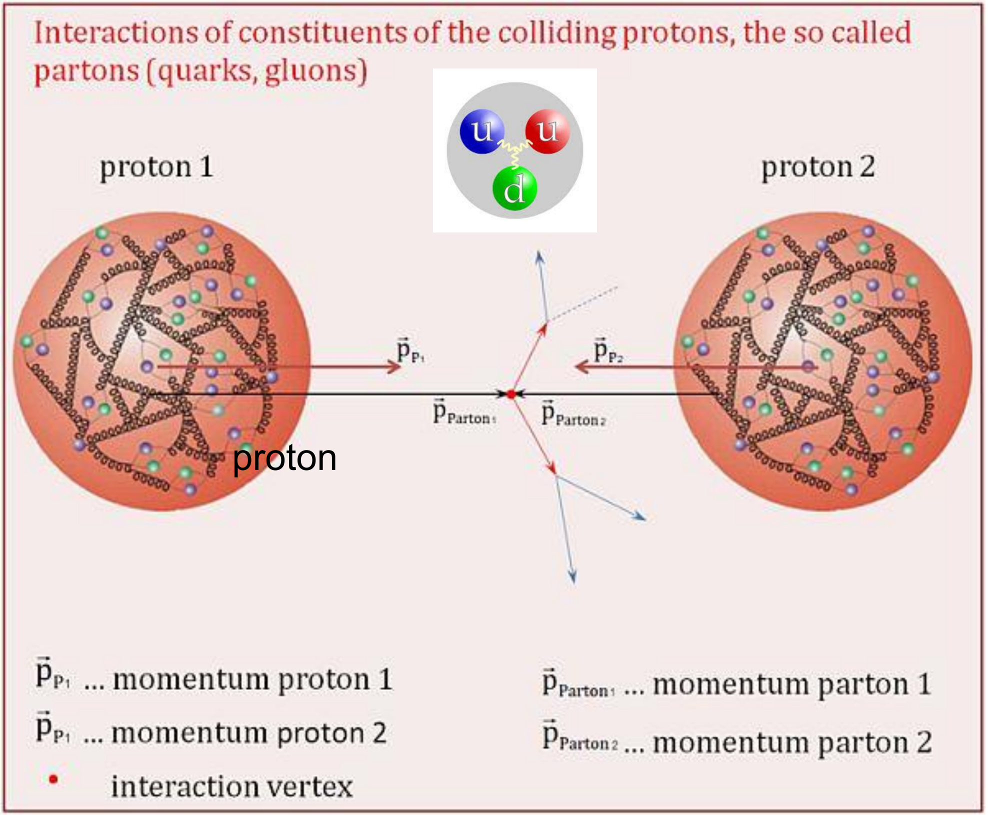


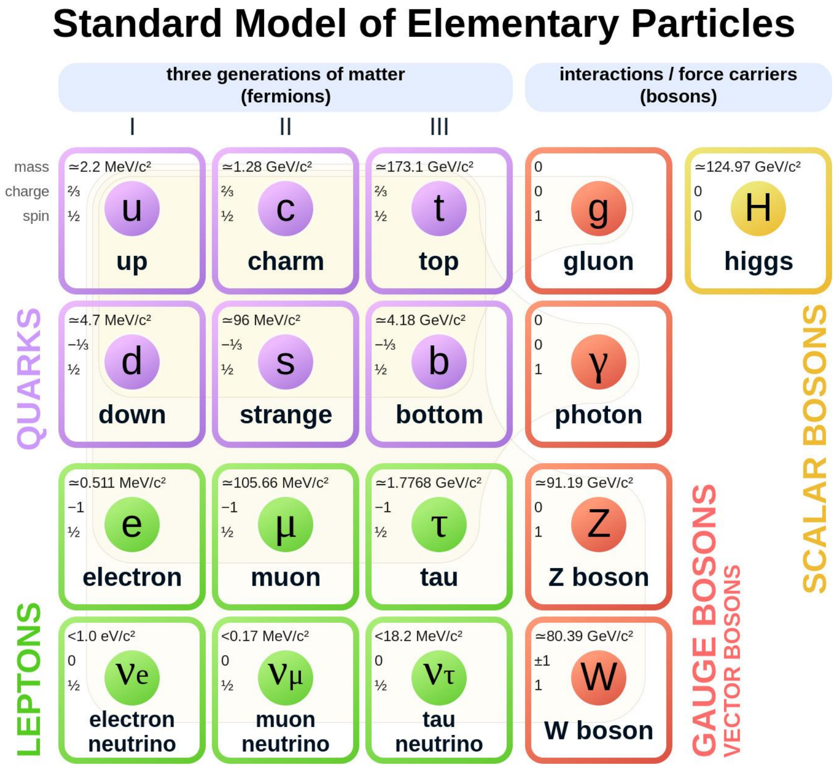
1. Introduction


Periodic Table of the Elements


proton
neutron
u
u
d
u
d
d


Standard Model of Elementary Particles
three generations of matter (fermions)
interactions / force carriers (bosons)
I
mass
charge
spin
≃2.2 MeV/c²
⅔
½
u
up
≃4.7 MeV/c²
−⅓
½
d
down
≃0.511 MeV/c²
−1
½
e
electron
0
0
1
g
gluon
0
0
1
γ
photon
QUARKS
LEPTONS
SCALAR BOSONS


Interactions of constituents of the colliding protons, the so called partons (quarks, gluons)
proton 1
proton 2
proton
u
u
d
$\vec{p}_{P_1}$
$\vec{p}_{P_2}$
$\vec{p}_{Parton_1}$
$\vec{p}_{Parton_2}$
$\vec{p}_{P_1}$ ... momentum proton 1
$\vec{p}_{P_1}$ ... momentum proton 2
interaction vertex
$\vec{p}_{Parton_1}$ ... momentum parton 1
$\vec{p}_{Parton_2}$ ... momentum parton 2


Standard Model of Elementary Particles
three generations of matter (fermions)
interactions / force carriers (bosons)
I
II
III
mass
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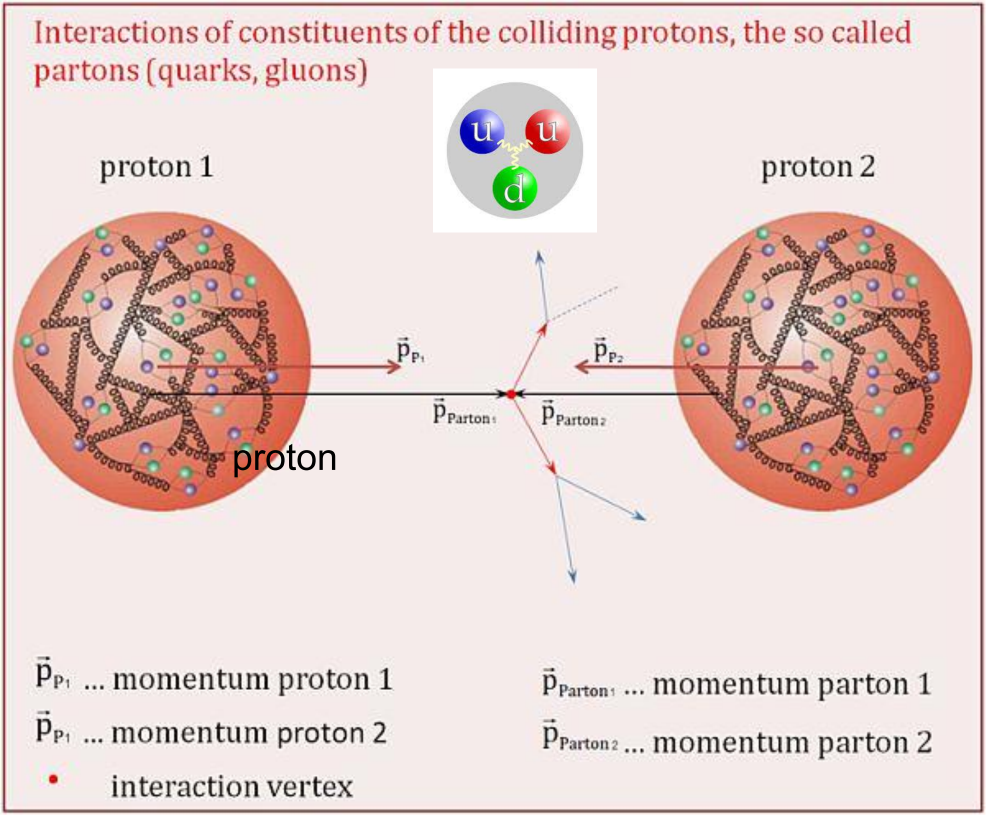
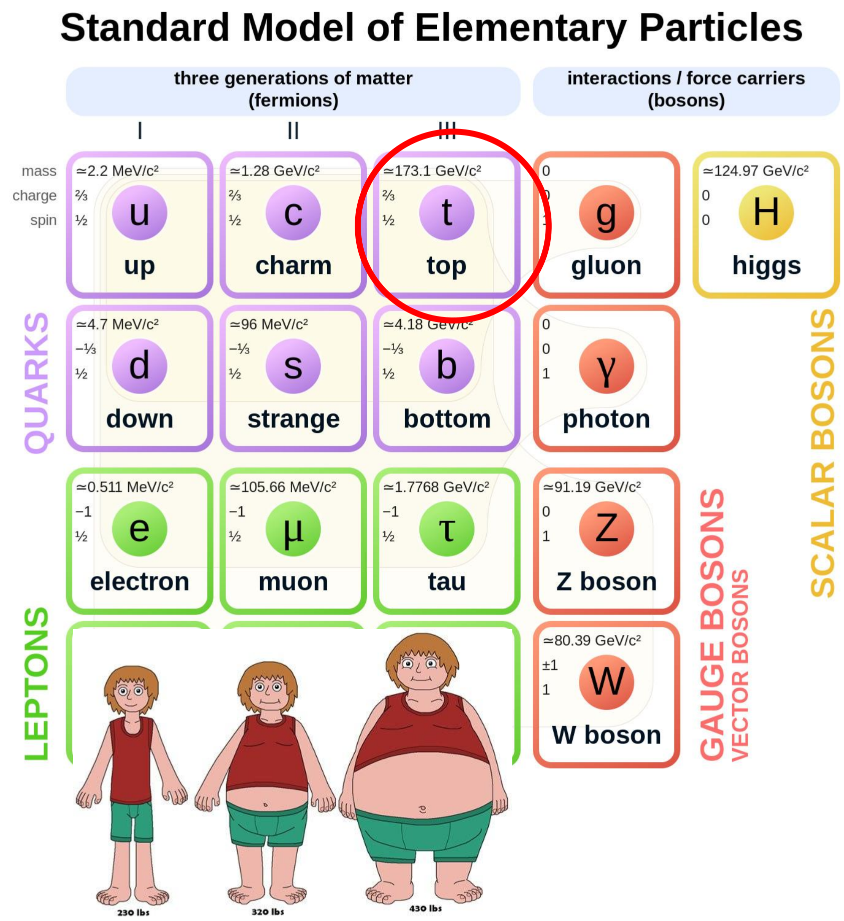
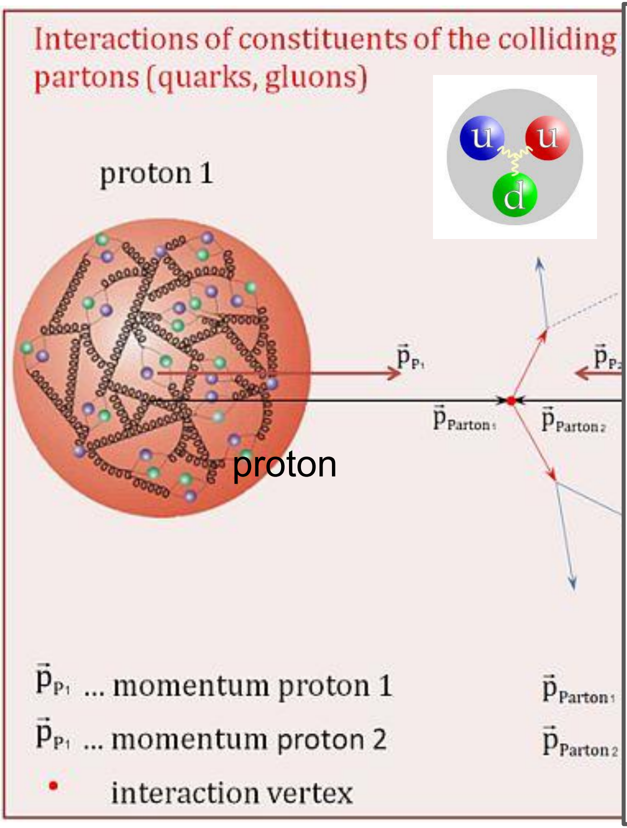
≃2.2 MeV/c²
⅔
½
u
up
≃1.28 GeV/c²
⅔
½
c
charm
≃173.1 GeV/c²
⅔
½
t
top
0
0
1
g
gluon
≃124.97 GeV/c²
0
0
H
higgs
≃4.7 MeV/c²
−⅓
½
d
down
≃96 MeV/c²
−⅓
½
s
strange
≃4.18 GeV/c²
−⅓
½
b
bottom
0
0
1
γ
photon
≃0.511 MeV/c²
−1
½
e
electron
≃105.66 MeV/c²
−1
½
μ
muon
≃1.7768 GeV/c²
−1
½
τ
tau
≃91.19 GeV/c²
0
1
Z
Z boson
<1.0 eV/c²
0
½
νe
electron neutrino
<0.17 MeV/c²
0
½
νμ
muon neutrino
<18.2 MeV/c²
0
½
ντ
tau neutrino
≃80.39 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS
VECTOR BOSONS
SCALAR BOSONS

