Measurements of W^+W^- production cross-sections in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector: first measurement of the boost asymmetry

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Significance of proton structure at high-energy scale

- **High-energy scale**: negligible interactions between partons

$$\rightarrow (\text{proton} + \text{X}) = \sum(\text{parton}_\text{i} + \text{X}_\text{i})$$

- **Pure physics of the structure of the proton**
  - Flavor asymmetry: $\bar{u}, \bar{d}, s(\bar{s})$
  - Intrinsic heavy quark?
- **A global test for QCD**
  - perturbative QCD calculation, α_s determination $\cdots$
- **Initial state description for hadron experiments**
  - PDF: leading systematic in many important topics:

    $sin\theta_W^{eff}$, m_W, Higgs differential, Z', W' ...

Significance of proton structure at high-energy scale

- **Initial state description for hadron experiments**
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    $sin\theta_W^{eff}$, m_W, Higgs differential, Z', W'...

$sin\theta_W^{eff}$, CMS (2025): $\sin^2\theta^{\ell}_{\mathrm{eff}} = 0.23152 \pm 0.00010\,(\mathrm{stat}) \pm 0.00015\,(\mathrm{exp}) \pm 0.00008\,(\mathrm{theo}) \pm 0.00027\,(\mathrm{PDF})$

m_W, CMS (2024):

Source of uncertainty	Impact (MeV) in m_W
Muon momentum scale	4.8
Muon reco. efficiency	3.0
W and Z angular coeffs.	3.3
Higher-order EW	2.0
p_T^V modeling	2.0
PDF	4.4
Nonprompt-muon backgrou	3.2
Integrated luminosity	0.1
MC sample size	1.5
Data sample size	2.4
Total uncertainty	9.9

Z', CMS (2021):

Uncertainty source	Impact on background [%] $m_{\ell\ell} > 1$ TeV ee	$m_{\ell\ell} > 1$ TeV μμ	$m_{\ell\ell} > 3$ TeV ee	$m_{\ell\ell} > 3$ TeV μμ
Lepton selection efficiency	6.8	0.8	6.4	1.3
Muon trigger efficiency	—	0.9	—	0.9
Mass scale	7.0	2.7	15.4	2.4
Dimuon mass resolution	—	0.1	—	0.6
Pileup reweighting	0.3	—	0.5	—
Trigger prefiring	0.5	—	0.2	—
PDF	3.7	3.0	9.4	10.2
Cross section for other simulated backgrounds	0.6	0.8	0.2	0.4
Z peak normalization	2.3	5.0	2.0	5.0
Simulated sample size	0.4	0.4	1.3	1.6

Proton structure study and PDF global analysis

- Non-perturbative parameterization at low Q:

$$u(x), \bar{u}(x), d(x), \bar{d}(x), s(x), \bar{s}(x), g(x)$$

e.g. $f_i(x, Q_0) = a_0 x^{a_1 - 1}(1-x)^{a_2} P_i(y; a_3, a_4, \ldots)$

+

- Perturbative QCD calculation:

Evolution to high Q

$$c(x), \bar{c}(x), b(x), \bar{b}(x) \ldots$$

- Other assumptions:

sum rules

$$\int u - \bar{u} = 2, \int d - \bar{d} = 1, \int q_{s,c,b} - \bar{q}_{s,c,b} = 0$$

SM assumptions

$\bar{u} = \bar{d}$ at $x \to 0$

...

fit

Better experimental measurements

↓

Better QCD global fit

↓

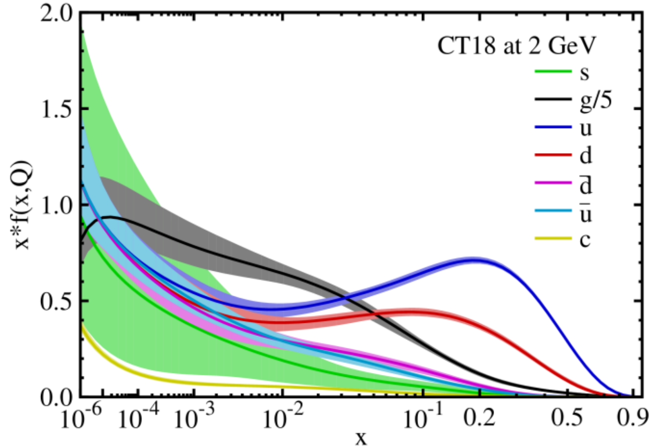
Better proton structure study

- Experimental measurements:

fit for the non-perturbative part

post-fit

$\not\parallel$ not a direct reflection of experiments



Better experimental measurements

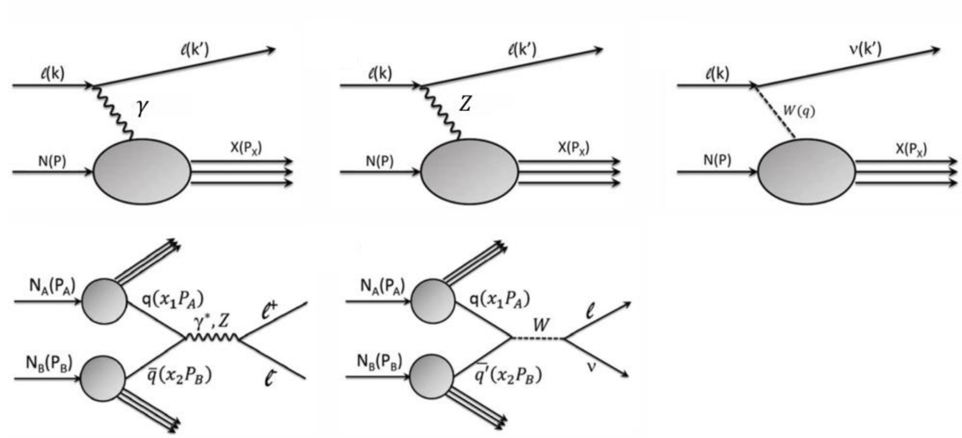
- **Previous experiments for high-energy scale proton structure:**

