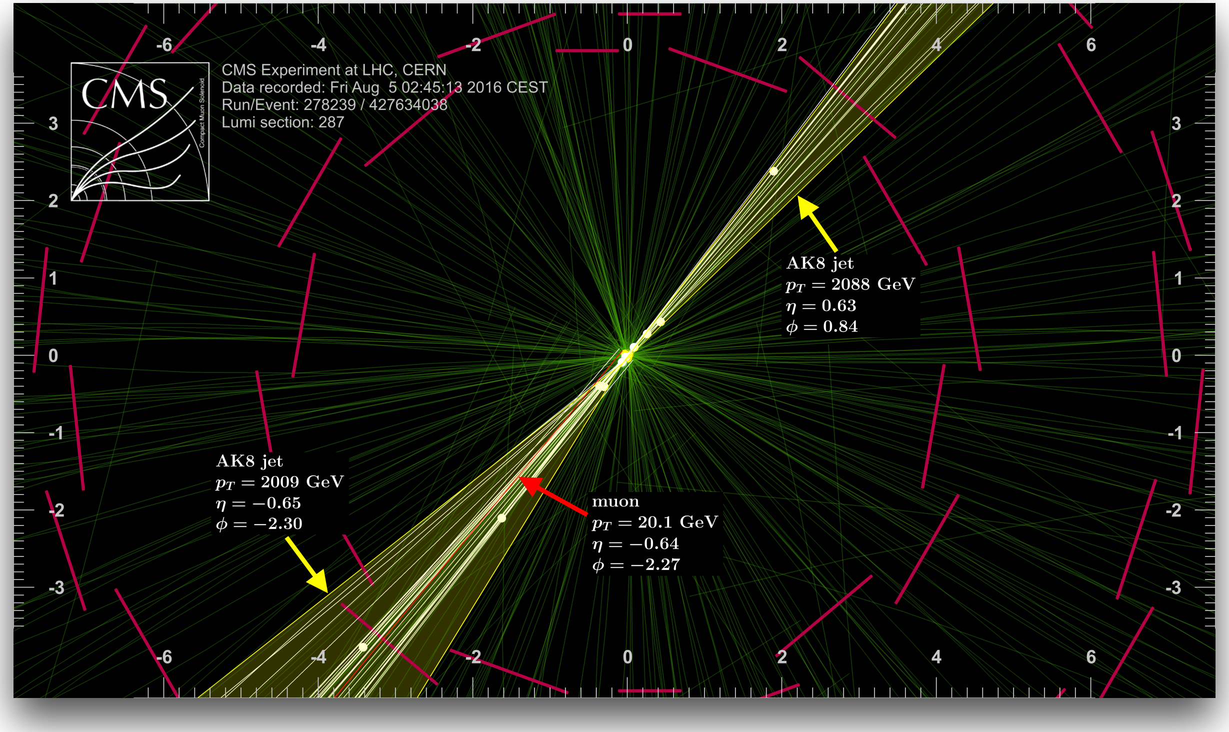
Hard QCD and Jet physics at LHC

(results form ATLAS and CMS)



1) **Inclusive jet productions**
2) **Jet substructure**
3) **V+jets**
4) **Some highlights**
5) **Double Parton Scattering**

LFC19 - 9-13 September 2019 - ECT*

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Credits to:
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Christine McLean

