Highlights from ICHEP:
SM measurements

Oleksandr Zenaiev (DESY)

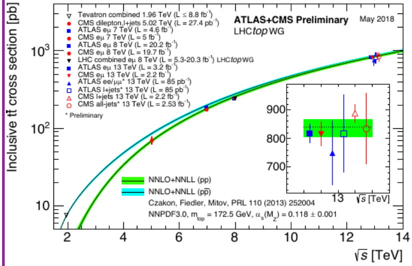
DESY, LHC discussion
23 July 2018

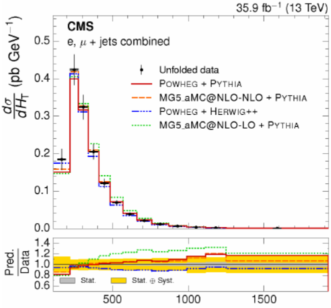
General overview

P. Langacker

- **Broad and exciting conference**
  - Experiment, phenomenology, theory, astro-particle, accelerator, detector, computing, education, diversity, applications
  - 1119 participants
    (213 women, 906 men)
  - 835 parallel talks in 16 sections
  - 41 plenary talks
  - 2 award lectures
  - 6 satellite meetings
  - 2 public lectures
  - 226 posters (3 award talks)
  - Director's panel
- ***Not* a detailed/complete summary** of SM talks

- Asia/Pacific: 560
- Europe: 414
- N/S America: 137
- Africa: 8
- Antarctica: 0





JHEP 1806 (2018) 002

Wide range of inclusive cross sections

- @ 5, 8.16, 13 TeV
- Constraining PDFs

Observation of top in p-Pb collisions

Wide range of differential cross sections

- Precision measurements of the SM
- Tuning $t\bar{t}$ production models
- Constraining EFTs

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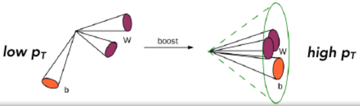
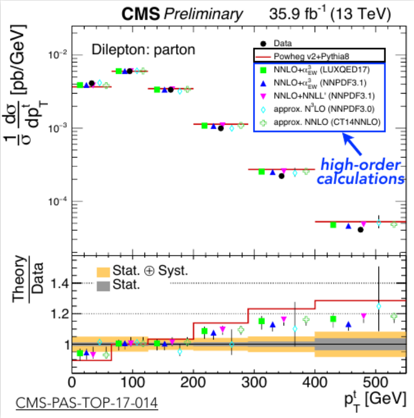
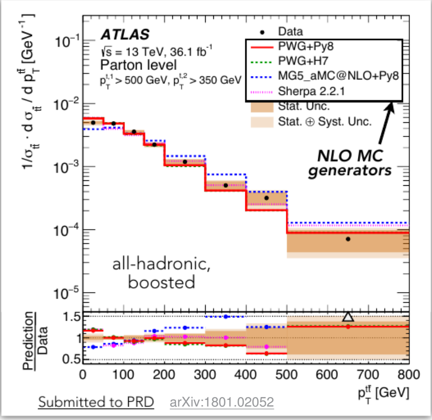
- *Abundance of measurements vs kinematic variables*
- *Test theory predictions, constrain SM parameters (m_{top}, α_S), constrain PDFs*
- *Sensitive to new physics*



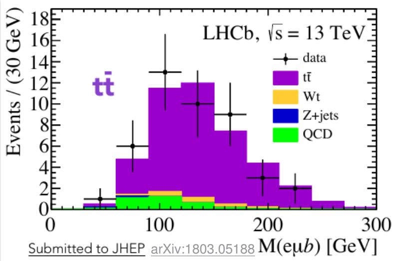
Mis-modeling in top p_T spectrum, improved, but not solved, by EW corrections





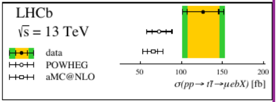
$\longrightarrow$ higher-order QCD and EW corrections are important for differential $\sigma(t\bar{t})$

Top quarks everywhere



Submitted to JHEP arXiv:1803.05188

Forward top production @ LHCb

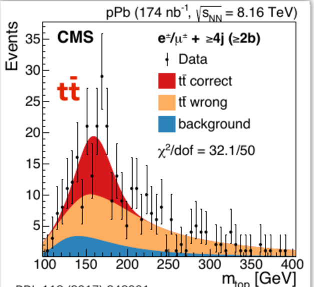


- $2<|\eta|<4.5$
- $\sigma_{tt,fid}$ = 126 ±19(stat) ±16(sys) ±5(lumi) fb

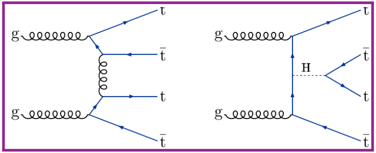
$\delta \sim 20\%$: entering precision era

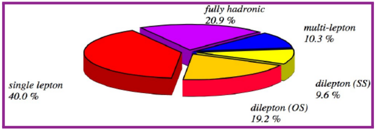
1st observation of tops in pPb collisions @ CMS

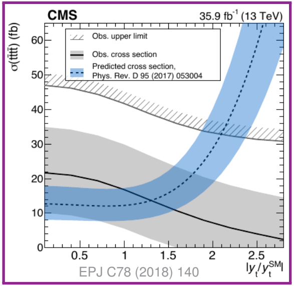
- Precise probe of nuclear gluon density
- **σ_{tt} = 45±8 nb**, consistent with predictions

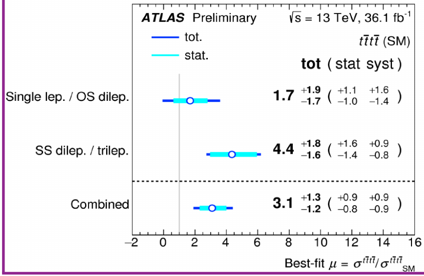


PRL 119 (2017) 242001

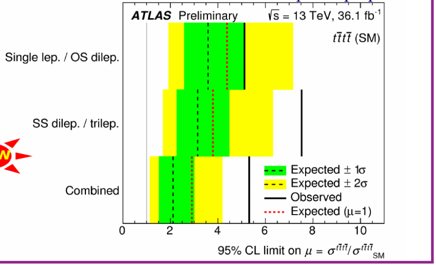








Paper in preparation

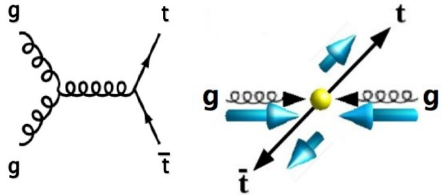


- SM *tttt* production may be enhanced by new physics (NP) contributions
- interpretation in various NP models