  cross-section measurements (DIS, Drell-Yan…)

  parton density mix

DIS

Drell-Yan



- **New measurements:**

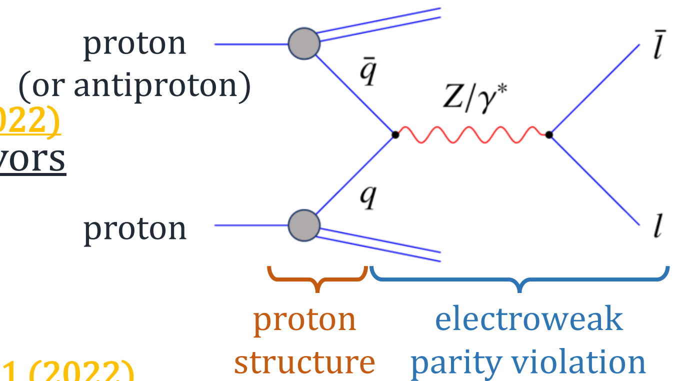
  asymmetries due to electroweak interaction → different quark densities individually

  (non-flavor: without big fragmentation uncertainty)

  parton density difference

  lower the mixing → closer to individual determination of each parton

Parton density differences



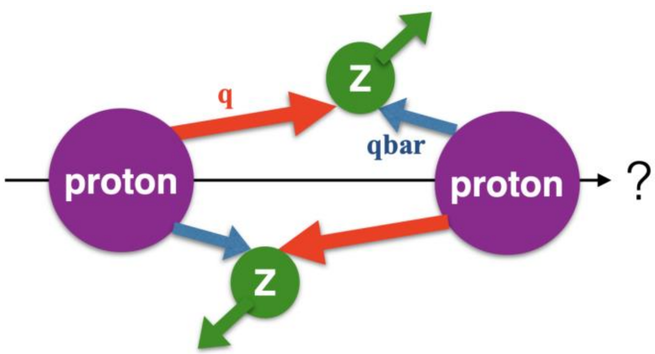
The first parton density difference : [Phys. Rev. D 106, 033001 (2022)]

- provide parton density difference between <u>different flavors</u>
- in single boson processes

The second parton density difference : [Phys. Rev. D 106, L051301 (2022)]

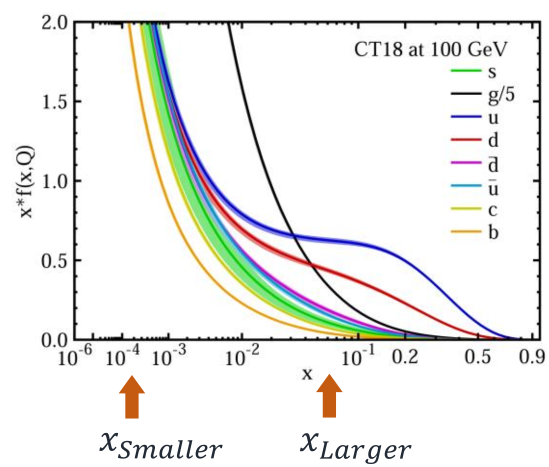
- provide parton density difference between <u>different x regions</u>
- in diboson processes

Bjorken variable x: the fraction of the parton momentum to the energy of the proton, $x = \frac{\sqrt{Q_T^2 + M^2}}{\sqrt{s}} \cdot e^{\pm Y}$



hadron collider: high energy → large x region mixing

$(q_i(x_L)\bar{q}_j(x_S) + \bar{q}_j(x_L)q_i(x_S))$



independent information at x_S and x_L in experiment

The second parton density difference

Phys. Rev. D 106, L051301 (2022)

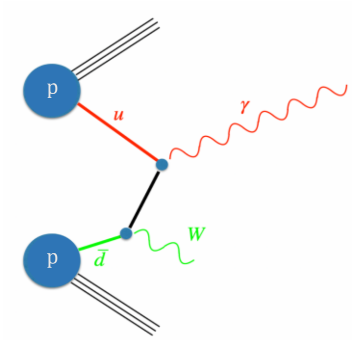
➡ provide distinct large and small x region quark information

Diboson productions and boost asymmetry

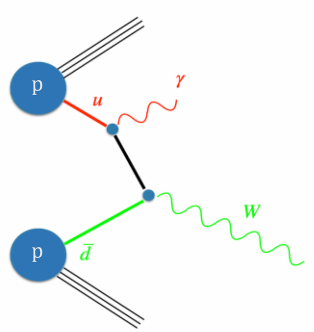
- $W\gamma, WZ$, and W^+W^-
- dominant subprocess: u-channel and t-channel

  comparison of the two bosons' kinematics → comparison of the two quarks' energies
- The boost asymmetry in VV' event can be defined as :

$$A_{\text{boost}}^{VV'} = \frac{N(|Y_V| > |Y_{V'}|) - N(|Y_V| < |Y_{V'}|)}{N(|Y_V| > |Y_{V'}|) + N(|Y_V| < |Y_{V'}|)}$$