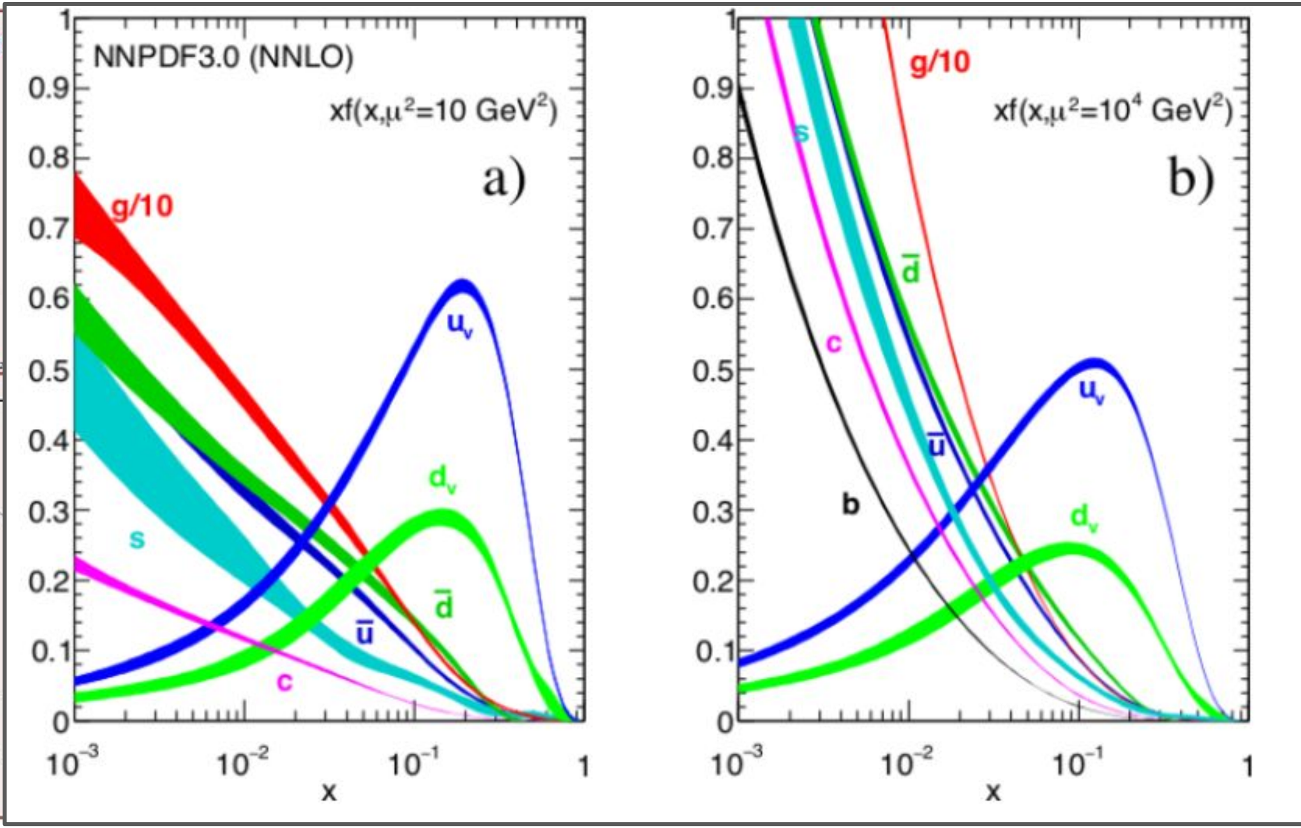
Introduction



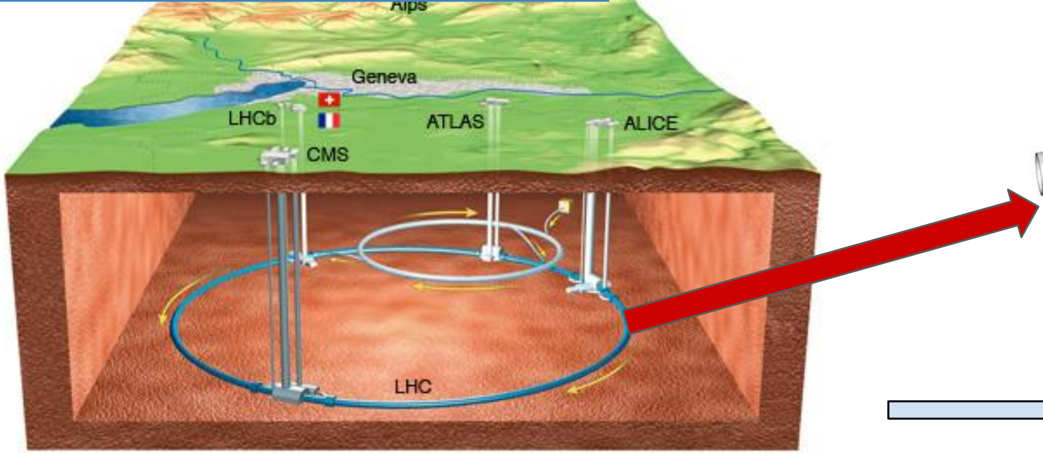


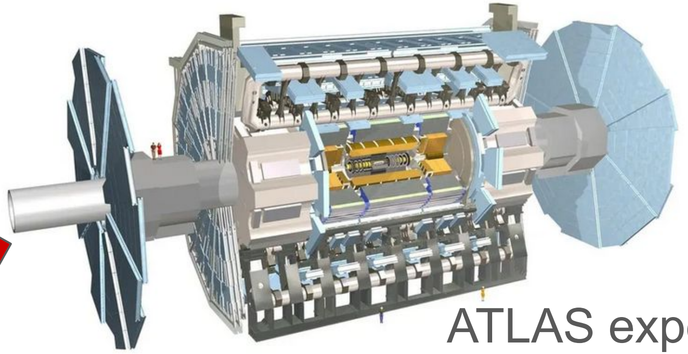
Parton distribution functions f(x,Q^2)



