Associated production of vector bosons and heavy-flavour quarks at the LHC

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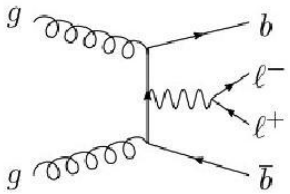
On behalf of the ATLAS and CMS collaborations

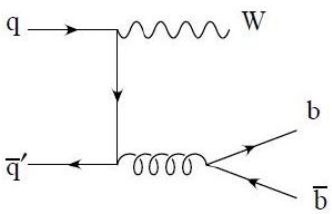
04/09/2013, QCD@LHC2013 - DESY

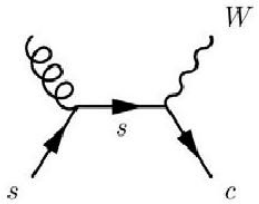
Motivations

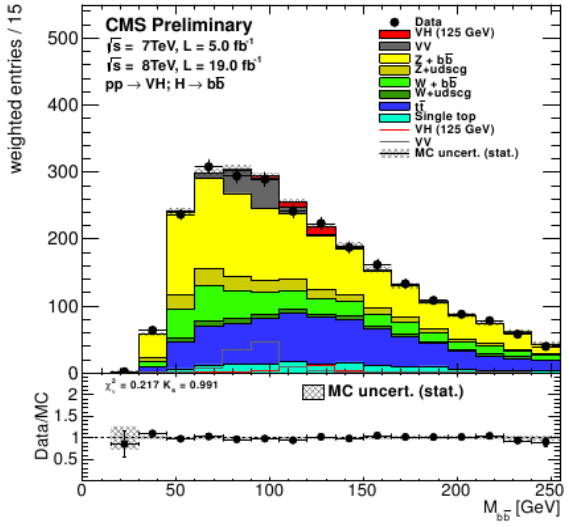
A test of perturbative QCD

- W+c: access to the strange-quark content of the proton ⇒ Improve PDF knowledge ⇒ essential to W mass measurement.
- W/Z+b$\bar{b}$: test of different b$\bar{b}$ production modes ⇒ Effect of the mass of the b quark on the production mechanisms ⇒ Resolve outstanding data-theory discrepancies.









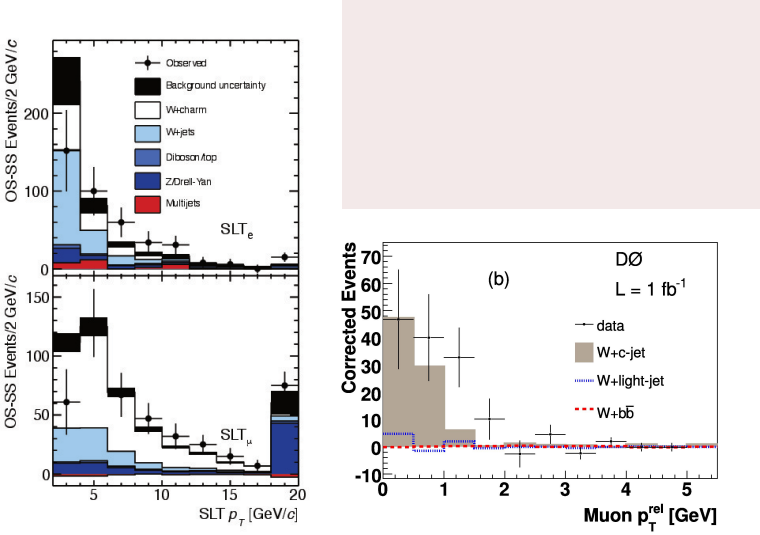
Benchmark and backgrounds to Higgs and New Physics

- Test of theoretical predictions.
- Main irreducible backgrounds in many channels.
- Sources of systematic uncertainties, e.g. for pp→VH, H→ b$\bar{b}$.

The measurements done in the past

W+charm

- CDF W+c Phys.Rev.Lett 110, 071801 (2013), 4.3 fb^{-1}
- D0 W+c Phys. Lett. B 666, 23 (2008), 1.0 fb^{-1}
- Both: good agreement with theoretical predictions, but statistically limited.

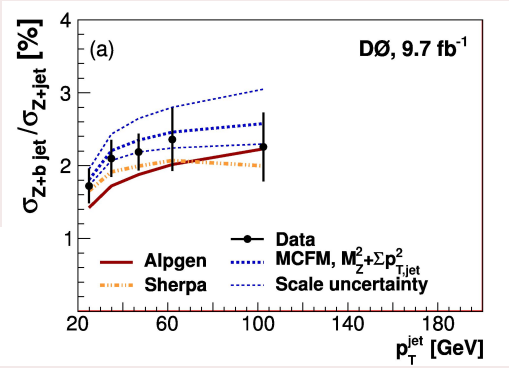


W/Z+b$\bar{b}$

- CDF W+b Phys. Rev. Lett. 104, 131801 (2010), 1.9 fb^{-1}
- D0 W+b Phys. Lett. B 718, 1314 (2013), 6.1 fb^{-1}
- CDF Z+b note 10594, 9.1 fb^{-1}
- D0 Z+b Phys. Rev. D 87, 092010 (2013) 9.7 fb^{-1}

CDF Data: $\frac{\sigma_{Z+bjet}}{\sigma_{Zjet}} = 2.08 \pm 0.18^{stat} \pm 0.27^{syst}\%$

MCFM	NLO $Q^2 = m_Z^2 + p_{T,Z}^2$	NLO $Q^2 =< p_{T,jet} >$
$\frac{\sigma(Z+b)}{\sigma(Z+jet)}$	1.8×10^{-2}	2.2×10^{-2}



W+b$\bar{b}$: history of disagreements with theory

DØ $\sigma_{W+b} \times \mathcal{BR}(W \to l\nu)$ with 6 fb^{-1}

Phys.Lett. B718 (2013) 1314-1320

Data	$1.05 \pm 0.03(stat) \pm 0.12(syst)$ pb
NLO MCFM	$1.34^{+0.41}_{-0.34}$ pb
SHERPA	1.21 pb
MADGRAPH	1.54 pb

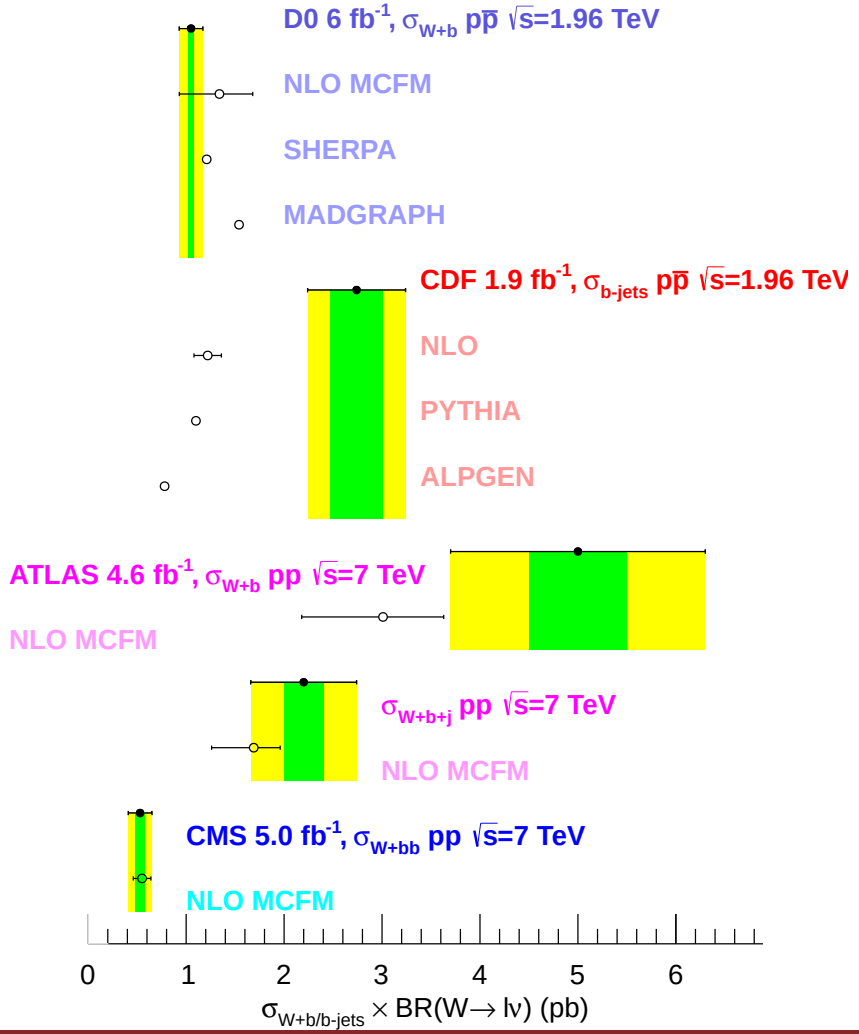
CDF $\sigma_{b-jets} \times \mathcal{BR}(W \to l\nu)$ with 1.9 fb^{-1}

Phys. Rev. Lett. 104, 131801 (2010)

Data	$2.74 \pm 0.27(stat) \pm 0.42(syst)$ pb
NLO	1.22 ± 0.14 pb
PYTHIA	1.10 pb
ALPGEN	0.78 pb

NLO=Campbell-Cordero-Reina

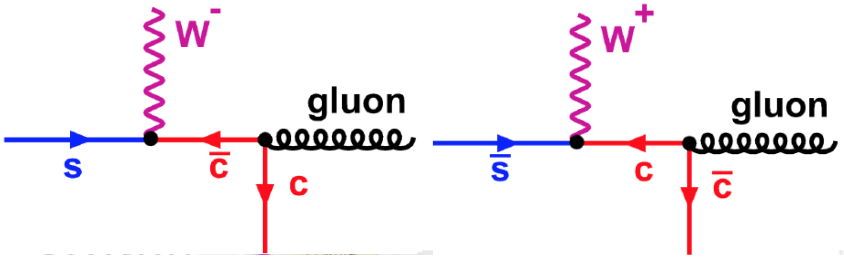
All measurements are particle level, within detector fiducial regions.



The newest and greatest results at the LHC

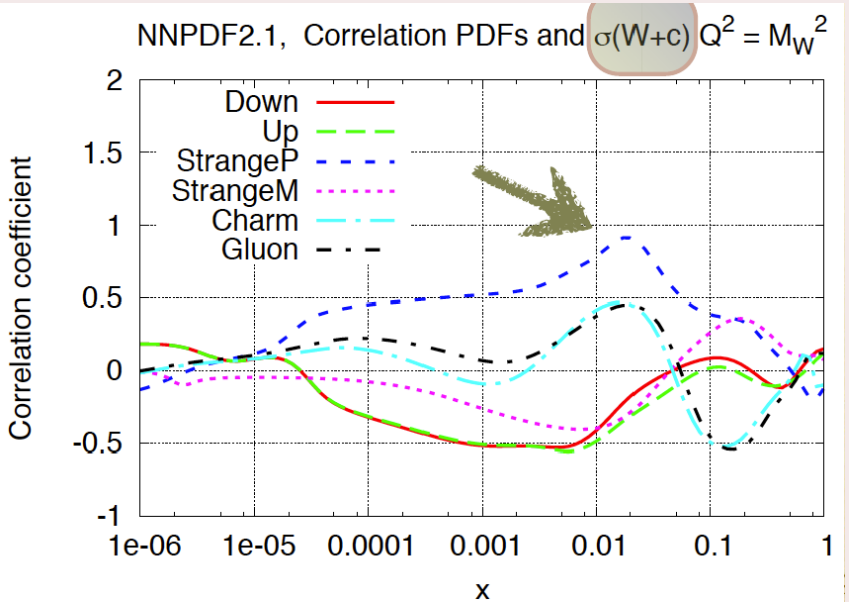
Measurement	ATLAS $\sqrt{s} = 7$ TeV	CMS $\sqrt{s} = 7$ TeV
W+c	CONF-2013-045	PAS-SMP-12-002
L	4.6 fb^{-1}	5.0 fb^{-1}
Total XS	YES	YES
Diff XS	YES	YES
Z+$b\bar{b}$	PLB **706** (2012) 295	JHEP **06** (2012) 126, PAS-SMP-13-004, PAS-EWK-11-015
L	36 pb^{-1}	2.0, 5.0 and 5.0 fb^{-1}
N_{jets}	>=1	>=1, >=1, -
$N_{b\text{-tagged jets}}$	>=1	>=1, 1 and >=2, -
$N_{B\text{-hadrons}}$	-	-, -, 2
Total XS	YES	YES, YES, YES
Diff XS	NO	NO, NO, YES
W+$b\bar{b}$	JHEP **06** (2013) 084	PAS-SMP-12-026
L	4.6 fb^{-1}	5.0 fb^{-1}
N_{jets}	1,>=1,>=2	2
$N_{b\text{-tagged jets}}$	1	2
Total XS	YES	YES
Diff XS	YES	NO

W+charm: a test of the strange-quark content of the proton



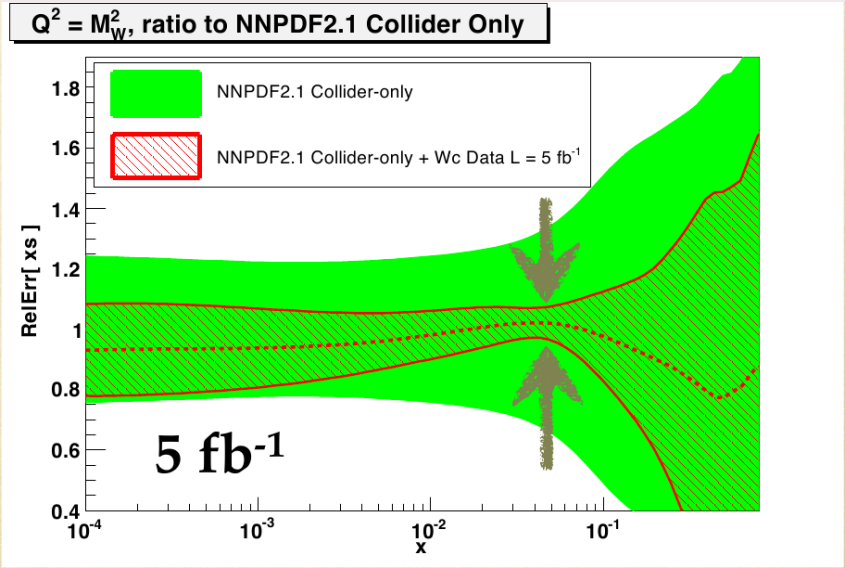
- Signature: a W($\rightarrow l\nu$) and a charm quark with opposite-sign charges
- Variables of interest: $\sigma(W+c)$, $\frac{\sigma(W^+ + \bar{c})}{\sigma(W^- + c)}$, $\frac{d\sigma(W+c)}{d\eta^l}$.

