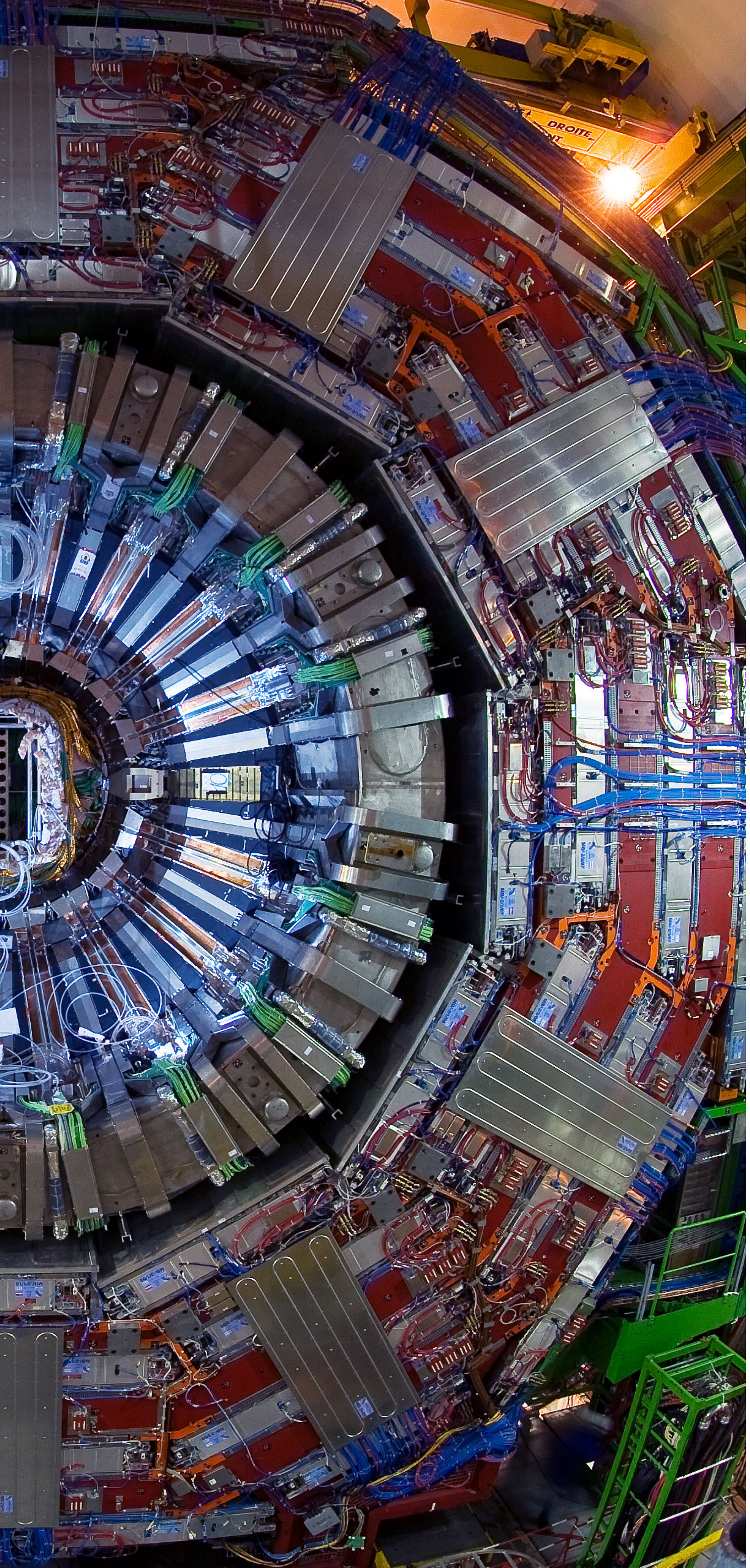


INFN Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DEGLI STUDI DI TRIESTE

CMS

Recent results on single vector boson plus jets production at CMS

Federico Vazzoler, on behalf of the CMS Collaboration

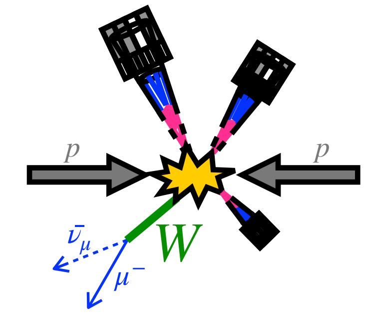
Incontri di Fisica delle Alte Energie,
Napoli, 09 Aprile 2019.

Motivation

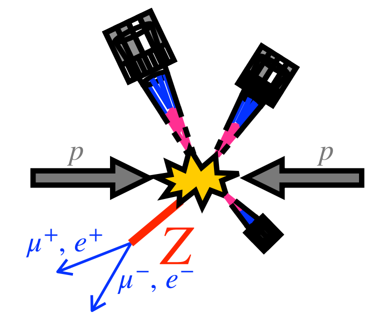
1. Precision measurements of V+jets differential production cross sections provide rigorous test of the SM:
   - Inputs for constraining PDFs, important to reduce uncertainties in many relevant cross sections measurements

2. V+jets measurements compared with Monte Carlo predictions:
   - Improve MC description of experimental data and higher order theoretical calculations

3. Important background for SM and BSM events (high boson p_T and N_{jets}):
   - Single top, $t\bar{t}$, VBF, WW scattering, H boson production, …



SMP-16-005



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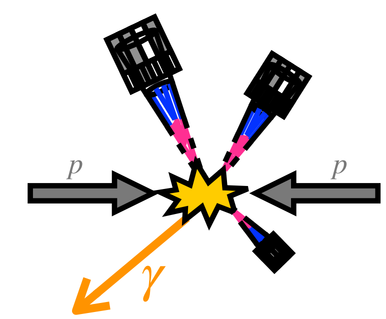

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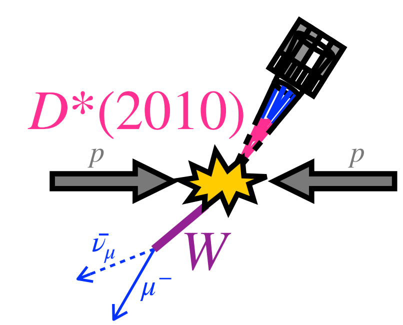
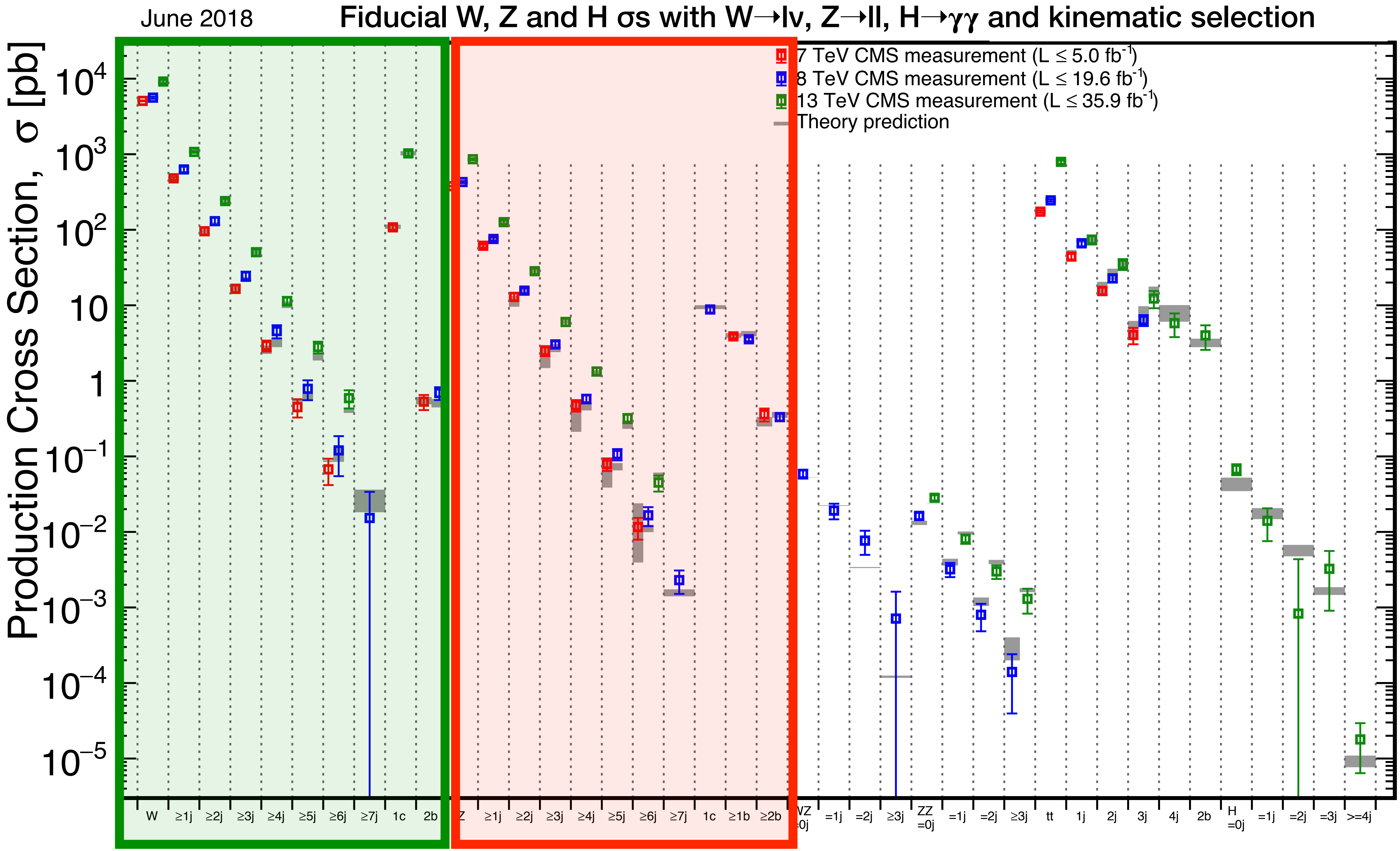


SMP-17-014
SMP-14-020
SMP-14-010

STATE OF THE ART @ RUN 2



W+jets

Z+jets

γ+jets

SMP-16-005 → W+jets
SMP-17-014 → W+c
SMP-14-020 → W+b

SMP-16-015 → Z+jets
SMP-14-010 → Z+b

SMP-16-003 → γ+jets

All results at: http://cern.ch/go/pNj7

THEORETICAL PREDICTIONS FOR V+jets CROSS SECTIONS

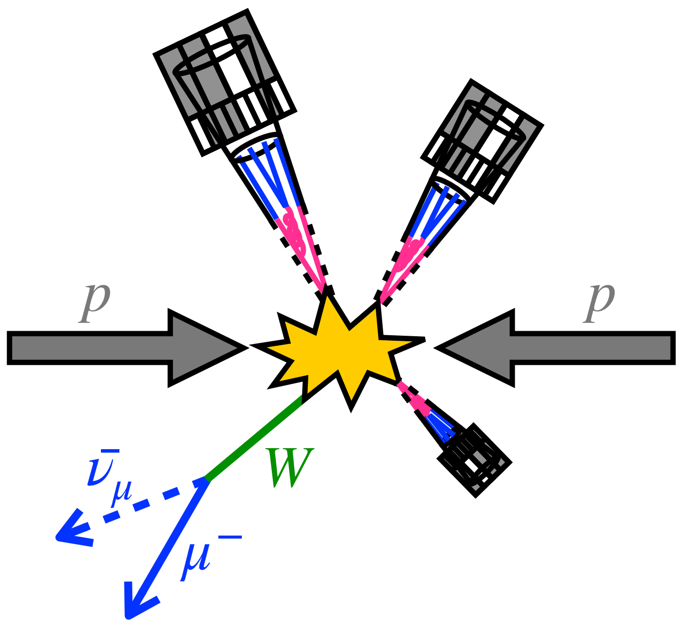
- **MadGraph5_aMC@NLO (ME) + PYTHIA8 (PS)**:
  - LO: up to 4 partons, kT-MLM matching, NNPDF 3.0 LO PDF, CUETP8M1 PYTHIA tune
  - NLO: up to 2 partons, FxFx matching, NNPDF 3.0 NLO PDF, CUETP8M1 PYTHIA tune
- **Geneva 1.0-RC2 (ME) + PYTHIA8 (PS)**:
  - NNLO DY production + NNLL higher order resummation
  - Only for Z+jets processes
- **Z/W+1 jet NNLO calculation**:
  - Using MCFM

CT14 PDF (Z)
NNPDF 3.0 NNLO (W)

Pileup contribution simulated with additional minimum-bias events superimposed on primary event

Samples	0 j	1 j	2 j	3 j	4 j	> 4 j
LO MG5_aMC	LO	LO	LO	LO	LO	PS
NLO MG5_aMC	NLO	NLO	NLO	LO	PS	PS
Geneva	NLO	NLO	LO	PS	PS	PS
Z/W+1 jet @ NNLO	-	NNLO	NLO	LO	-	-

W+jets



SMP-16-005

Muon:

$p_T(\mu) > 25$ GeV

$|\eta| < 2.4$

$M_T > 50$ GeV

Jets:

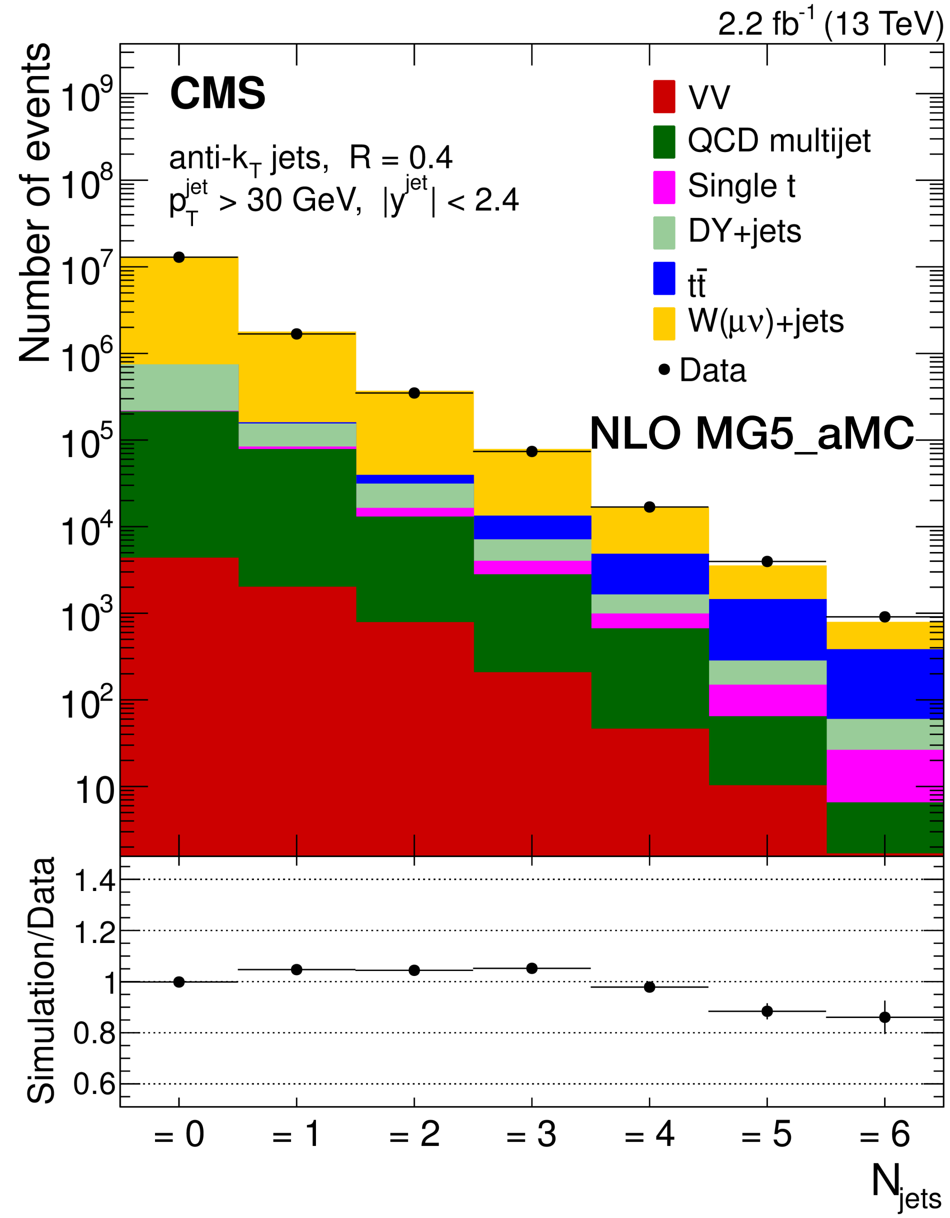
anti-kT $(R = 0.4)$

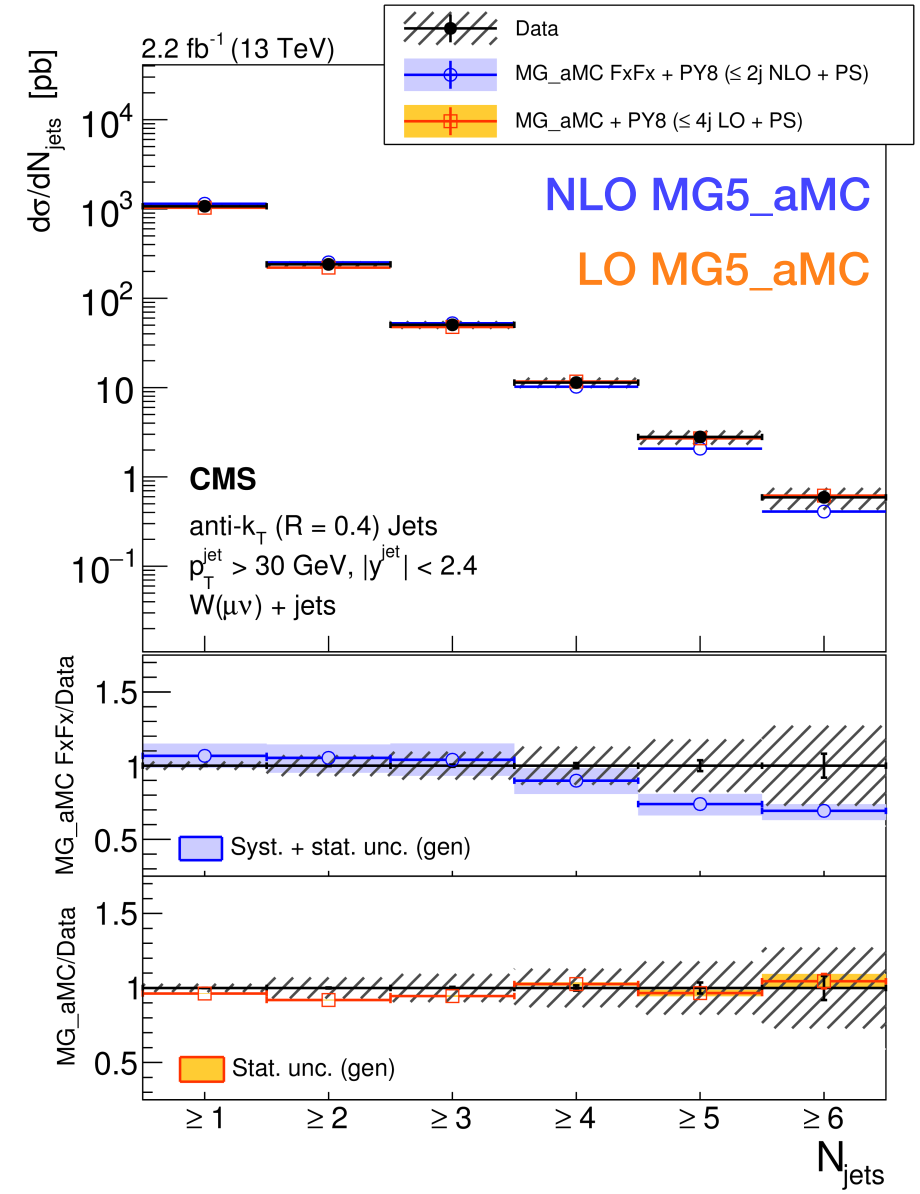
$p_T(j) > 30$ GeV

$|\eta| < 2.4$

$\Delta R(jet, \mu) > 0.4$

N_{jets}

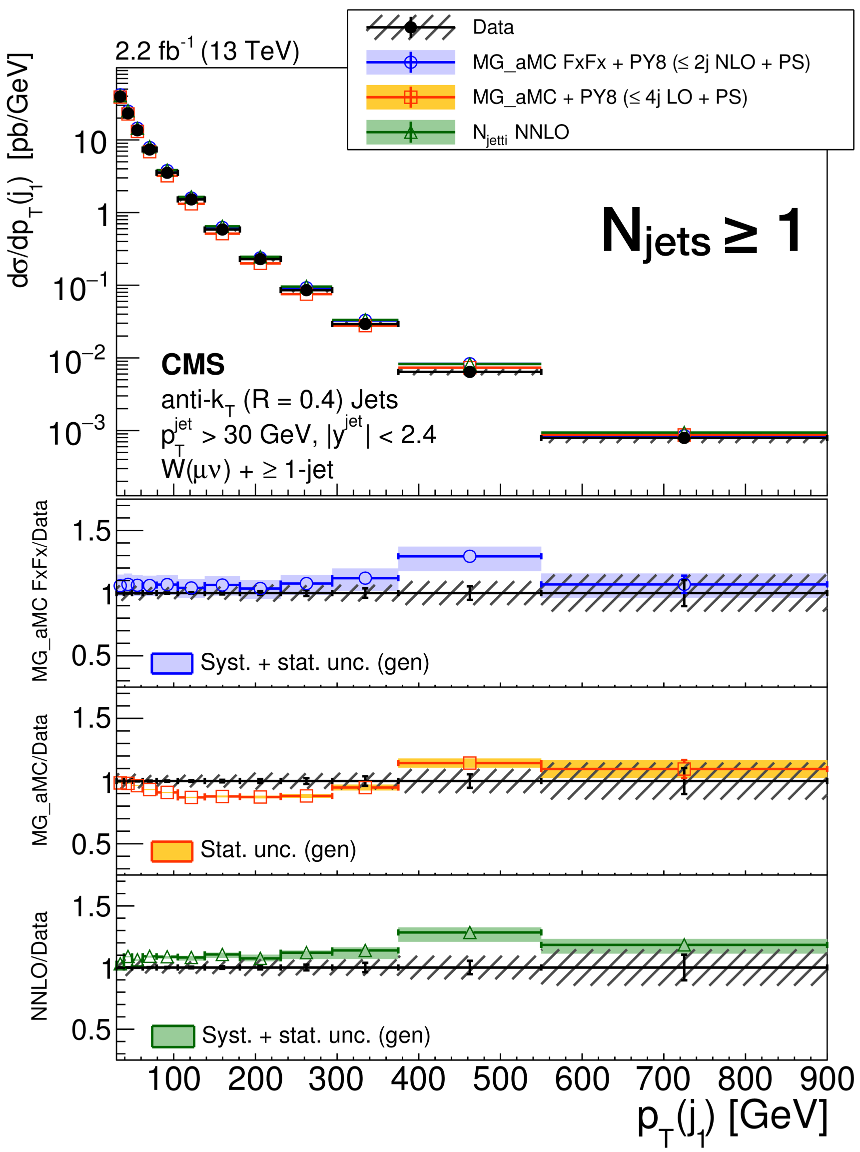




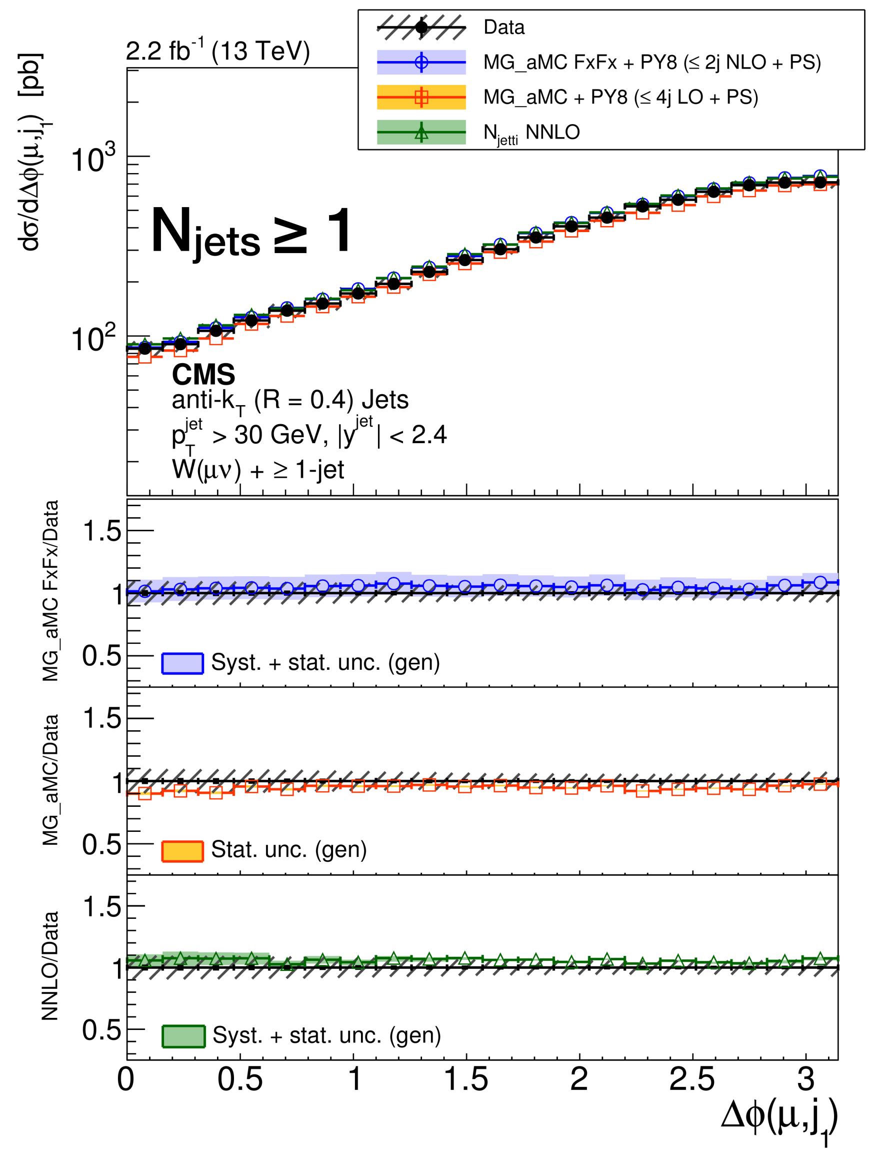
- pp collisions @13 TeV, 2.2 fb^{-1} data (2015)
- Detector resolution corrected (unfolding)
- Dominant background: $t\bar{t}$ production (data-driven estimation)
- Other backgrounds: MC and data driven (QCD)
- Differential cross-section as a function of N_{jets}, jet p_T and eta, jets H_T, angular correlations between muon and jet(s)