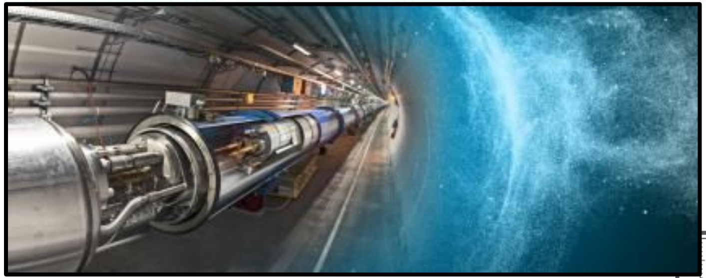


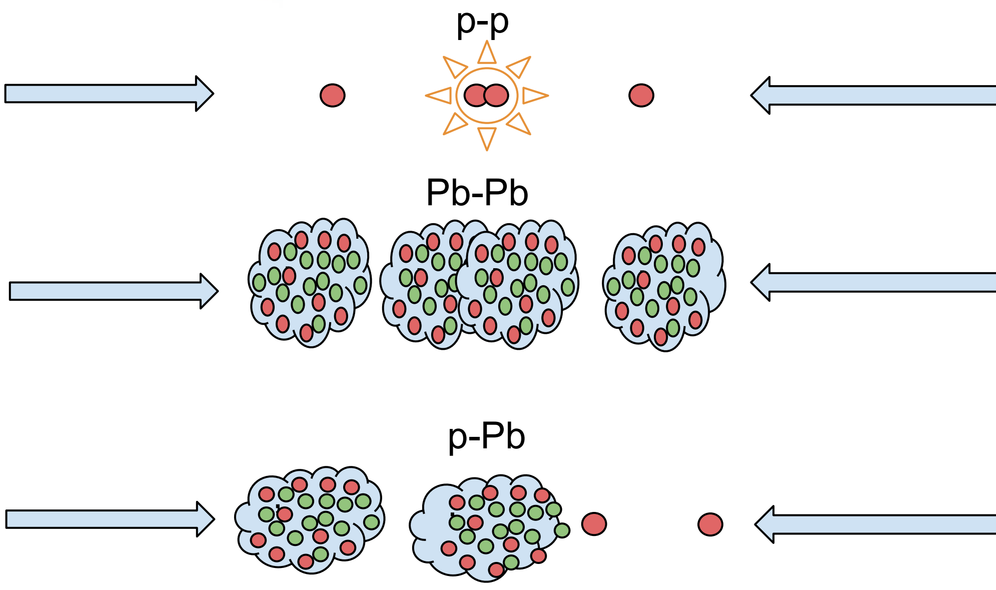
Introduction



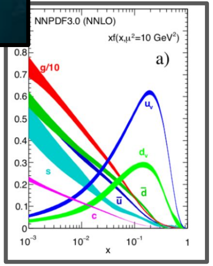


ATLAS experiment





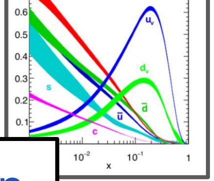
Do the probabilities / parton distribution functions change?

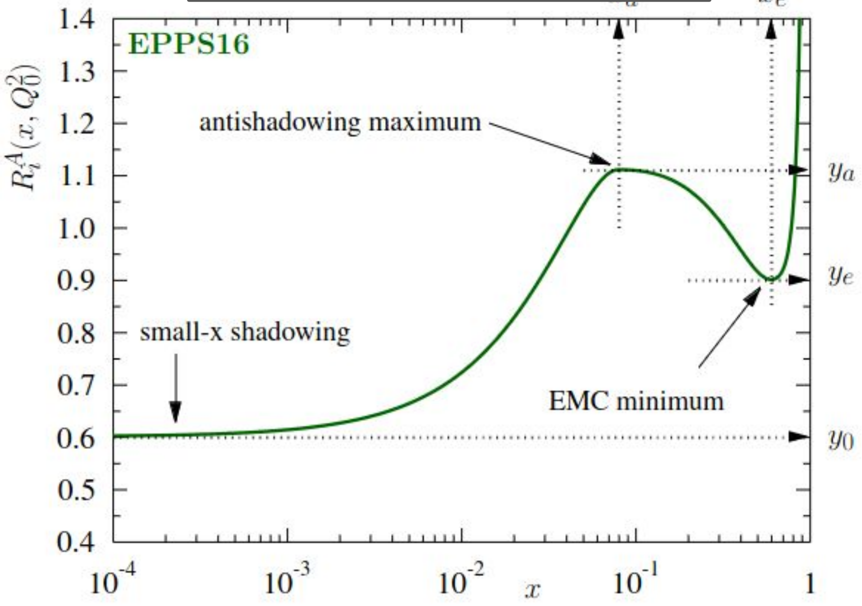


Introduction

$$R_i^A(x,Q^2) = \frac{f_i^{\mathrm{p}/A}(x,Q^2)}{f_i^{\mathrm{p}}(x,Q^2)}$$

Do the probabilities / parton distribution functions change? Yes





Unexplored kinematic region

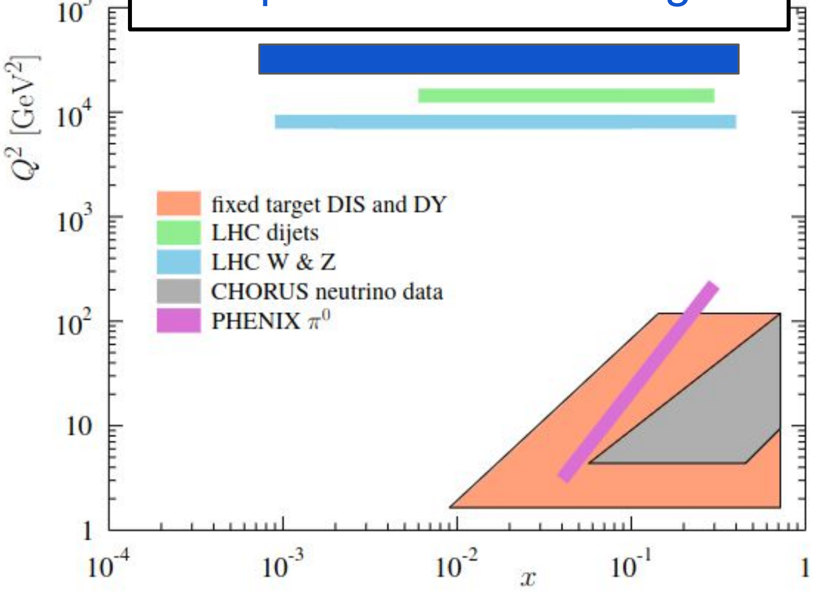
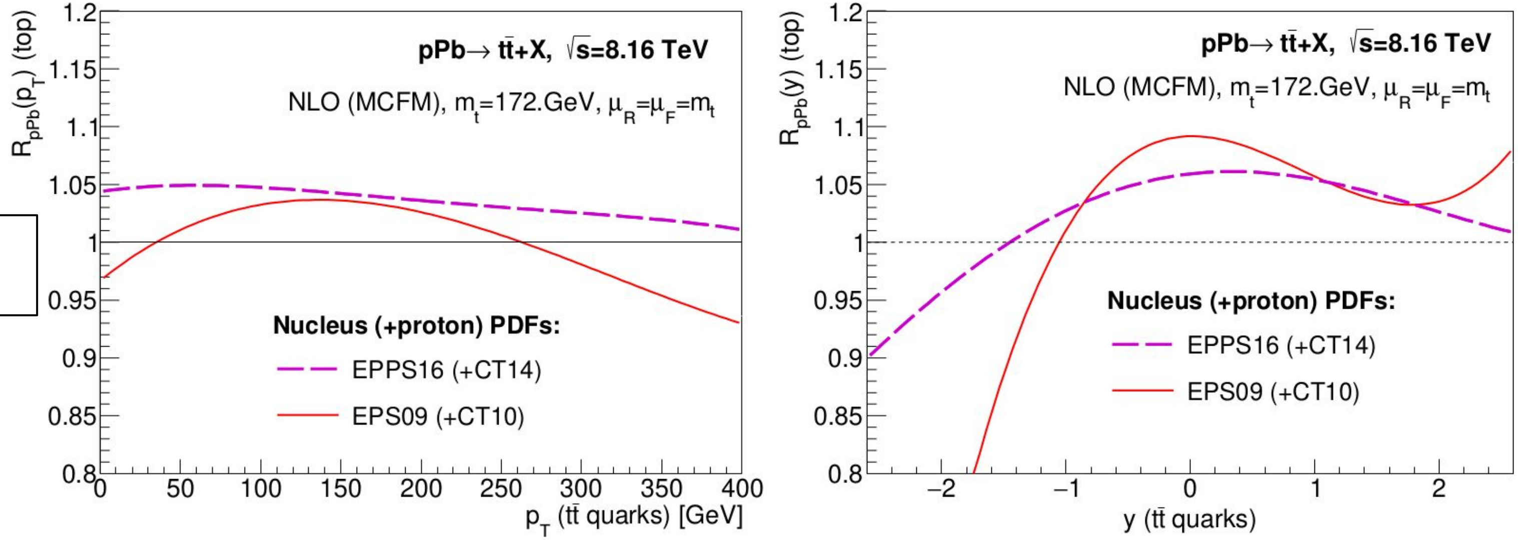


Figure 1: *Left: Typical form of PDF modifications in a nucleus. Right: Kinematic reach of the data used in nPDF global analyses. Figures from Ref.* [11].

https://arxiv.org/pdf/1802.05927.pdf

- Top quarks provide novel probes of nuclear modifications to parton distribution functions (nPDF) in a poorly constrained kinematic region (PRD 93, 014026 (2016)).

$$R_{pPb} = \sigma_{pPb} / \sigma_{pp}$$



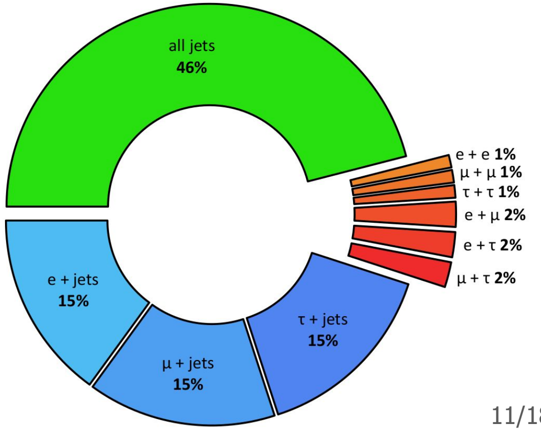
Nuclear modification factor as a function of p_T (left) and rapidity (right) for $t\bar{t}$ production in the lepton+jets channel at $\sqrt{s_{NN}}$ = 8.16 TeV.

Review of predictions of hard probes in *p*+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 and 8.16 TeV and comparison with data R. Vogt (LLNL, Livermore and UC, Davis) e-Print: 1908.11534[hep-ph]

Introduction

- Top quarks provide novel probes of nuclear modifications to parton distribution functions (nPDF) in a poorly constrained kinematic region (PRD 93, 014026 (2016)).