1) **Inclusive jet productions**
2) Jet substructure
3) V+jets
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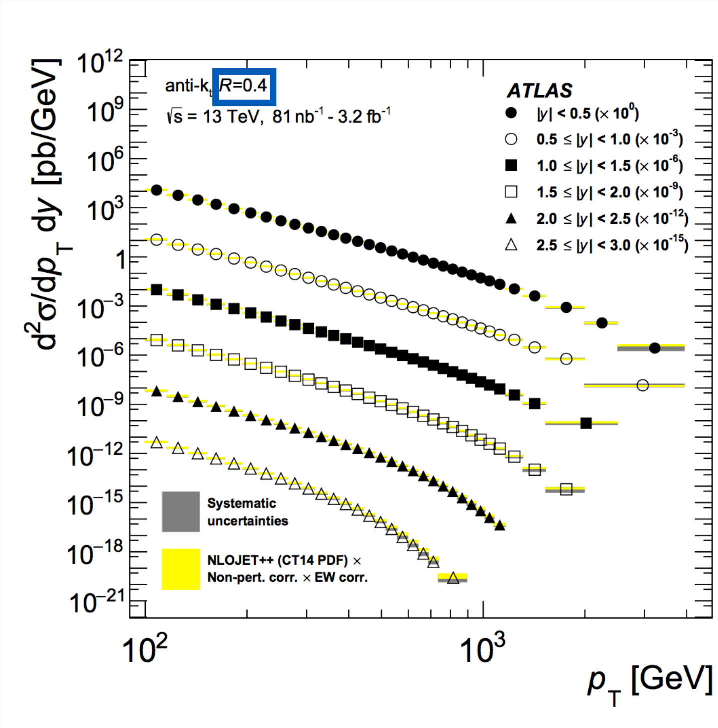
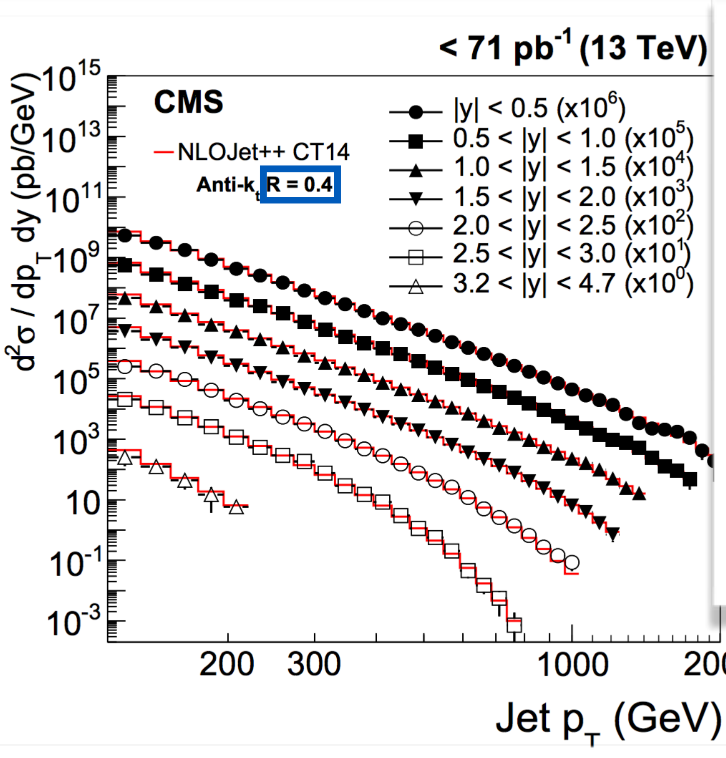
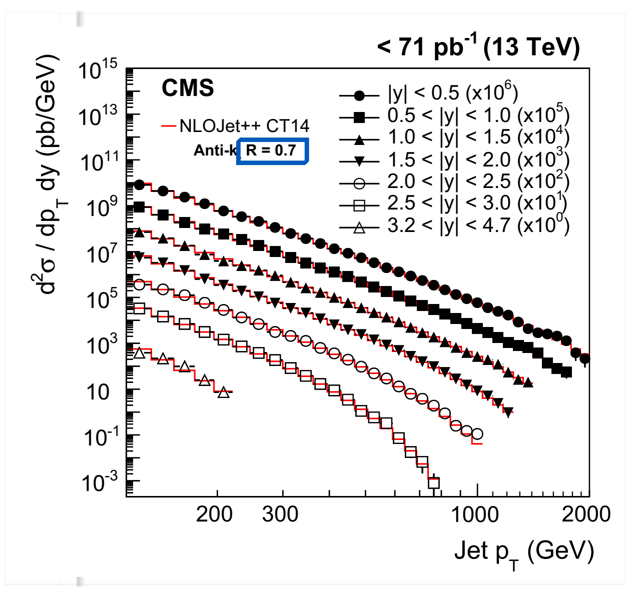
Inclusive jet production