W+jets

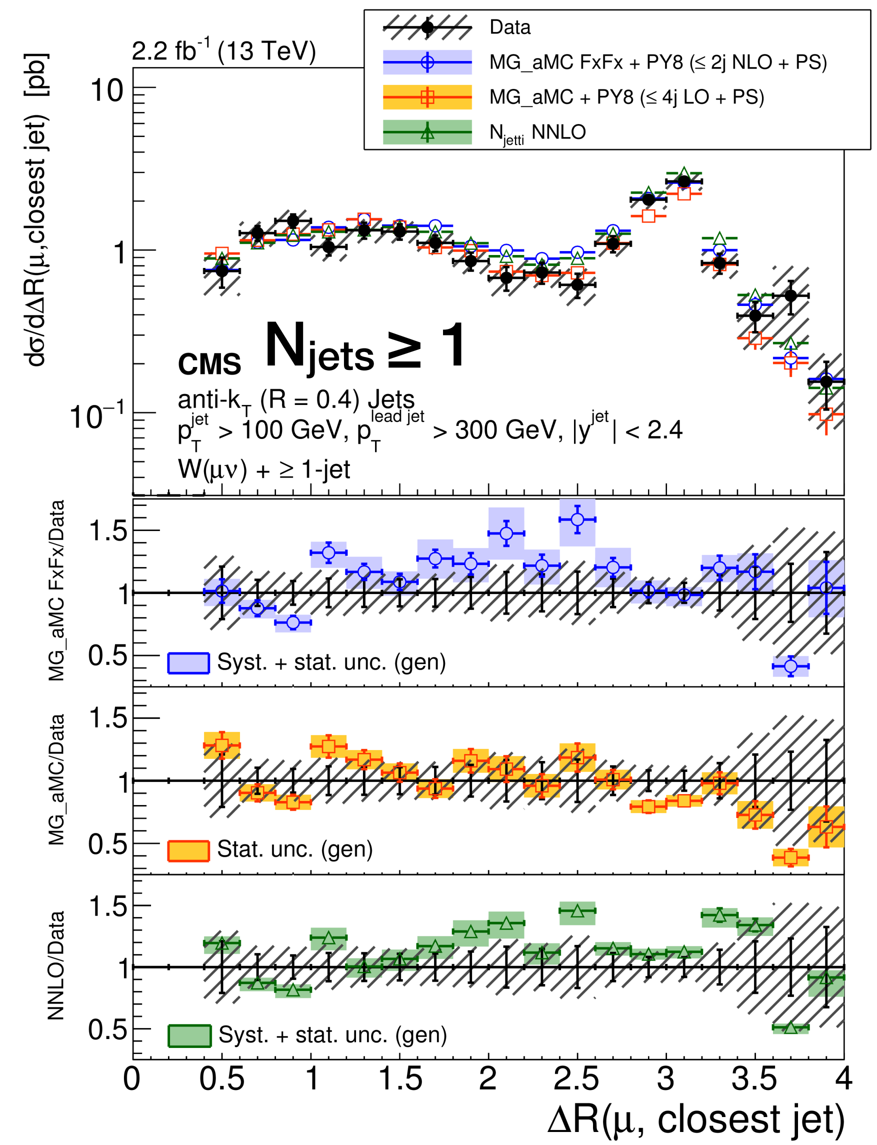
$p_T(j)$



$\Delta\phi(\mu,j)$



$\Delta R(\mu,j)$



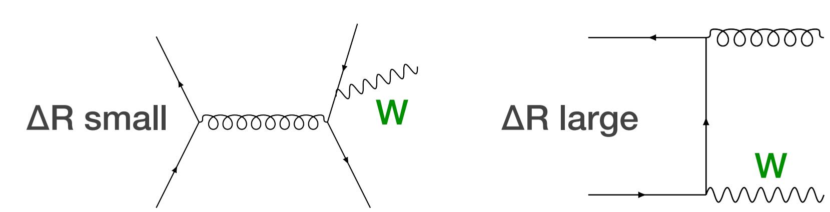
LO MG5_aMC: underestimation at low p_T

NLO MG5_aMC + **W+1j@NNLO**: good description of measurements

$\Delta\phi$: sensitive to implementation of particle emission and other nonperturbative effects modelled by PS algorithm

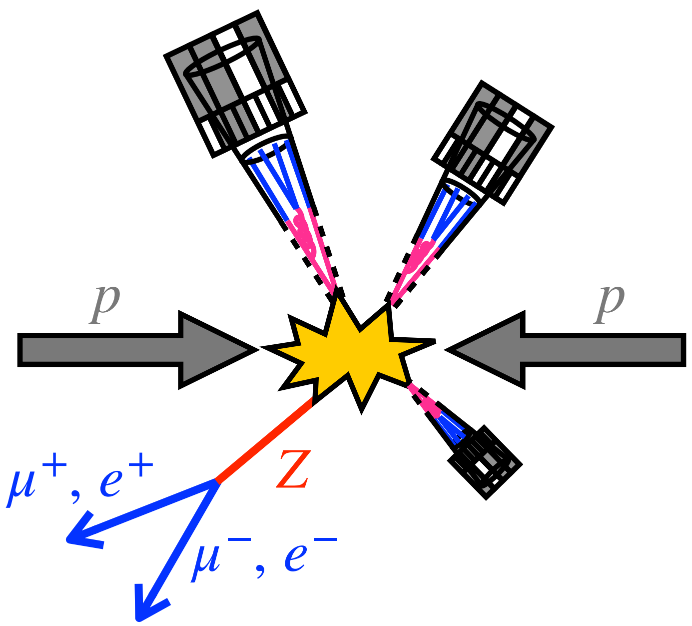
LO MG5_aMC + **NLO MG5_aMC** + **W+1j@NNLO**: good modelling

ΔR: sensitive to EW radiative production of W boson



LO MG5_aMC + **NLO MG5_aMC** + **W+1j@NNLO**: decent modelling

Z+jets



SMP-16-015

Leptons:

$p_T(l) > 20$ GeV

$|\eta| < 2.4$

$M_{ll} = 91 \pm 20$ GeV

Jets:

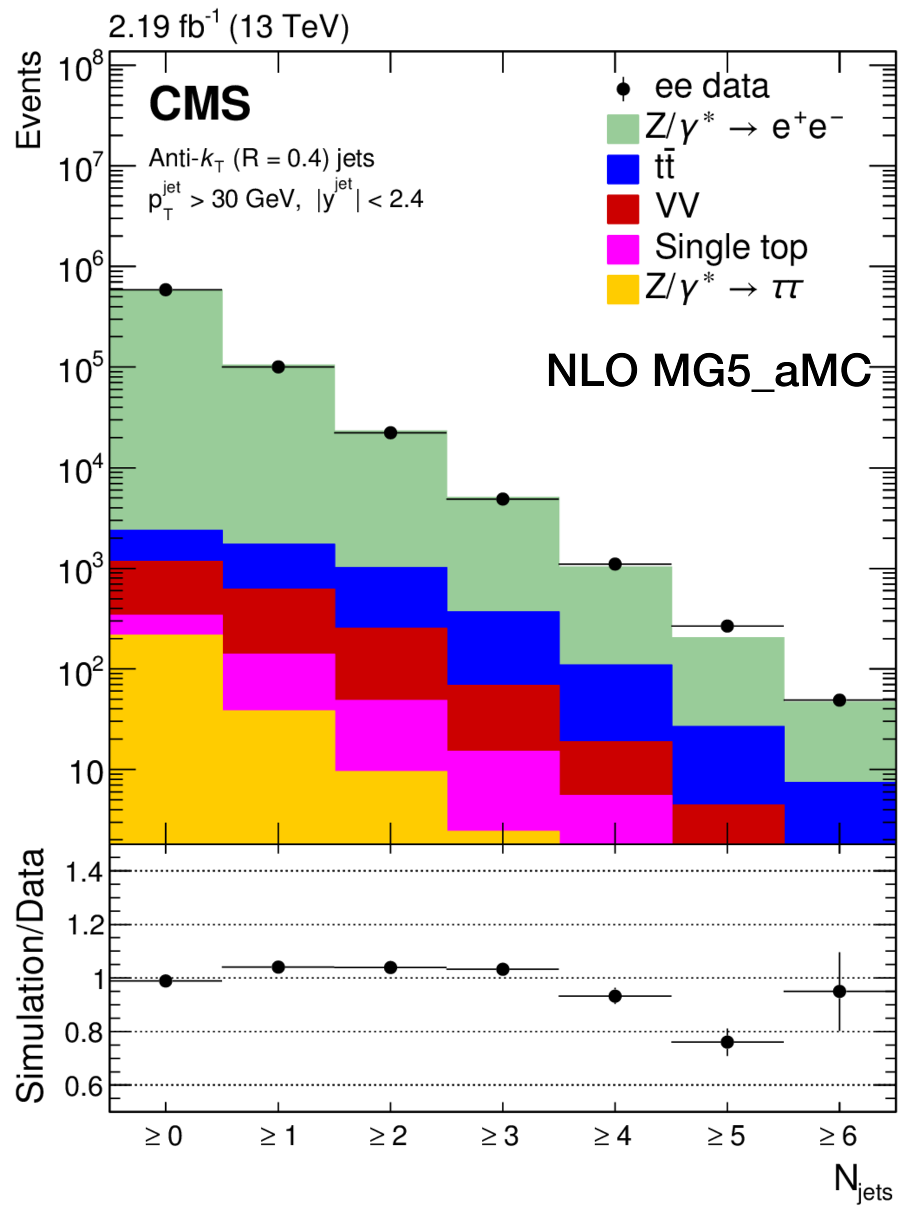
anti-kT $(R = 0.4)$

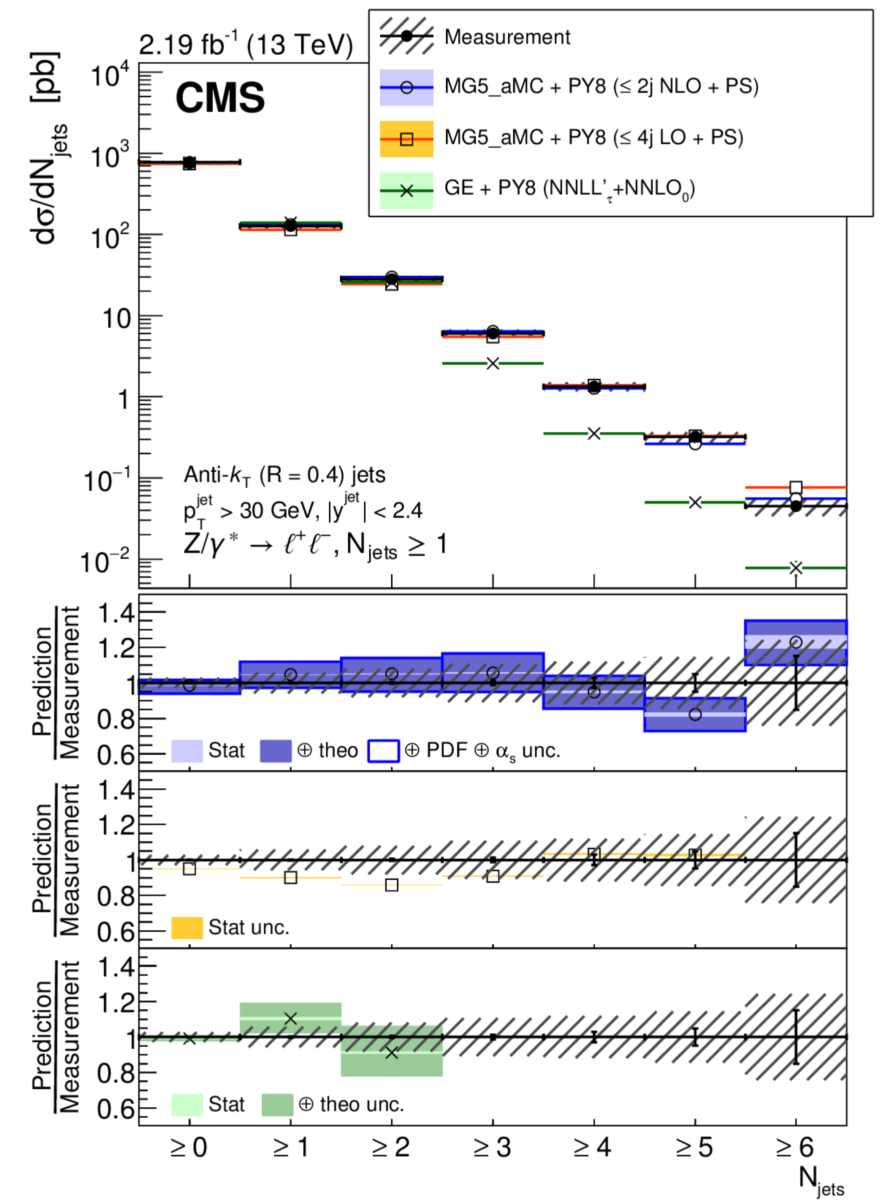
$p_T(j) > 30\ GeV$

$|\eta| < 2.4$

$\Delta R(jet, l) > 0.4$

N_{jets}

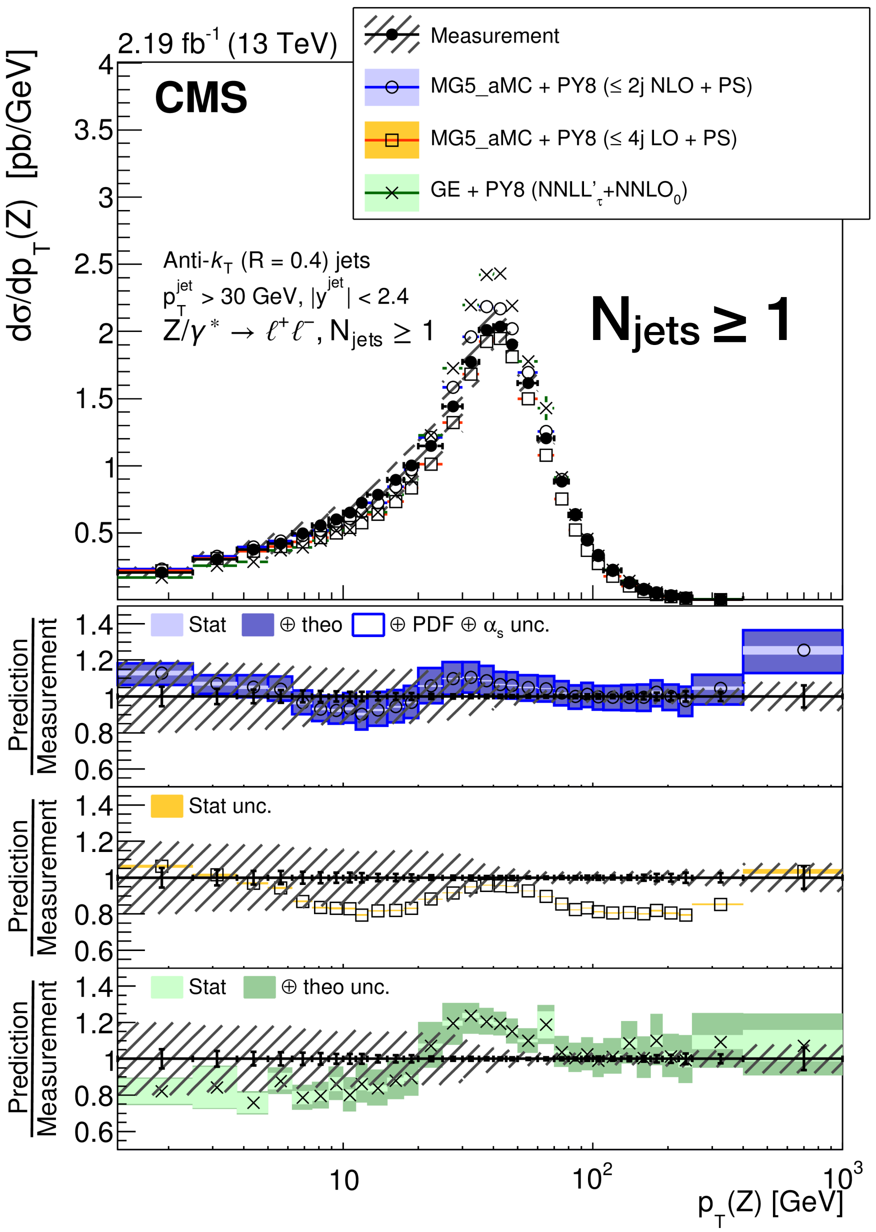




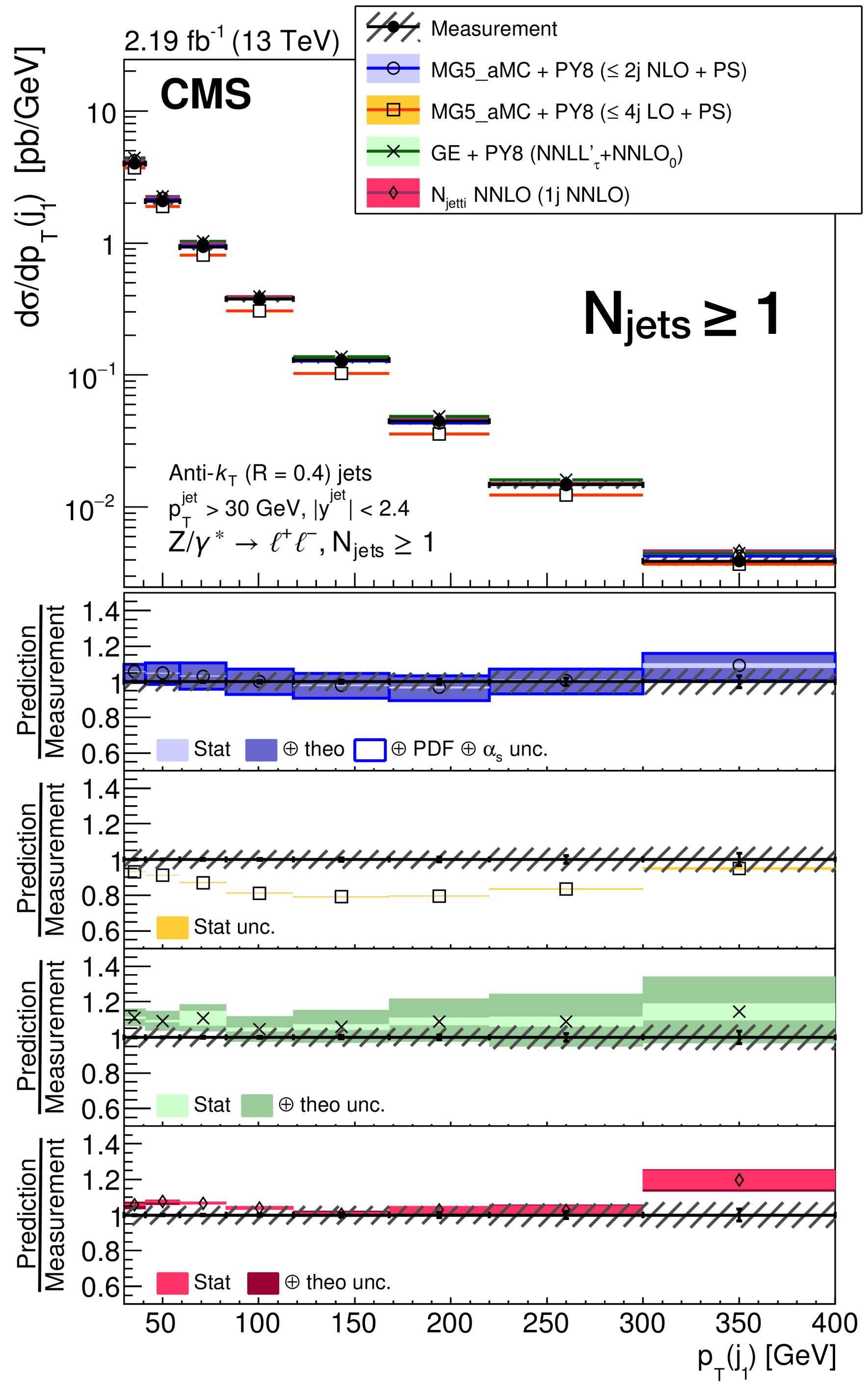
- pp collisions @13 TeV, 2.2 fb^{-1} data (2015)
- Correction for detector resolution (unfolding)
- Dominant background: $t\bar{t}$ production (data-driven estimation)
- Other backgrounds: from MC
- Differential cross-section as a function of Z boson p_T, jet p_T and eta, **transverse momenta balance, jet-Z balance (JZB)**

Z+jets

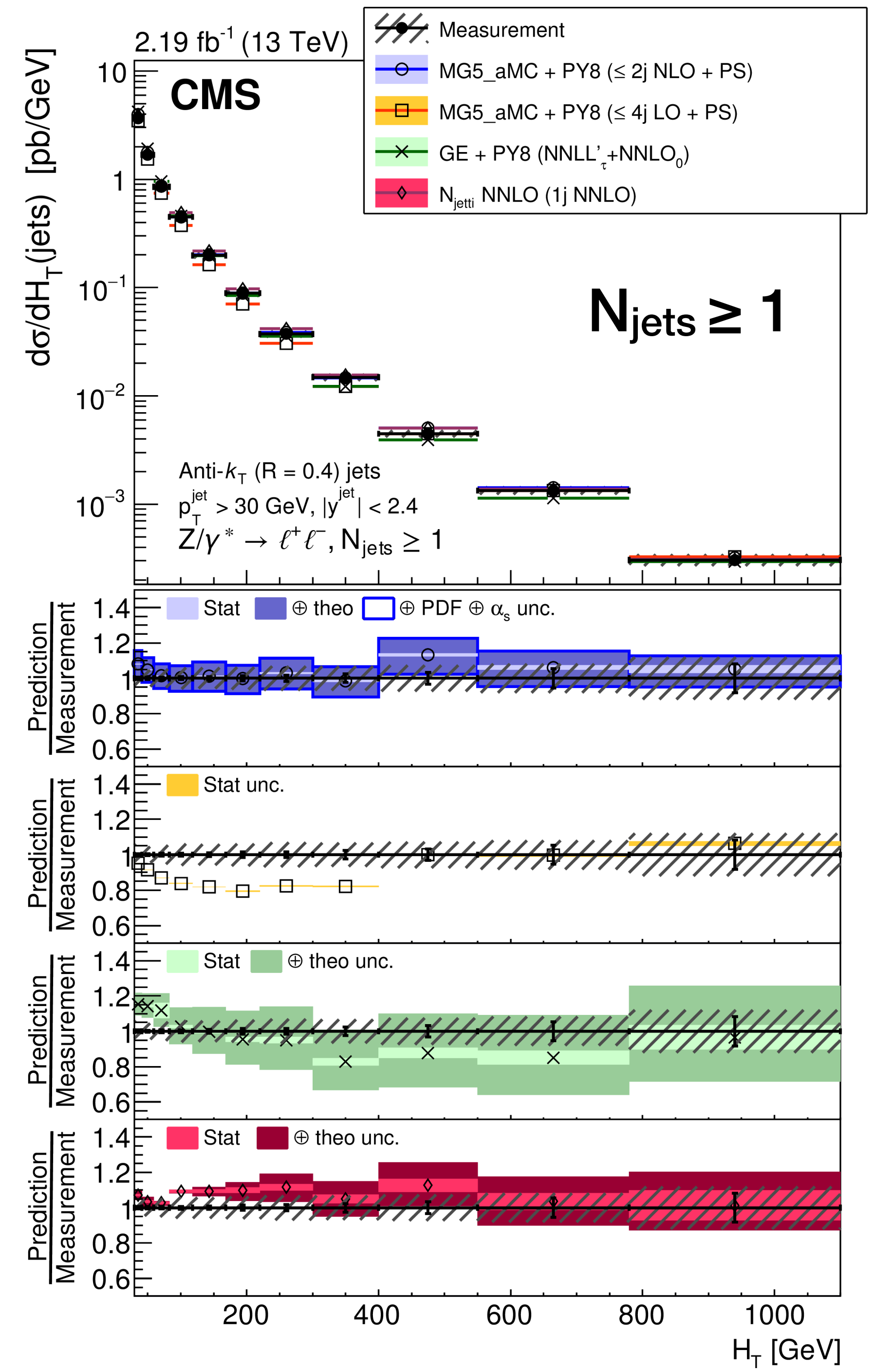
p_T (Z)



p_T (leading j)



H_T



GENEVA: shape of p_T (leading j) well modelled. H_T underestimated. p_T (Z) well modelled except for the central region

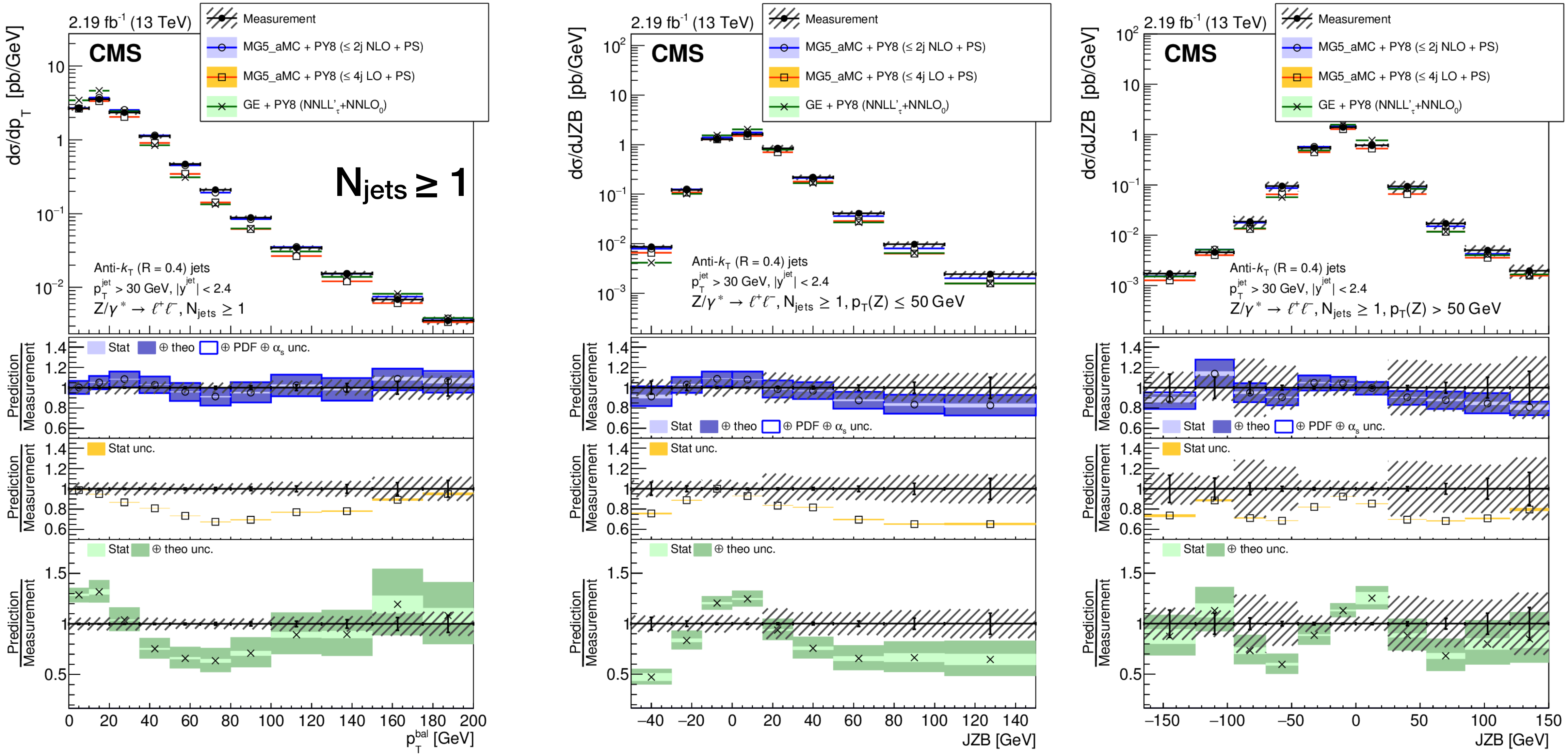
NLO MG5_aMC + Z+1j@NNLO: good description of the observables

LO MG5_aMC: distributions differ significantly

NLO needed to describe data

Z+jets

p_T^{bal} — JZB: $p_T(Z) \leq 50$ GeV — $p_T(Z) \geq 50$ GeV



$N_{jets} \geq 1$ → possibility to study multiple (soft) gluon emission!