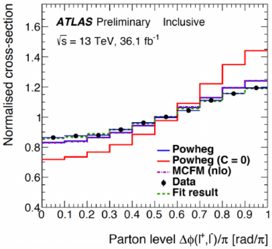
MANCHESTER 1824

Spin Correlations

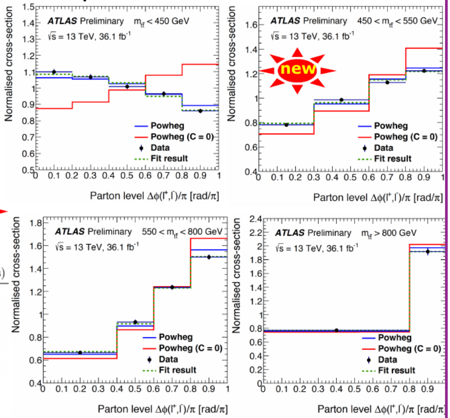
- Top quarks decay before fragmentation
  - Spin information is preserved
- Hadron colliders: top quarks produced un-polarized, but
  - New physics (NP) could induce polarization
    - e. g. NP causing forward-backward $t\bar{t}$ asymmetry → more left-handed tops
  - Correlation between top and antitop spin can be extracted



- Fitting spin and no-spin hypotheses to parton-level distributions



new



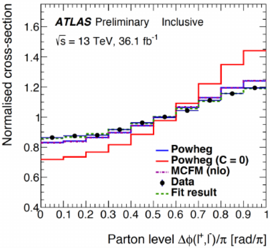
new

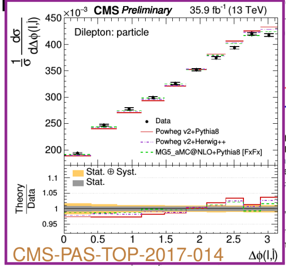
Region	f_{SM}	Significance (incl. theory uncertainties)
$m_{t\bar{t}} < 450$ GeV	$1.11 \pm 0.04 \pm 0.13$	0.85 (0.84)
$450 < m_{t\bar{t}} < 550$ GeV	$1.17 \pm 0.09 \pm 0.14$	1.00 (0.91)
$550 < m_{t\bar{t}} < 800$ GeV	$1.60 \pm 0.24 \pm 0.35$	1.43 (1.37)
$m_{t\bar{t}} > 800$ GeV	$2.2 \pm 1.8 \pm 2.3$	0.41 (0.40)
inclusive	$1.250 \pm 0.026 \pm 0.063$	3.70 (3.20)

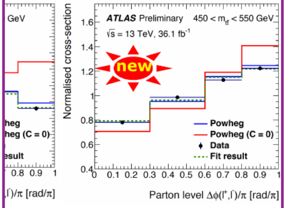
- Spin correlations higher than SM prediction by 3.7σ (3.2σ including theory uncertainty)

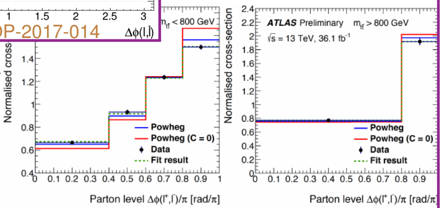
ATLAS-CONF-2018-027

- Fitting spin and no-spin hypotheses to parton-level distributions









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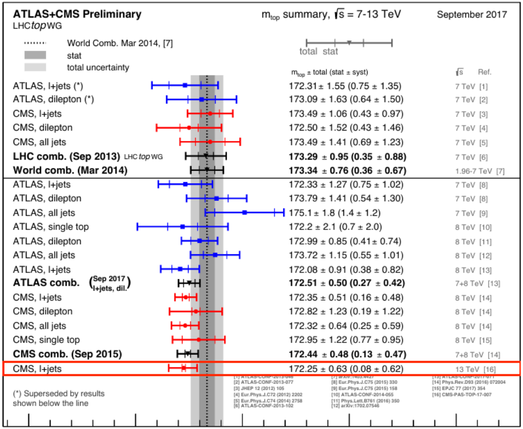
- Spin correlations higher than SM prediction by 3.7σ (3.2σ including theory uncertainty)

ATLAS-CONF-2018-027

- *Key SM parameter*
- *Test EW vacuum stability*

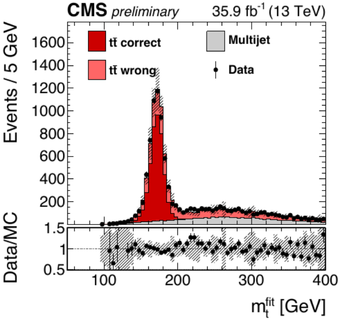
CMS-PAS-TOP-17-008

NEW @ ICHEP



LHCTopWGSummaryPlots

13 TeV, l+jets

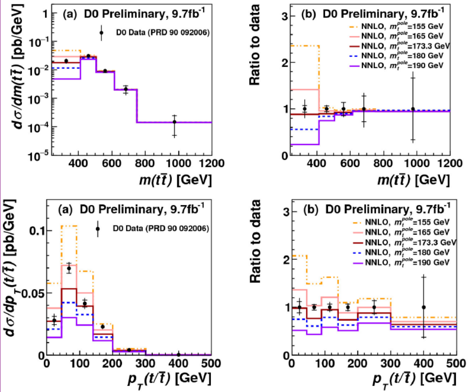


CMS all-jet (13 TeV)

172.34 ±0.20 (stat+JSF)

±0.76 (syst) GeV

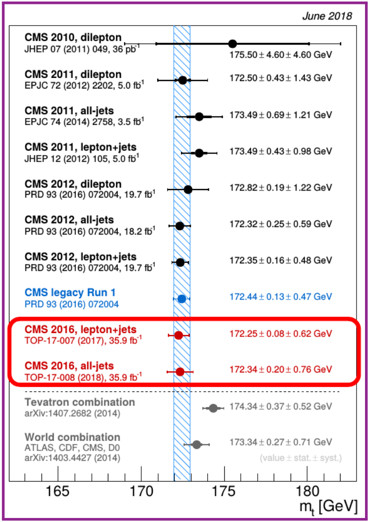
Top Mass from Differential Cross Section

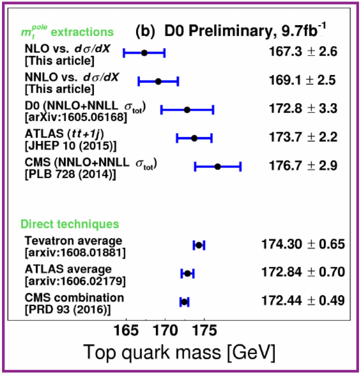


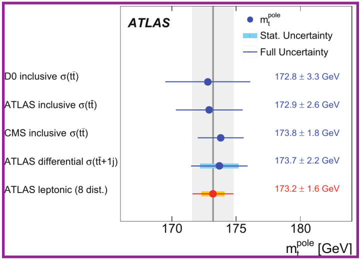
- Data taken from published lepton+jets measurement (PRD 90, 092006 (2014))
- Pole mass is extracted for both NLO and NNLO PDF sets from MSTW2008, CT10, NNPDF2.3 and HERAPDF
- Here compared to NNLO pQCD calculations (Czakon, Fiedler, Heymes, Mitov, JHEP, 1605, 034 (2016)) with MSTW 2008.
- Sensitivity mainly at the threshold in m(tt) and for lower p_T(t)

$m_t = 169.1 \pm 2.5$ GeV

Final result is imminent with smaller uncertainties and slightly shifted central value.