Sensitivity of PDF to σ(W+c)



Courtesy of Juan Rojo (CERN)

Predicted impact on PDF uncertainties

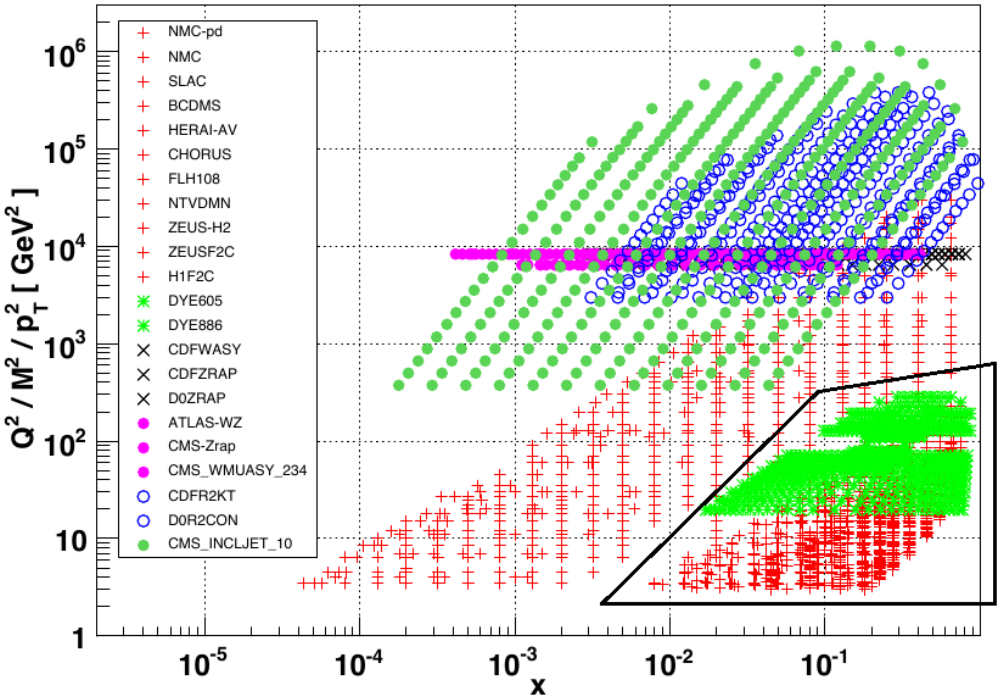


Courtesy of Juan Rojo (CERN)

https://indico.cern.ch/getFile.py/access?contribId=10&resId=0&materialId=slides&confId=145744

PDFs and the strange-quark content of the proton

- Different PDFs implement different strange-quark fractions.
- MSTW2008 and NNPDF2.3: s $<<$ d for all x.
- CT10: s $<$ d for all x.
- epWZ: s$\simeq$d at x$=$ 0.01.
- NNPDF2.3coll: input only from Hera/Tevatron/LHC, s $>$ d for all x.
- Neutrino DIS data from NuTeV: favour strange-antistrange asymmetry. Implemented in NNPDF23.



Excluded in collider-only PDF set

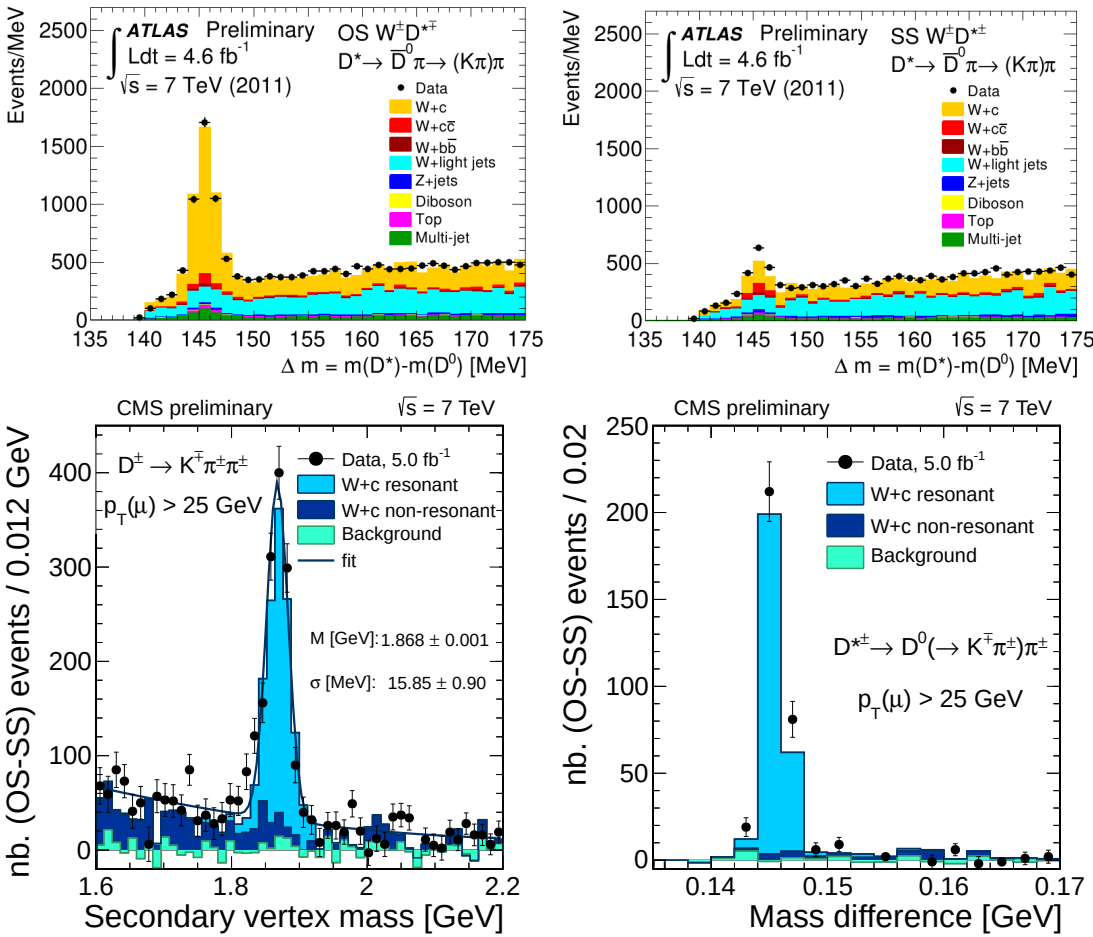
The experimental method

- $W \rightarrow l\nu$: single isolated high-p_T lepton (e or μ) $\Rightarrow$ Trigger.
- Charm tagging of jets $\Rightarrow$ very difficult experimentally: b-quark contamination, large systematic uncertainties, no easy access to jet charge.

- Winning strategy: reconstruct charm-decay resonances:

Decay chain	BR
$c/\bar{c} \rightarrow D^{\pm} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}$	$2.08 \pm 0.10\,\%$
$c/\bar{c} \rightarrow D^{\star\pm}(2010) \rightarrow D^0\pi^{\pm}$	$17 \pm 1\,\%$
$D^0 \rightarrow K^{\mp}\pi^{\pm}$	$3.88 \pm 0.05\,\%$
$D^0 \rightarrow K^{\mp}\pi^{\pm}\pi^0$	$13.9 \pm 0.05\,\%$
$D^0 \rightarrow K^{\mp}\pi^{\pm}\pi^{\mp}\pi^{\pm}$	$8.1 \pm 0.2\,\%$
$c/\bar{c} \rightarrow \mu\nu + X$	$9.1 \pm 0.5\,\%$

- In practice: displaced secondary vertex with 2 or 3 tracks and mass constraints, or a soft muon.
- In CMS only, use SV inside a jet.
- b jets: higher track multiplicity.



Systematics and theoretical predictions

ATLAS CONF-2013-045

Source	Systematic uncertainty	
	$\sigma(W^{\pm}D^{\mp})/\sigma(W^{\pm})$	$\sigma(W^{\pm}D^{*\mp})/\sigma(W^{\pm})$
Tracking efficiency	6.5%	6.8%
Secondary vertex reconstruction	0.4%	0.4%
D^{*+} isolation	–	2%
Lepton trigger, reconstruction and identification	1.1%	1.1%
Jet veto	2%	2%
W yields	1.4%	1.4%
Background in $W^{\pm}D^{(*)\mp}$ events	0.5%	0.4%
Fitting procedure	0.8%	1%
Correction for detector effects	1.1%	0.9%
D/D^{*} relative branching fractions	2.1%	2.2%
Electron fiducial extrapolation	0.6%	0.6%
Total	7.4%	8.0%

Source	Systematic uncertainty	
	$\sigma(W^{\pm}D^{\mp})$	$\sigma(W^{\pm}D^{*\mp})$
Ratio measurement $\sigma(W^{\pm}D^{(*)\mp})/\sigma(W^{\pm})$	7.4%	8.0%
Lepton trigger, reconstruction and identification	1.7%	1.7%
Lepton $E(p)$ resolution	< 0.1%	< 0.1%
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.4%	0.4%
Extrapolation (Theory)	0.7%	0.7%
Luminosity	1.8%	1.8%
Total	7.8%	8.4%

TOTAL = ~8%

- Detector level: Alpgen+Herwig+Jimmy, Pythia 6 with EvtGen.
- xs predictions: **hadron-level aMC@NLO+Herwig++**, with different PDF sets.

CMS PAS-SMP-12-002

Source	$p_{\mathrm{T}}^{\mu} > 25$ GeV $\Delta_{\mathrm{syst}}[\%]$	$p_{\mathrm{T}}^{\ell} > 35$ GeV $\Delta_{\mathrm{syst}}[\%]$
MC statistics	1.6	1.3
Lepton efficiency, resolution	0.8	1.5
Muon efficiency in charm decay	1.4	1.5
Vertex reconstruction	1.8	1.7
Pileup	0.9	0.8
Jet energy scale	3.0	1.7
$\not{E}_{\mathrm{T}}$	2.0	2.0
$\mathcal{B}(\mathrm{c} \to \mathrm{D}^{\pm} \to \mathrm{K}^{\mp}\pi^{\pm}\pi^{\pm})$	1.5	1.5
$\mathcal{B}(\mathrm{c} \to \mathrm{D}^{*\pm}(2010) \to \mathrm{D}^{0} \to \mathrm{K}^{\mp}\pi^{\pm})$	0.7	0.6
$\mathcal{B}(\mathrm{c} \to \ell)$	2.6	2.7
ISR and Q^2-matching	0.2	0.2
Fragmentation function	0.8	0.6
Other theory uncertainties on $\mathcal{A}\,\epsilon$	0.8	0.7
DY background	1.4	0.9
Luminosity	2.2	2.2
Total	6.3	5.7

TOTAL= ~6%

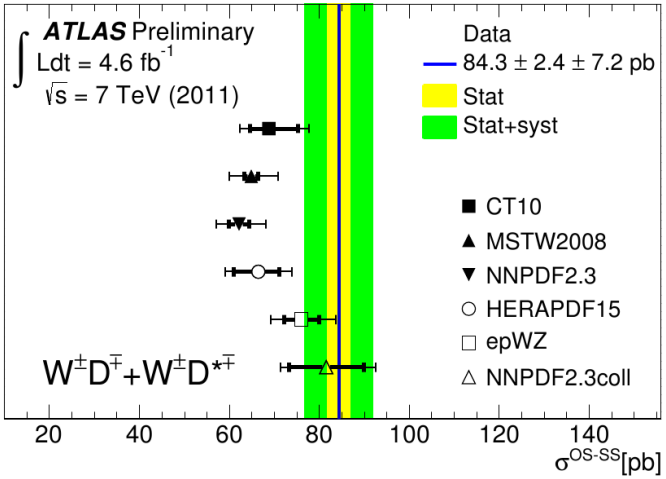
- Detector level: Madgraph+Pythia.
- xs predictions: **parton-level MCFM** with different PDF sets.