Observables

$$p_T^{bal} = |p_T(Z) + \sum_{jets} p_T(j_i)|$$

$$\text{JZB} = |\sum_{jets} p_T(j_i)| - |p_T(Z)|$$

NEW!

Imbalance due to:

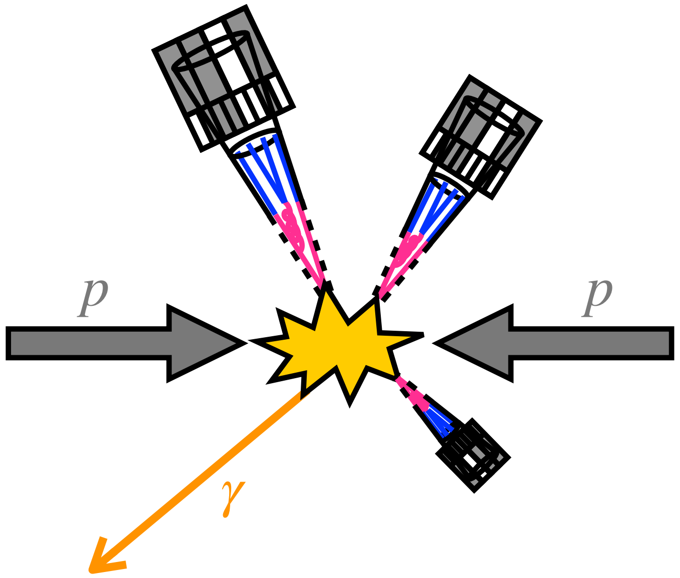
1. Activity in forward region (dominant).
2. Gluon radiation in central region.

NLO MG5_aMC: good agreement with data.

LO MG5_aMC + **GENEVA**: discrepancies with data. LO accuracy for 2 partons in final state.

NLO correction important to describe hadronic activity

γ+jets



SMP-16-003

Photon:

$E_T^\gamma > 190\ GeV$

$|\eta| < 2.5$

$H/E < 0.08\ (0.05)$

$Iso_{chg} + Iso_{neu}$

$\sigma_{i\eta i\eta} < 0.015\ (0.045)$

Jet:

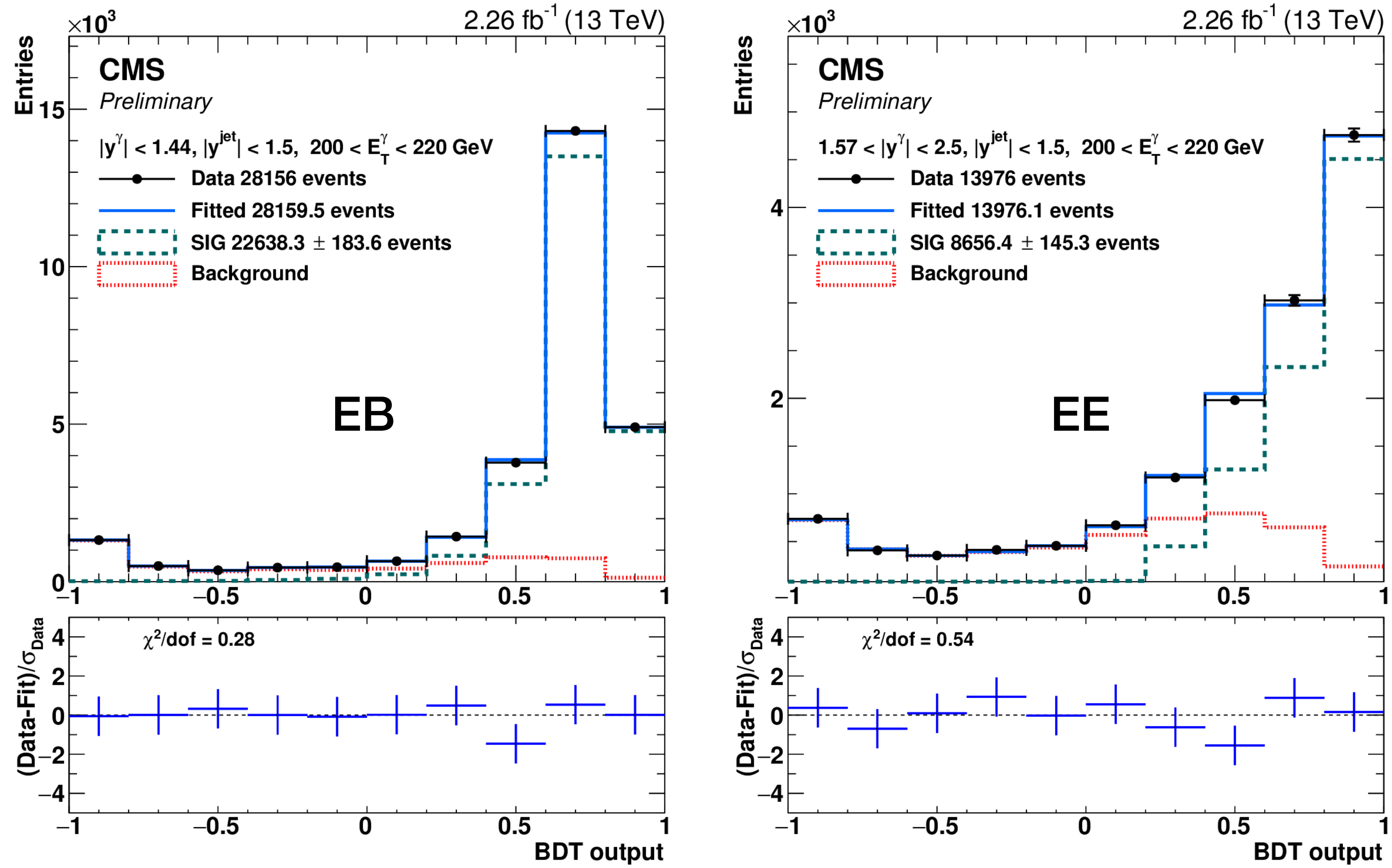
anti-kT $(R = 0.4)$

$p_T(j) > 30\ GeV$

$|\eta| < 2.4$

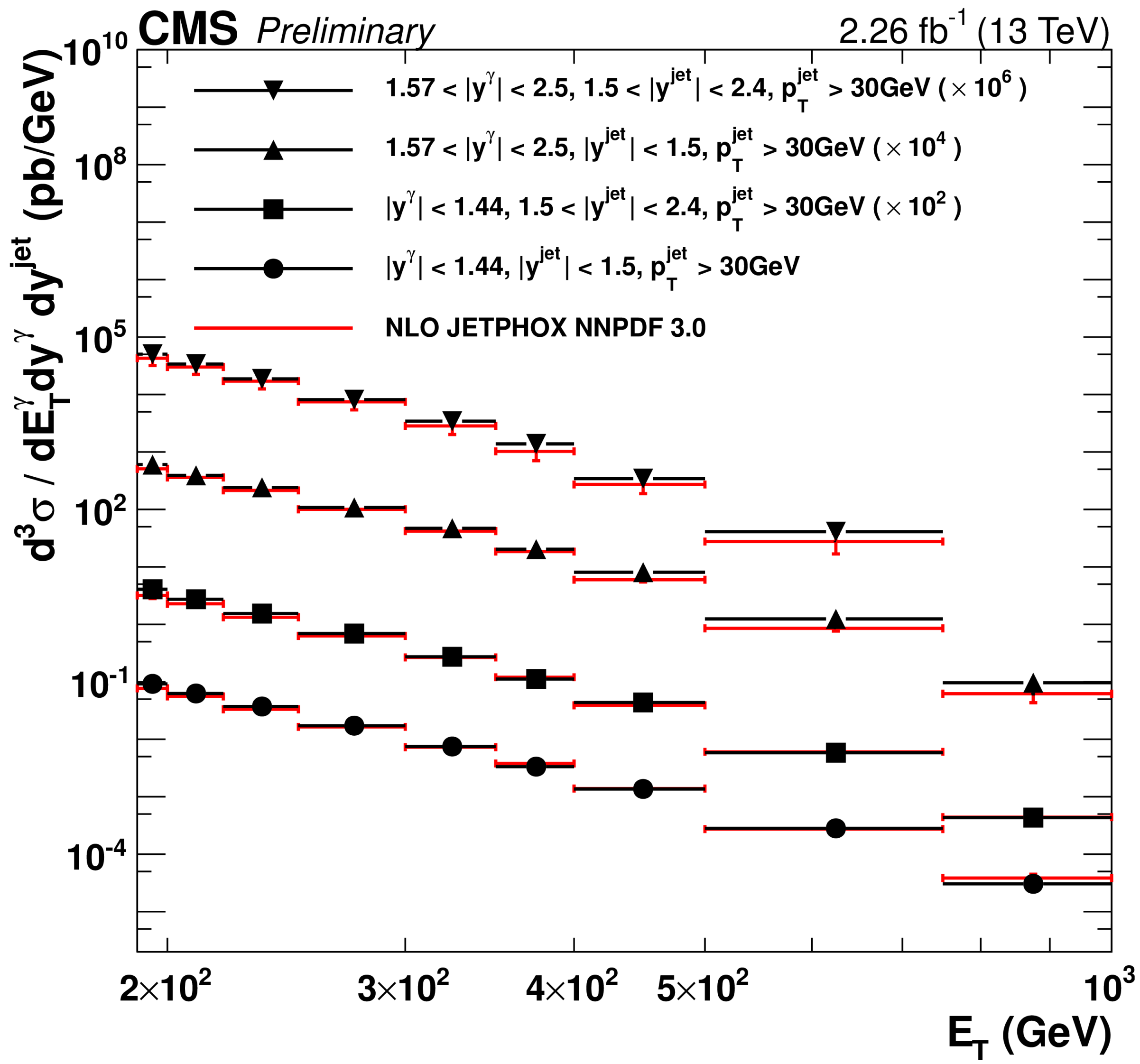
$\Delta R(j, l) > 0.4$

BDT distributions



- pp collisions @13 TeV, 2.26 fb^{-1} data (2015).
- Correction for detector resolution (unfolding).
- Dominant background: QCD multijet production (EM decays of neutral hadrons).
- MVA analysis: photon yield extracted from **BDT templates** of **signal** and **background** (control region).
- Measured cross-sections compared to **NLO QCD calculations** JETPHOX 1.3.1

$d^3\sigma / dE_T^\gamma dy^\gamma dy^{jet}$

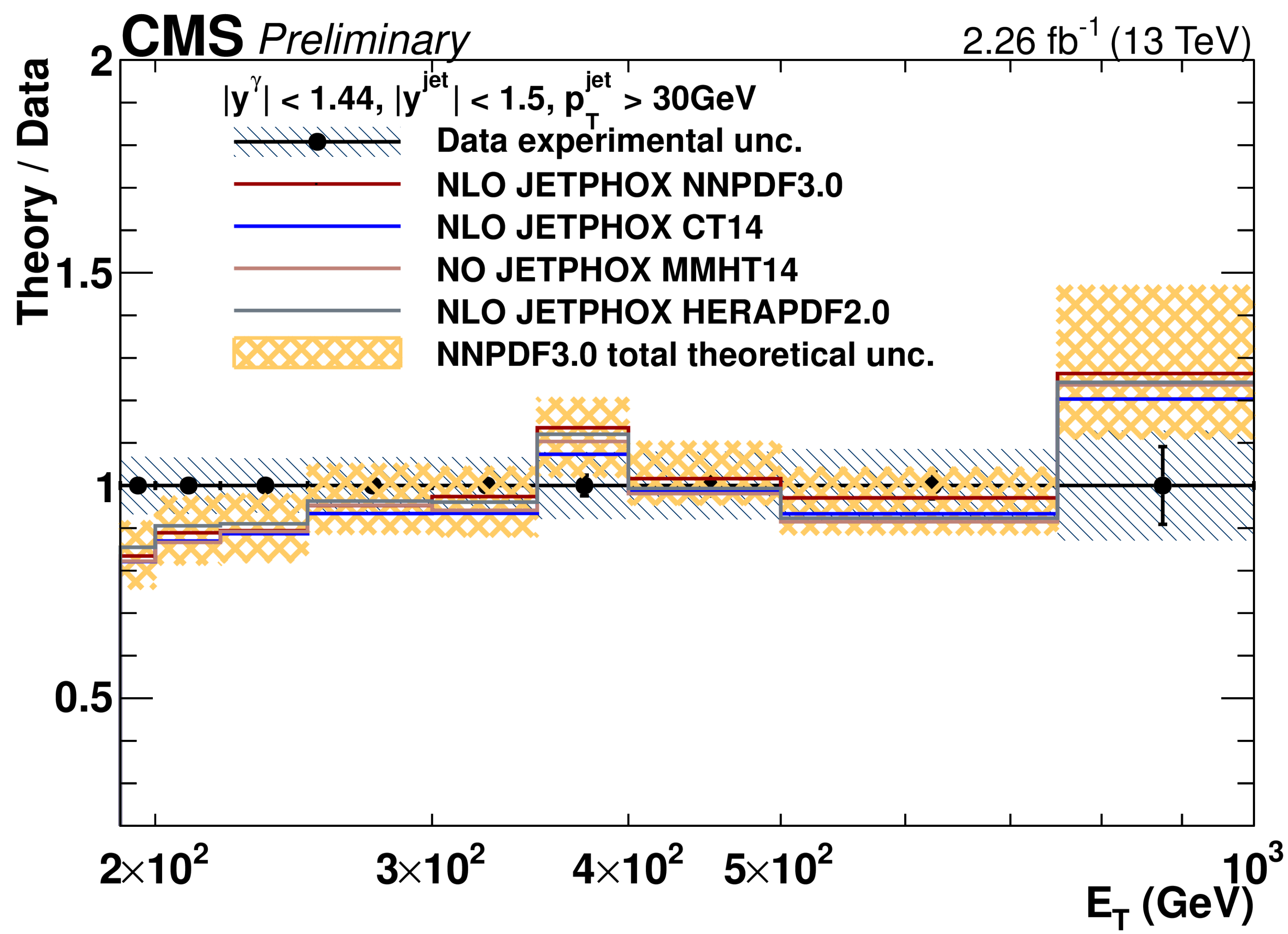


Measured cross-sections wrt. CMS measurements @ 7 TeV:

- Cross-sections increased by factor 3-5.
- Extension of the E_T range from 300 GeV to 1 TeV.