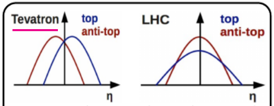


- CMS: new precise direct m_t measurements at Run 2
- D0: better m_t^{pole} precision using differential x-sections
  $\rightarrow$ not (yet) fully exploited at LHC

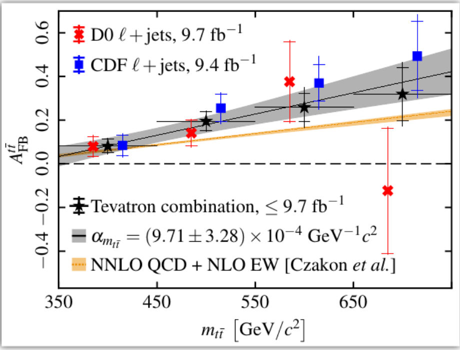
Top properties: $A_{FB}(tt)$

PRL 120, 042001 (2018)

- Forward-backward asymmetry, $A_{FB}(tt)$ @ Tevatron
  - Combination of final CDF/D0 results
  - Use rapidity difference & resulting asymmetry between decay leptons



$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y_{t\bar{t}} > 0) - N(\Delta y_{t\bar{t}} < 0)}{N(\Delta y_{t\bar{t}} > 0) + N(\Delta y_{t\bar{t}} < 0)}$$



Agreement within 1.3σ

2

Top properties: $A_{FB}(tt)$

PRL 120, 042001 (2018)

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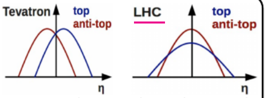

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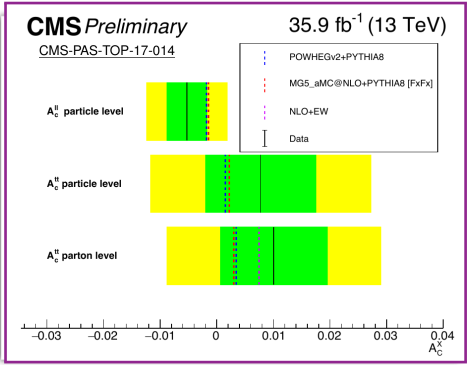

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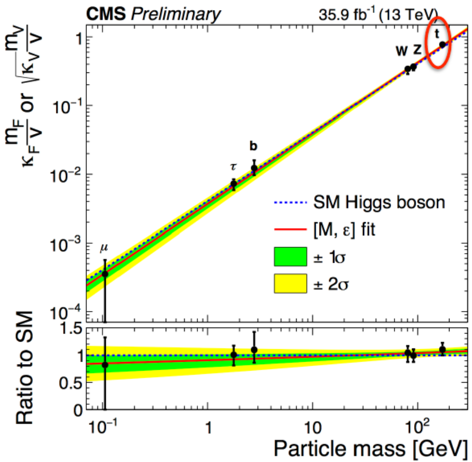
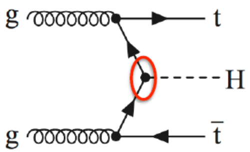
Coupling to top-quark

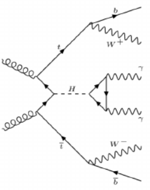


ttH production

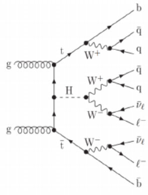


- Yukawa coupling proportional to fermion mass
  - Largest coupling to **top quarks**
  - Very sensitive to new physics!

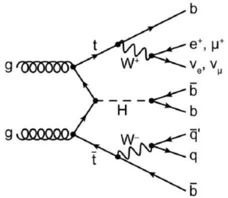
Measuring ttH production



$H \to ZZ^* \to 4\ell$
$H \to \gamma\gamma$



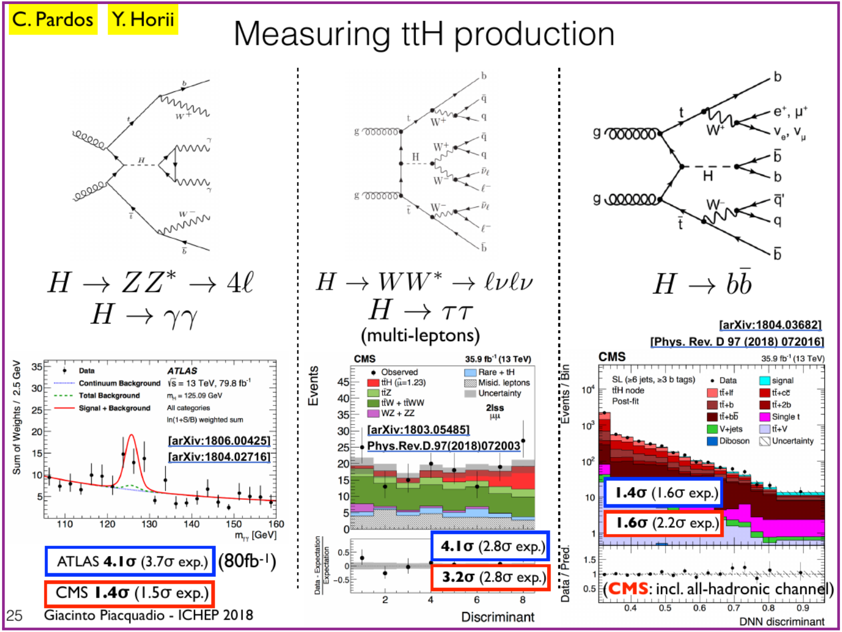
$H \to WW^* \to \ell\nu\ell\nu$
$H \to \tau\tau$
(multi-leptons)