Photon more forward



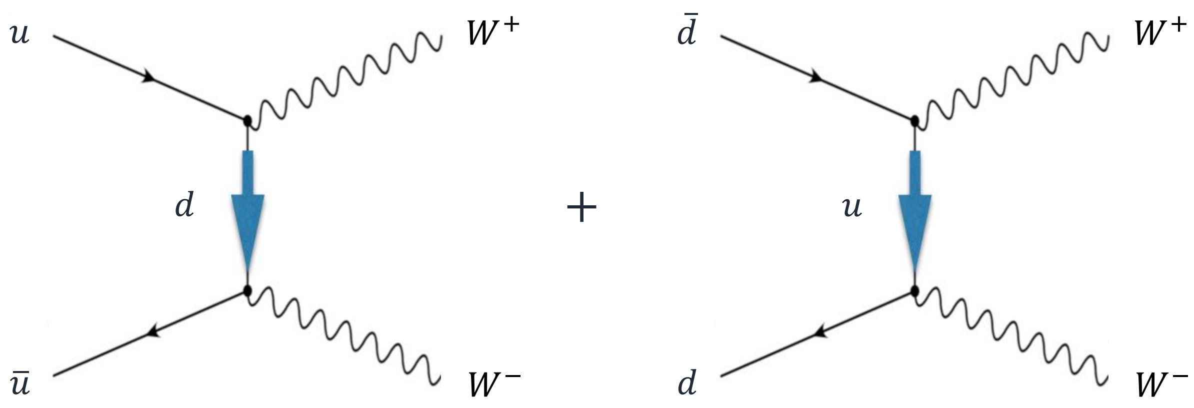
W more forward

Boost Asymmetry in W^+W^- process

[Phys. Rev. D 106, L051301 (2022)](#)

- The boost asymmetry in W^+W^- event can be defined as :

$$A_{Boost}^{WW} = \frac{N(|\eta_{\ell^+}| > |\eta_{\ell^-}|) - N(|\eta_{\ell^+}| < |\eta_{\ell^-}|)}{N(|\eta_{\ell^+}| > |\eta_{\ell^-}|) + N(|\eta_{\ell^+}| < |\eta_{\ell^-}|)}$$



- A_{boost}^{WW} represents to the difference between :

	$\lvert\eta_{l^+}\rvert > \lvert\eta_{l^-}\rvert$	$\lvert\eta_{l^+}\rvert < \lvert\eta_{l^-}\rvert$
$\boldsymbol{W^+W^-}$	$u(x_L)\bar{u}(x_S) + \bar{d}(x_L)d(x_S)$	$\bar{u}(x_L)u(x_S) + d(x_L)\bar{d}(x_S)$

First Measurement of the Boost Asymmetry

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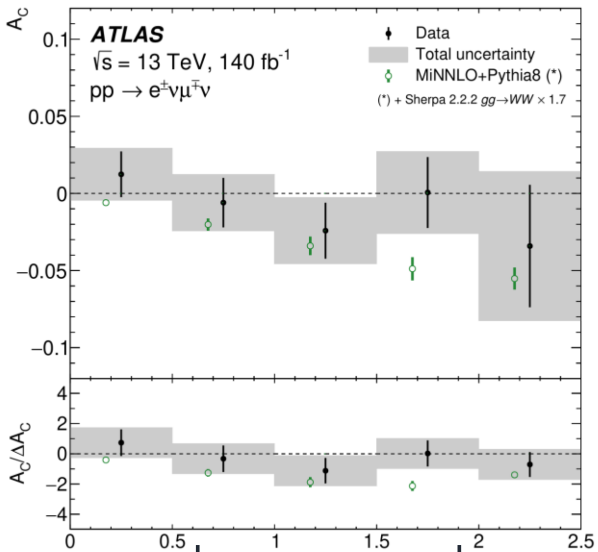
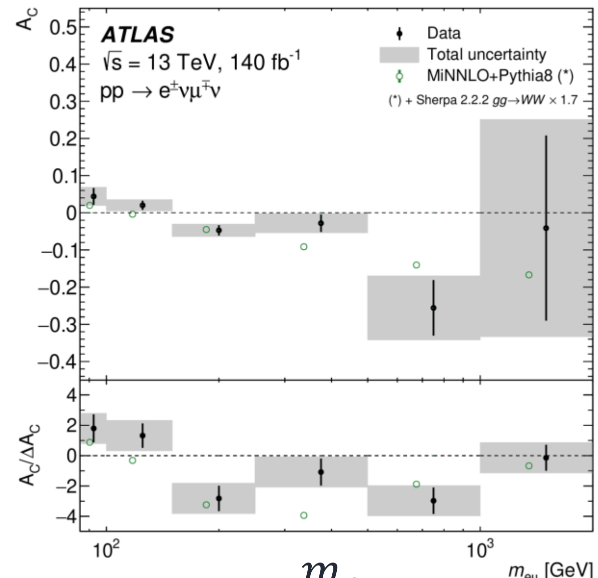
- The boost asymmetry in W^+W^- process :

$$A_\mathrm{C} = -0.004 \pm 0.008\ (\mathrm{stat.}) \pm 0.006\ (\mathrm{syst.})$$

NNPDF3.0NNLO prediction $= -0.023 \pm 0.003$



$||\eta_{l^+}| - |\eta_{l^-}||$



$m_{e\mu}$

$e\mu$ opening angle & $e\mu$ energy

Difference between x_q and $x_{\bar{q}}$ in the initial state

Event selection in signal regions

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- The number of events is reduced by rejecting background :