Phase space and total cross sections

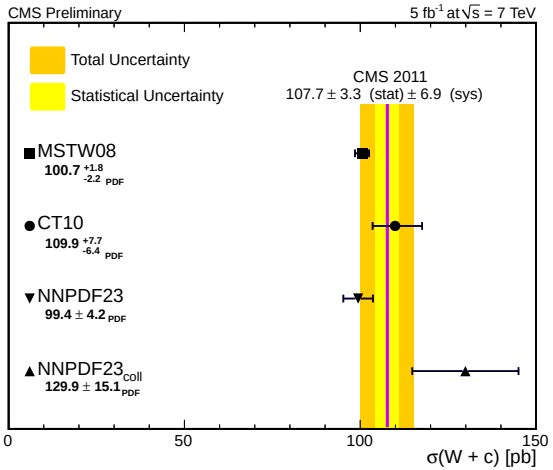
Selection	ATLAS	CMS
$p_T^\mu >$	20 GeV	25 GeV
$\lvert\eta^\mu\rvert <$	2.4	2.1
$p_T^e >$	25 GeV	35 GeV
$\lvert\eta^e\rvert <$	2.47	2.4
$E_T^{miss} >$	25 GeV	-
$m_T^W >$	40 GeV	-

N_{Jets}	< 3	$>= 1$
min p_T^{jet} (GeV)	25	25
min $\lvert\eta^{jet}\rvert$	2.5	2.5
min $p_T^{D^{(*)\pm}}$	8 GeV	-
min $\lvert\eta^{D^{(*)\pm}}\rvert$	2.2	-

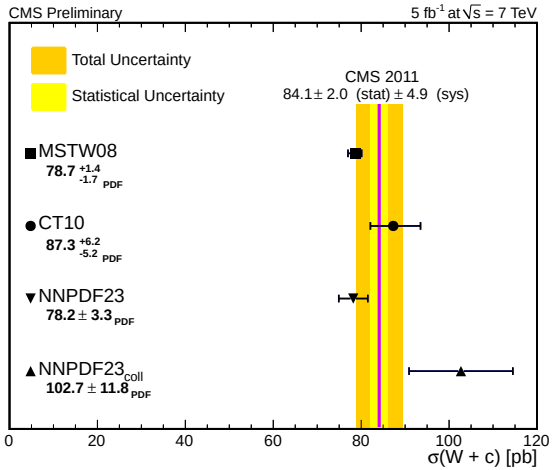
- ATLAS: probing lower D p_T, keep $D^{\star\pm}$ and $D^\pm$ separated,
- CMS: individual measurements corrected for all BR and combined.



⇒ **Different measurements compared with different theoretical predictions lead to different observations.**



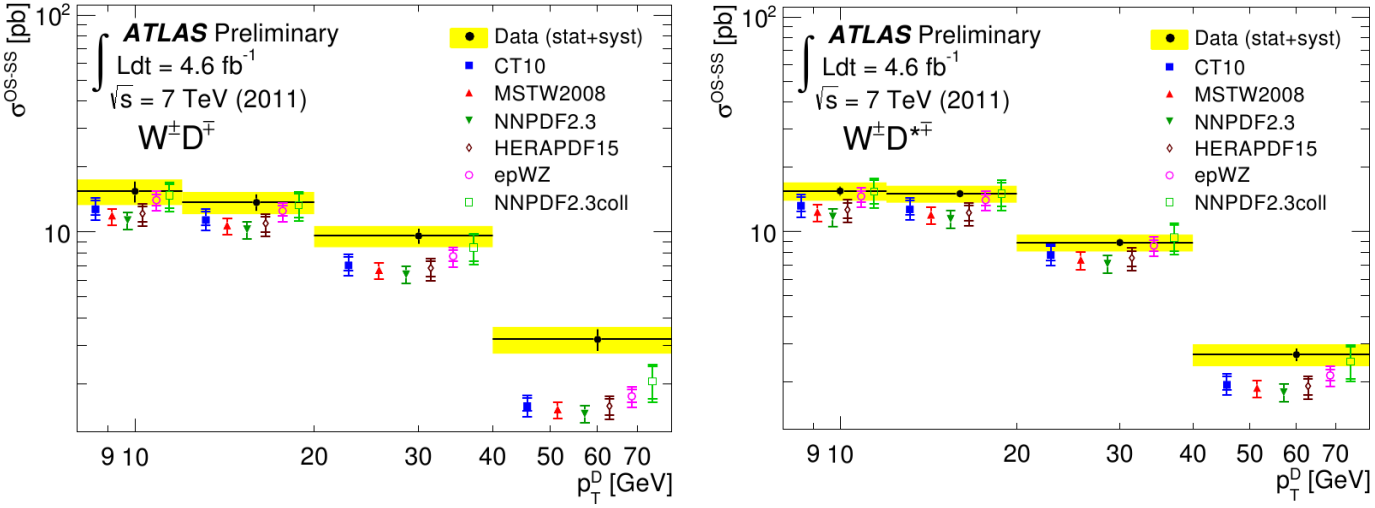
μ $p_T > 25$ GeV



l =e or μ $p_T > 35$ GeV

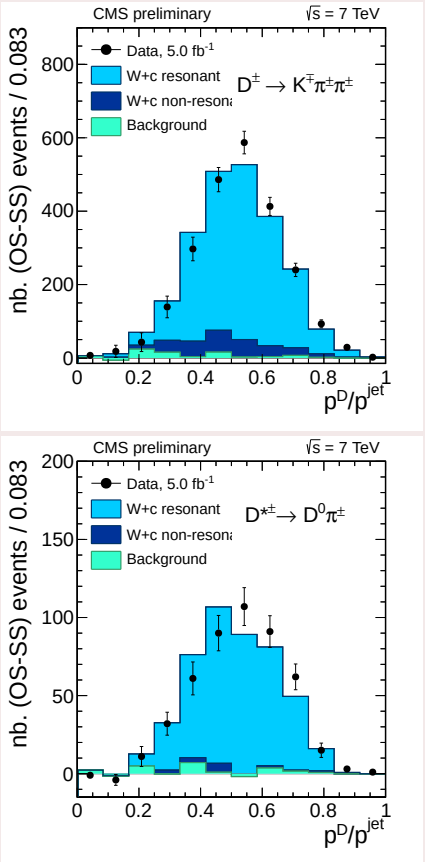
Differential cross sections vs p_T^D

ATLAS-CONF-2013-045



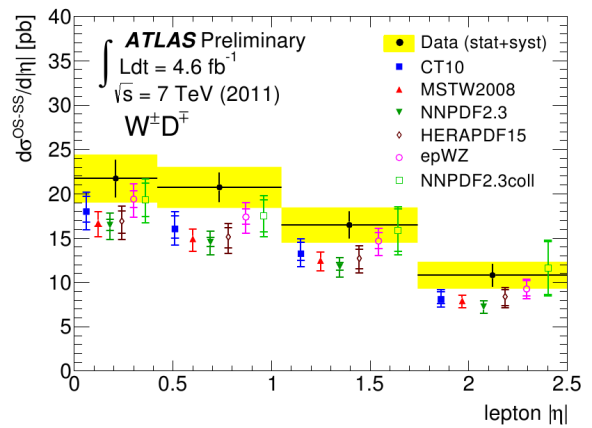
- Good agreement with epWZ and NNPDF2.3coll at low p_T^D.
- Harder $p_T^{D^\pm}$ spectrum in data compared to aMC@NLO+Herwig++ for all PDF sets ⇒ testing charm fragmentation.
- Also seen with CMS data (detector level) compared to Madgraph+Pythia.

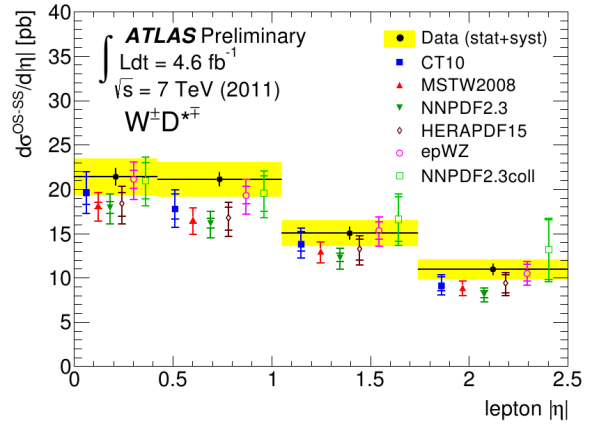
CMS (detector level)



Differential cross sections vs $|\eta'|$ for each decay mode

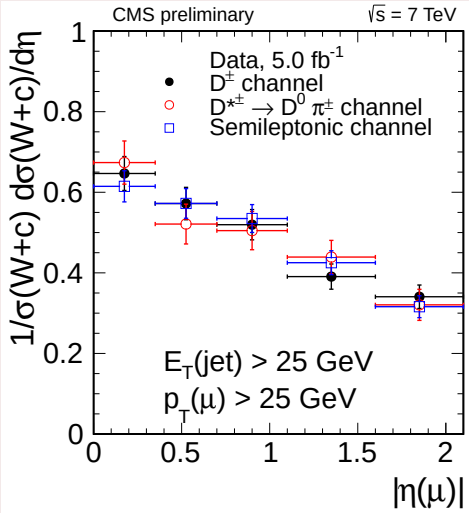
ATLAS $p_T^l > 20$ GeV

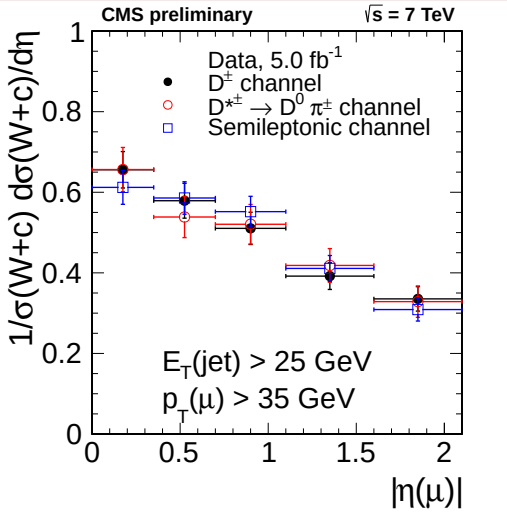


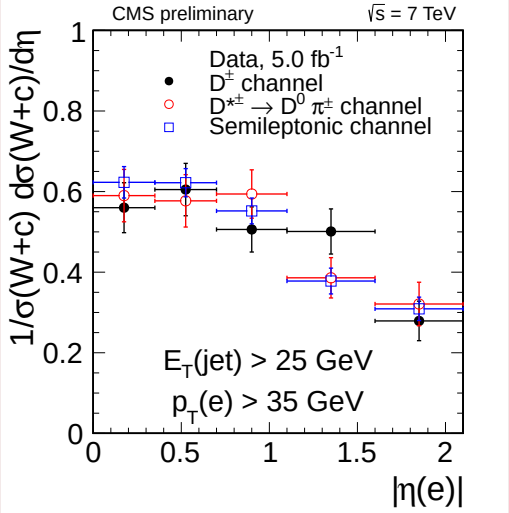


Shapes similar, data favours PDF with higher strange content.

CMS $p_T^l > 25$ and 35 GeV



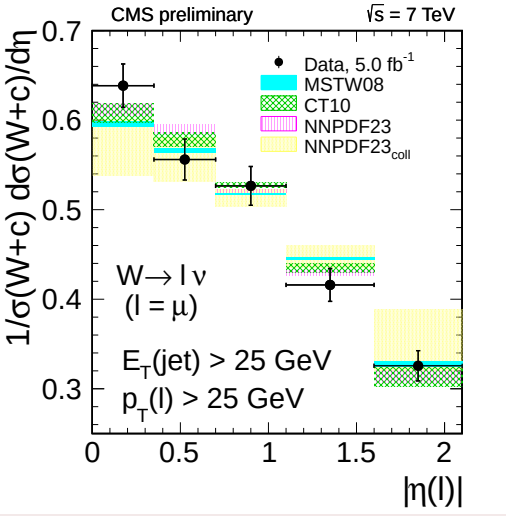


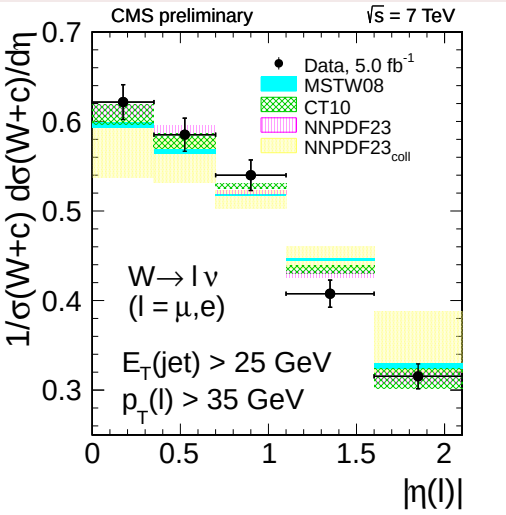


Good agreement between channels after correcting for c⟶ D-hadron BR based on PDG measurements.