$H \to b\bar{b}$

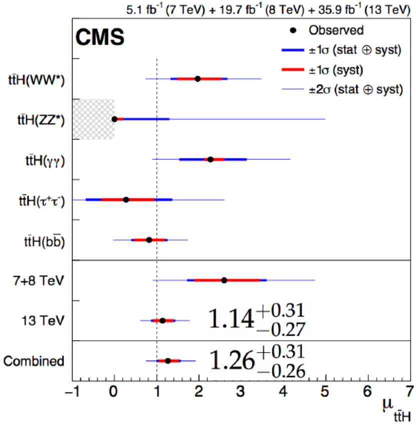
Higher purity ←

Higher σ x BR →

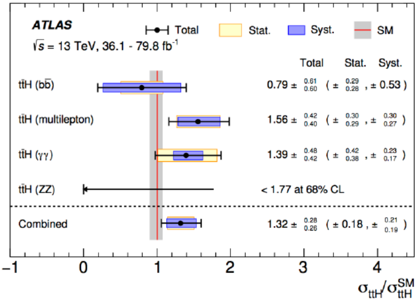

C. Pardos
Y. Horii
Measuring ttH production
$H \to ZZ^* \to 4\ell$
$H \to \gamma\gamma$
$H \to WW^* \to \ell\nu\ell\nu$
$H \to \tau\tau$
(multi-leptons)
$H \to b\bar{b}$
[arXiv:1806.00425]
[arXiv:1804.02716]
ATLAS $\sqrt{s}$ = 13 TeV, 79.8 fb^{-1}
m_H = 125.09 GeV
All categories
ln(1+S/B) weighted sum
Data
Continuum Background
Total Background
Signal + Background
Sum of Weights / 2.5 GeV
$m_{\gamma\gamma}$ [GeV]
ATLAS 4.1σ (3.7σ exp.) (80fb^{-1})
CMS 1.4σ (1.5σ exp.)
CMS 35.9 fb^{-1} (13 TeV)
Observed
ttH ($\hat{\mu}$=1.23)
ttZ
ttW + ttWW
WZ + ZZ
Rare + tH
Misid. leptons
Uncertainty
2lss μμ
[arXiv:1803.05485]
Phys.Rev.D.97(2018)072003
Events
Data - Expectation / Expectation
Discriminant
4.1σ (2.8σ exp.)
3.2σ (2.8σ exp.)
[arXiv:1804.03682]
[Phys. Rev. D 97 (2018) 072016]
CMS 35.9 fb^{-1} (13 TeV)
SL (≥6 jets, ≥3 b tags)
ttH node
Post-fit
Data
signal
tt+lf
tt+cc
tt+b
tt+2b
tt+bb
Single t
V+jets
tt+V
Diboson
Uncertainty
Events / Bin
Data / Pred.
DNN discriminant
1.4σ (1.6σ exp.)
1.6σ (2.2σ exp.)
(CMS: incl. all-hadronic channel)
25 Giacinto Piacquadio - ICHEP 2018

Combination of ttH measurements

Phys.Rev.Lett. 120 (2018) 231801



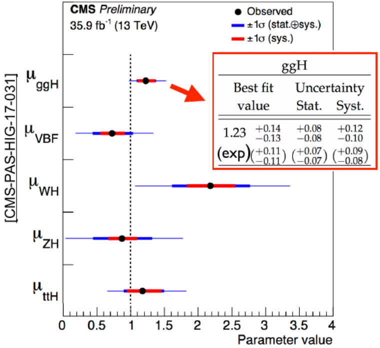
[arXiv:1806.00425]

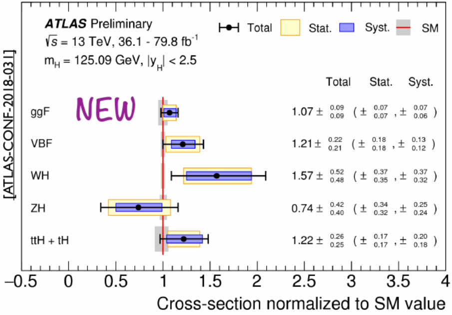


CMS
Run-1+Run-2: **5.2σ** (4.2σ exp.)

ATLAS (up to 80 fb⁻¹)
Run-2: **5.8σ** (4.9σ exp.)
Run-1+Run-2: **6.3σ** (5.1σ exp.)

Observation of ttH production!



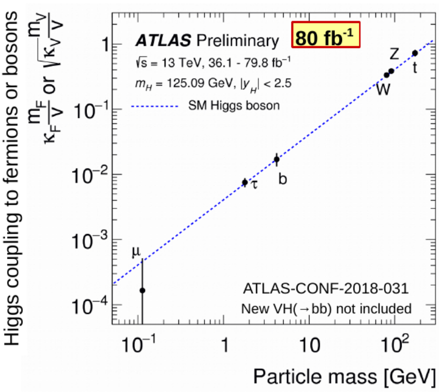


- **9-11% precision on** ggF cross section by each experiment, compatible with SM
- State-of-the-art theory prediction (N3LO QCD+NLO EW [JHEP **1605** (2016) 058]), which has **~5% uncertainty.**
- All main production modes, **ggF**, **VBF**, **VH** and **ttH** have now been observed!!

Significance obs (exp.)	**ATLAS+CMS Run-1**	**ATLAS** (single exp)
VBF	**5.4σ** (4.6σ)	**6.5σ** (5.3σ)
VH	**3.5σ** (4.2σ)	**5.3σ*** (4.8σ)
ttH	**4.4σ** (2.0σ)	**5.8σ** (5.3σ)

* including VH, H → bb (80 fb^{-1})

Key feature:
Higgs coupling depends on the particle mass



All couplings to high mass particles measured.
Next challenge: muon, charm-quark...

+ detailed cross-section measurements !

Interaction with gauge bosons:

$H \to ZZ^*$ ATLAS-CONF-2018-018
Well established in run-1

$H \to WW^*$ ATLAS-CONF-2018-004
6.3 (5.2) σ obs (exp) (run-2 only)

Yukawa coupling to fermions:

Top-quark: ttH **80 fb⁻¹**
6.3σ (5.1σ) obs (exp) arXiv:1806.00425

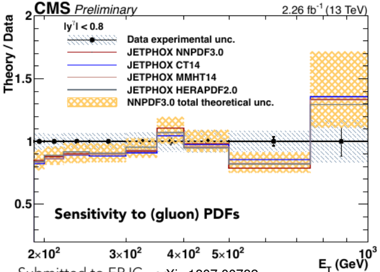
Beauty-quark $H \to bb$: **80 fb⁻¹** New
5.4σ (5.5σ) obs (exp) ATLAS-CONF-2018-036

Tau-lepton: $H \to \tau\tau$
6.4σ (5.4σ) obs (exp) ATLAS-CONF-2018-021

Muon $H \to \mu\mu$: **80 fb⁻¹** New
$\sigma_{limit}/\sigma_{SM}$<2.1 (obs) ATLAS-CONF-2018-026