	Requirement	Criteria
Electron	p_T	$> 27\,\mathrm{GeV}$
	$\lvert\eta\rvert$	$\in [0\,,\,1.37) \cup (1.52\,,\,2.47)$
	Identification	`TightLH` working point
	Isolation	`Gradient`
	Impact parameters	$\lvert d_0/\sigma_{d_0}\rvert < 5$; $\lvert z_0 \cdot \sin\theta\rvert < 0.5\,\mathrm{mm}$
Muon	p_T	$> 27\,\mathrm{GeV}$
	$\lvert\eta\rvert$	< 2.5
	Identification	`Medium` working point
	Isolation	`Tight_FixedRad`
	Impact parameters	$\lvert d_0/\sigma_{d_0}\rvert < 3$; $\lvert z_0 \cdot \sin\theta\rvert < 0.5\,\mathrm{mm}$
b-jets	p_T	$> 20\,\mathrm{GeV}$
	$\lvert\eta\rvert$	< 2.5
	Pile-up suppression	jet-vertex tagger [91] for $p_\mathrm{T} < 60\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.4$
	b-tagging	DL1r, 85% efficiency working point
Jets	p_T	$> 30\,\mathrm{GeV}$
	$\lvert\eta\rvert$	< 4.5
	Pile-up suppression	jet-vertex tagger [91] for $p_\mathrm{T} < 60\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.4$
Event	Leptons	1 electron and 1 muon of opposite electric charge; no additional lepton with $p_\mathrm{T} > 10\,\mathrm{GeV}$, `Loose` isolation, and `LooseLH` (electron) / `Loose` (muon) identification
	Number of b-jets	0
	$m_{e\mu}$	$> 85\,\mathrm{GeV}$

$W^+W^- \to e^\pm \upsilon \mu^\mp \nu$

Rejecting $t\bar{t}$ production

(the largest background)

Rejecting Drell-Yan production

(the second largest background)

Other Motivations for W^+W^- Analysis

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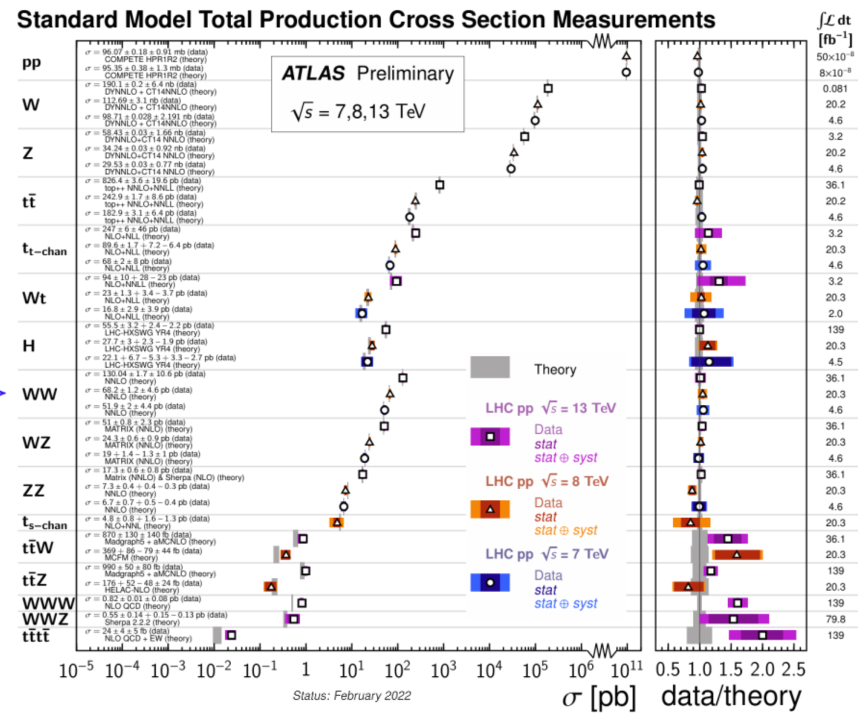
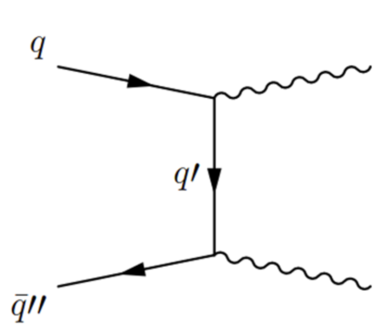
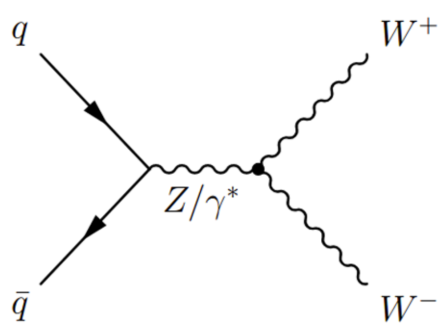
- W^+W^- production is a key process to test self-couplings predicted by the EW sector of the SM
  - Stringent tests of physics BSM
  - Sensitive to new physics via aTGCs
- Interesting test for QCD corrections
  - Important to verify and tune the simulation tools used to describe EW processes produced in association with jets
- Important background in other SM and BSM measurements (e.g. $H \to WW$)