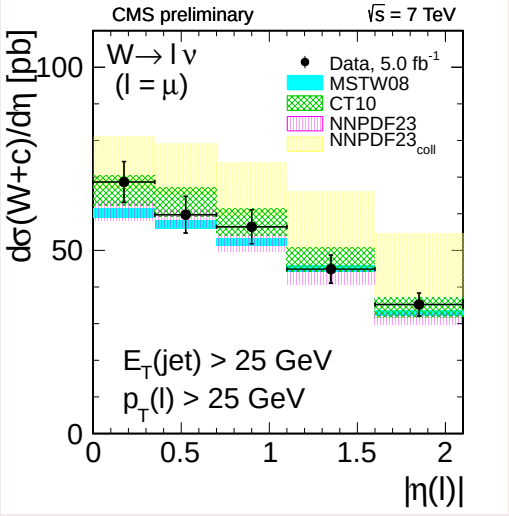
Total differential cross sections vs $|\eta^l|$ CMS-PAS-SMP-12-002

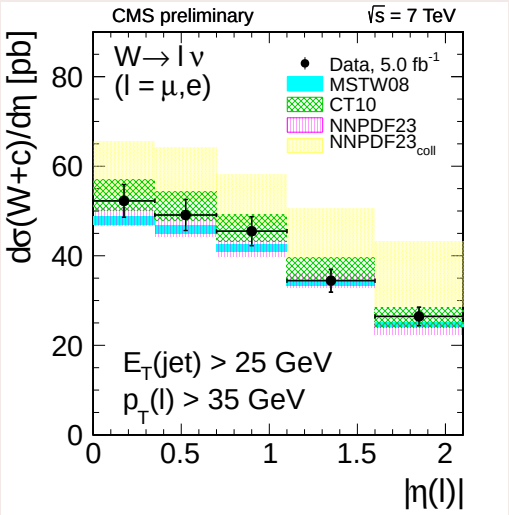
$\frac{1}{\sigma(W+c)} \times \frac{d\sigma(W+c)}{d\eta^l}$



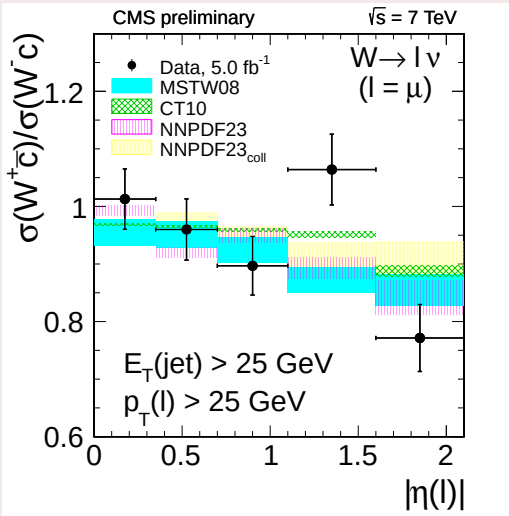


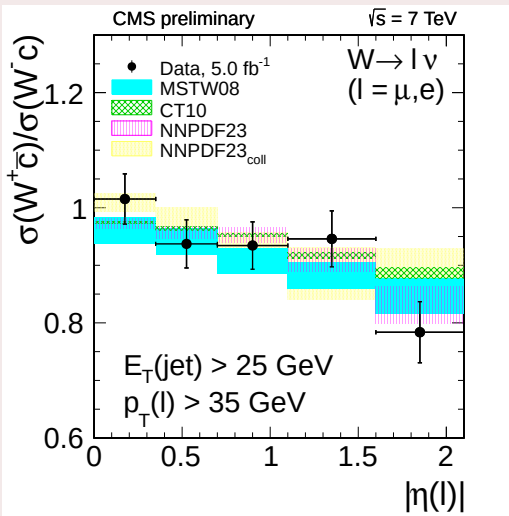
Absolute $\frac{d\sigma(W+c)}{d\eta^l}$



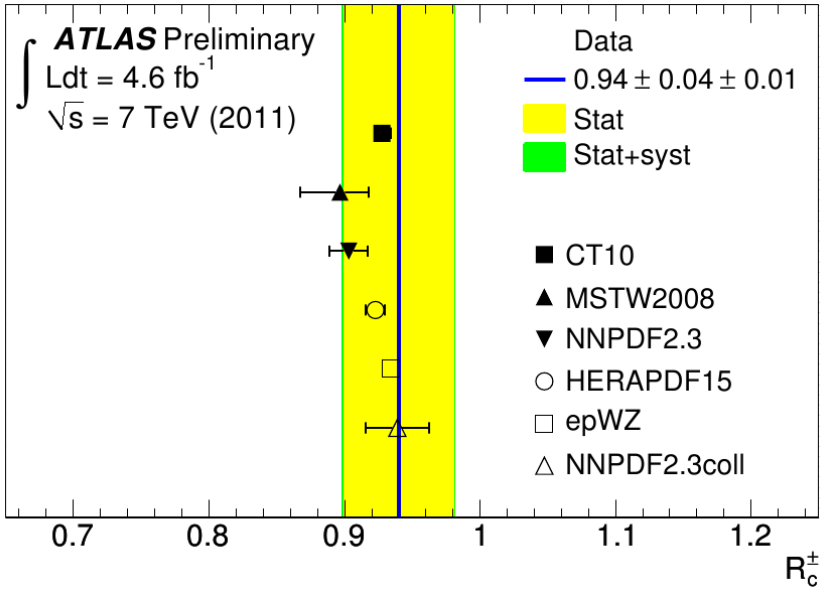


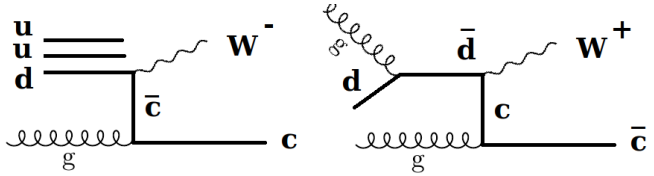
Charge ratio $\frac{\sigma(W^+ + \bar{c})}{\sigma(W^- + c)}$

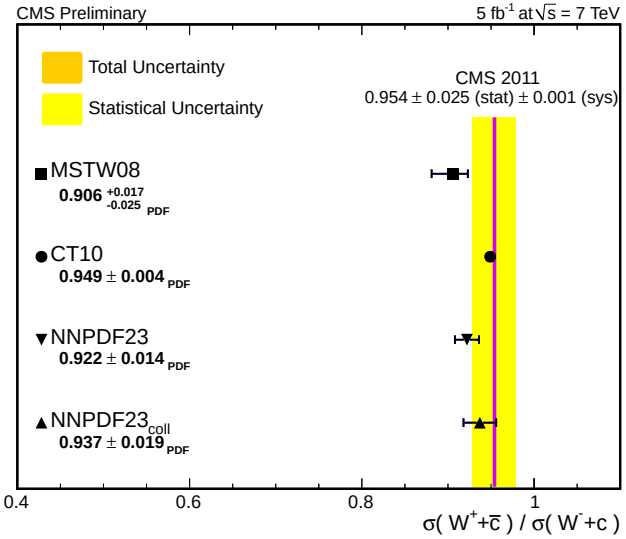


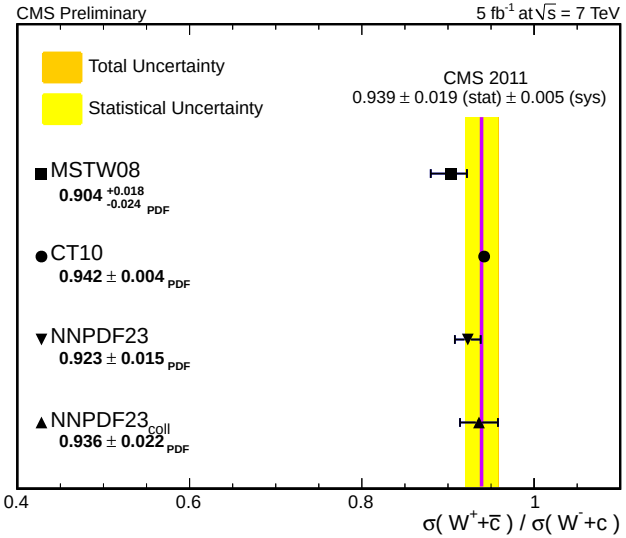


Charge ratio





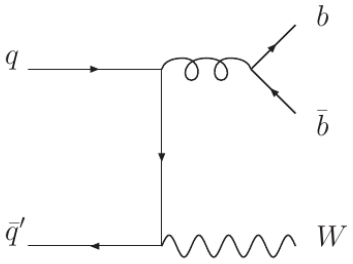


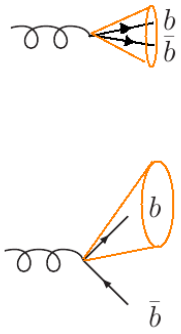


- Expected ratio just from effect of d valence quark component: 95%.
- Similar observations ATLAS/CMS: best agreement with NNPDF23coll.
- Measurements do not support asymmetry strange-antistrange.

W/Z and b quarks: a bit of theoretical considerations...

- Different topologies ⇒ different calculation tricks.
- Difficulty: resummations necessary when 1 b is soft, collinear or not to the other b.
- Large uncertainties / disagremeent with data not unexpected for the exclusive 1 b multiplicity: W+b and W+b+j cases.
- Note: experimentally, 1 b-tagget jet = 1 jet with 1 or 2 b.
- The 2 high-p_T b case is easier to calculate: better agreement expected.
- Two calculation schemes: 4FS (aka FFS) and 5FS (aka VFS).



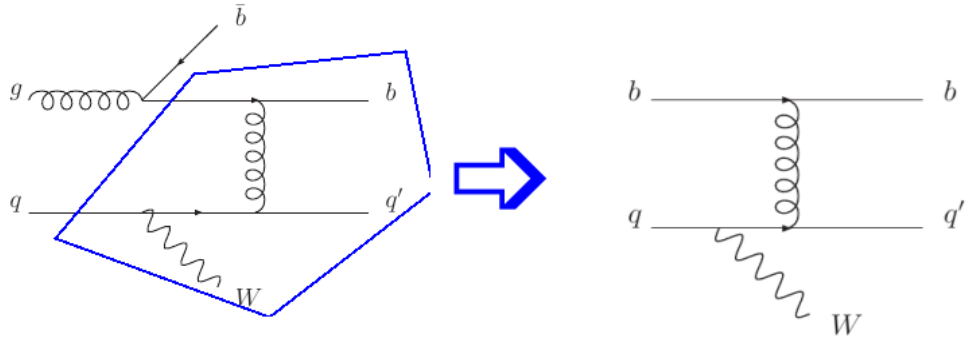


1 jet with 2 b's

1 jet with 1 b

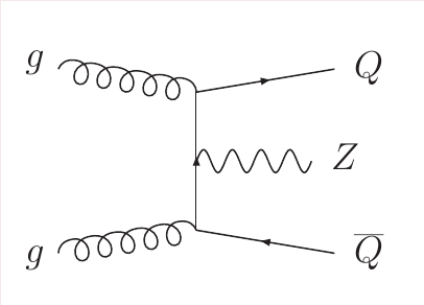
escapes

2 jets



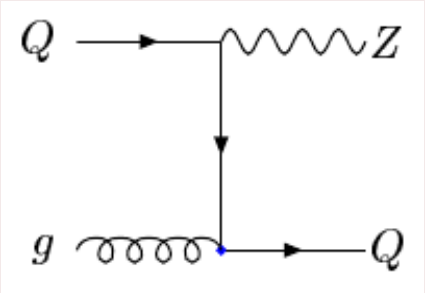
The effect of the b-quark mass

The 4-flavour scheme



- Explicit $g \to b\bar{b}$: divergences in $\alpha_S ln(\frac{m_Z}{m_b}) \Rightarrow$ keep b massive.
- 1 or 2 b observed.
- NLO: aMC@NLO.
- LO: Alpgen, Madgraph.

The 5-flavour scheme



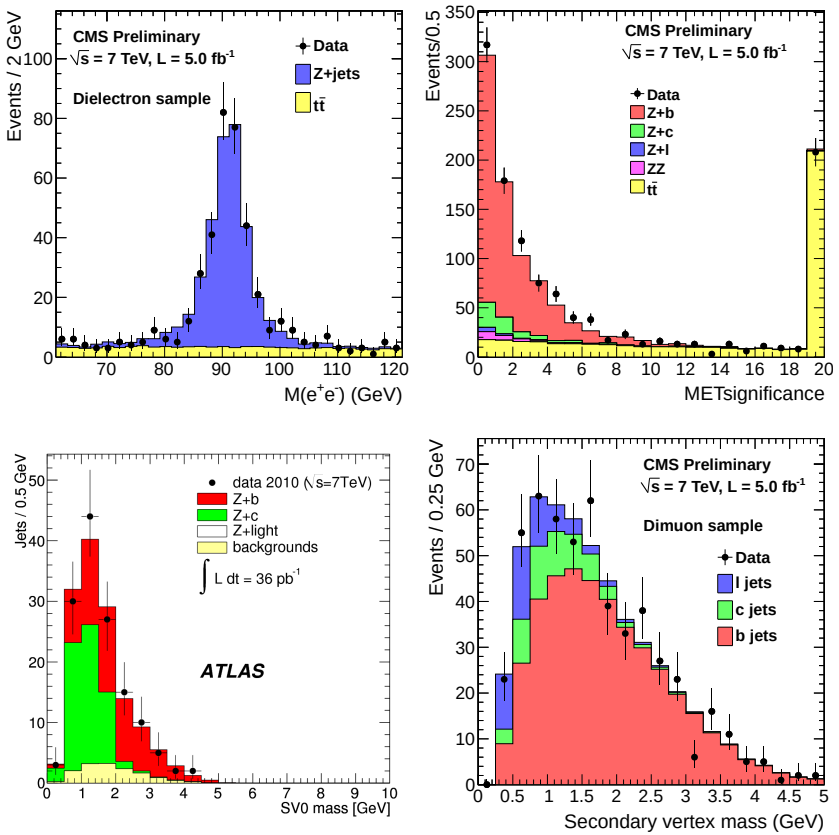
- Allow b as initial state parton: terms in α_S and $\frac{1}{ln(\frac{m_Z}{m_b})}$
- $g \to bb$ inside b-PDF, b can be kept massless.
- NLO: MCFM.
- LO: Madgraph.

Jet matching and merging of ME multiplicities

- ME vs PS: additional complication in 4F!!

Z+b(b) : Analysis strategy using b jets

- Trigger on dielectron and dimuon decays of the Z boson: two high p_T isolated leptons.
- Use b-tagging based on displaced secondary vertices.
- Main backgrounds:
  - from ttbar, estimated with template fit to the dilepton invariant mass.
  - from light and charm jets, estimated with template fit to the secondary vertex mass;
- Compare distributions at detector level with simulation.
- Correct for detector-level effects, acceptance and efficiencies to extract total cross sections at particle level.