ATLAS - JHEP 05 (2018) 195
CMS - EPJC 76 (2016) 451







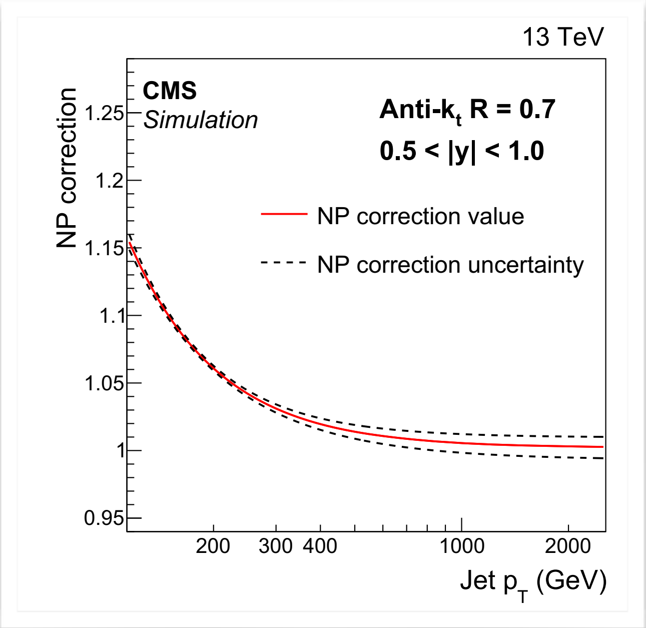
$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{\epsilon\mathcal{L}}\frac{N_j}{\Delta p_T \Delta y}$$

Double differential inclusive jet cross section

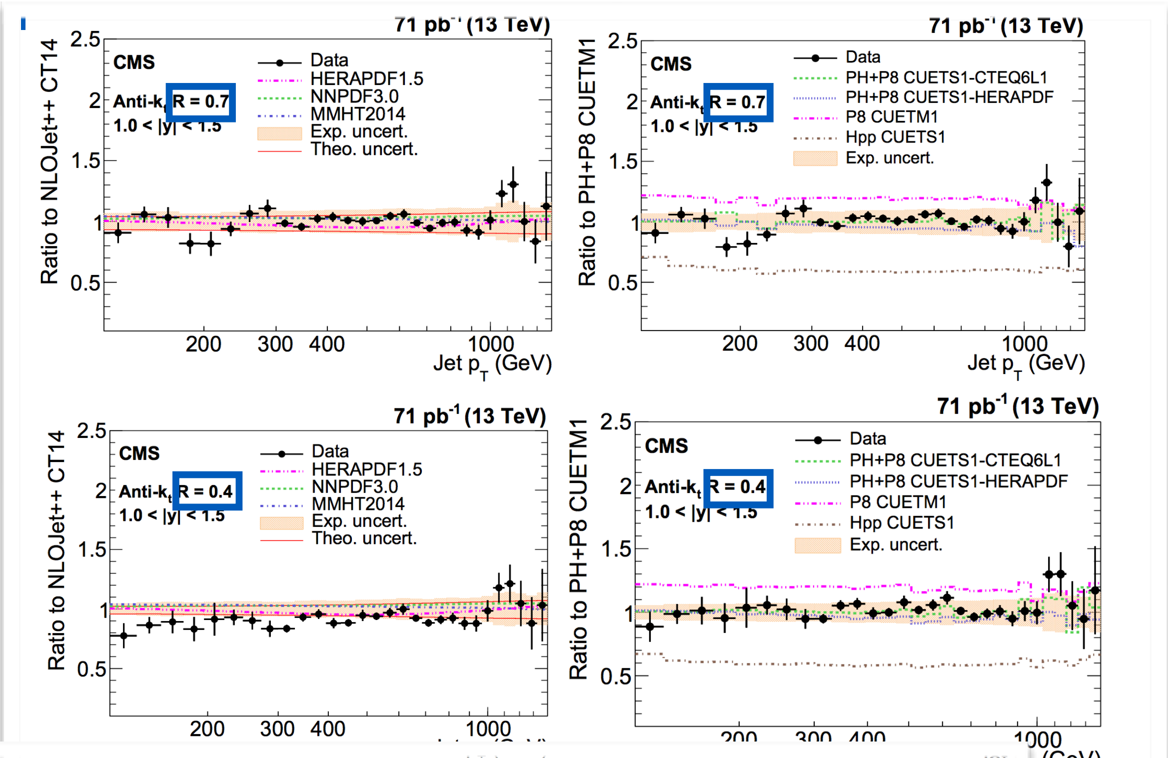
Predictions of perturbative NLO precision + EW and NP corrections (hadronisation and soft MPI),