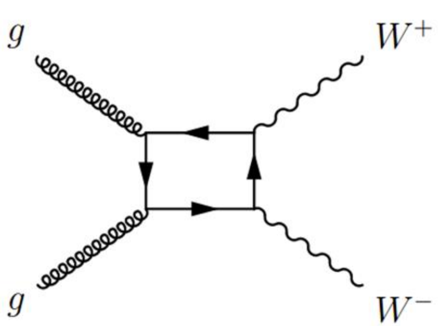




t-channel



s-channel



non-resonant gg fusion

Total cross-section

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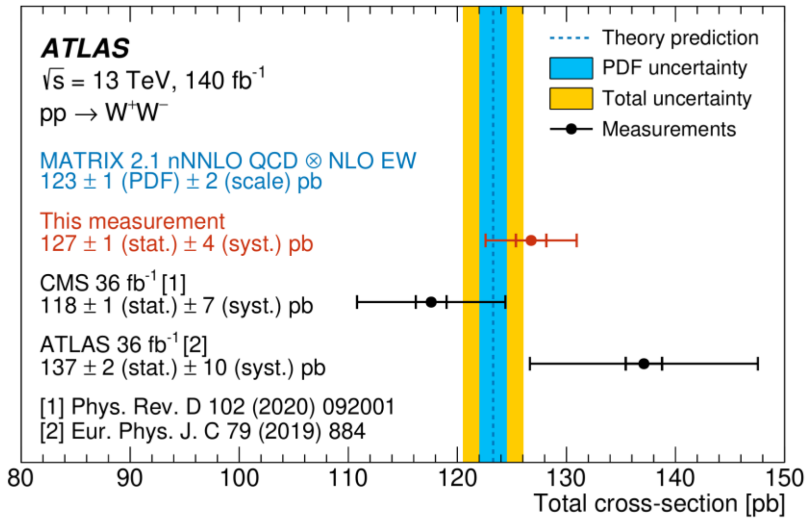
- Tevatron:
  - [CDF 1.8 TeV][CDF 1.96 TeV][D0 1.96 TeV]
- LHC:
  - ATLAS: [7 TeV][8 TeV (0-jet)][13 TeV, 3 fb^{-1}][13 TeV, 36 fb^{-1}][13 TeV ($\geq$ 1-jet), 139 fb^{-1}]
  - CMS: [5 TeV][7 TeV][8 TeV][13 TeV, 35.9 fb^{-1}] [13.6 TeV, 34.8 fb^{-1}]
- Most precise W^+W^- cross section measurement in hadron-hadron collisions:

$$\sigma_{\text{total}} = 127 \pm 1 \ (\text{stat.}) \pm 4 \ (\text{syst.}) \pm 1 \ (\text{lumin.}) \, \text{pb}$$

13 TeV, 140 fb^{-1}



Data-driven backgrounds

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Top background: *b*-tag counting

- Determine both number of $t\bar{t}$ events and probability ε_b of finding b-jets from event yields in one and two b-tag CRs
- Estimate yields in each bin of 0-b-jet region by extrapolation

$$\begin{cases} N_{2b}^{t\bar{t}} = N^{t\bar{t}} \cdot C_b \varepsilon_b^2\,, \\ N_{1b}^{t\bar{t}} = N^{t\bar{t}} \cdot 2\varepsilon_b \left(1 - C_b \varepsilon_b\right)\,, \\ N_{0b}^{t\bar{t}} = N^{t\bar{t}} \cdot \left(1 - 2\varepsilon_b + C_b \varepsilon_b^2\right) \end{cases}$$

$$\Rightarrow \quad N_{0b}^{t\bar{t}} = \frac{C_b}{4} \frac{\left(N_{1b}^{t\bar{t}} + 2N_{2b}^{t\bar{t}}\right)^2}{N_{2b}^{t\bar{t}}} - N_{1b}^{t\bar{t}} - N_{2b}^{t\bar{t}}$$

- Corrections C_b from MC are needed
  - Correlations between finding 1st and 2nd jet
  - Modelling uncertainties evaluated on C_b

$$C_b = \frac{4 \cdot N_{\mathrm{MC}}^{t\bar{t}} N_{2b,\mathrm{MC}}^{t\bar{t}}}{\left(N_{1b,\mathrm{MC}}^{t\bar{t}} + 2 \cdot N_{2b,\mathrm{MC}}^{t\bar{t}}\right)^2}$$

Fake lepton background: fake factor

- Prompt leptons are well-modeled in MC.
- loose ≡ Loose selection but rejecting Tight
- Fake factor for electrons and muons separately, and computed from Dijet CR from data in bins of $(p_T^l, |\eta^l|)$:

$$f = \frac{N_{\mathrm{tight}}^{\mathrm{fake}}}{N_{\mathrm{loose}}^{\mathrm{fake}}} = \frac{N_{\mathrm{tight}}^{\mathrm{Data}} - N_{\mathrm{loose}}^{\mathrm{prompt\ MC}}}{N_{\mathrm{loose}}^{\mathrm{Data}} - N_{\mathrm{loose}}^{\mathrm{prompt\ MC}}}$$

Dijet event selection
GRL
Trigger
Trigger matching
$N_\ell = 1$ and $p_T^\ell > 15$ GeV
$N_{\mathrm{jet}} > 0$
$p_T^{\mathrm{tag\,jet}} > 25(30)$ GeV
$\lvert\eta\rvert^{\mathrm{tag\,jet}} < 2.5\ (2.5, 4.5)$
$\lvert\Delta\phi(l,j)\rvert > 2.8$
$E_T^{\mathrm{miss,track}} + m_T < 50$ GeV
b-jet veto
ID or AntiID lepton

$$\Rightarrow \quad N_{\mathrm{tight}}^{\mathrm{fake}} = f_e \left(N_{\mathrm{tight}-\mu,\mathrm{loose}-e}^{\mathrm{Data}} - N_{\mathrm{tight}-\mu,\mathrm{loose}-e}^{\mathrm{prompt\ MC}}\right) + f_\mu \left(N_{\mathrm{tight}-e,\mathrm{loose}-\mu}^{\mathrm{Data}} - N_{\mathrm{tight}-e,\mathrm{loose}-\mu}^{\mathrm{prompt\ MC}}\right)$$