- ttbar production in Heavy Ion collisions measured by CMS in two Phys.Rev.Lett.'s
  - *p*+Pb $\sqrt{s_{NN}}$ = 8.16 TeV :: (PRL 119, 242001 (2017)) (lepton+jets)
    L =174 nb^{-1}, $\sigma_{t\bar{t}}$ = 45 ± 8 nb, significance over 5 σ
  - Pb+Pb $\sqrt{s_{NN}}$ = 5.02 TeV:: (PRL 125, 222001 (2020)) (dilepton)
    L =1.7 nb^{-1}, $\sigma_{t\bar{t}}$ = 2.54 (+0.84 -0.74) μb, significance 4 σ
- In ATLAS observation of $t\bar{t}$ in pPb data individually in lepton+jets and dilepton channels - **this talk**
  - *p*+Pb data from 2016 with Integrated luminosity L = 164.6 nb^{-1}
  - Nucleon-nucleon center-of-mass energy $\sqrt{s_{NN}}$= 8.16 TeV
  - The first measurement using the **dilepton** channel in p+Pb collisions.
  - All the plots can be found in the Conf Note ATLAS-CONF-2023-063



$$\textbf{lepton + jets :} \quad t\bar{t} \rightarrow WbW\bar{b} \rightarrow \ell\nu_\ell bq\bar{q}'\bar{b}$$

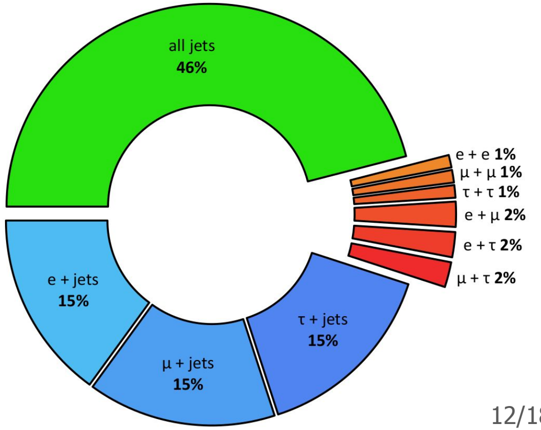
$$\textbf{dilepton :} \quad t\bar{t} \rightarrow WbW\bar{b} \rightarrow \ell\nu_\ell b\ell\bar{\nu}_\ell\bar{b}$$

Introduction

Challenge: low stats, ATLAS SW, isMC, btagging, JES, lepton SFs -- custom, matching

$$\textbf{lepton + jets :} \quad t\bar{t} \rightarrow WbW\bar{b} \rightarrow \ell\nu_\ell bq\bar{q}'\bar{b}$$

$$\textbf{dilepton :} \quad t\bar{t} \rightarrow WbW\bar{b} \rightarrow \ell\nu_\ell b\ell\bar{\nu}_\ell\bar{b}$$



2. Event Selection

lepton+jets

Channel	Selection
e+jets	1 isolated electron with **p_T > 18 GeV** 0 isolated muons At least 4 jets with **p_T > 20 GeV**
μ+jets	1 isolated muon with **p_T > 18 GeV** 0 isolated electrons At least 4 jets with **p_T > 20 GeV**
ee	2 isolated electrons with **p_T > 18 GeV** 0 isolated muons Opposite Sign, **m_{ll} > 45 GeV** Veto m_{ll} in 80 – 100 GeV, At least 2 jets with **p_T > 20 GeV**
$\mu\mu$	2 isolated muons with **p_T > 18 GeV** 0 isolated electrons Opposite Sign, **m_{ll} > 45 GeV** Veto m_{ll} in 80 – 100 GeV, At least 2 jets with **p_T > 20 GeV**
eμ	1 isolated electron with **p_T > 18 GeV** 1 isolated muon with **p_T > 18 GeV** Opposite Sign, **m_{ll} > 15 GeV** At least 2 jets with **p_T > 20 GeV**

First measurement

dilepton

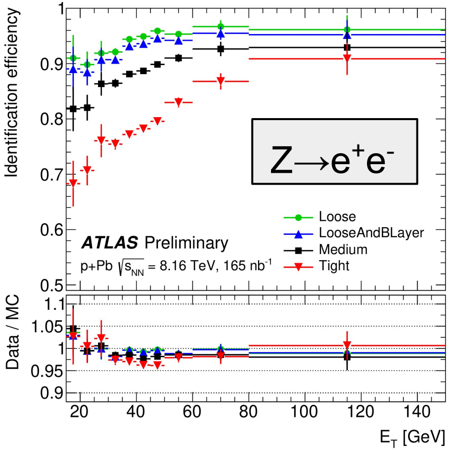
Background composition:

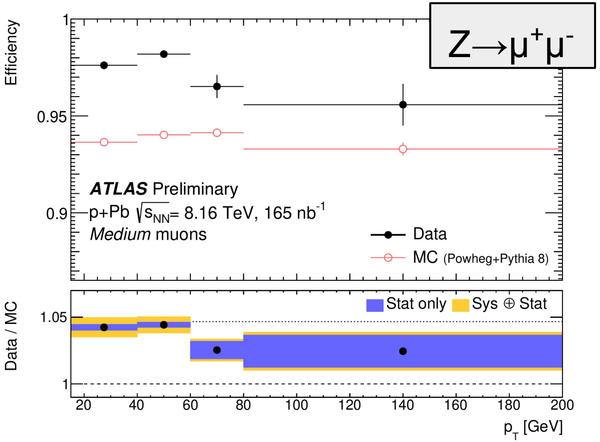
- Single top
- W +jets
  - W+b
  - W+c
  - W+light
- Z +jets
  - Z+b
  - Z+c
  - Z+light
- Diboson
- Fake lepton

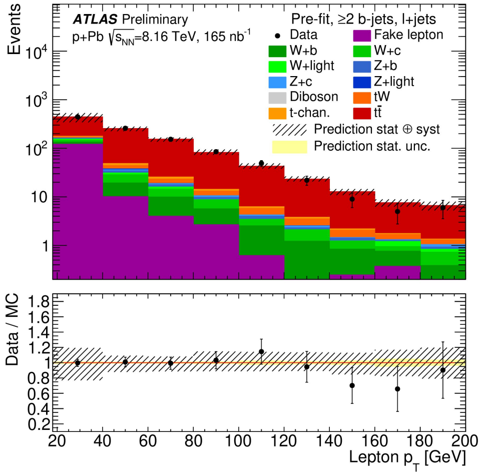
Regions:
=0b control
=1b and ≥2b signal

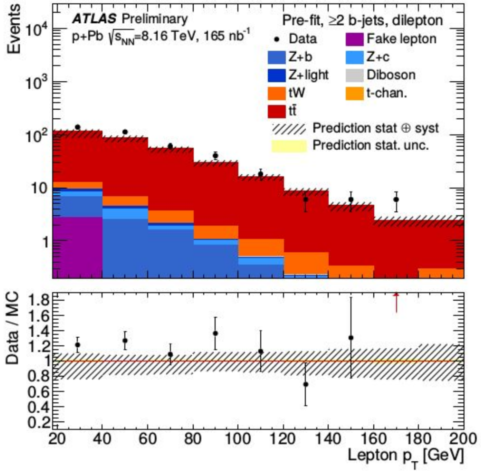
3. Performance Studies

- Electrons must have $\mathbf{p_T > 18}$ **GeV** and $|\eta| < 2.47$, pass Medium identification and be isolated.
- Muons must have $\mathbf{p_T > 18}$ **GeV** and $|\eta| < 2.5$, pass Medium requirements and be isolated.
- Low-pileup egamma calibration and dedicated electron and muon scale factors are applied (EGAM-2022-01).
- Fake lepton background is estimated from data using the matrix-method technique.



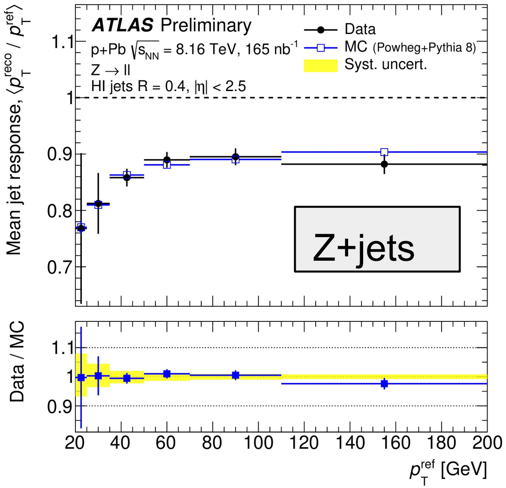


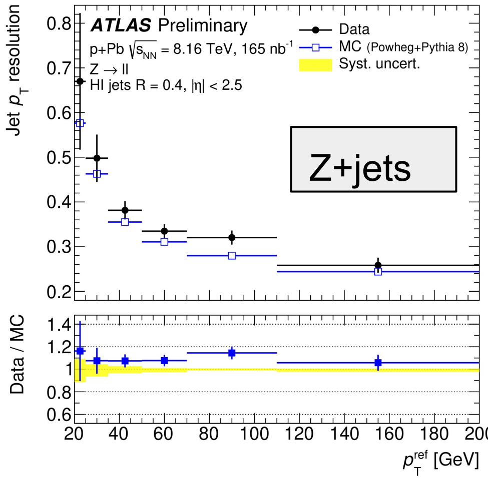


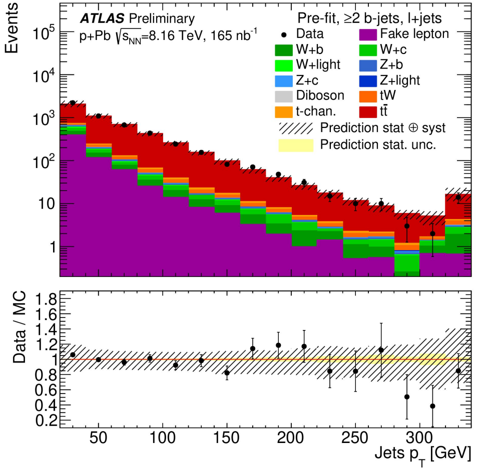


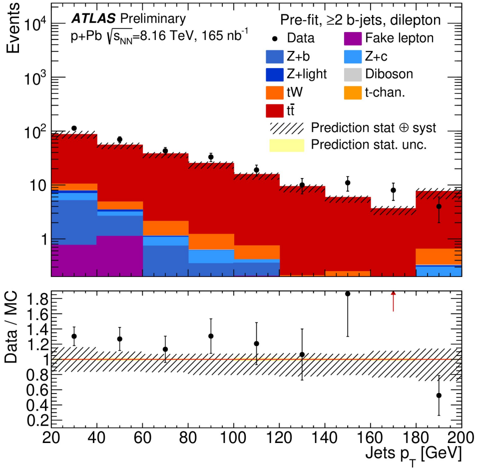
Performance Studies :: Jets

- Jets are reconstructed using the anti-k_t algorithm with jet radius of R = 0.4.
- Jets are required to have **p_T > 20 GeV** and $|\eta| < 2.5$.
- Jet kinematics are corrected event-by-event for the contribution from the underlying event.
- Jets are calibrated using simulation and in-situ measurements of the absolute energy scale (JETM-2023-001).
- Jets with b-hadrons are tagged using multivariate technique (EPJ C 79 (2019) 970).