Charm-quark: $H \to cc$:
$\sigma_{limit}/\sigma_{SM}$<104 (obs) PRL 120 (2018) 211802

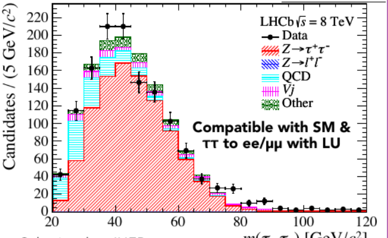
(Up to) triple differential γ(+jets)



Submitted to EPJC arXiv:1807.00782

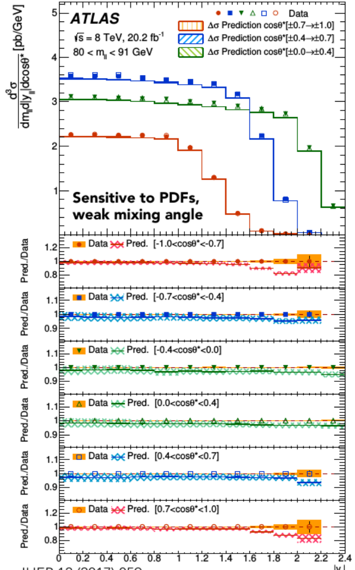
Forward $Z\to\tau^+\tau^-$

arXiv:1806.05008



Submitted to JHEP

Triple differential Drell-Yan

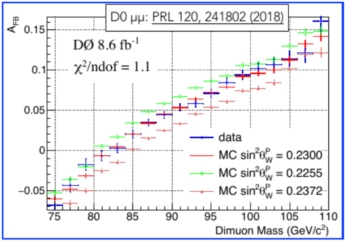


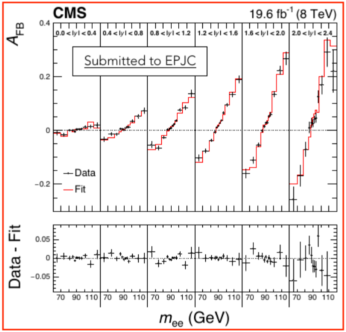
JHEP 12 (2017) 059

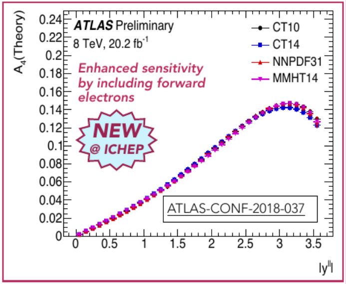
Effective leptonic weak mixing angle

$\sin^2\theta_{eff}^{lept}$ -- key SM parameter

- Exploit forward-backward asymmetry (A_{FB}) in Drell-Yan ee/μμ events
  - Fit mass (Tevatron) or mass & rapidity (CMS) dependence of observed A_{FB} to SM predictions as function of $\sin^2\theta_{eff}^{lept}$
  - Extract from angular coefficient A_4 (ATLAS) in mass/rapidity bins

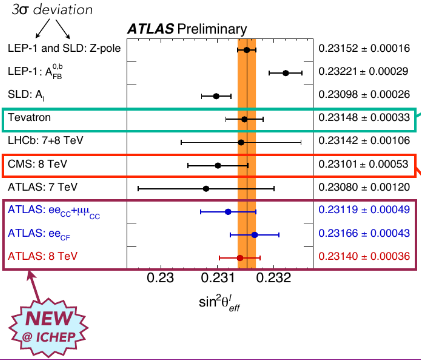


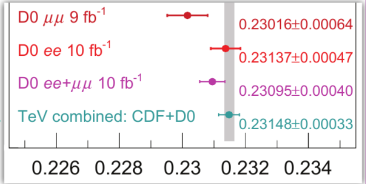


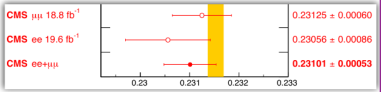


Effective leptonic weak mixing angle

CDF/D0 combination: PRD 97, 112007 (2018)
D0 μμ: PRL 120, 241802 (2018)
CMS: Submitted to EPJC
ATLAS: ATLAS-CONF-2018-037



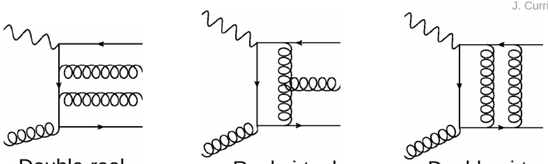




For LHC, statistics and PDF uncertainties are dominant
→ Run 2 and HL LHC data improve statistics
→ simultaneous PDF + $\sin^2\theta_{eff}$ might reduce PDF uncertainties

DIS jet production in NNLO

J. Currie, et al. [RPL 117 (2016) 042001]
J. Currie, et al. [JHEP 1707 (2017) 018]



$$\mathrm{d}\sigma^{RR,S}_{NNLO} \approx \underbrace{X(\{p_X\})}_{\text{antenna}} \overbrace{\mathrm{d}\Phi_3(\{p_X\})}^{\text{Antenna PS}} \times \underbrace{|\mathcal{M}(\{\widetilde{p_m}\})|^2}_{\text{reduced ME}} \overbrace{\mathrm{d}\Phi_m(\{\widetilde{p_m}\})}^{\text{reduced PS}} \times \underbrace{\mathcal{J}(\{\widetilde{p_m}\})}_{\text{jet function}}$$

A bit of history

- 1973 asymptotic freedom of QCD
  [PRL 30(1973) 1343 & 1346]
- 1993 NLO studies of DIS jet cross sections
  [Phys. Rev. D49 (1994) 3291]
- 2016 NNLO corrections for DIS jets
  [Phys. Rev. Lett. 117 (2016) 042001], [arXiv:1703.05977]

Antenna subtraction

- Cancellation of IR divergences with local subtraction terms
- Construction of (local) counter terms
- Move IR divergences across different phase space multiplicities

- NNLO jet predictions for ep and pp appeared recently
- Provides improved description w.r.t NLO, allows precise extraction of PDFs and α_s

Strong coupling in NNLO from jets

α_s from individual data sets

- High experimental precision
- Scale uncertainty is largest (theory) error
- All fits with good χ^2
  -> consistency of data

Main result

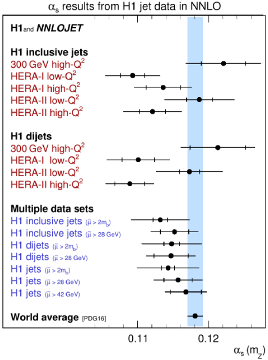
- Inclusive jets & dijets
  μ>28GeV, 91 data points