Validation regions for Data-driven backgrounds

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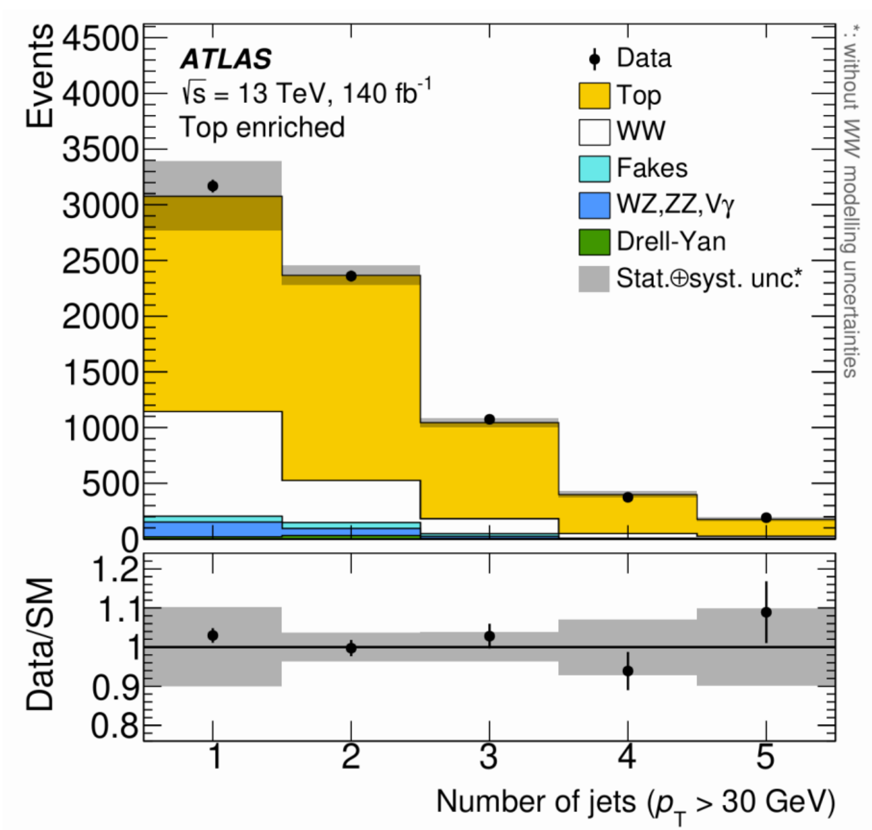
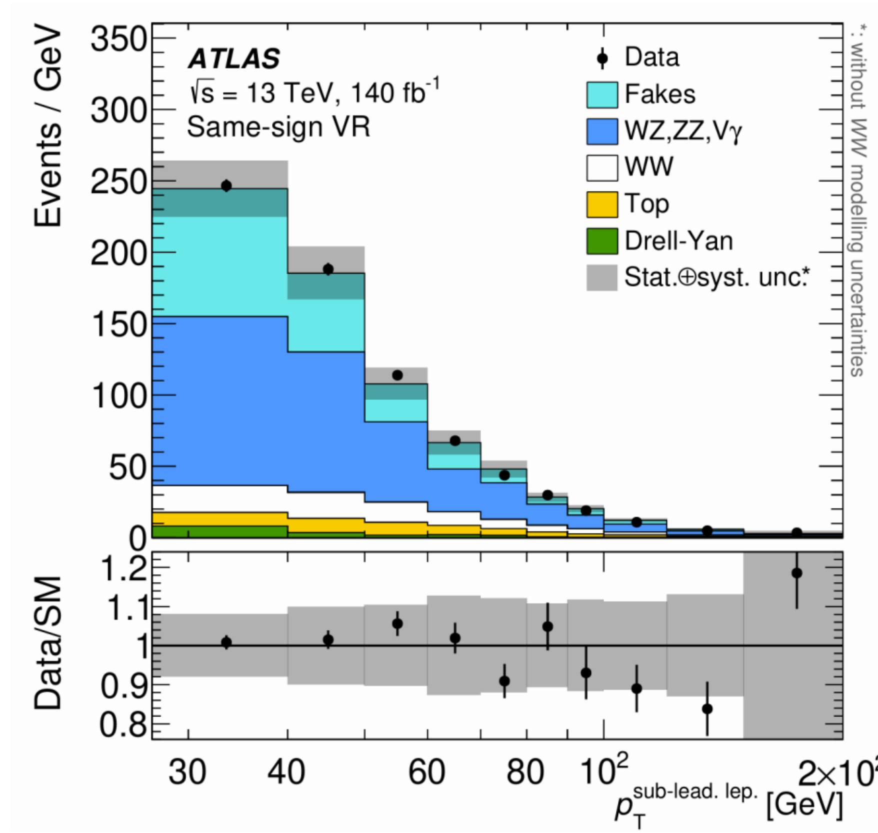
Top background: *b*-tag counting