Theoretical uncertainties from the scale, PDF, α_S , and NP (soft MPI and hadronisation)

In the phase space accessible with the new data, this measurement provides a first indication that **jet physics is as well understood at √s=13 TeV as at smaller centre-of-mass energies**.



Inclusive jet production

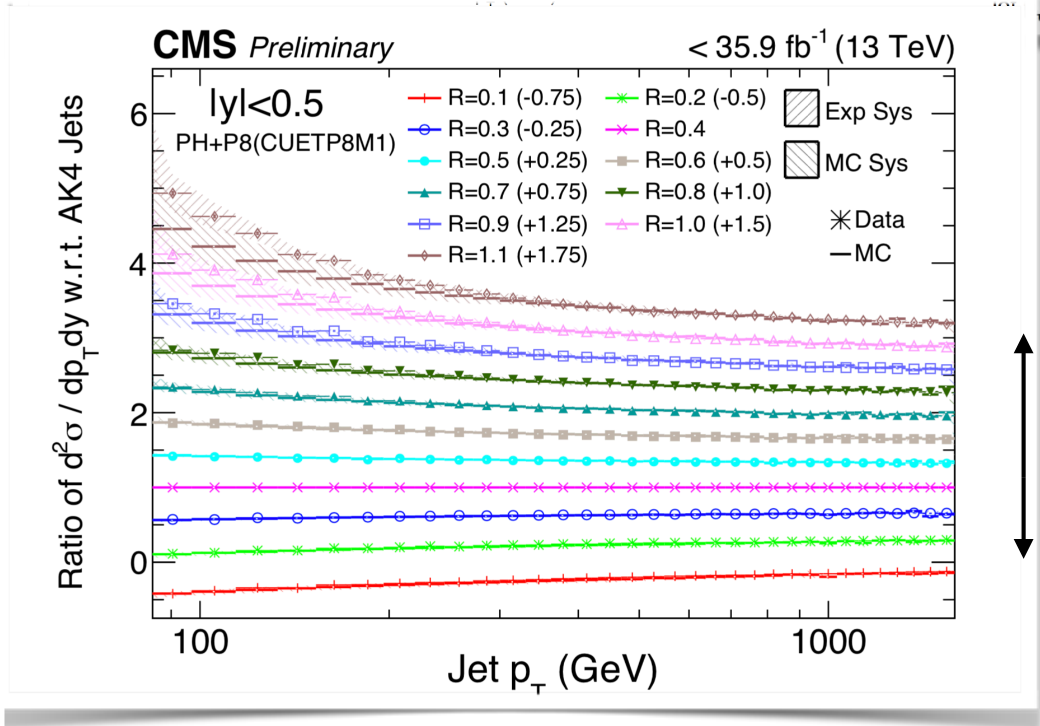


Fixed order NLO predictions (+ NP and EW corrections) overestimates for R=0.4 due to missing PS and soft gluon resummation.

NLO prediction matched to PS (PowHeg+Pythia8) more effective overall

The cross section for a jet size of 0.4, is best described by NLO matched to parton showering, hadronisation, and multiparton interactions.