Systematic uncertainties

CMS PAS-SMP-13-004

	$\mu\mu$ (%)		ee (%)	
	Z+1b	Z+2b	Z+1b	Z+2b
Uncorrelated				
b-purity	3.0	12.7	3.3	15.1
tt	1.7	3.8	1.7	4.8
Dilepton selection	1.0	1.0	2.0	2.0
MC statistics	0.9	4.2	1.2	5.1
Correlated				
b-tag efficiency SFs	3.6	9.0	3.6	9.0
JES	2.0	3.6	2.0	3.6
Theory	1.8	3.0	1.8	3.0
Luminosity	2.2	2.2	2.2	2.2
ZZ	0.4	1.2	0.5	1.4
JER	0.6	0.7	0.6	0.7
Pile-up	0.3	0.3	0.3	0.3
Mistag	0.0	0.1	0.0	0.1
Tot. Stat. unc.	0.9	4.5	1.0	5.4
Tot. Syst. unc.	6.3	17.4	6.7	19.8

ATLAS PLB **706** (2012) 295

Source	SV0-mass Fit (%)	Acceptance (%)
Both Electron and Muon		
b-tagging efficiency	1.7	9.1
SV0-mass templates	3.5	-
Model dependence	2.7	10.0
Jet energy scale	0.7	4.0
$t\bar{t}$ cross-section	2.0	-
MPI model	negl.	1.0
Electron only		
MC statistics	negl.	1.3
Multi-jet background	1.6	-
Electron efficiency	negl.	5.0
Total Electron	5.6	15.0
Muon only		
MC statistics	negl.	1.3
Multi-jet background	0.7	-
Muon efficiency	negl.	2.0
Total Muon	5.4	14.3
Total Systematic Uncertainty	+21% -16%	

Inclusive cross section results

ATLAS with 36 pb^{-1}, PLB **706** (2012) 295

- dressed ee or $\mu\mu$ with $p_T^l > 20$ GeV and $|\eta^l| < 2.5$, $76 < M_{ll} < 106$ GeV,
- anti-k$_T$ 0.4 jets (with neutrinos) $p_T > 25$ GeV, $|y| < 2.1$, ΔR(j,l)> 0.5, with weakly-decaying b-hadron $p_T > 5$ GeV within $\Delta R < 0.3$.

Experiment	$3.55^{+0.82}_{-0.74}$(stat)$^{+0.73}_{-0.55}$(syst) $\pm$ 0.12(lumi) pb
MCFM	3.88 ± 0.58 pb
ALPGEN	2.23 ± 0.01 (stat only) pb
SHERPA	3.29 ± 0.04 (stat only) pb

CMS with 2 fb^{-1}, JHEP **06** (2012) 126

- Inclusive with respect to lepton acceptance, $60 < M_{ll} < 120$ GeV.
- anti-k$_T$ 0.5 jets (without neutrinos) $p_T > 25$ GeV, $|\eta| < 2.1$, ΔR(j,l)> 0.5, with any b-hadron within $\Delta R < 0.5$.

Data	5.84 ± 0.08 (stat.) ± 0.72(syst.)$^{+0.25}_{-0.55}$ (theory) pb
MCFM	3.97 ± 0.47 pb

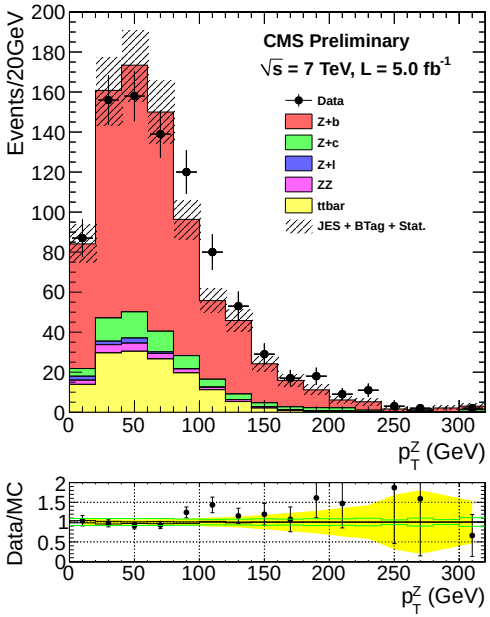
CMS with 5 fb^{-1}, PAS-SMP-13-004

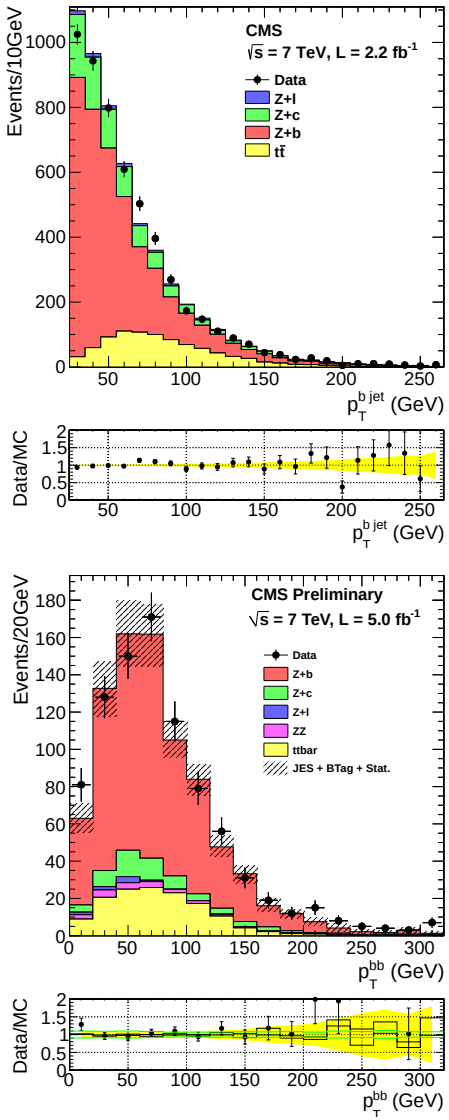
- dressed ee or $\mu\mu$ with $p_T^l > 20$ GeV and $|\eta^l| < 2.4$, $76 < M_{ll} < 106$ GeV,
- anti-k$_T$ 0.5 jets (with neutrinos) $p_T > 25$ GeV, $|\eta| < 2.1$, ΔR(j,l)> 0.5, with any b-hadron within $\Delta R < 0.5$.

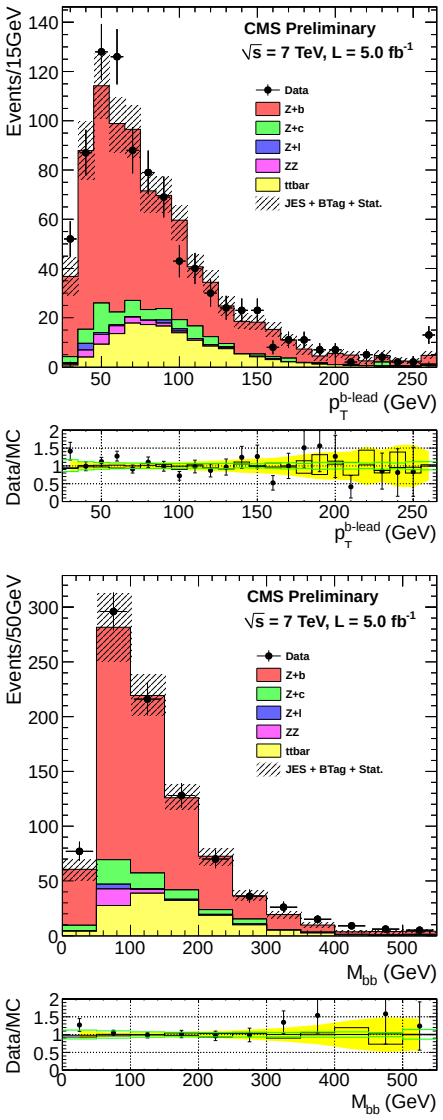
Multiplicity bin	Measured	MadGraph 5F	MadGraph 4F
σ(Z($\ell\ell$)+1b) (pb)	$3.52 \pm 0.02 \pm 0.20$	3.66 ± 0.02	3.11 ± 0.03
σ(Z($\ell\ell$)+2b) (pb)	$0.36 \pm 0.01 \pm 0.07$	0.37 ± 0.01	0.38 ± 0.01
σ(Z($\ell\ell$)+b) (pb)	$3.88 \pm 0.02 \pm 0.22$	4.03 ± 0.02	3.49 ± 0.03
σ(Z($\ell\ell$)+b)/σ(Z($\ell\ell$)+j) (%)	$5.15 \pm 0.03 \pm 0.25$	5.35 ± 0.02	4.60 ± 0.03

Data-MC comparisons at the detector level

- JHEP **06** (2012) 126 and CMS-PAS-SMP-13-004.
- Globally good description by MG 5F.
- Some tensions for pT(b), pT(Z).



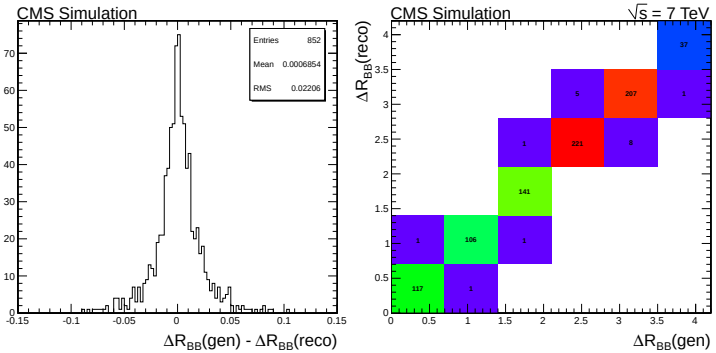




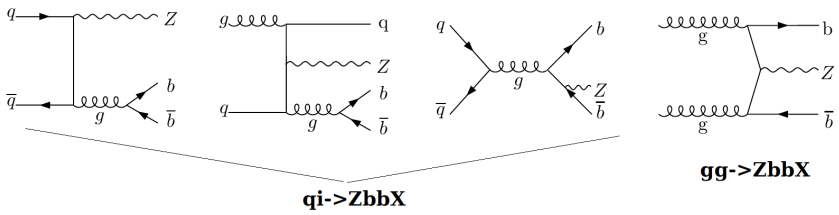
Z+BB: Analysis strategy using b-hadrons CMS-EWK-11-015

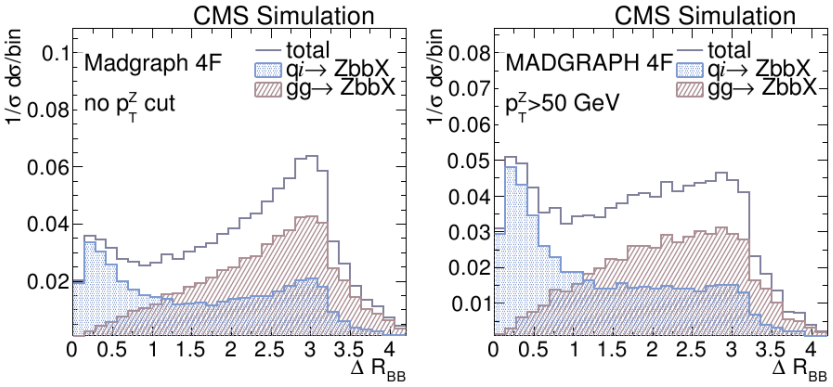
IVF: the Inclusive Vertex Finder

- Reconstruct B hadrons using tracks
- Access very small angular separation $\Delta R \simeq 0.05$.



- Trigger on dielectron and dimuon decays of the Z boson: two high p_T isolated leptons.
- Main backgrounds:
  - from ttbar, estimated with template fit to the dilepton invariant mass.
  - from charm decay contamination, estimated from MC (no data measurement available to date for Z+b$\bar{b}$ +c and Z+c$\bar{c}$).
- Correct for detector-level effects, acceptance and efficiencies to extract total and differential cross sections at particle level.
- Study angular correlation variables as a function of Z boson p_T: access to boosted regions.



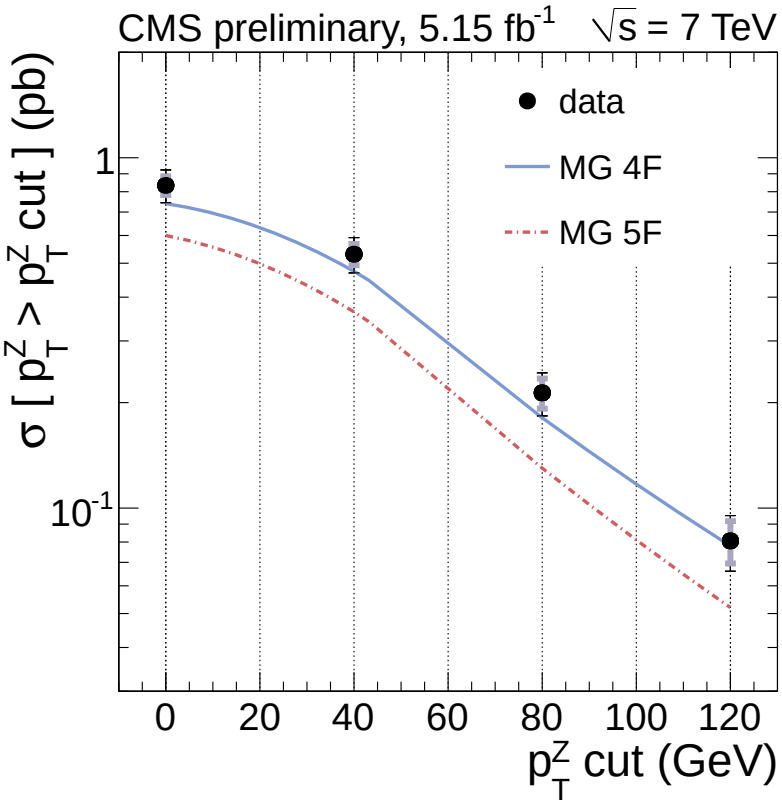


Systematics and total cross sections vs pT(Z)