Cross-sections in **agreement with NLO JETPHOX NNPDF3.0 predictions** in all kinematic regions.

Theory / Data

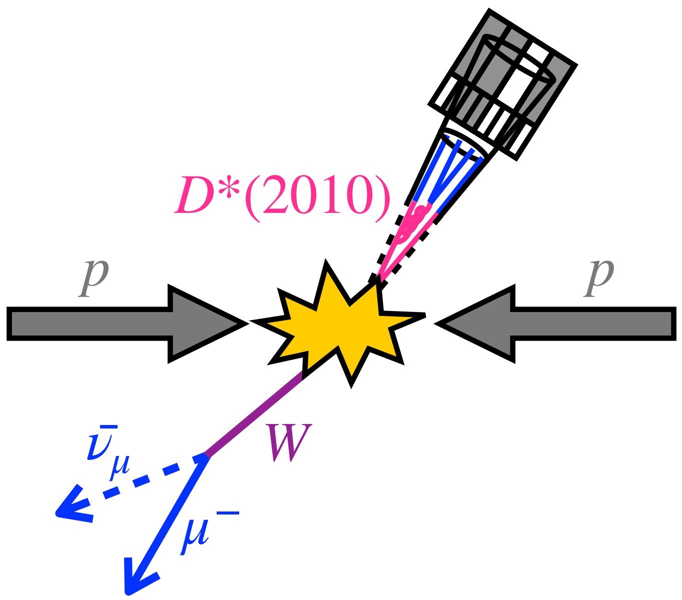


Sensitivity to gluon density function of wide range (x, Q^2).

Ratio of theoretical prediction with various PDF sets also studied.

Good agreement between data and theory + new NNLO calculation = **sensitivity to constrain gluon PDF**

W+c



SMP-17-014

Muon:

$p_T(\mu) > 26\ GeV$

$|\eta| < 2.4$

$M_T > 50\ GeV$

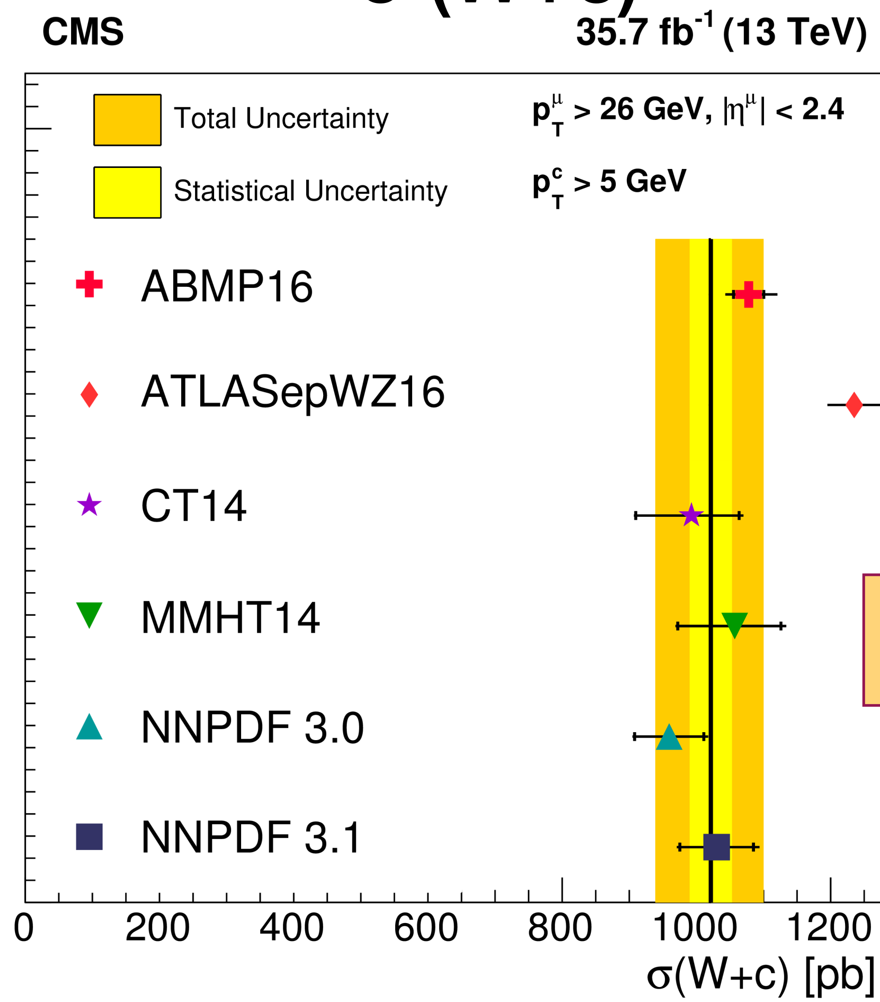
D*(2010):

$p_T(D^*) > 5\ GeV$

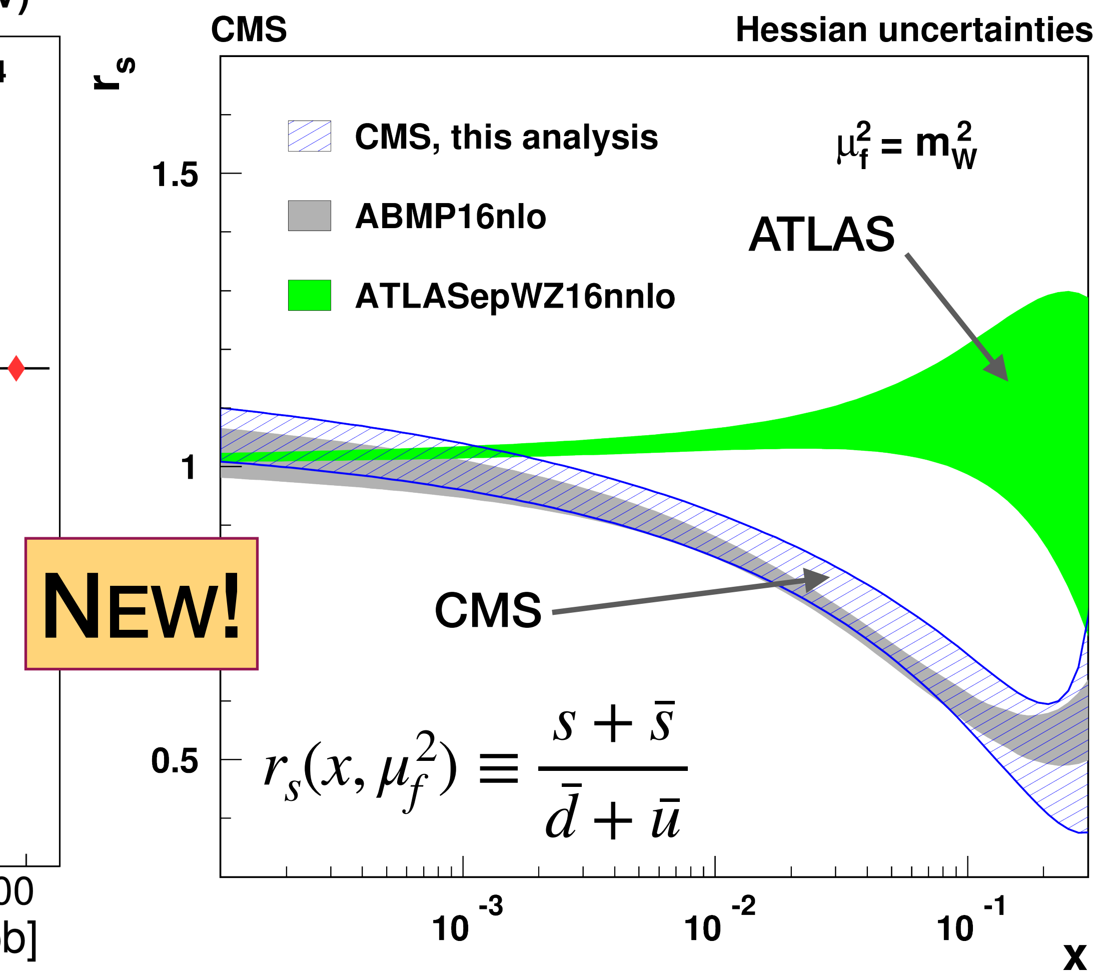
D^0 reconstruction.

D identification: mass difference method.*

σ (W+c)



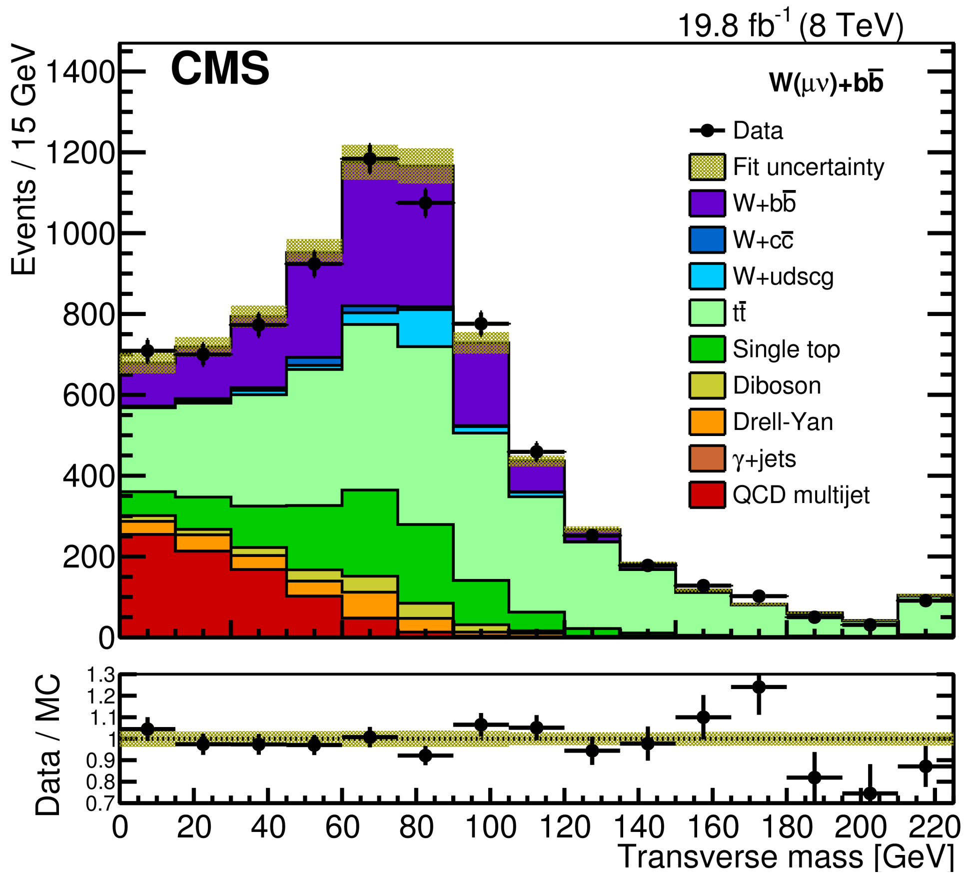
$r_s(x, \mu^2_f)$



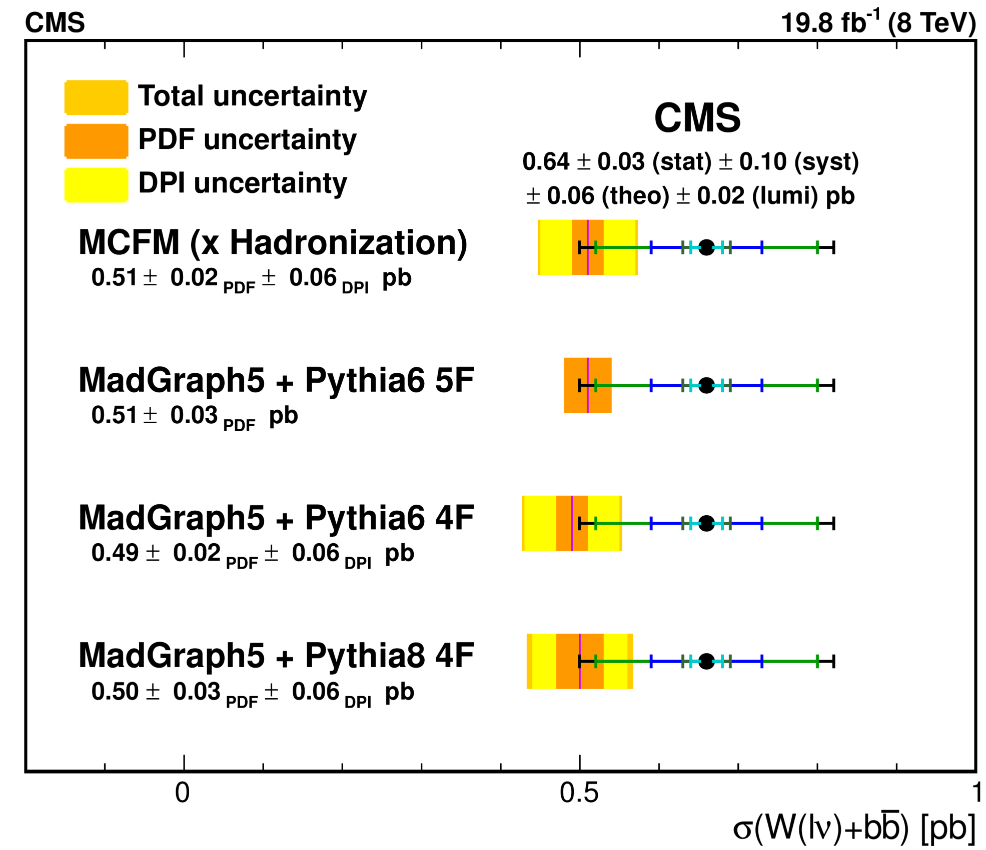
- pp collisions @13 TeV, 35.7 fb^{-1} data (2016)
- W+c measurement: probe proton strange quark content
- Dominant background: cc from gluon splitting. Data-driven reduction using charge sign of W and D*
- Measured cross-section compared to **NLO QCD predictions (MCFM)** using several **PDF sets**
- Good agreement except for ATLASepWZ16nnlo: **do not** support hypothesis of **enhanced strange quark** contribution in **proton sea** (ATLAS, dx.doi.org/10.1140/epjc/s10052-017-4911-9)