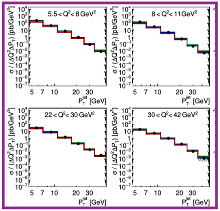
$$\alpha_s(m_Z) = 0.1157\,(20)_{\rm exp}\,(6)_{\rm had}\,(3)_{\rm PDF}\,(2)_{\rm PDF\alpha_s}\,(3)_{\rm PDFset}\,(27)_{\rm scale}$$

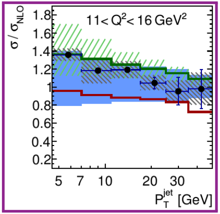
- Moderate exp. precision (due to μ>28GeV)
- Scale uncertainty dominates
- PDF uncertainties negligible

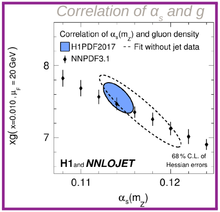
Smallest exp. uncertainty

- Fit to all data: $\Delta\alpha_s$ = $(9)_{\rm exp}$



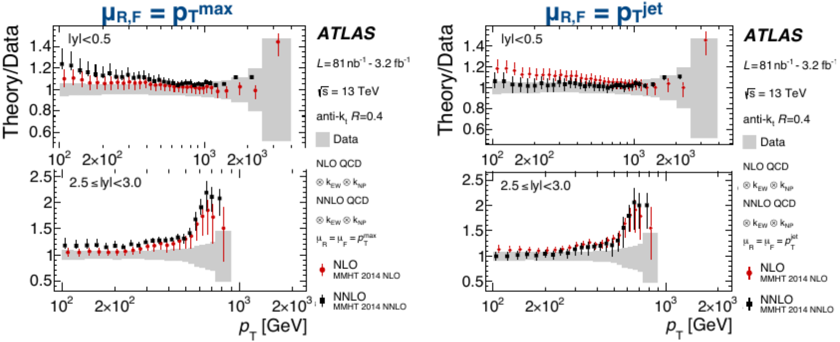






- Two new comprehensive jet measurements performed by H1 recently [EPJ C77 (2017) 215] [EPJ C75 (2015) 65]
  $\rightarrow$ *contribute to legacy HERA measurements*
- New data are confronted with NNLO predictions
  $\rightarrow$ *good agreement between data and theory*
  $\rightarrow$ *precise determination of α_s and constraints on PDFs*

- NNLOJET with MMHT2014 NNLO PDF for **two $\mu_{R,F}$ scales** (p_T^{max} & p_T^{jet})
- **Significant scale-choice dependence seen for NNLO at low-p_T**
- Possible explanation is dependence on NNLO PDF *approximations*
  - May not reflect large NNLO corrections at low-p_T
  - Still under investigation



- Seems to be more challenging than for *ep* . . .

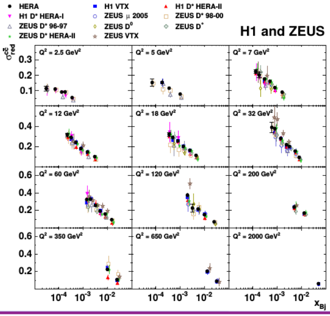
But do we really have NNLO for jets?

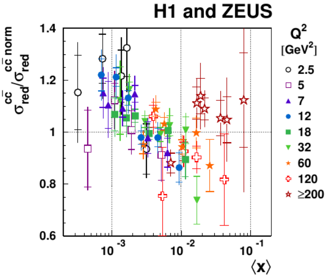
- *jets include c and b, which are not known at NNLO*
- *presently c and b are treated as massless at all scales*

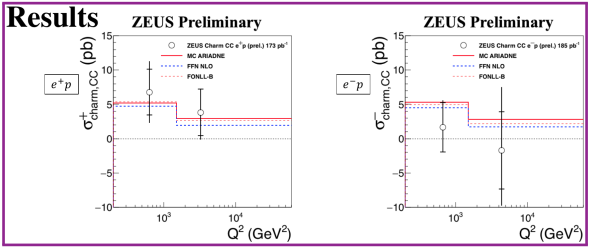
- improvement in precision w.r.t previous HERA results for charm
- first combined HERA results for beauty
- enable precise determination of charm and beauty masses
- reveal tension in describing both HF and inclusive HERA data

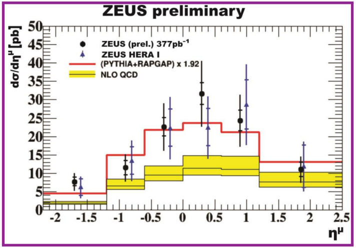
$$m_c(m_c) = 1290^{+46}_{-41}(\text{fit})^{+62}_{-14}(\text{mod})^{+3}_{-31}(\text{par})\ \text{MeV}$$

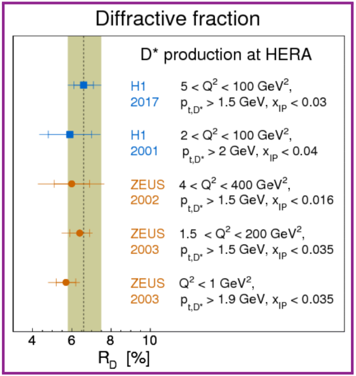
$$m_b(m_b) = 4049^{+104}_{-109}(\text{fit})^{+90}_{-32}(\text{mod})^{+1}_{-31}(\text{par})\ \text{MeV}$$











- Measurement of charm production in charged current *ep*

  → possible constraints on strangeness in proton, important for future colliders (LHeC, EIC)
- Measurement of beauty production

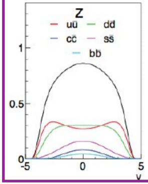
  → good agreement with NLO QCD
- Measurement of D^* in diffractive DIS

  → validates collinear factorisation in diffractive DIS

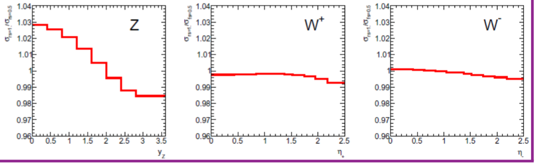
Little is known about strange sea
→ can be constrained by W,Z LHC data at NNLO

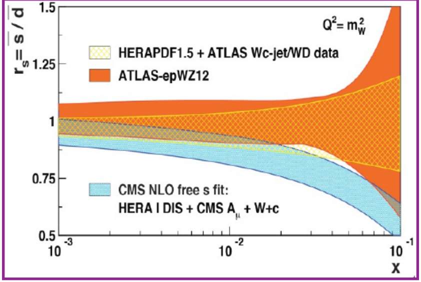
sbar(x) = 0.5 dbar(x) ⟶ sbar(x) = dbar(x)

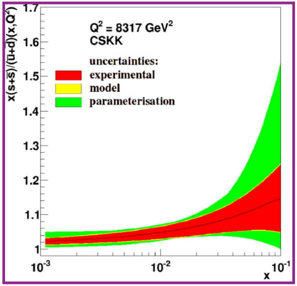
Phys.Rev. D98 (2018) 014027



small effect ~ 4%
→ can we see it?
→ yes we can!