Phase space

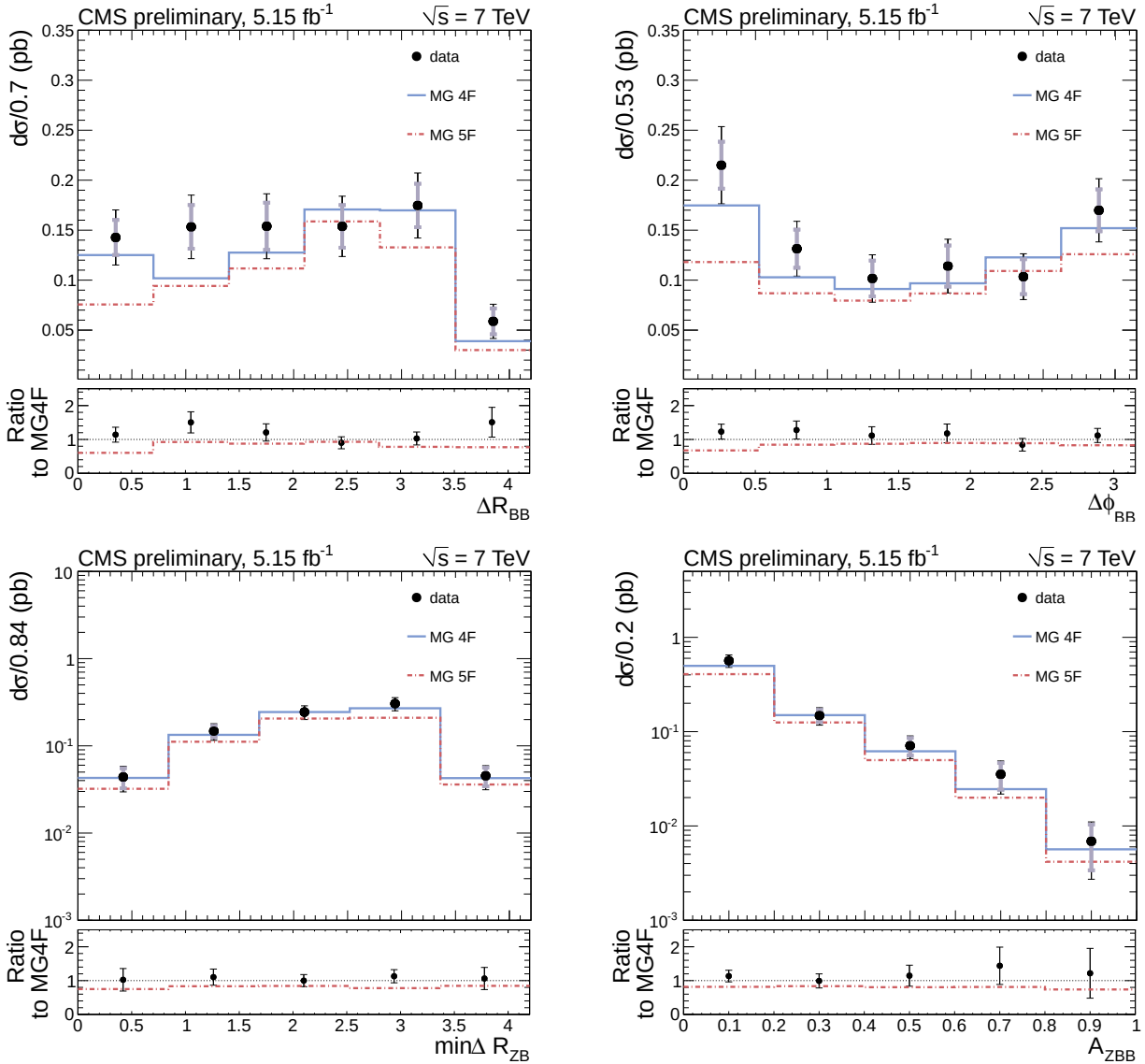
- Dressed ee or $\mu\mu$ with $p_T^l > 20$ GeV and $|\eta^l| < 2.4$, $81 < M_{ll} < 101$ GeV,
- 2 B hadrons $p_T > 15$ GeV, $|\eta| < 2.0$.

Source	Uncertainty (%)
Dilepton channel combination	± 2
IVF efficiency scale factors	± 12
B purity	± 2.1
Bin-to-bin migrations (ΔR_{BB}, minΔR_{ZB})	$\pm(1-2)$
Bin-to-bin migrations ($\Delta\phi_{BB}$, A_{ZBB})	$\pm(3-4)$
MC statistics - Differential	$\pm(2-3.7)$
MC statistics - Total	$\pm(1-3.5)$
Integrated luminosity	± 2.2



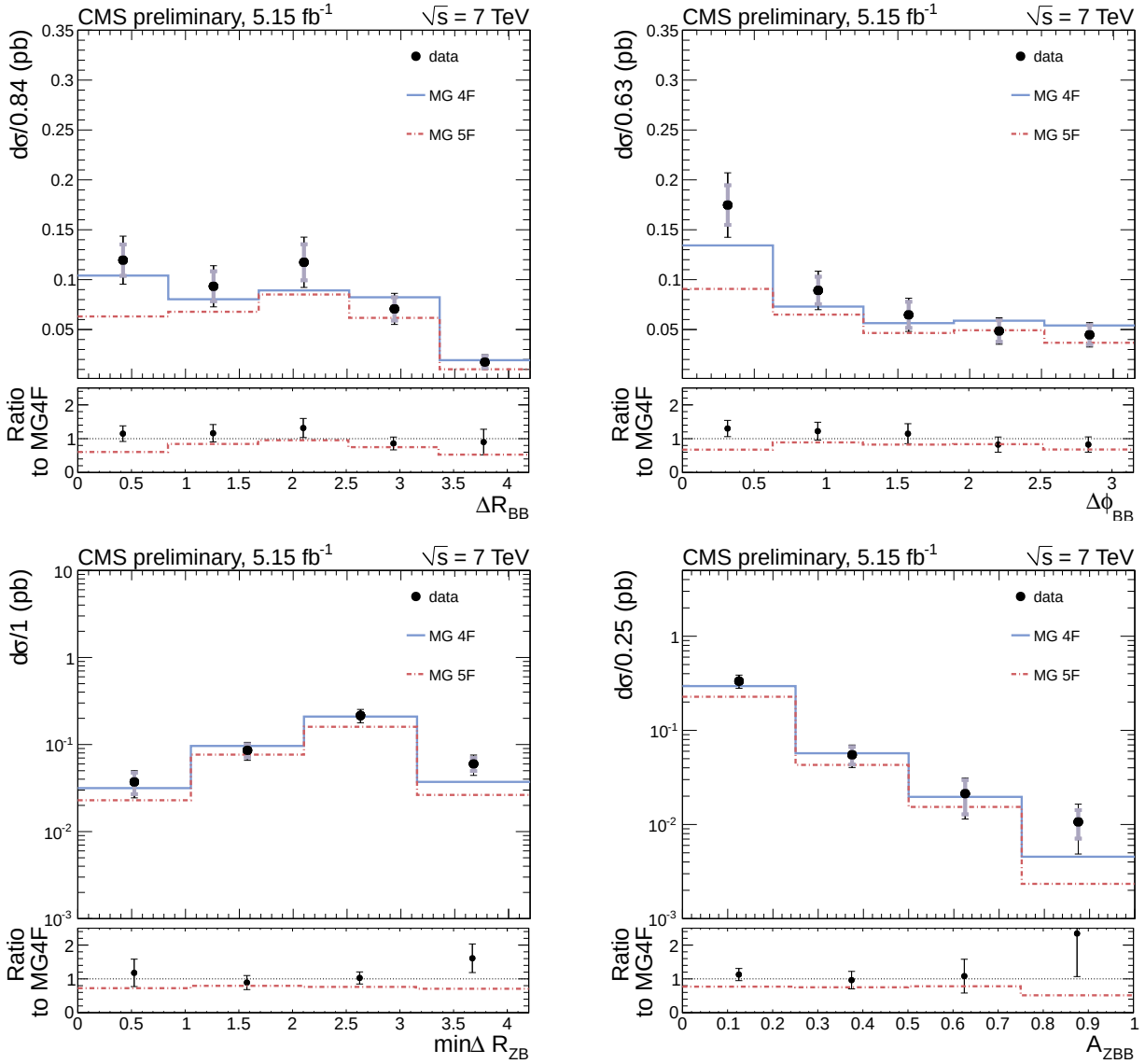
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11015
- Better agreement in shape and normalisation with MG 4F.
- 5F, normalised to inclusive NNLO Z production cross section from FEWZ, underpredict the production rate.

Differential cross sections, with no pT(Z) requirement



- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults\EWK11015
- B-B system: better description of colinear region with 4F.
- Z-B system: good description with both 4F and 5F.
- Paper coming soon: comparison to more models, better understanding of 4F generators.

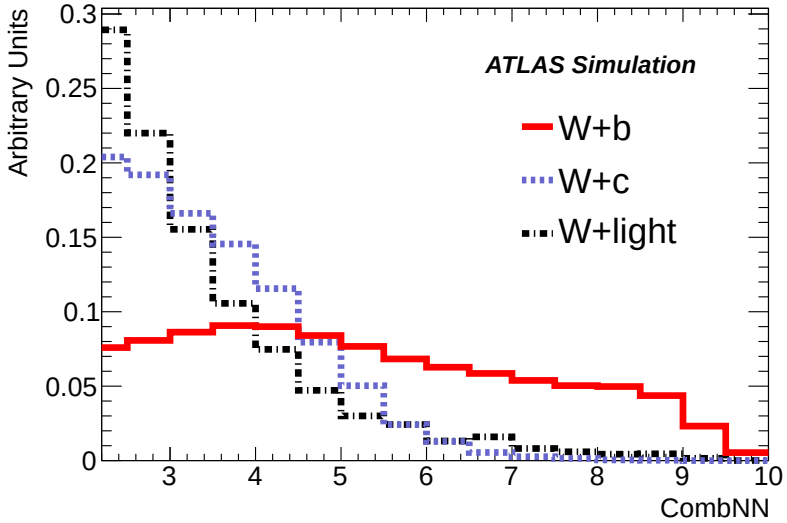
Differential cross sections, with pT(Z)> 50 GeV

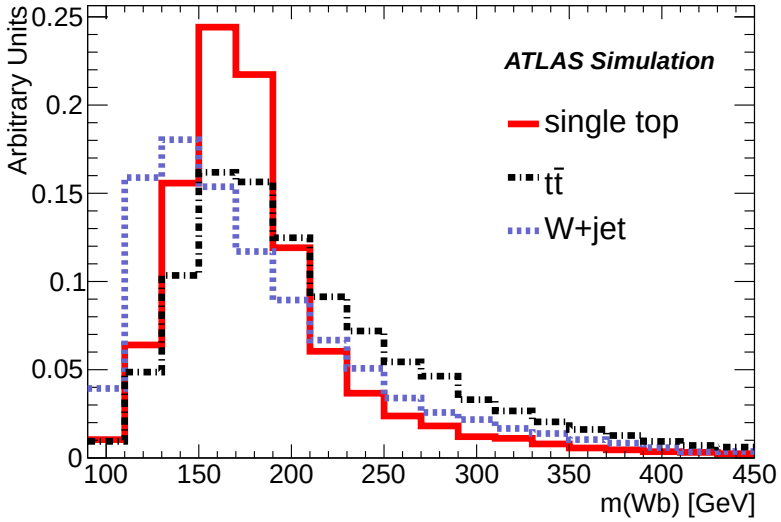


- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults\EWK11015
- Enhancement of the colinear region.
- Confirms better description with 4F, although data yields still higher.
- Sensitivity to the choice of α_S scale in the gluon splitting vertex.

W+b at ATLAS: measurement strategy JHEP 06 (2013) 084

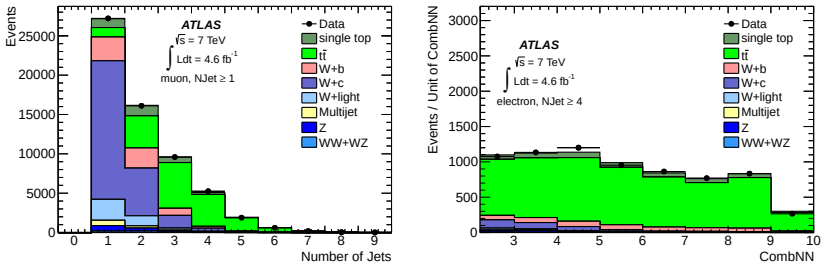
- Trigger on W decay to e, μ, with $p_T^l > 25$ GeV and $|\eta^l| < 2.5$, $m_T^W > 60$ GeV, $E_T^{miss} > 25$ GeV.
- Require at most 2 jets anti-k_T 0.4, $p_T > 25$ GeV, $|y| < 2.1$, ΔR(j,l)$> 0.5 \Rightarrow$ reject background from $t\bar{t}$.
- Require exactly 1 b-tagged jet (detector level).
- Increase b-quark content and estimate purity using neural-network discriminating variable based on displaced vertices: combNN.
- Discriminate between b quarks from top using template fits in control and signal regions.
- Unfold to final states with 1, or $>= 1$ particle-level b jet (weakly-decaying b-hadron $p_T > 5$ GeV within $\Delta R < 0.3$).