Fake lepton background: fake factor



Differential distributions

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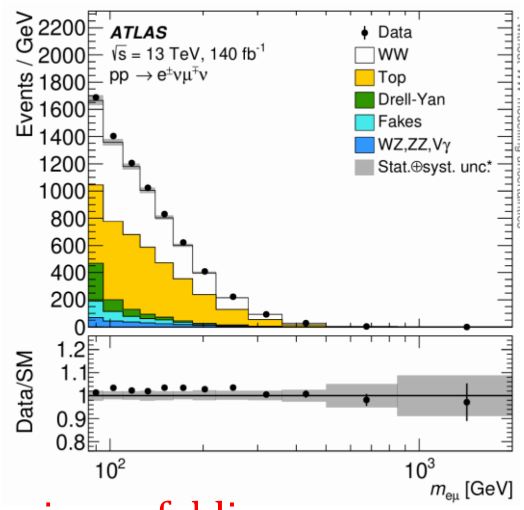
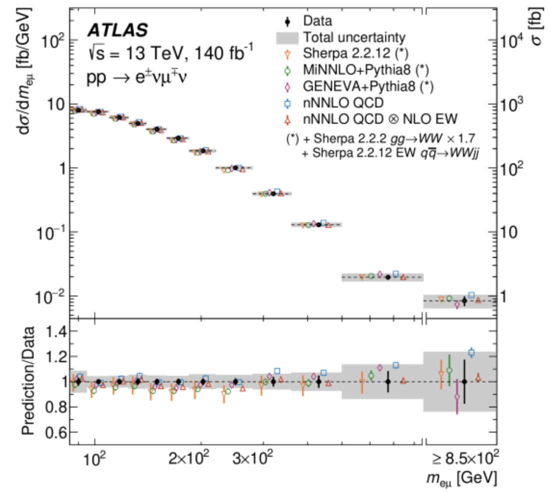
Cross-sections are measured differentially as a function of :

- the transverse momentum of the leading lepton, $p_{\mathrm{T}}^{\text{lead. lep.}}$,
- the transverse momentum of the sub-leading lepton, $p_{\mathrm{T}}^{\text{sub-lead. lep.}}$,
- the transverse momentum of the dilepton system, $p_{\mathrm{T},e\mu}$,
- the absolute rapidity of the dilepton system, $|y_{e\mu}|$,
- the invariant mass of the lepton pair, $m_{e\mu}$,
- the azimuthal separation of the two leptons, $\Delta\phi_{e\mu}$,
- $|\cos\theta^*| = |\tanh(\Delta\eta_{e\mu}/2)|$, which is sensitive to the spin structure of the W-boson pair [23],[1]
- the magnitude $E_{\mathrm{T}}^{\text{miss}}$ of the missing transverse momentum $\vec{p}_{\mathrm{T}}^{\text{miss}}$, defined as the negative vectorial sum of the transverse momenta of all visible particles,
- the scalar sum of $E_{\mathrm{T}}^{\text{miss}}$ and the lepton transverse momenta, $H_{\mathrm{T}}^{\text{lep.+MET}}$,
- the transverse mass of the dilepton system and the missing transverse momentum,[2] $m_{\mathrm{T},e\mu}$,
- the scalar sum of all jet and lepton transverse momenta, S_{T}, and
- the jet multiplicity.

$m_{e\mu}$



Bayesian unfolding



EFT constrain

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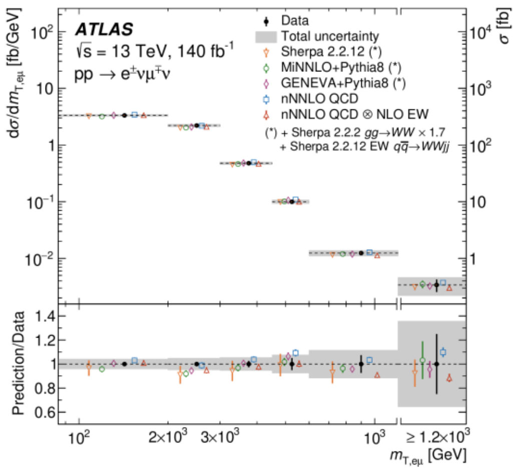
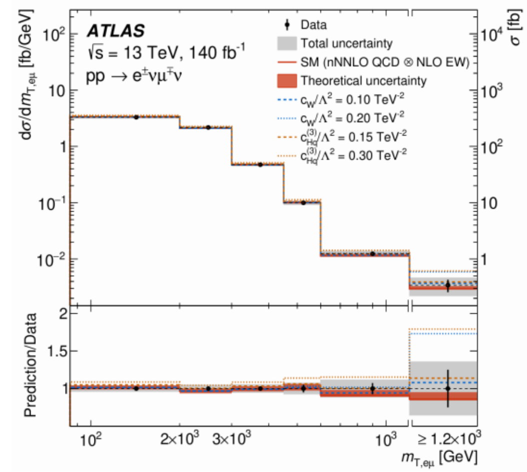
- SMEFT Lagrangian : $$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \dots$$

Measured $m_{\mathrm{T},e\mu}$ differencial



Comparison with SMEFT predictions

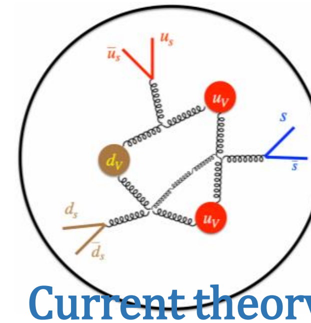


- Constrain :