PDF set dependence inside theoretical uncertainty



NLO+PS - clustering parameter

Larger uncertainty for low_pT and large radius

Large R - underlying event (MPI)

Underlying-event (MPI): $(\delta p_T)_{UE} \sim \mathbf{R}^2$

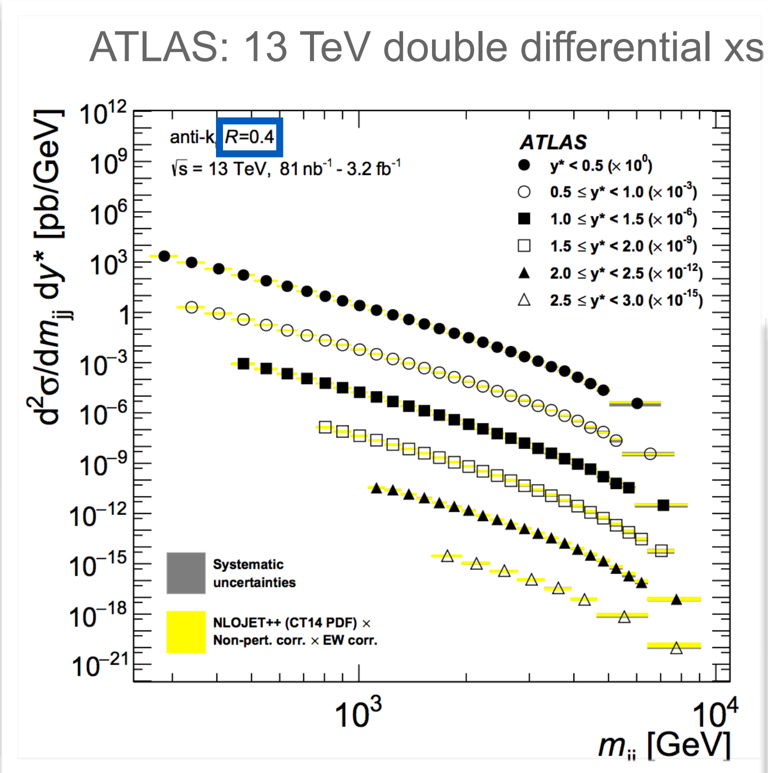
Hadronization: $(\delta p_T)_{HAD} \sim \mathbf{R}^{-1}$

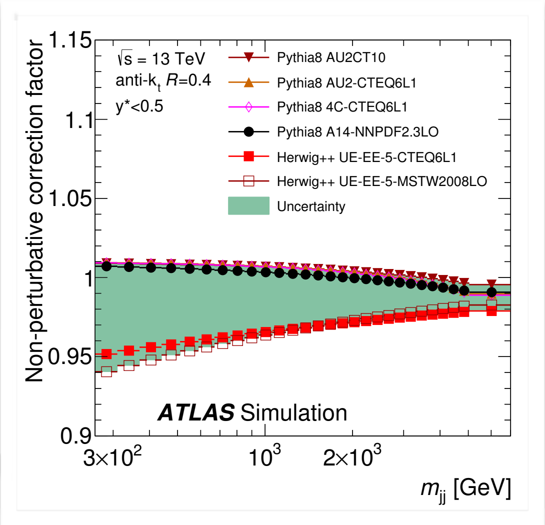
Parton shower: $(\delta p_T)_{PS} \sim \ln \mathbf{R}^{-1}$

Small R - HAD+PS

Di-jet production

ATLAS - JHEP 05 (2018) 195





Uncertainties in the NLO QCD cross-section

1) Renormalisation and factorisation scale is dominant:

10% at about m_{jj} = 300 GeV in the central rapidity bin

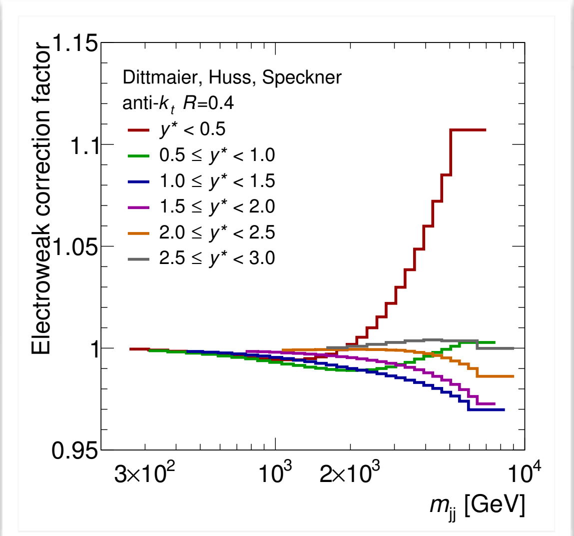
50% in the highest m_{jj} bins in the most forward rapidity region