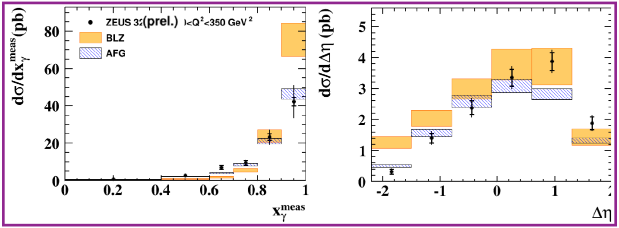


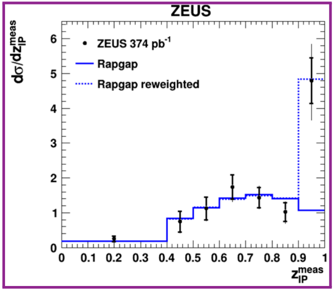


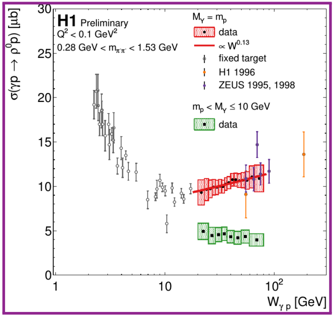
→ There is no tension between the HERA data and the LHC data or between the LHC data sets

Other new results from HERA (2)

P. Bussey, A. Bolz







- Isolated photons in DIS

  → good agreement with NLO QCD based on collinear factorisation
- Isolated photons in diffractive PHP

  → evidence for direct Pomeron interactions
- Exclusive ρ^0 in PHP

  → tests of phenomenological models in the energy gap between fixed-target and previous HERA results

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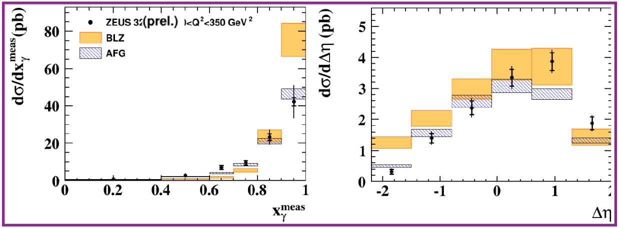

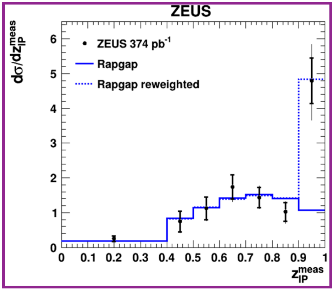

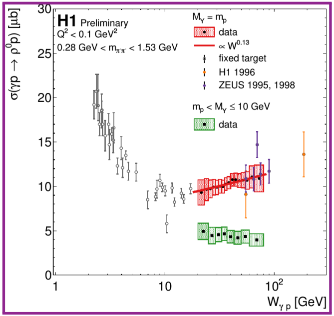

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⇒ *many new results from HERA presented at ICHEP*

Thank you for attention!

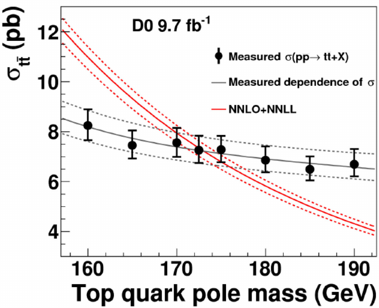
BACKUP

Top Pole Mass from Total Cross Section

- Total cross section depends on pole mass.
- Pole mass is the real part of the pole in the top-quark propagator – theoretically well defined.
- Measured cross section shows (weaker) top mass dependence due to acceptance variation.
- Use Bayesian flat prior for top mass.
- Extract pole mass (with MSTW2008):

$$m_t = 172.8 \pm 1.1\,(\text{theo.})\,^{+3.3}_{-3.1}\,(\text{exp.})\,\text{GeV}$$
$$m_t = 172.8^{+3.4}_{-3.2}\,(\text{tot.})\,\text{GeV}$$

Phys. Rev. D 94, 092004 (2016)



EW measurements: $\sin^2\theta_{eff}$ at D0

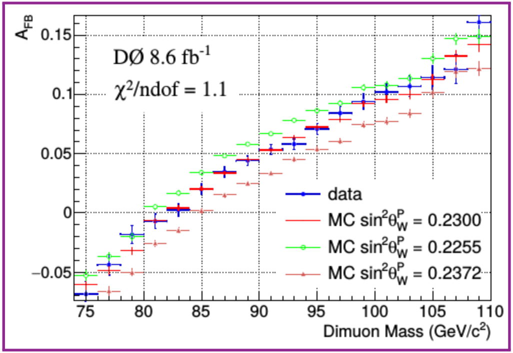
Phys.Rev.Lett. 120 (2018) 24

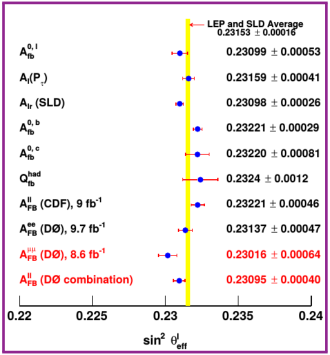
$\sin^2\theta_W^{\mathrm{p}}$	0.22994
Statistical uncertainty	0.00059
Systematic	
Momentum calibration	0.00002
Momentum smearing	0.00004
Background	0.00003
Efficiencies	0.00001
Total systematic	0.00005
PDF	0.00024
Total	0.00064

TABLE I: Measured $\sin^2\theta_W^{\mathrm{p}}$ value and corresponding uncertainties. All uncertainties are symmetric. Higher order corrections are not included.

	e^+e^- channel	$\mu^+\mu^-$ channel	Combined
$\sin^2\theta_{\mathrm{eff}}^{\ell}$	0.23137	0.23016	0.23095
Statistical	0.00043	0.00059	0.00035
Systematic	0.00009	0.00006	0.00007
PDF	0.00017	0.00024	0.00019
Total	0.00047	0.00064	0.00040

TABLE II: Combined measurement of $\sin^2\theta_{\mathrm{eff}}^{\ell}$ and breakdown of its uncertainties, together with the corresponding input values. All uncertainties are symmetric.