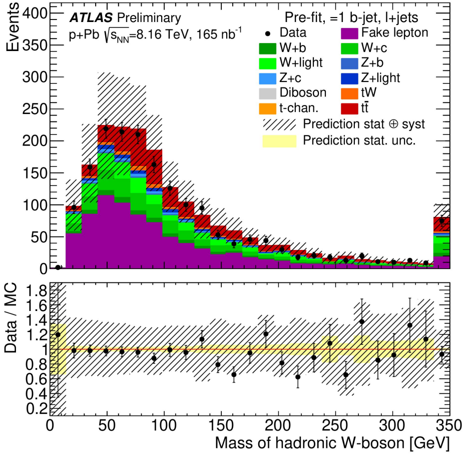
4. Pre-fit Plots

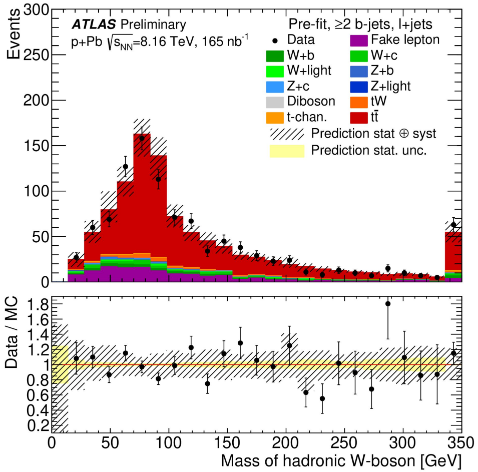
Pre-fit Plots

1b region

2b inclusive region

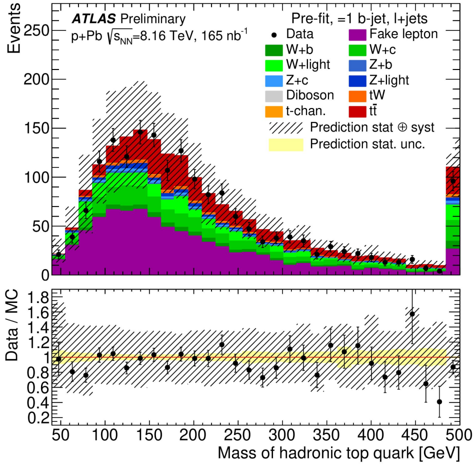
Hadronically decaying W boson

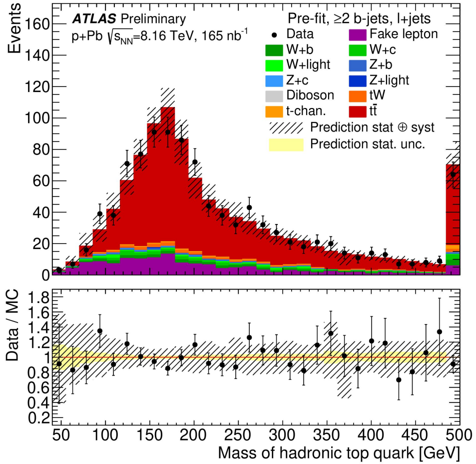




Agreement between data and Monte Carlo within total uncertainty band.

Hadronically decaying top quark





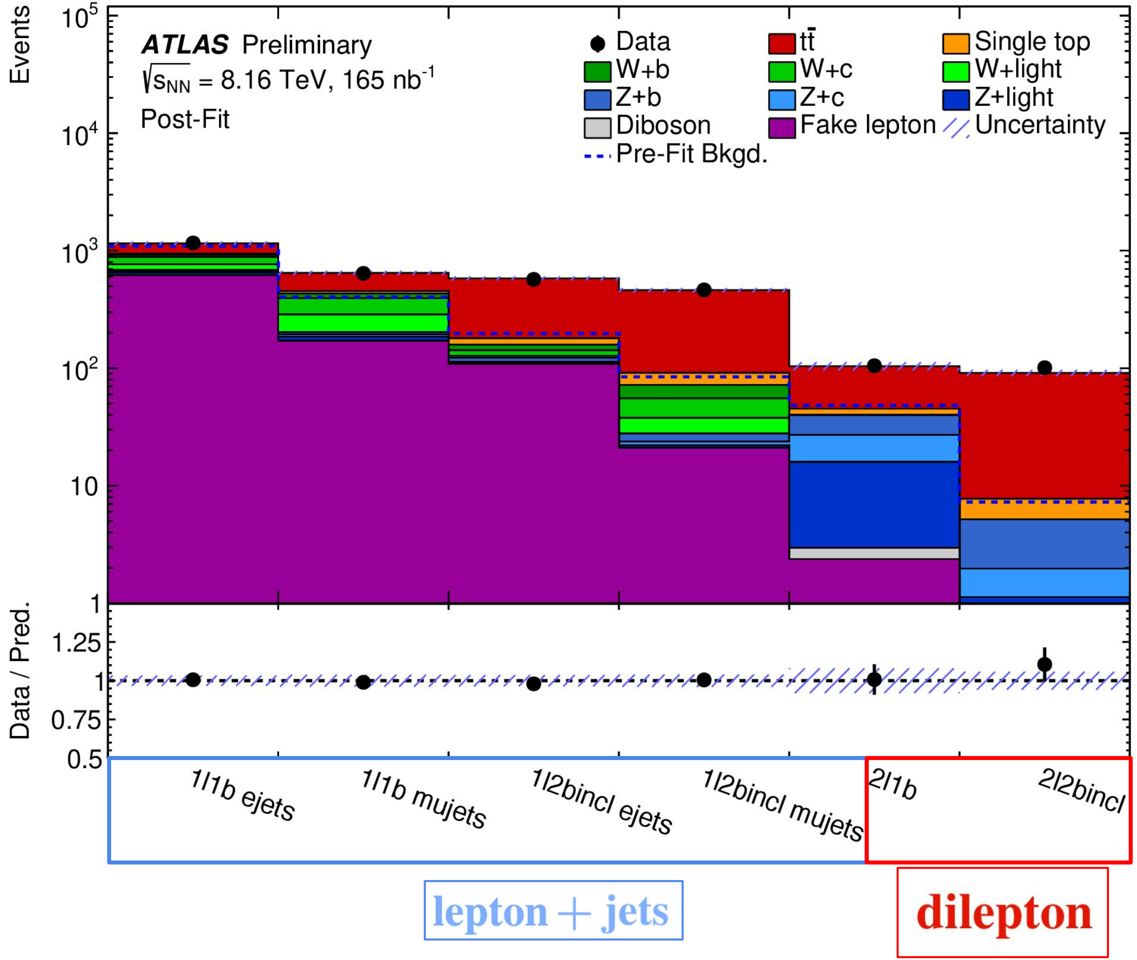
5. Fitting Procedure

- Six signal regions:
  lepton + jets
  - 4j1b1l ejets,
  - 4j2bincl1l ejets,
  - 4j1b1l mujets,
  - 4j2bincl1l mujets.
  - 2j1b2l,
  - 2j2bincl2l.

  dilepton

- Two b-jet categories:
  - exactly 1 b-jet (1b),
  - at least 2 b-jets (2bincl).

- $H_T^{l,j}$ is the scalar sum of all lepton and jet p_T.
- The signal strength $\mu_{t\bar{t}} = \sigma_{t\bar{t}}^{measured} / \sigma_{t\bar{t}}^{theory}$ determined by the fit to $H_T^{l,j}$ data distributions.



Fit Procedure

- Six signal regions:

  lepton + jets
  - 4j1b1l ejets,
  - 4j2bincl1l ejets,
  - 4j1b1l mujets,
  - 4j2bincl1l mujets,

  dilepton
  - 2j1b2l,
  - 2j2bincl2l.

- Two b-jet categories:
  - exactly 1 b-jet (1b),
  - at least 2 b-jets (2bincl).