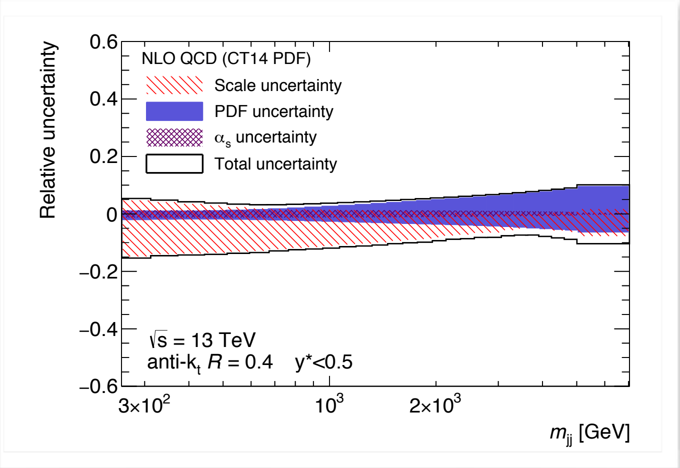
2) PDF uncertainties vary from 2% to 12%

3) Contribution from the α_S uncertainty is about 2% at low m_{jj} and negligible elsewhere

4) Non-perturbative correction derived using Pythia 8 with the A14 tune with the NNPDF2.3 LO PDF set

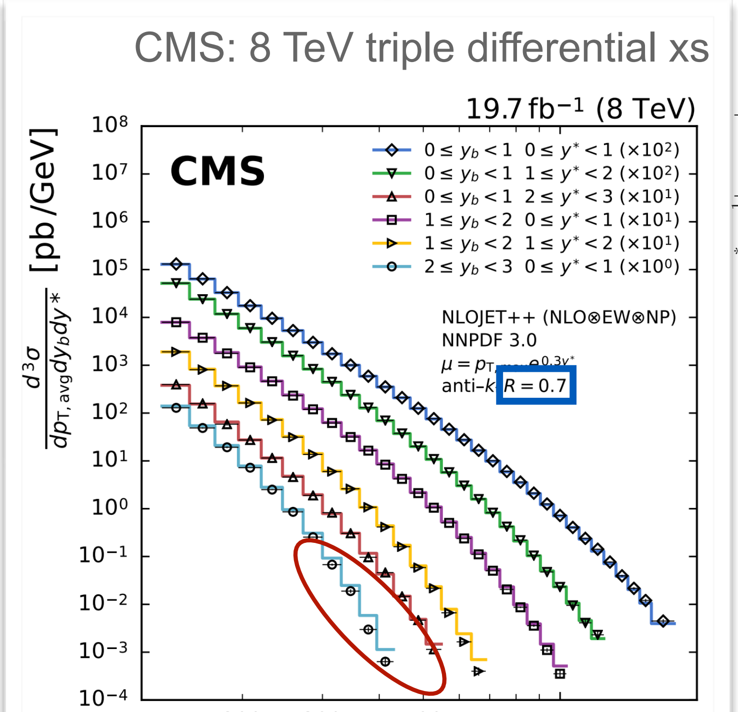
5) EW correction reaches 11% at m_{jj}=7 TeV for central rapidity