Channel	ee_{CC}	$\mu\mu_{CC}$	ee_{CF}	$ee_{CC}+\mu\mu_{CC}$	$ee_{CC}+\mu\mu_{CC}+ee_{CF}$
Central value	0.23148	0.23123	0.23166	0.23119	0.23140
	Uncertainties				
Total	68	59	43	49	36
Stat.	48	40	29	31	21
Syst.	48	44	32	38	29
	Uncertainties in measurements				
PDF (meas.)	8	9	7	6	4
p_T^Z modelling	0	0	7	0	5
Lepton scale	4	4	4	4	3
Lepton resolution	6	1	2	2	1
Lepton efficiency	11	3	3	2	4
Electron charge misidentification	2	0	1	1	< 1
Muon sagitta bias	0	5	0	1	2
Background	1	2	1	1	2
MC. stat.	25	22	18	16	12
	Uncertainties in predictions				
PDF (predictions)	37	35	22	33	24
QCD scales	6	8	9	5	6
EW corrections	3	3	3	3	3

	CT10	CT14	MMHT14	NNPDF31
$\sin^2\theta^\ell_{\mathrm{eff}}$	0.23118	0.23141	0.23140	0.23146
	Uncertainties in measurements			
Total	39	37	36	38
Stat.	21	21	21	21
Syst.	32	31	29	31

$$\frac{d\sigma}{dp_T^{\ell\ell}\, dy^{\ell\ell}\, dm^{\ell\ell}\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^{\ell\ell}\, dy^{\ell\ell}\, dm^{\ell\ell}} \Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big\}$$

LO:
$$\frac{d\sigma}{dy^{\ell\ell}\, dm^{\ell\ell}\, d\cos\theta} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dy^{\ell\ell}\, dm^{\ell\ell}}\Big\{(1+\cos^2\theta) + A_4\cos\theta\Big\}$$

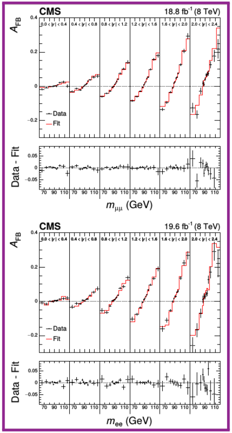


Table 2: Summary of experimental systematic uncertainties in $\sin^2\theta^{\ell}_{eff}$

Source	Muons	Electrons
Size of MC event sample	0.00015	0.00033
Lepton selection efficiency	0.00005	0.00004
Lepton momentum calibration	0.00008	0.00019
Background subtraction	0.00003	0.00005
Modeling of pileup	0.00003	0.00002
Total	0.00018	0.00039

Channel	Not constraining PDFs	Constraining PDFs
Muons	0.23125 ± 0.00054	0.23125 ± 0.00032
Electrons	0.23054 ± 0.00064	0.23056 ± 0.00045
Combined	0.23102 ± 0.00057	0.23101 ± 0.00030

Modeling parameter	Muons	Electrons
Dilepton p_T reweighting	0.00003	0.00003
μ_R and μ_F scales	0.00011	0.00013
POWHEG MINLO Z+j *vs.* Z at NLO	0.00009	0.00009
FSR model (PHOTOS *vs.* PYTHIA 8)	0.00003	0.00005
Underlying event	0.00003	0.00004
Electroweak $\sin^2\theta^{\ell}_{eff}$ *vs.* $\sin^2\theta^{u,d}_{eff}$	0.00001	0.00001
Total	0.00015	0.00017

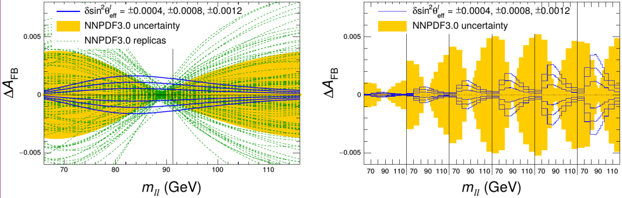
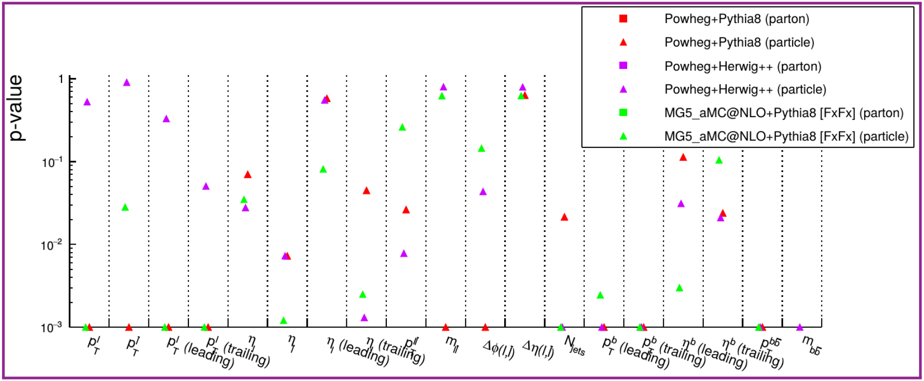


Table 3: The χ^2/ndof and p values quantifying the agreement between theoretical predictions and data for normalised, particle-level measurements are shown.

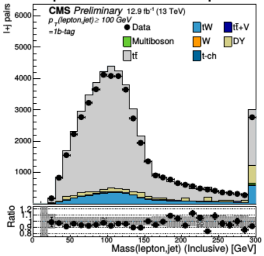
	POWHEG+PYTHIA8		POWHEG+HERWIG++		MG5_aMC@NLO+PYTHIA8	
	χ^2/ndof	p-val.	χ^2/ndof	p-val.	χ^2/ndof	p-val.
...						
$\Delta\phi(l,\bar{l})$	35/9	$< 10^{-3}$	17/9	0.044	13/9	0.146



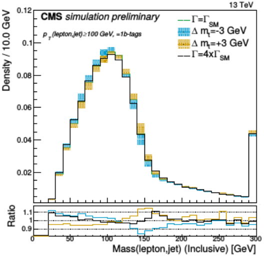
Top quark width at 13 TeV [CMS-PAS-TOP-16-019]

- **Hypotheses tested:**

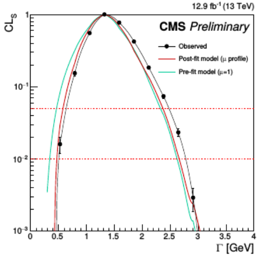
compare the SM expectation for different width scenarios to data



Data to templates with $\Gamma_{t,SM}$ vs $4 \cdot \Gamma_{t,SM}$



hypotheses separation measured via CL_s criterion



$0.6 < \Gamma_t < 2.5$ GeV at 95% CL,
expected bounds at 95% CL:
$0.6 < \Gamma_t < 2.4$ GeV

⇒ the most precise direct bound of the top quark width performed to date!

⇒ systematically limited by MC modeling