- $H_T^{l,j}$ is the scalar sum of all lepton and jet p_T.
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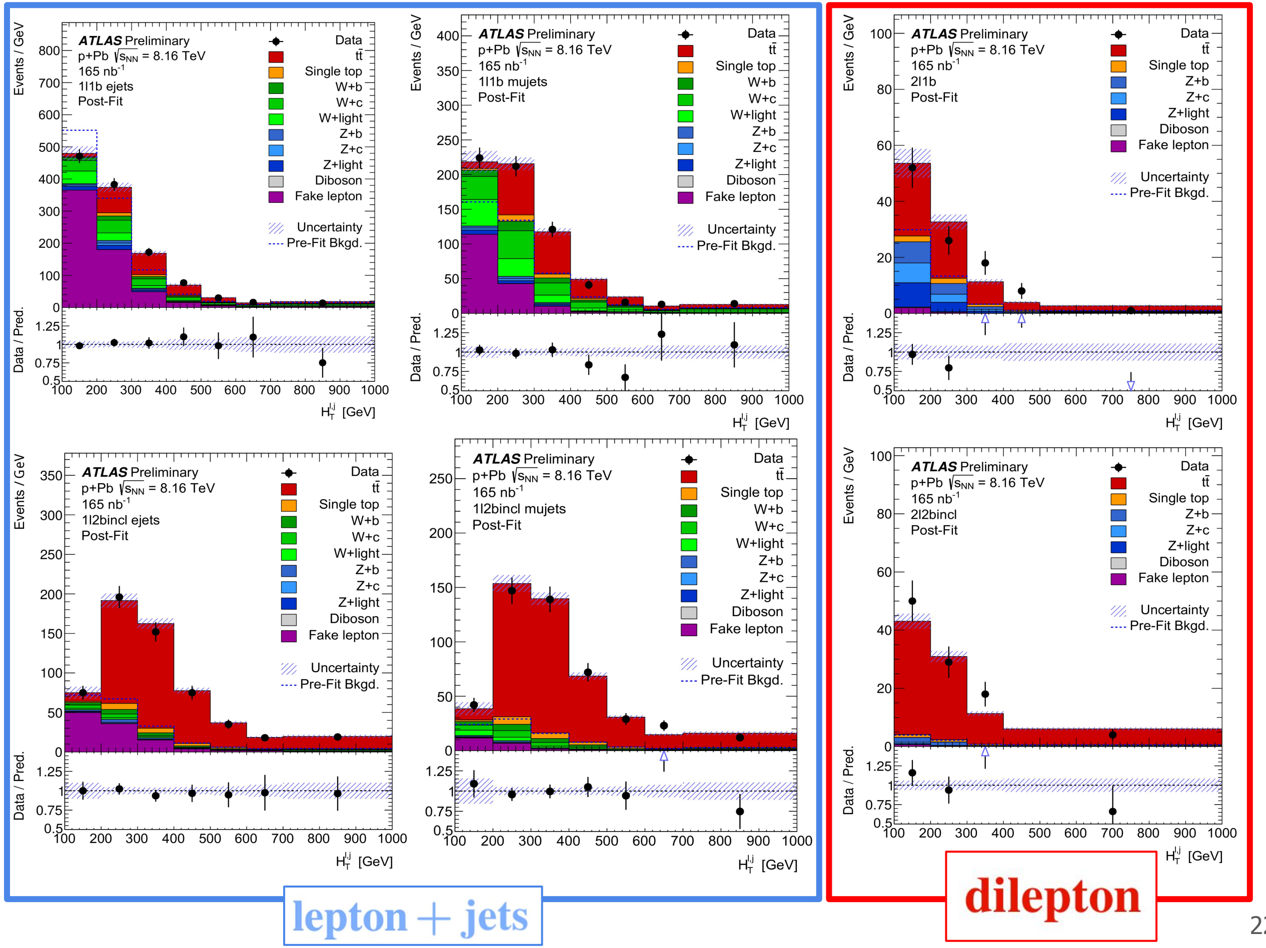
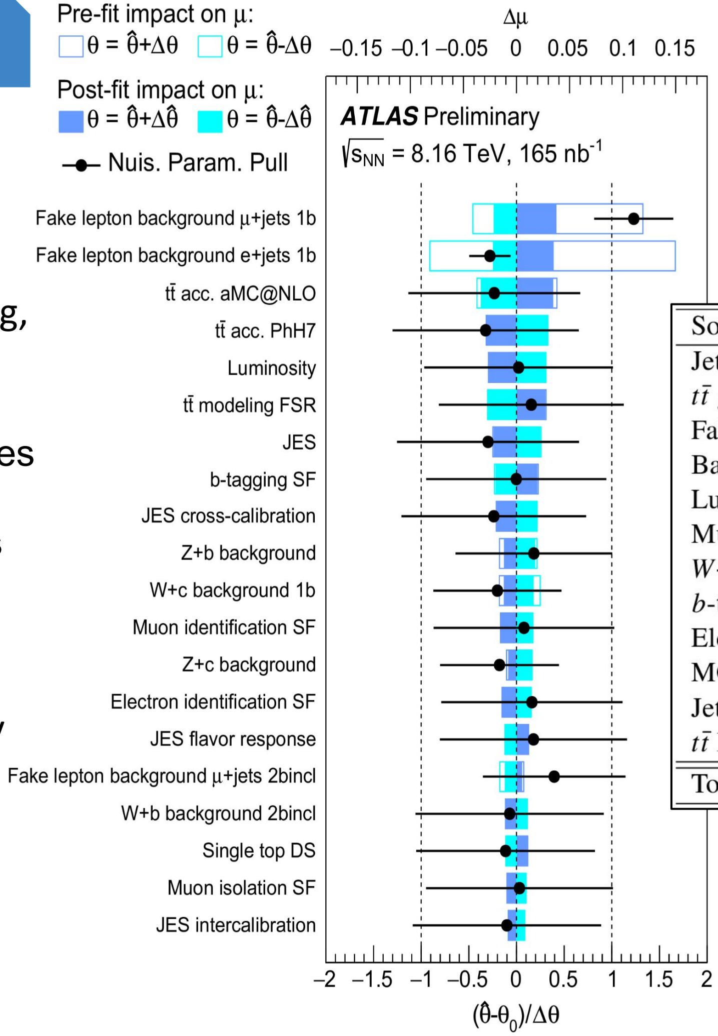


Fit Procedure :: Systematic Unc.

- Systematic uncertainties arise from the lepton and jet reconstruction, b-tagging, fake-lepton background, the signal and background modeling, and luminosity.
- Leading systematic uncertainties in the ranking plot are fake lepton background in 1b e+jets and μ+jets regions
- The main systematic uncertainties include jet energy scale and signal modelling.



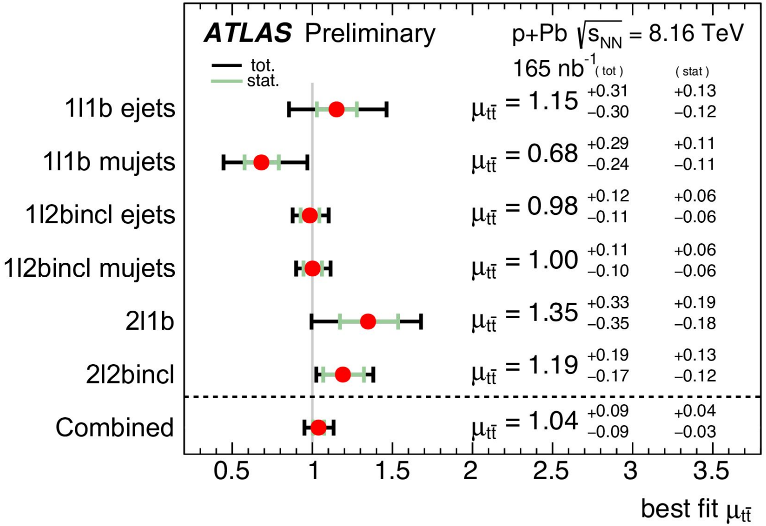
Source	unc. up	unc. down
Jet energy scale	+0.048	-0.044
$t\bar{t}$ generator	+0.048	-0.043
Fake-lepton background	+0.030	-0.027
Background	+0.030	-0.025
Luminosity	+0.029	-0.025
Muon systs.	+0.024	-0.021
W+jets	+0.023	-0.020
b-tagging	+0.022	-0.021
Electron systs.	+0.018	-0.017
MC statistical uncertainties	+0.011	-0.010
Jet energy resolution	+0.005	-0.004
$t\bar{t}$ PDF	+0.001	-0.001
Total syst.	+0.088	-0.081

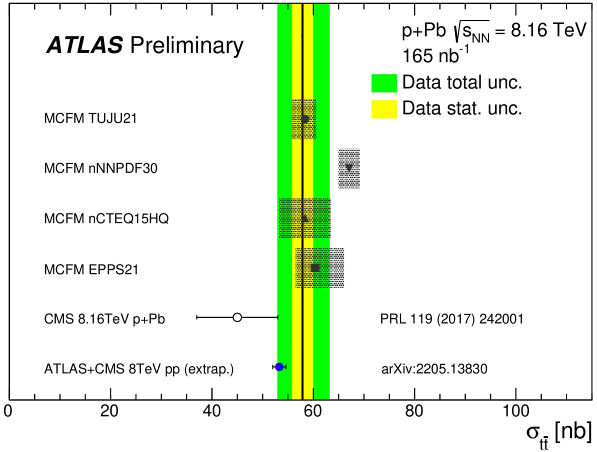
The total systematic uncertainty amounts to **9%**.

6. Conclusion

Conclusion

- The top-quark pair production cross section (ATLAS-CONF-2023-063) is measured to be $\sigma_{t\bar{t}}$ = 57.9 ± 2.0 (stat.) + 4.9 - 4.5 (syst.) nb.
- The total uncertainty amounts to 9%, which makes it the most precise $t\bar{t}$ measurement in Heavy Ion collisions.
- The significance is well over 5 σ in the lepton+jets and dilepton channels separately.
- The cross section is compared to the CMS measurement in the p+Pb system.
- The result is consistent with the scaled cross section in pp collisions, extrapolated to √s = 8.16 TeV.
- A good agreement is found with NNLO calculation based on several nPDF sets.

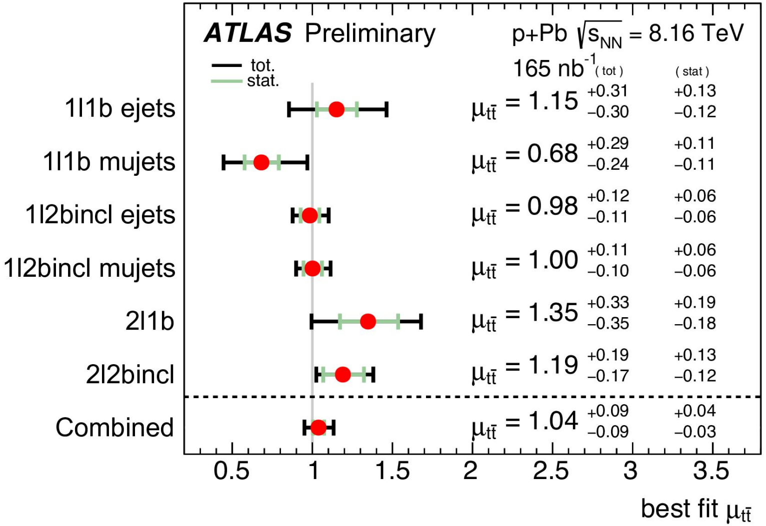


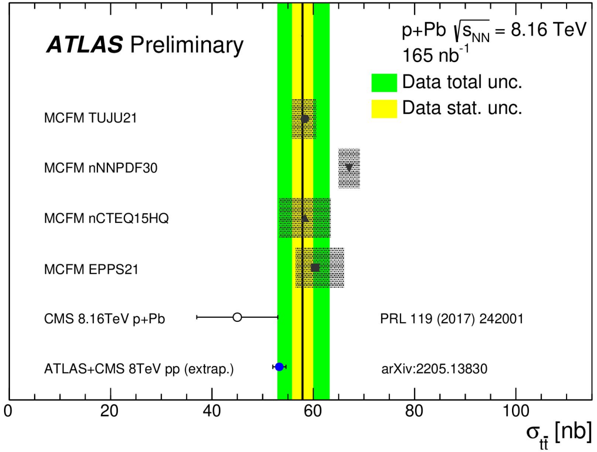


Conclusion

Thank you!