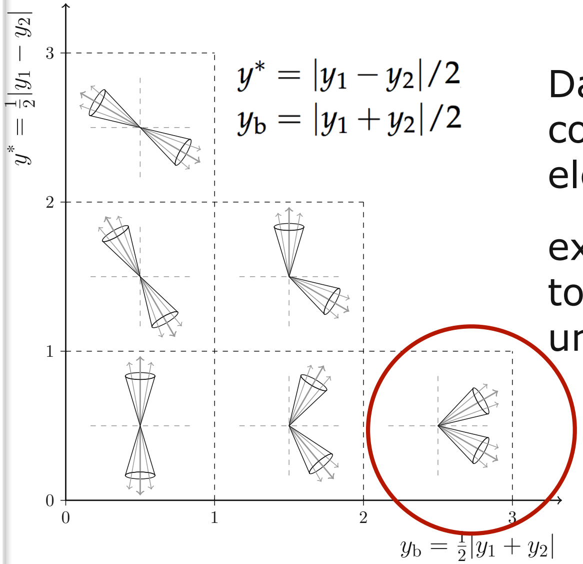


Di-jet production

CMS - EPJC 77 (2017) 746


CMS: 8 TeV triple differential xs

$$p_{\mathrm{T,avg}} = (p_{\mathrm{T},1} + p_{\mathrm{T},2})/2$$

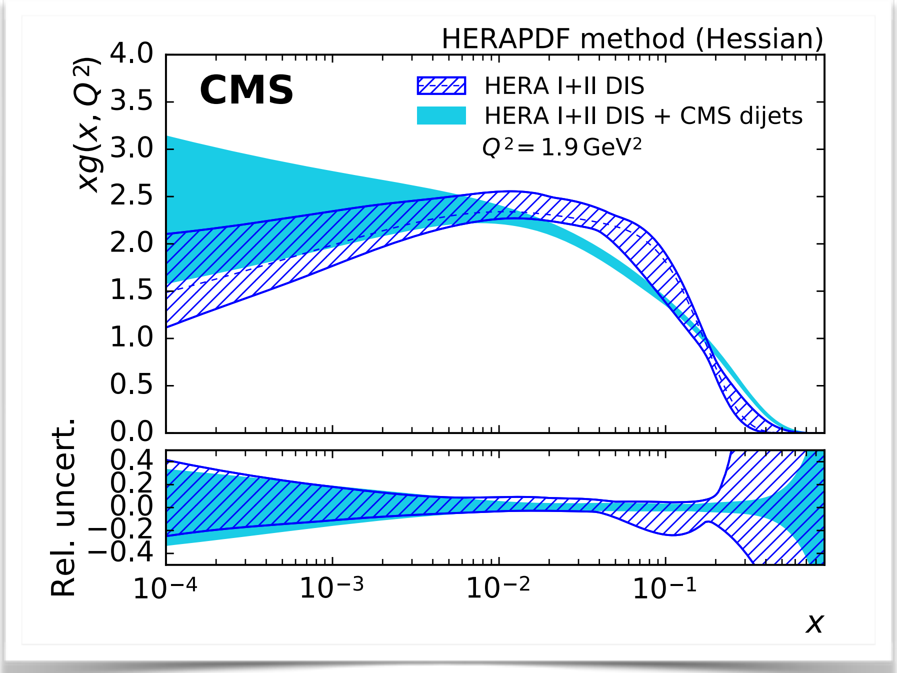


$$y^* = |y_1 - y_2|/2$$
$$y_b = |y_1 + y_2|/2$$

Data well described by NLO predictions corrected for non-perturbative and electroweak effects

except for highly boosted event topologies that suffer from large uncertainties in PDFs

...the precise data constrain the PDFs, especially in the highly boosted regime that probes the highest fractions *x*



An increased gluon PDF at high *x* is obtained and the overall uncertainties of the PDFs, are significantly reduced.

The strong coupling constant $\alpha_S(M_Z)$ is extracted together with the PDFs in agreement with previous measurements:

$$\begin{aligned} \alpha_S(M_Z) &= 0.1199 \pm 0.0015\,(\mathrm{exp}) \\ &\quad \pm 0.0002\,(\mathrm{mod})\,{}^{+0.0002}_{-0.0004}\,(\mathrm{par})\,{}^{+0.0031}_{-0.0019}\,(\mathrm{scale}) \\ &= 0.1199 \pm 0.0015\,(\mathrm{exp})\,{}^{+0.0031}_{-0.0020}\,(\mathrm{theo}), \end{aligned}$$

Dominants uncertainty is theoretical, expected to be reduced using pQCD NNLO predictions

1) **Inclusive jet productions**
2) **Jet substructure**
3) **V+jets**
4) **Some highlights**
5) **Double Parton Scattering**

Jet structure

Jet physics and jet substructure is an area in which experimental and theoretical approaches meet together. Cross-pollination and collaboration between the two communities

1) Search for new physics (push toward higher mass and reduced x-sec)

2) Standard Model measurements (e.g. in boosted topologies)

A quest for a deeper understanding of jet substructure algorithms has contributed to a renewed interest in all-order calculations in Quantum Chromodynamics (QCD).