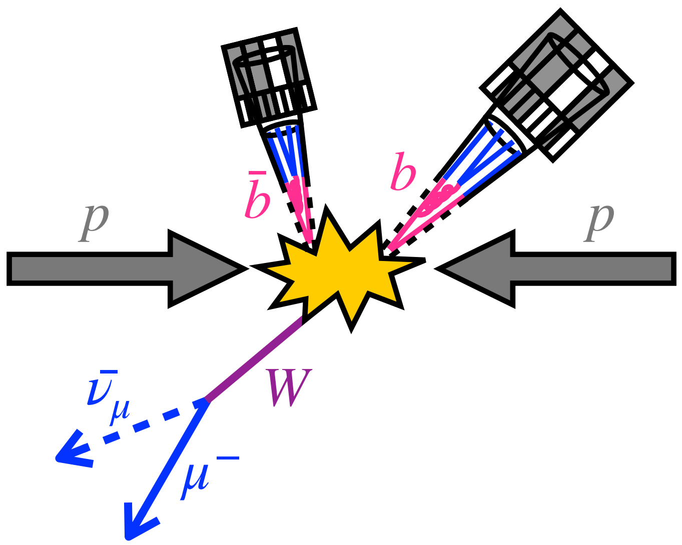
W+2b

M_T



σ (W+2b)





SMP-14-020

Leptons:

$p_T(l) > 30$ GeV

$|\eta| < 2.1$

Jets:

anti-kT $(R = 0.4)$

CSV b-tagging

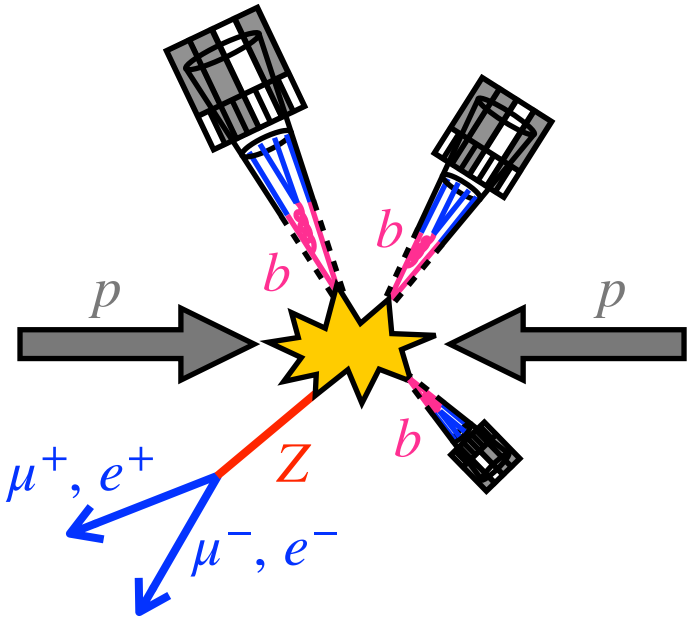
$p_T(j) > 25$ GeV

$|\eta| < 2.4$

$\Delta R(jet, l) > 0.4$

- pp collisions @8 TeV, 19.8 fb^{-1} data (2012)
- W+2b measurement: probe proton bottom quark content
- Leptonic decays (μ or e) + 2b jets.
- Dominant background: tt̄ production (data-driven estimation)
- Measured cross-section compared to **LO predictions** using several **flavour scheme**
- **Good agreement between data and theory**

Z+b



SMP-14-010

Leptons:

$p_T(l) > 20$ GeV

$|\eta| < 2.4$

$M_{ll} = 91 \pm 20$ GeV

Jets:

anti-kT $(R = 0.4)$

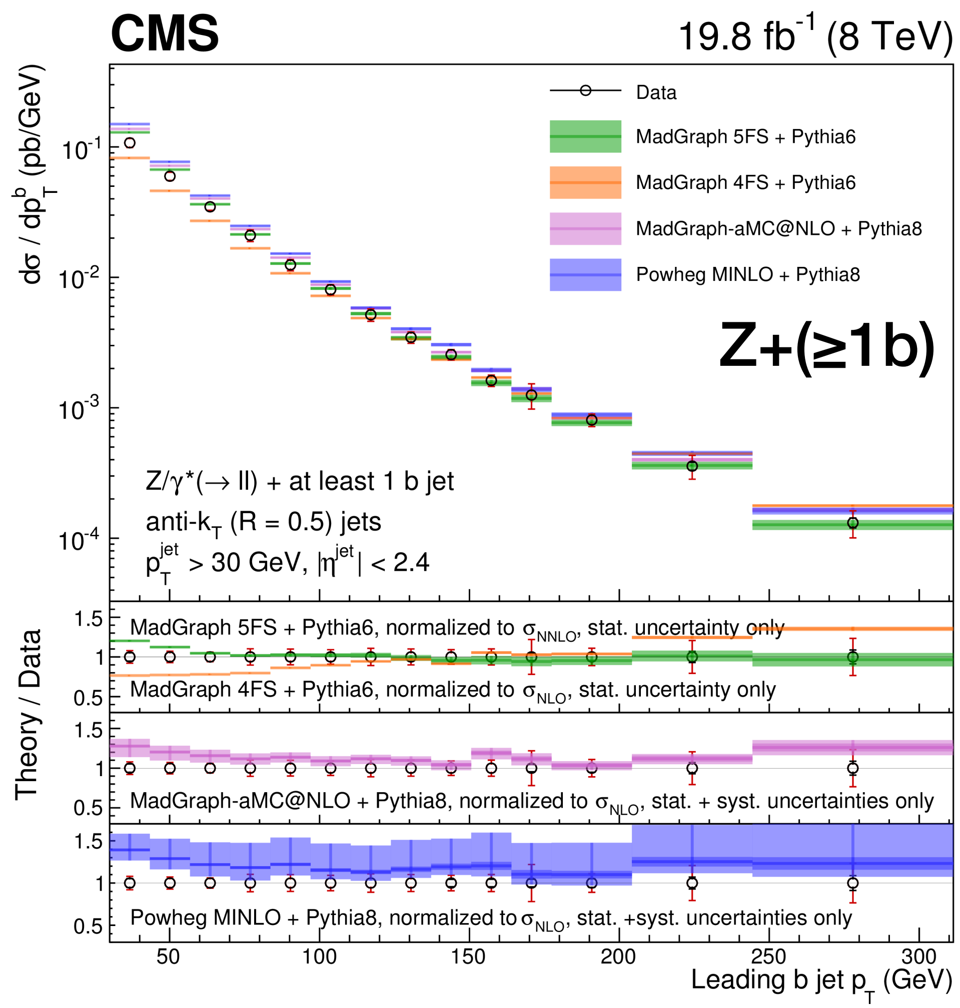
CSV b-tagging

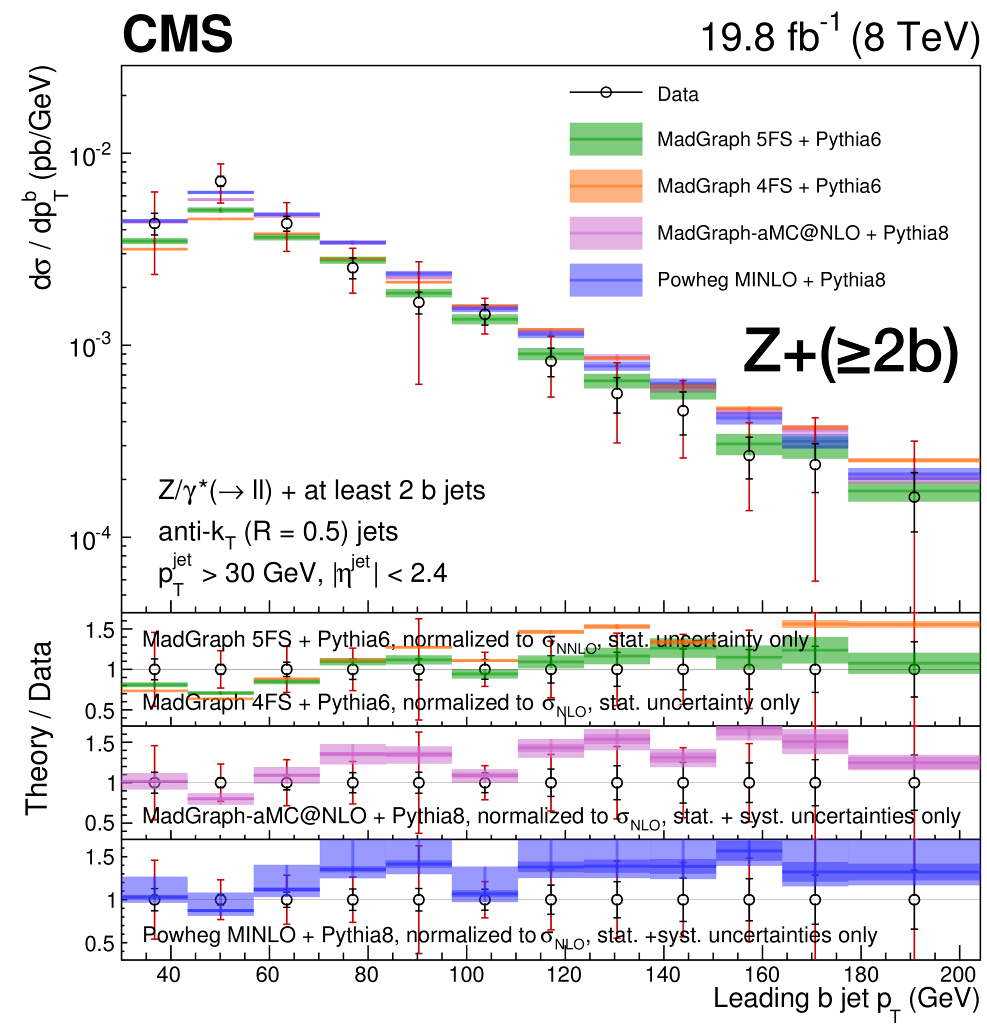
$p_T(j) > 30$ GeV

$|\eta| < 2.4$

$\Delta R(jet, l) > 0.4$

p_T (jet)





- pp collisions @8 TeV, 19.8 fb^{-1} data (2012)
- Z+b measurement: probe proton bottom quark content
- Leptonic decays (μ or e) + 2b jets
- Dominant background: $t\bar{t}$ production (data-driven estimation)
- Measured cross-section compared to **LO(NLO) predictions** using several **flavour scheme**
- **Good agreement between data and theory**

Conclusions

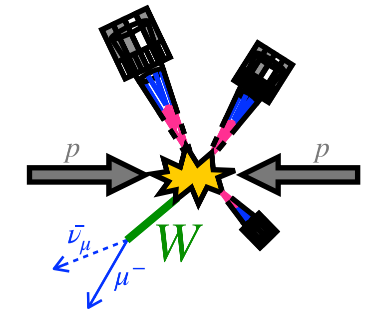
1. CMS has provided a **broad range** of V+jets measurements exploiting **8-13 TeV** pp collisions at LHC.

2. High precision achieved in inclusive and differential cross-sections using new experimental methods and larger datasets.

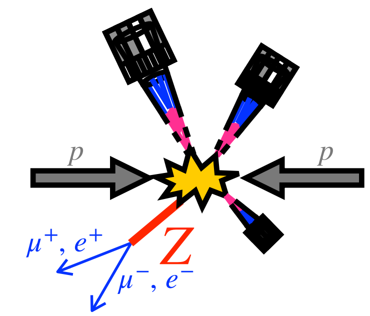
3. Measurements generally in good agreement with with predictions (NLO ME calculations, PS models and N(NLO) fixed-order theoretical calculations).