	$O(\Lambda^{-2})$, individual		$O(\Lambda^{-4})$, individual		$O(\Lambda^{-4})$, profiled	
	Expected	Observed	Expected	Observed	Expected	Observed
c_W	$[-3.5, 3.2]$	$[-3.5, 3.4]$	$[-0.16, 0.16]$	$[-0.18, 0.18]$	$[-0.17, 0.16]$	$[-0.18, 0.18]$
c_{HD}	$[-8.9, 9.8]$	$[-11, 8]$	$[-7, 21]$	$[-8, 21]$	$[-7, 21]$	$[-8, 21]$
c_{HWB}	$[-8.4, 9.2]$	$[-10, 8]$	$[-1.5, 1.7]$	$[-1.7, 1.9]$	$[-1.7, 1.7]$	$[-1.8, 1.9]$
$c_{Hq}^{(1)}$	$[-2.5, 2.4]$	$[-2.2, 2.8]$	$[-0.27, 0.24]$	$[-0.29, 0.27]$	$[-0.29, 0.29]$	$[-0.31, 0.31]$
$c_{Hq}^{(3)}$	$[-0.69, 0.66]$	$[-0.7, 0.68]$	$[-0.28, 0.22]$	$[-0.31, 0.24]$	$[-0.3, 0.27]$	$[-0.34, 0.29]$
c_{Hu}	$[-3.2, 3.0]$	$[-3.0, 3.4]$	$[-0.31, 0.29]$	$[-0.35, 0.32]$	$[-0.32, 0.31]$	$[-0.35, 0.33]$
c_{Hd}	$[-11, 11]$	$[-11, 11]$	$[-0.45, 0.46]$	$[-0.5, 0.51]$	$[-0.49, 0.49]$	$[-0.52, 0.53]$

Backup

Proton structure study at high-energy scale



Current theory

QCD improved parton model

Main physics questions:

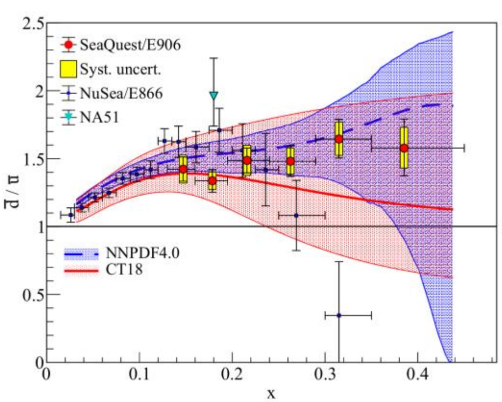
A series of experiments that the current model cannot explain.

- **SU(2) flavor asymmetry:**

$(\bar{u}, \bar{d})$ **comparative** density

Current theory: $\bar{u} = \bar{d}$

Experiment: $\boldsymbol{\bar{d} > \bar{u}}$



SeaQuest: [*Nature* **590**, 561–565 (2021)]

- **SU(3) flavor asymmetry:**

$(s, \bar{s})$ vs $(\bar{u}, \bar{d})$ **comparative** density

Current theory: $s + \bar{s} = \bar{u} + \bar{d}$

Experiment: $\boldsymbol{(s + \bar{s}) \sim \frac{1}{2}(\bar{u} + \bar{d})}$

$$\kappa_s = \frac{\int_0^1 x[s(x,\mu^2) + \bar{s}(x,\mu^2)]dx}{\int_0^1 x[\bar{u}(x,\mu^2) + \bar{d}(x,\mu^2)]dx} \sim [0.33, 0.59]$$

Experiment (year)	QCD order	κ_s
CDHS (1982)	LO	0.52 ± 0.09
CCFR (1993)	LO	$0.373^{+0.048}_{-0.041} \pm 0.018$
CCFR (1995)	NLO	$0.477^{+0.051}_{-0.050}{}^{-0.017}_{+0.036}$
CHARMII (1999)	LO	$0.388^{+0.074}_{-0.061} \pm 0.067$
NOMAD (2000)	LO	$0.48^{+0.09}_{-0.07}{}^{+0.17}_{-0.12}$
NuTeV (2001)	LO	$0.38 \pm 0.08 \pm 0.043$
NuTeV (2007)	NLO	
CHORUS (2008)	NLO	$0.33 \pm 0.05 \pm 0.05$
NOMAD (2013)	NNLO	0.591 ± 0.019

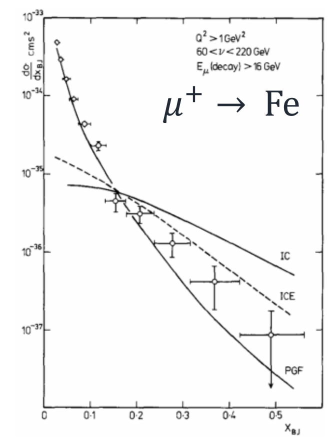
Review: [*Prog. Part. Nucl. Phys.* 79 (2014) 95–135]

- **Intrinsic heavy quark:**

$(c, \bar{c})$ vs $(\bar{u}, \bar{d})$ **comparative** density

Current: perturbative QCD dominant

Experiment: **may have non-perturbative contribution**



EMC: [*Phys. Lett. B* 110 (1982) 73]

What is our long-term plan?

An independent full analysis of hadron collider data aims to determine a set of specific proton structure information.

- Physics difference between old DIS data and hadron collider data

$$\sigma(Z), \sigma(W^+), \sigma(W^-)$$

$$P^u(A_{FB}^{LHC}),\ P^d(A_{FB}^{LHC}),$$

$$P^u(A_{FB}^{Tevatron}),\ P^d(A_{FB}^{Tevatron})$$

$$A_{boost}^{W^+\gamma},\ A_{boost}^{W^-\gamma},\ A_{boost}^{WW}$$