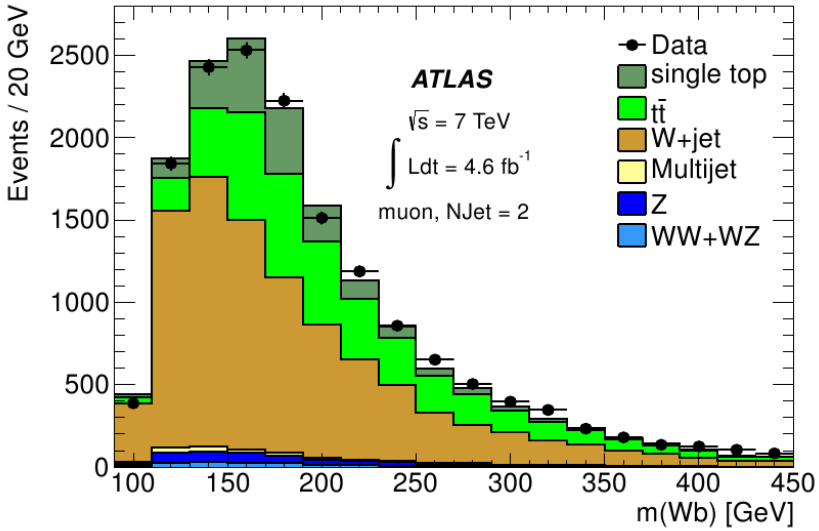


Estimation of the top background

JHEP **06** (2013) 084



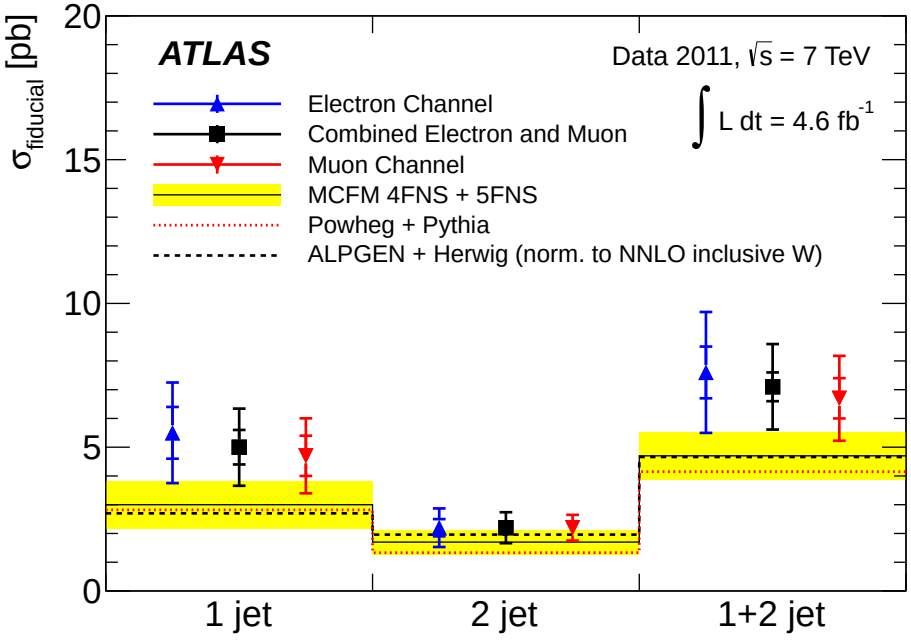
- $t\bar{t}$: template fit of the CombNN variable in control region ($>= 4$ jets). Use MC to extrapolate in signal region.
- Single top: template fit of the m_{Wb} distribution, cross-checked with $H_T = p_T^l + E_T^{miss} + \sum p_T^{jets}$. In 1-jet region: use predictions from AcerMC with large systematics.
- Single top very similar to W+b signal: provide also measurement of the sum of the two processes.



Systematics and total cross sections

JHEP **06** (2013) 084

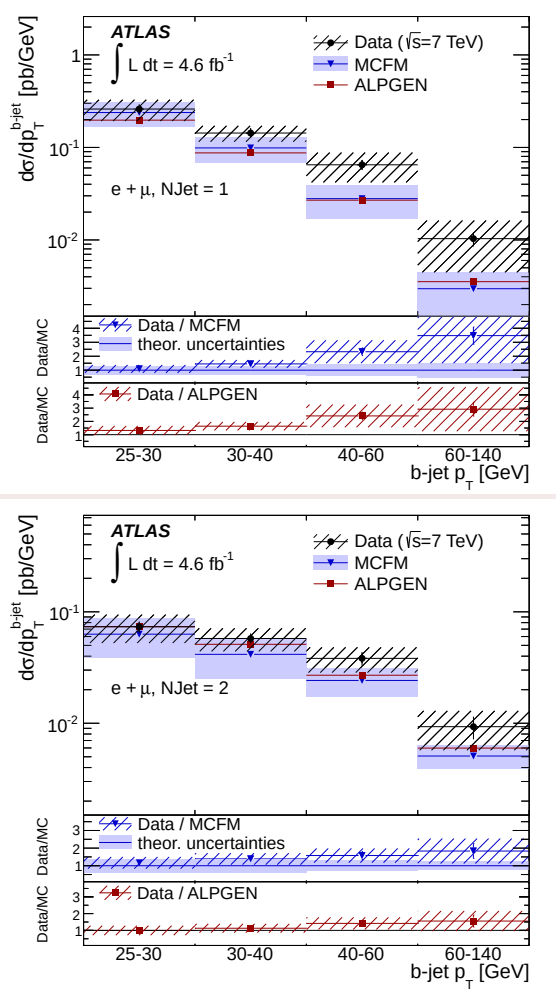
Fiducial cross-section [pb]			
	1 jet	2 jet	1+2 jet
σ_{fid}	5.0	2.2	7.1
Statistical uncertainty	0.5	0.2	0.5
Systematic uncertainty	1.2	0.5	1.4
Breakdown of systematic uncertainty [%]			
Jet energy scale	15	15	15
Jet energy resolution	14	4	8
b-jet efficiency	6	4	5
c-jet efficiency	1	1	0
light-jet efficiency	1	3	2
ISR/FSR	4	8	3
MC modelling	8	4	6
Lepton resolution	1	1	0
Trigger efficiency	1	2	2
Lepton efficiency	1	2	1
$E_{\text{T}}^{\text{miss}}$ scale	3	6	2
$E_{\text{T}}^{\text{miss}}$ pile-up	2	2	2
b-jet template	3	5	4
c-jet template	4	2	3
light-jet template	0	0	0
Multijet template	2	2	2
Total syst. uncertainty	24	23	20



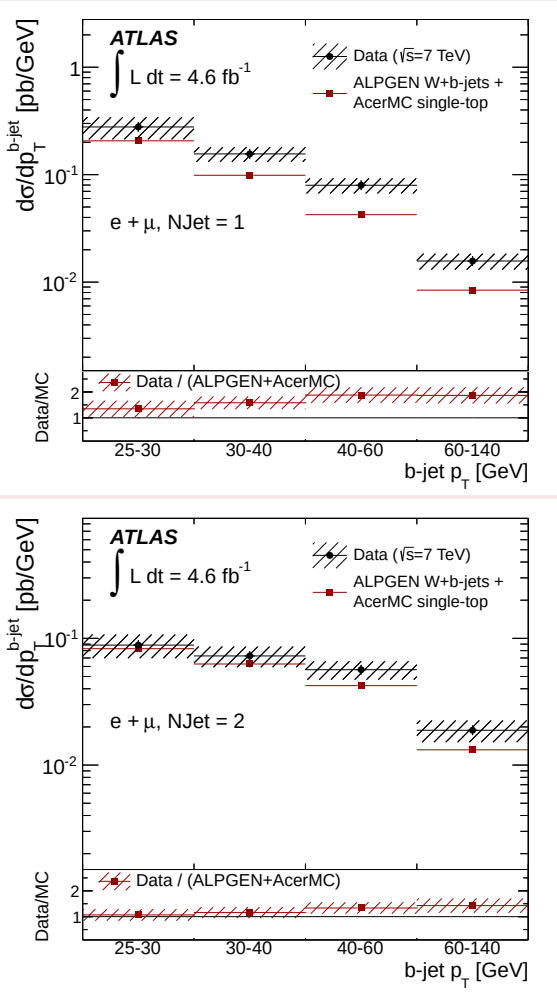
- 1- and 2-jet bins in agreement with theory.
- 1-jet bin: consistent within 1.5σ with NLO predictions.

Differential cross sections as a function of p_T^b

W+b process



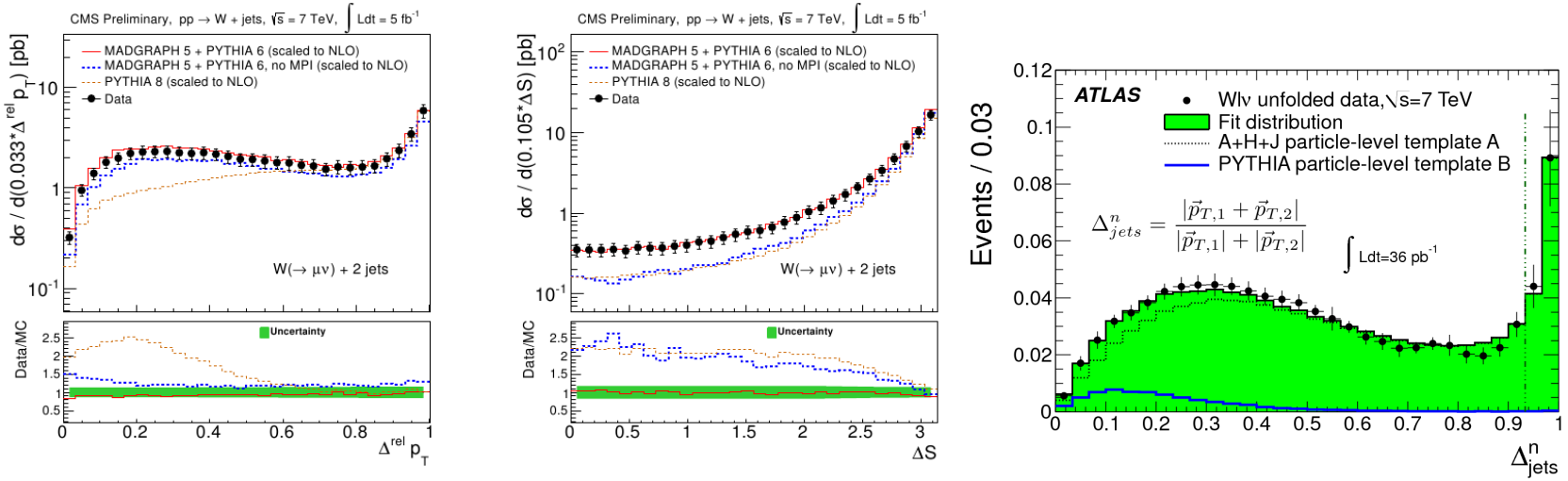
W+b + single top



- JHEP **06** (2013) 084.
- Data-MC discrepancy increases with increasing jet p_T: higher production rate than predicted.
- Increasing jet p_T $\Leftrightarrow$ Enhancement of colinear gluon splitting component ? $\Rightarrow$ Confirmation of Z+2B-hadrons observations ?
- Without subtracting single top: reduced systematics $\Rightarrow$ better sensitivity, depending on single top calculations.

A parenthesis on double parton scattering in W+2j / W+b$\bar{b}$ channel

- W+b$\bar{b}$ sensitive to DPS = tail of MPI model.
- Alpgen+Herwig+Jimmy/Madgraph+Pythia: shown to model it well in W+2j events (arXiv:1301.6872 and CMS-PAS-FSQ-12-028).

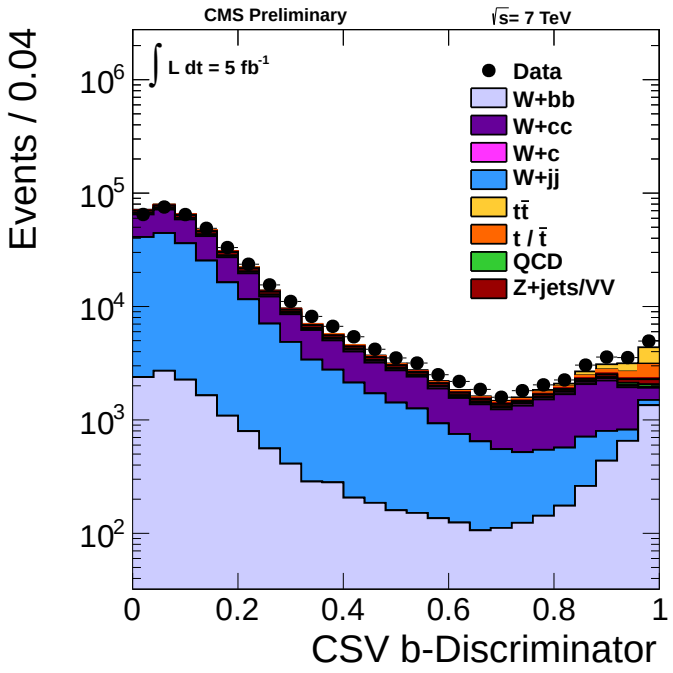


- W+2j vs W+b$\bar{b}$?? Need a measurement !
- Estimation by ATLAS for W+b: $\frac{\sigma_{DPS}}{\sigma_{SPS+DPS}} = 20\%$,and W+b+j: $\frac{\sigma_{DPS}}{\sigma_{SPS+DPS}} = 15\%$ with systematics from ATLAS W+2j measurement of σ_{eff}, i.e. about 40% (arXiv:1301.6872).
- Estimation by CMS for W+b$\bar{b}$: $\frac{\sigma_{DPS}}{\sigma_{SPS+DPS}} = 15\%$ using also ATLAS σ_{eff}.