Ongoing discussion 4pm - Praha Troja Občerstvení Slalom



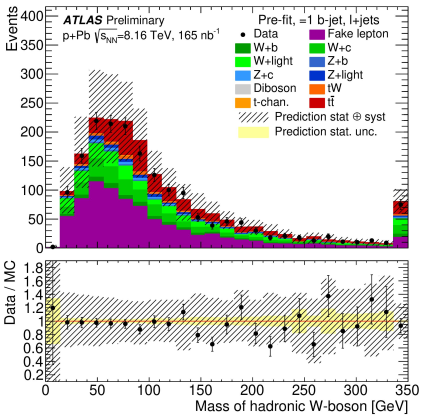


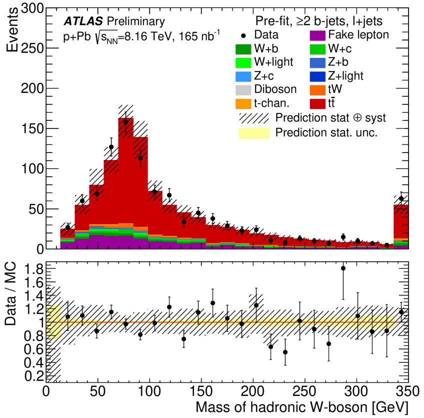
Back-up :: W and Top

1b region

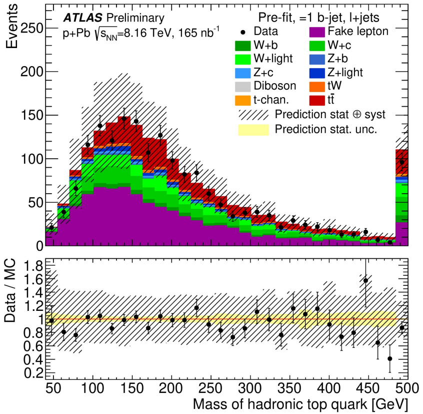
2b inclusive region

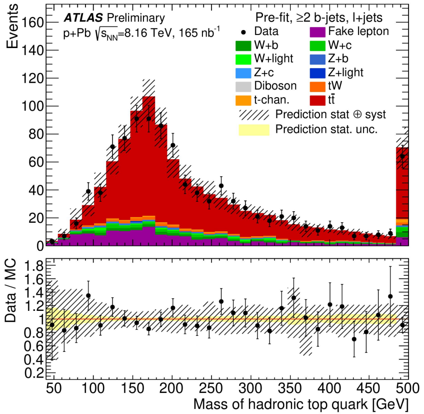
Hadronically decaying W boson
- Use 2 highest non-btag jets in p_T





Hadronically decaying top quark
- 4-vector of hadronically decaying W boson + b-jet which is further in DR from the lepton