4. Future improvements:

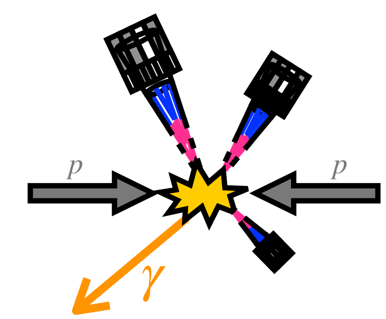
   - Trying to go beyond NLO. testing new generations of MC (DIRE, VINCIA, GENEVA, SHERPA)
   - Constrain systematic uncertainties
   - Improve unfolding and statistical techniques



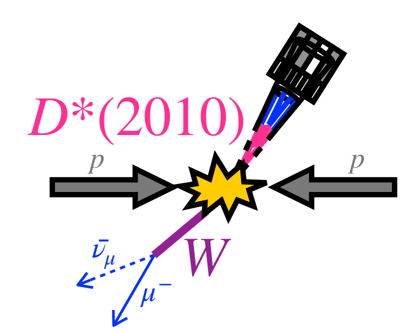
SMP-16-005



SMP-16-015



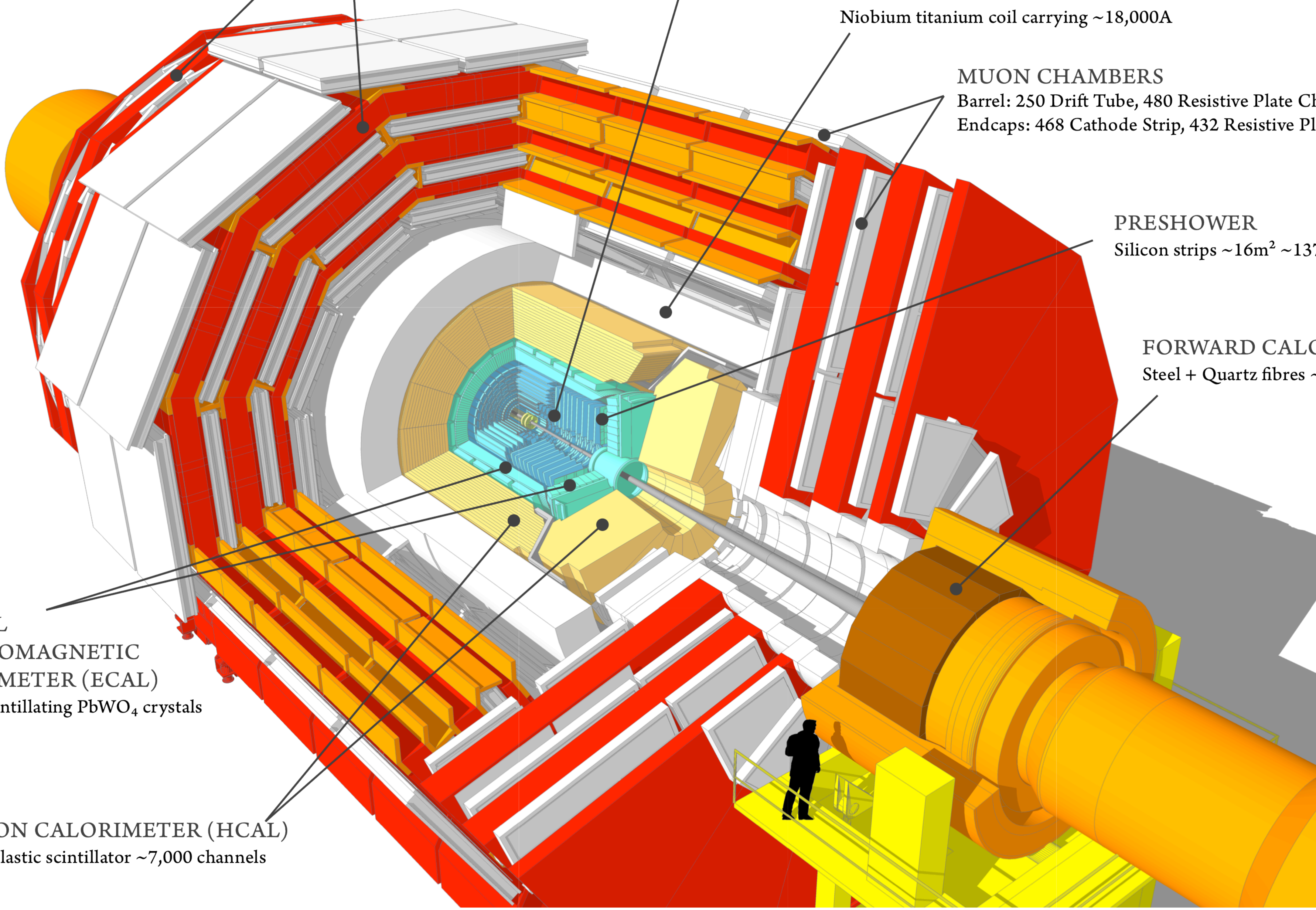
SMP-16-003



SMP-17-014
SMP-14-020
SMP-14-010

BACKUP

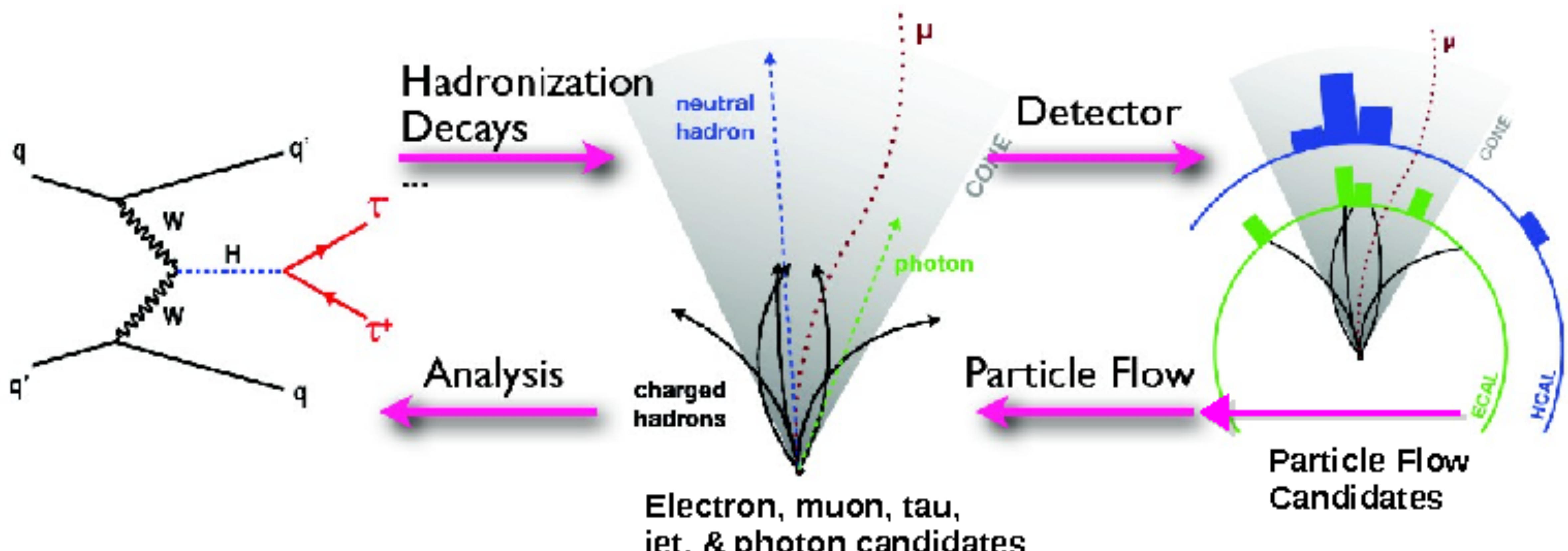
THE CMS EXPERIMENT



THE CMS PARTICLE-FLOW ALGORITHM

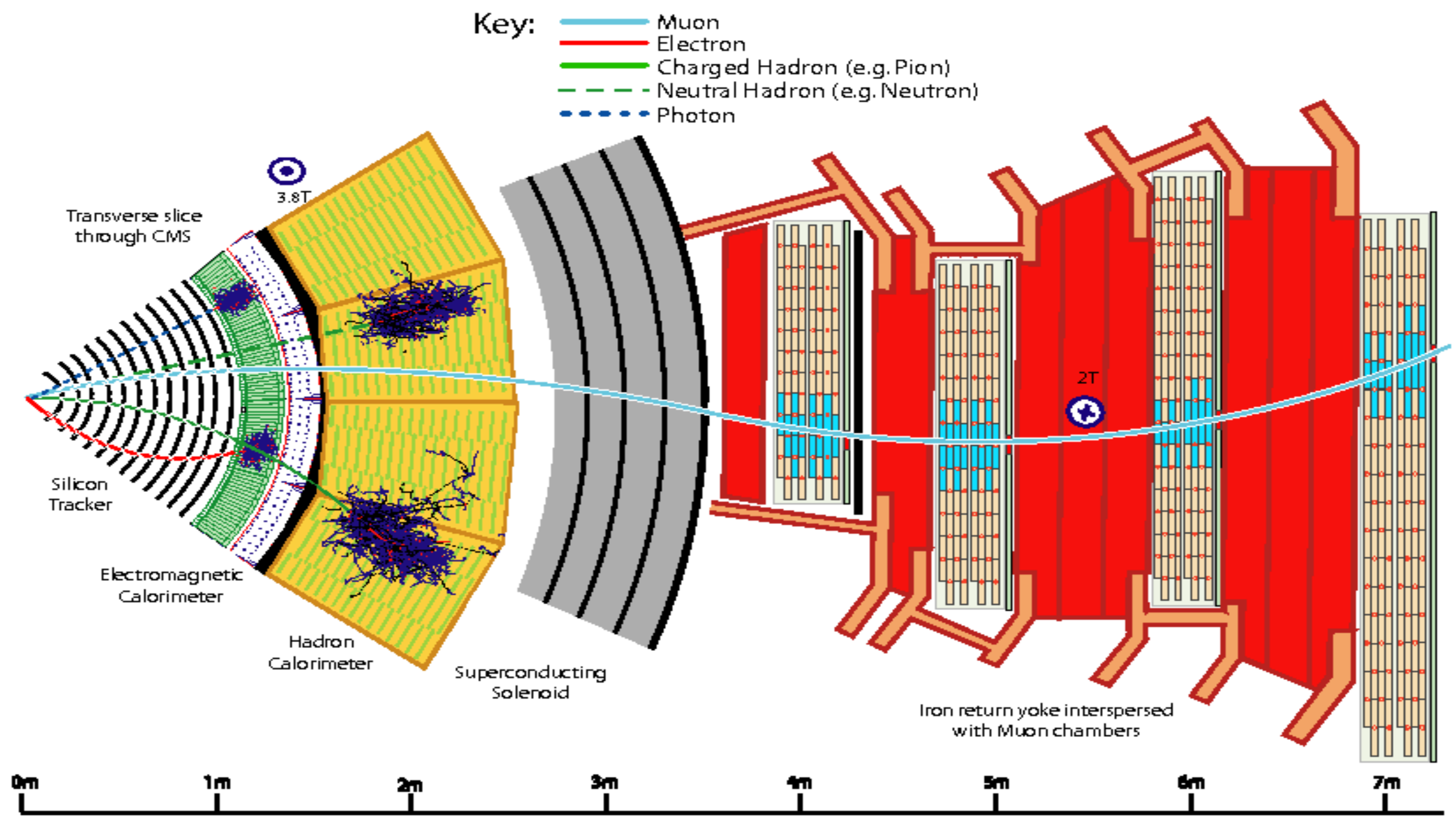
Reconstruction and identification: combination of information from the various elements of the CMS detector:

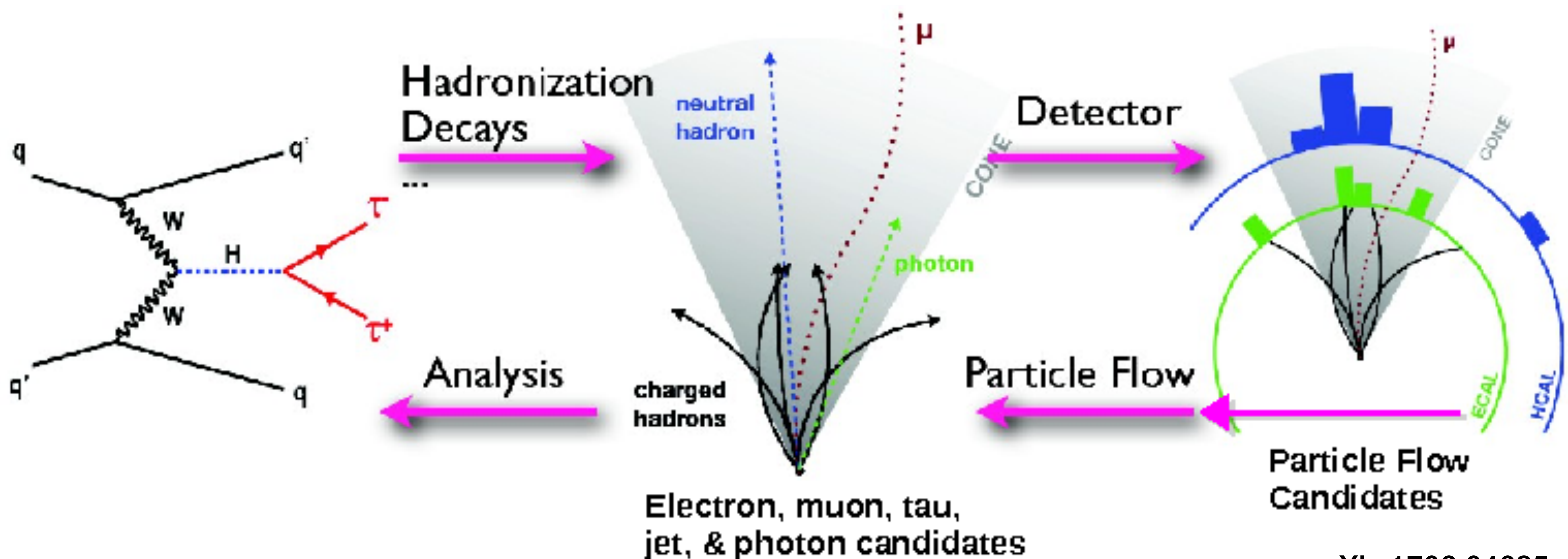
- **Energy of photons** → ECAL measurement.
- **Energy of electrons** → combination of electron momentum (tracker) + energy of the corresponding ECAL cluster + sum of all bremsstrahlung photons.
- **Muon momentum** → track curvature in tracker and muon system.
- **Energy of charged hadrons** → momentum (tracker) + matching ECAL and HCAL energy deposits. Correction for response function of the calorimeters to hadronic showers.
- **Energy of neutral hadrons** → corrected ECAL + HCAL energy.



arXiv:1702.04685

THE CMS PARTICLE-FLOW ALGORITHM





arXiv:1702.04685