W+b$\bar{b}$ at CMS: measurement strategy

- Trigger on W decay to μ, with $p_T^{\mu} > 25$ GeV and $|\eta^{\mu}| < 2.1$, $m_T^W > 45$ GeV.
- Require exactly 2 jets anti-k_T 0.5, $p_T > 25$ GeV, $|\eta| < 2.4$, ΔR(j,l)$> 0.5 \Rightarrow$ reject background from $t\bar{t}$.
- Require exactly 2 b-tagged jets using discriminating variable based on displaced vertices $\Rightarrow$ only small contamination from light and charm quarks.
- Extract yields using simultaneous template fits in signal and top control regions.
- Cross-check templates from MC in individual control regions: Z, $t\bar{t}$, single top. QCD: data-driven template.
- Compare kinematic distributions at detector level.
- Extract total cross section at particle level: correct for detector resolution, acceptance and efficiencies.

CMS-PAS-SMP-12-026

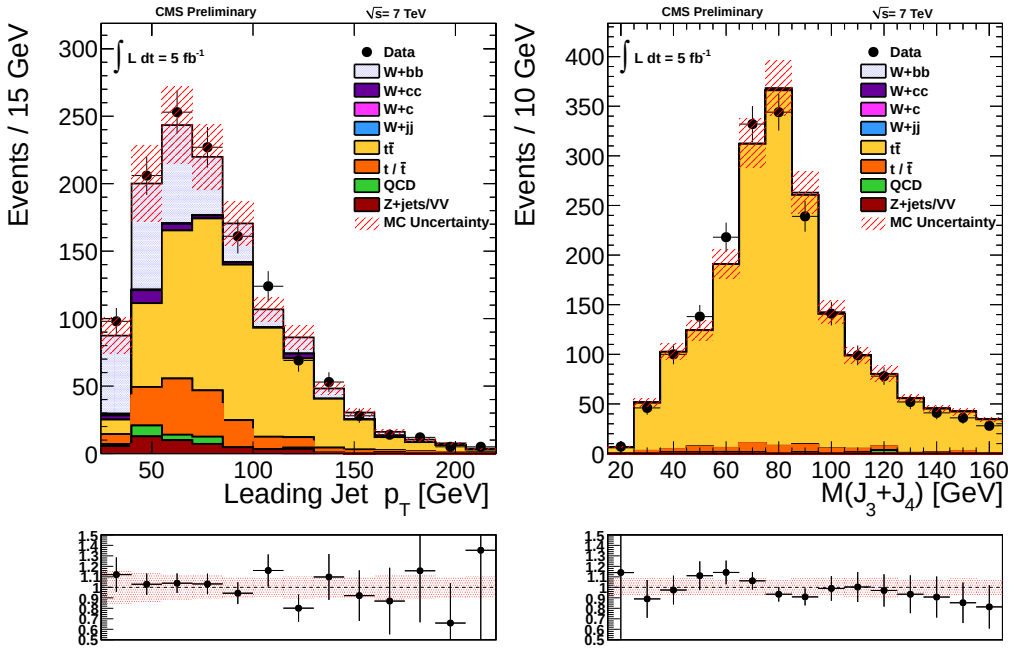


Measurement of the total cross section

Systematic uncertainties

- Nuisance parameters in the fit.
- Dominant source: 6% per b-tagged jet from b-tagging.

CMS-PAS-SMP-12-026

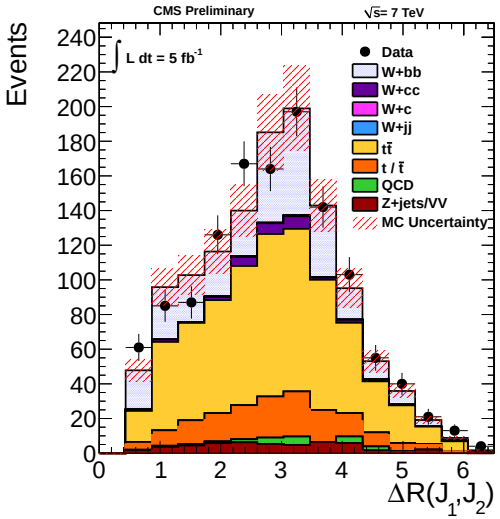


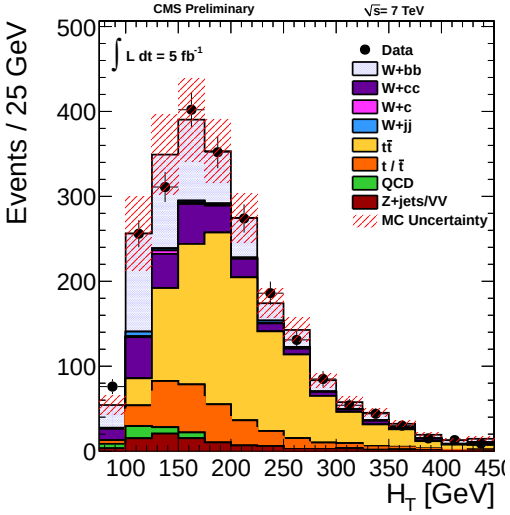
Process	Prediction	Fitted Yield
$W + b\bar{b}$	332 ± 66	300 ± 60
$W + c$, $W + c\bar{c}$	21 ± 4	20 ± 4
W+usdg	1.5 ± 0.2	1 ± 1
Z+jets	31 ± 3	32 ± 3
$t\bar{t}$	596 ± 35	647 ± 52
Single top	160 ± 13	170 ± 13
WW, WZ	19 ± 3	17 ± 3
QCD	33 ± 17	33 ± 16
Total	1194 ± 78	1220 ± 82
Observed Events	1230 ± 35	

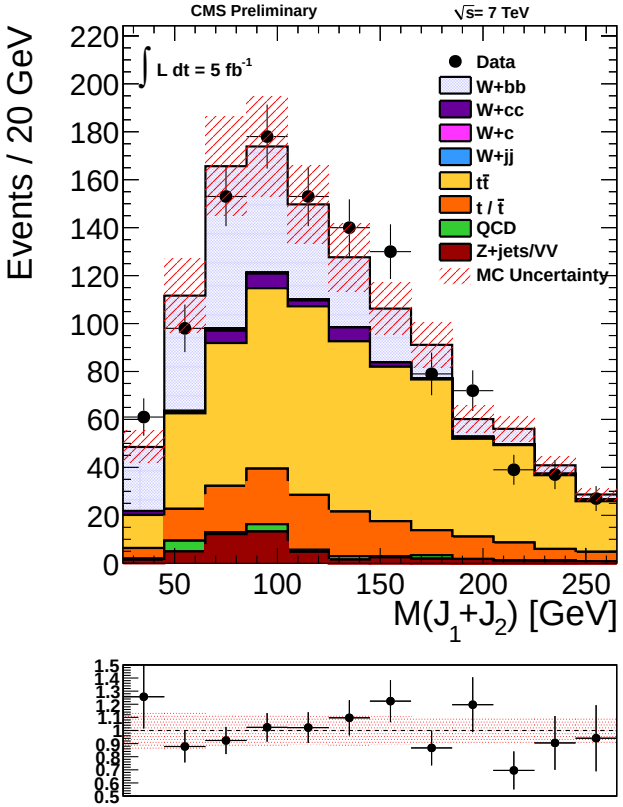
Results

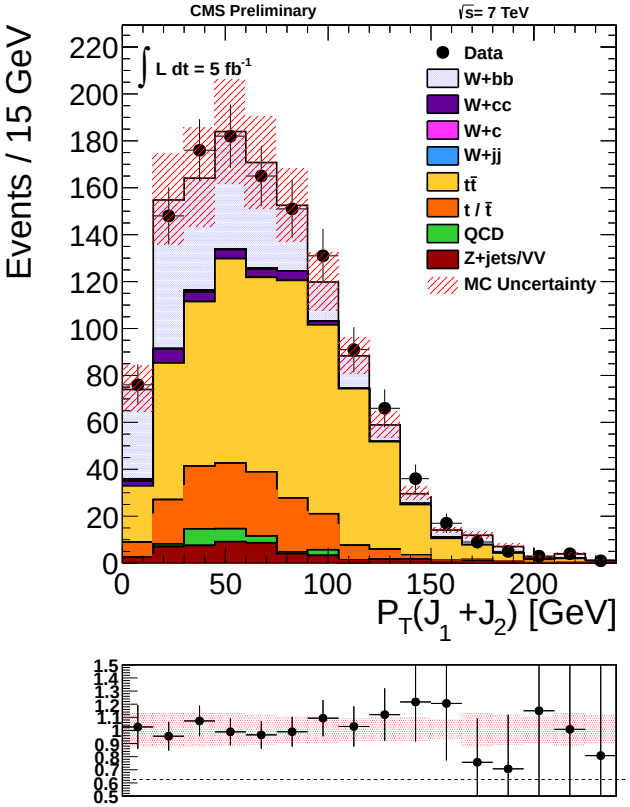
- Data particle level $\sigma(W+b\bar{b}) = 0.53 \pm 0.05$ (stat.)± 0.09 (syst.) ± 0.06 (theo.) ± 0.01 (lum.) pb.
- Correction to parton level: 0.92 ± 0.01.
- MCFM parton level: 0.52 ± 0.03 pb.
- Very good agreement data-MC.

Data-MC comparisons at detector level CMS-PAS-SMP-12-026







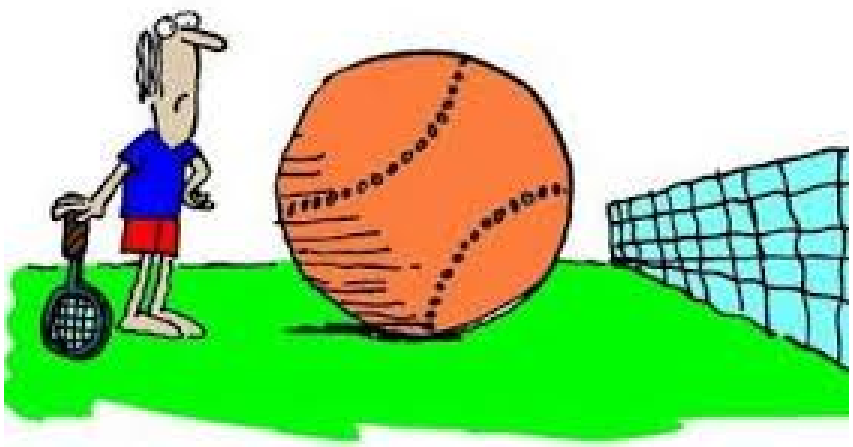


⇒ Good agreement between data and Madgraph+Pythia 5F predictions, normalised to the data with the template fit used to extract the cross section.

Conclusion and Outlook

- W+charm measurements allow to probe strange PDF:
  - improve PDF uncertainties.
  - discimination between PDF sets.
  - Parton-level CMS measurements favour s<d when compared to MCFM predictions, whereas hadron-level ATLAS measurements favour higher strange content when compared to aMC@NLO+Herwig++ predictions.
- Hints of higher charm fragmentation observed in data.
- Z+$b\bar{b}$ measurements show good agreement with MC and NLO calculations. 1-b and 2-b final states have been probed, missing 1b+1jet configuration to cover everything.
- W+$b\bar{b}$ measurements complementary between ATLAS covering W+1b, W+1b+1j+X, W+2b (with only 1 b-tag)+X, and CMS covering W+2b (with 2 b-tags). Comparison with theory shows better agreement in the 2-jet bin and slight under-estimation by the theory in the 1-jet bin.
- New results published or in final review phases, with aim at making results available in RIVET.
- Shall we send the ball back to the theorists court ?

Thank you for your attention



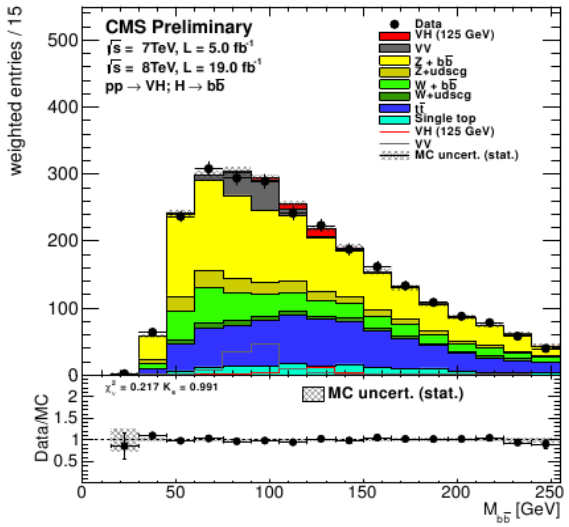
- More results in parallel session talks:
  - M. Ishitsuka: W/Z/top ATLAS 04/09/2013 14:00
  - M.Marone: W/Z/top CMS 04/09/2013 14:25
  - W+c at ATLAS and CMS 04/09/2013 14:25

Backups

BACKUPS

Impact of V+bb on the VH, H→bb analysis

- V+jets: dominant systematic uncertainty, from data-driven estimate / MC shapes
- PAS-HIG-13-012, Table8



Source	Type	Yield uncertainty (%) range	Contribution to uncertainty (%)	Removal effect on total uncertainty (%)
Luminosity	normalization	2.2-4.4	< 2	< 0.1
Lepton efficiency and trigger (per lepton)	normalization	3	< 2	< 0.1
$Z(\nu\nu)H$ triggers	shape	3	< 2	< 0.1
Jet energy scale	shape	2–3	5.0	0.5
Jet energy resolution	shape	3–6	5.9	0.7
Missing transverse energy	shape	3	3.2	0.2
b-tagging	shape	3–15	10.2	2.1
Signal cross section (scale and PDF)	normalization	4	3.9	0.3
Signal cross section (p_T boost, EWK/QCD)	normalization	2/5	3.9	0.3
Signal Monte Carlo statistics	shape	1–5	13.3	3.6
Backgrounds (data estimate)	normlization	10	15.9	5.2
Single-top (simulation estimate)	normalization	15	5.0	0.5
Dibosons (simulation estimate)	normalization	15	5.0	0.5
MC modeling (V+jets and $t\bar{t}$)	shape	10	7.4	1.1