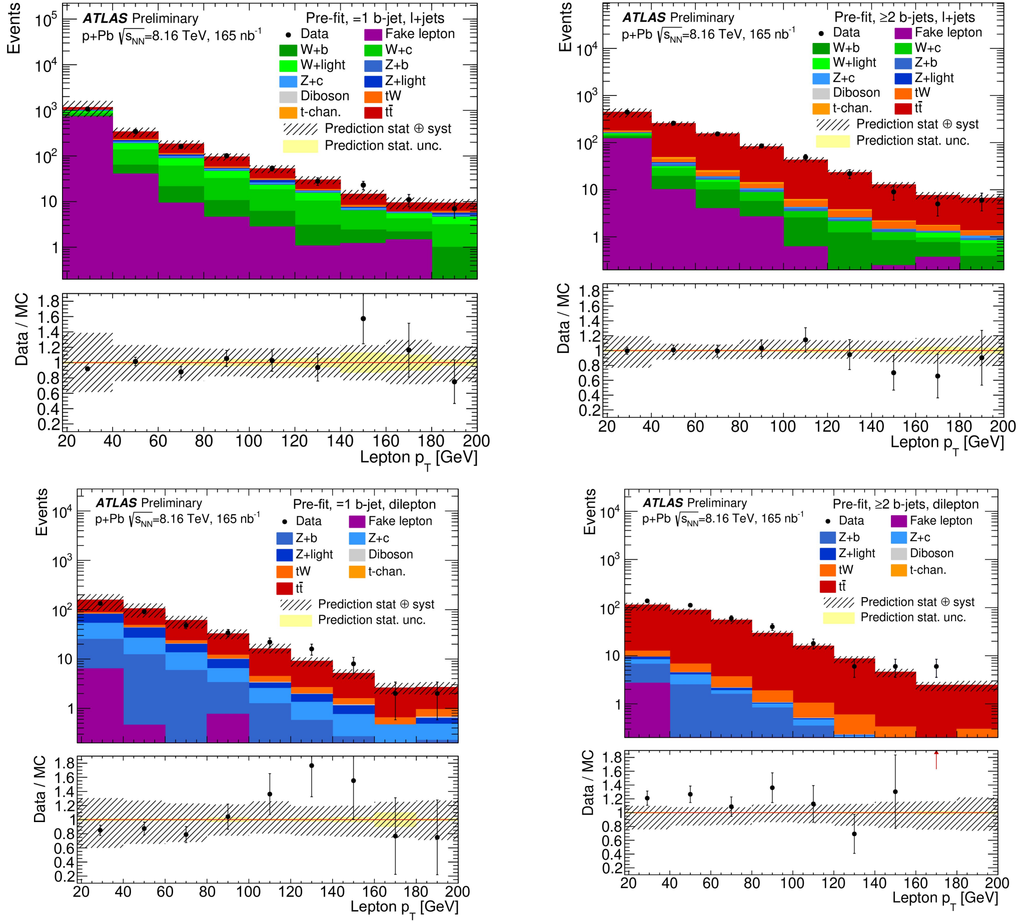




1b region | 2b inclusive region

lepton+jets

dilepton

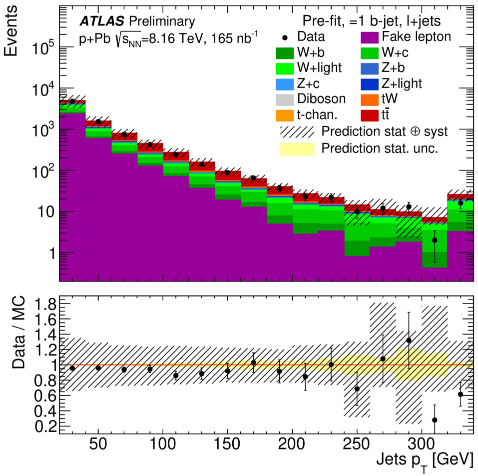


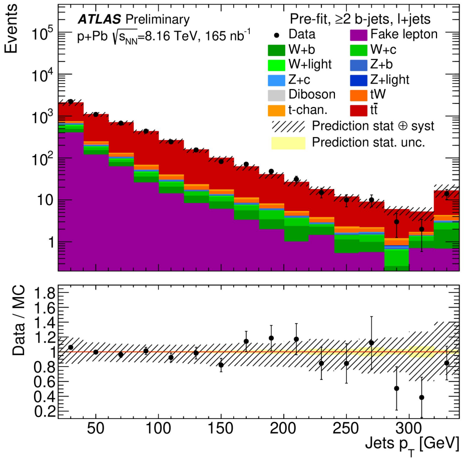
Back-up :: Jets p_T

1b region

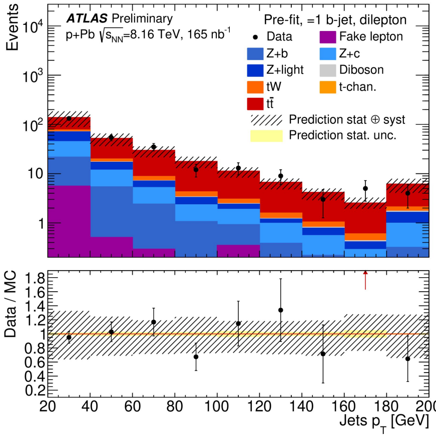
2b inclusive region

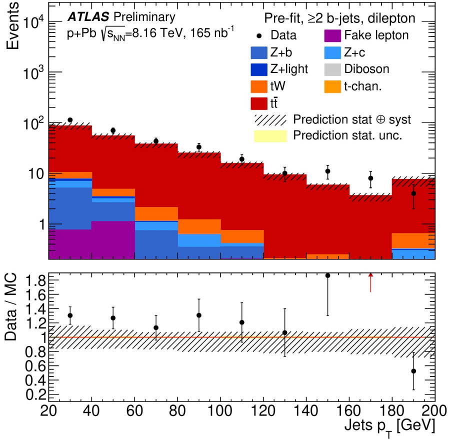
lepton+jets





dilepton





Back-up :: Correlation Matrix

ATLAS Preliminary

	Fake lepton background e+jets 1b	Fake lepton background e+jets 2bincl	Fake lepton background μ+jets 1b	Fake lepton background μ+jets 2bincl	HI to PF jet matching	W+c-jets background	W+light-jets background	Z+b-jets background	Z+c-jets background	Z+light-jets background	$t\bar{t}$ acc. PhH7	$t\bar{t}$ acc. aMC@NLO	$t\bar{t}$ shape aMC@NLO	$t\bar{t}$ h_{damp} shape	$\mu_{t\bar{t}}$
Fake lepton background e+jets 1b	100.0	62.2	72.0	31.4	-75.4	-8.5	-19.4	3.9	5.2	-2.7	-1.2	5.7	4.6	2.1	24.1
Fake lepton background e+jets 2bincl	62.2	100.0	42.6	36.3	-74.5	0.3	8.0	-0.3	9.3	6.5	-3.4	-4.3	2.3	1.5	4.5
Fake lepton background μ+jets 1b	72.0	42.6	100.0	22.9	-50.5	-8.3	-45.4	1.1	2.6	0.2	-0.9	14.0	-1.2	0.9	27.9
Fake lepton background μ+jets 2bincl	31.4	36.3	22.9	100.0	-37.3	-0.7	5.8	-0.6	4.3	2.2	-0.4	-1.6	-4.4	1.2	5.9
HI to PF jet matching	-75.4	-74.5	-50.5	-37.3	100.0	4.1	-10.6	-5.9	-9.2	-6.2	0.1	5.9	-13.4	-0.6	-4.8
W+c-jets background	-8.5	0.3	-8.3	-0.7	4.1	100.0	-32.1	2.4	4.3	1.6	0.1	-23.9	-4.6	-0.0	-16.6
W+light-jets background	-19.4	8.0	-45.4	5.8	-10.6	-32.1	100.0	1.2	3.7	1.5	0.5	-4.3	-0.1	1.1	2.5
Z+b-jets background	3.9	-0.3	1.1	-0.6	-5.9	2.4	1.2	100.0	-41.5	-9.5	5.9	-1.0	-2.4	-0.2	-13.4
Z+c-jets background	5.2	9.3	2.6	4.3	-9.2	4.3	3.7	-41.5	100.0	-38.7	11.3	-13.6	-3.5	-0.1	-16.5
Z+light-jets background	-2.7	6.5	0.2	2.2	-6.2	1.6	1.5	-9.5	-38.7	100.0	1.7	-2.1	-1.5	-0.2	3.7
$t\bar{t}$ acc. PhH7	-1.2	-3.4	-0.9	-0.4	0.1	0.1	0.5	5.9	11.3	1.7	100.0	-1.1	-0.6	-0.1	-31.7
$t\bar{t}$ acc. aMC@NLO	5.7	-4.3	14.0	-1.6	5.9	-23.9	-4.3	-1.0	-13.6	-2.1	-1.1	100.0	2.4	1.8	36.8
$t\bar{t}$ shape aMC@NLO	4.6	2.3	-1.2	-4.4	-13.4	-4.6	-0.1	-2.4	-3.5	-1.5	-0.6	2.4	100.0	30.5	1.3
$t\bar{t}$ h_{damp} shape	2.1	1.5	0.9	1.2	-0.6	-0.0	1.1	-0.2	-0.1	-0.2	-0.1	1.8	30.5	100.0	4.7
$\mu_{t\bar{t}}$	24.1	4.5	27.9	5.9	-4.8	-16.6	2.5	-13.4	-16.5	3.7	-31.7	36.8	1.3	4.7	100.0

Back-up :: Differences to CMS Meas.

Analysis conditions	ATLAS	CMS
channel	lepton+jets, dilepton	lepton + jets
min lepton p_T [GeV]	18	30
Lepton $\|\eta\|$	< 2.4 (2.47)	< 2.1
Min jet p_T [GeV]	20	25
Int lumi [nb^{-1}]	164.6	174

Back-up :: Differences to CMS Meas.

Uncertainties [%]	ATLAS	CMS
Int lumi	2.4	5
stat.	3	8
B-tagging + JES	5	13
Extra JES	-	4
background	4	7
Lepton trigger and reco	3	4
total	9	18

Back-up :: p+Pb CMS

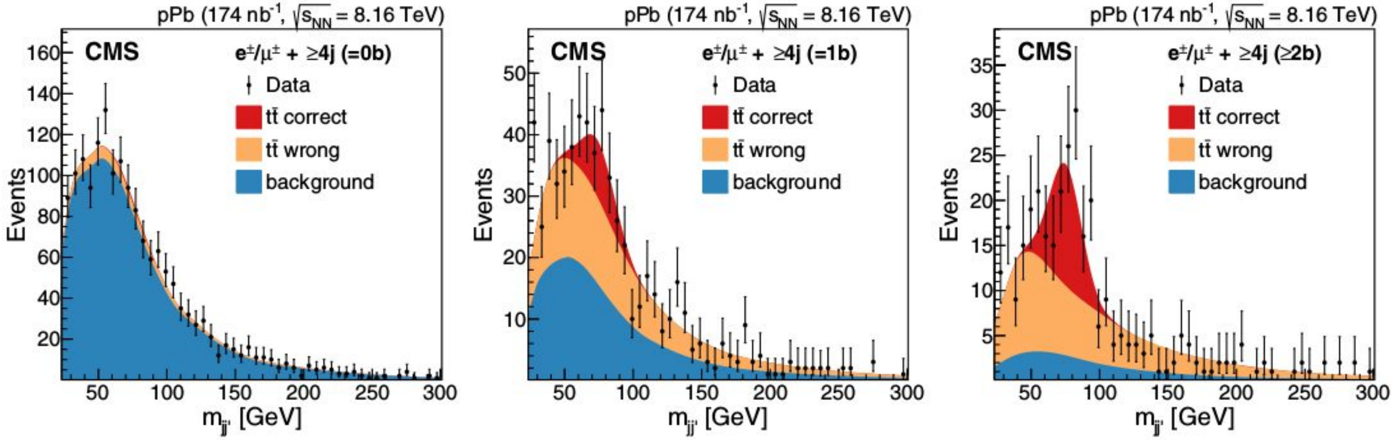


FIG. 1. Invariant mass distributions of the W candidate, $m_{jj'}$, in the 0 (left), 1 (center), and 2 (right) b-tagged jet categories after all selections. The red and orange areas correspond to the signal simulation (correct and wrong assignments, respectively), while the blue one corresponds to the estimated nontop background contributions. The error bars indicate the statistical uncertainties.

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Back-up :: p+Pb CMS

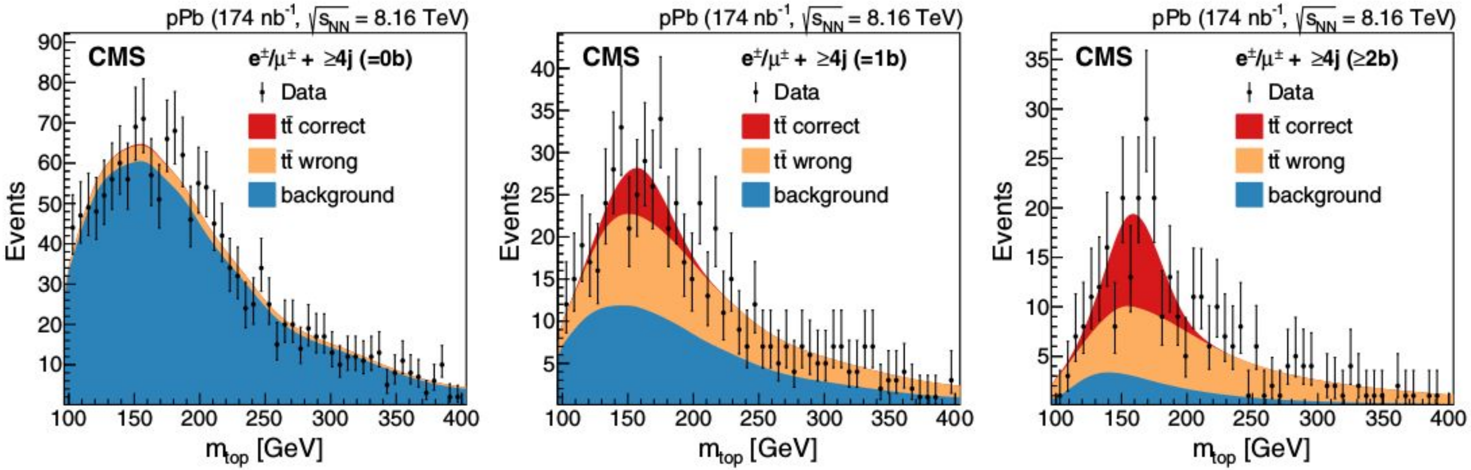

FIG. 2. Invariant mass distributions of the $t \to jj'b$ candidates, m_{top}, in the 0 (left), 1 (center), and 2 (right) b-tagged jet categories after all selections. All signal and background parameters are kept fixed to the outcome of the $m_{jj'}$ fit. Symbols and patterns are the same as in Fig. 1.

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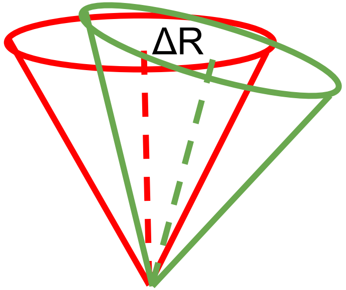
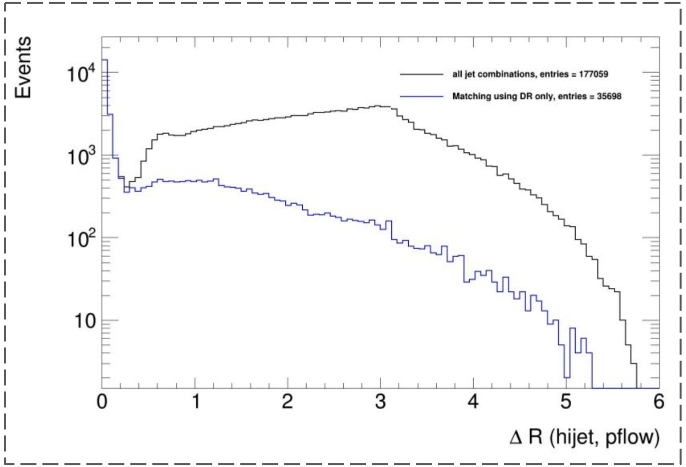
	b-tag info	MET
PFlow Jets	✓	✓
HI Jets	✗	✗

HI matched to PFlow Jets ✓



HI jet is assigned as a b-tagged if matched PFlow jet is b-tagged and is within **dR = 0.3** distance to the HI jet.



	b-tag info	MET
PFlow Jets	✓	✓
HI Jets	✗	✗

HI matched to PFlow Jets	✓	
Moving from H_T^{all} -> H_T^{jl}		✓

- To perform matching:
  - Matching based on event no.
  - Matching based on leading lepton eta (phi) for V+jets bkg