An increasing impact in the study of heavy-ion collisions, or with the exploration of deep-learning techniques.

Technical

Disentangle different “kinds” of jets (initiators, boosted, radiation…)

Prong finders - multiple hard cores in the jet reducing the contamination from bg QCD jets:

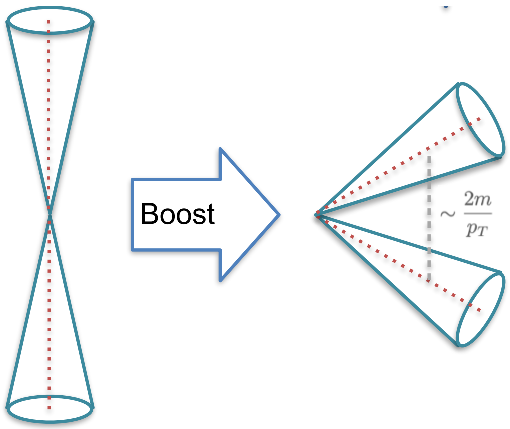
- QCD jets would be 1-prong objects
- W/Z/H jets would be two-pronged
- boosted top jets would be three-pronged
- an elusive new resonance with a boosted decay into two Higgs bosons, both decaying to a bb_bar pair would be a 4-prong object, ...

Radiation constraints - exploiting the energy correlation and the colour structure with the different soft-gluon radiation patterns:

- a softer QCD radiation is expected from a colorless object (an EW-boson jet)
- quark-initiated jets are expected to radiate less soft gluons than gluon-initiated jets

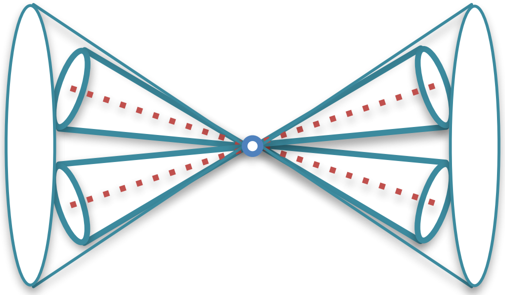
Groomers. Large-radius jets are sensitive to soft backgrounds (such as the UE and pileup) . “Grooming” tools remove the soft radiation far from the jet axis. Groomers share similarities with prong finders: removing soft contamination and keeping the hard prongs are closely related.

How?

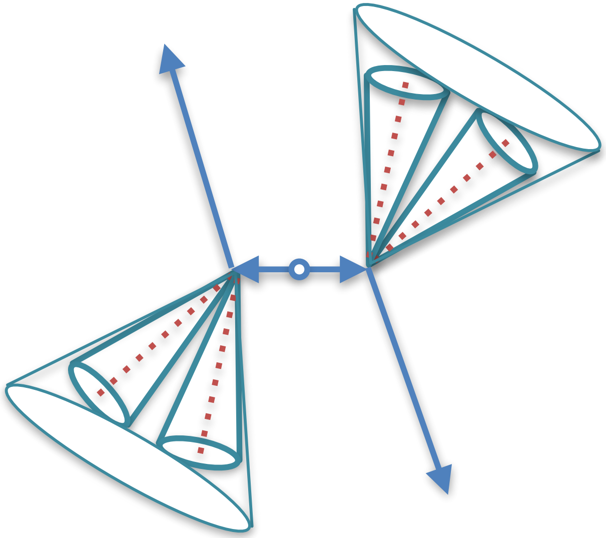


$$\Delta R_{ij} \sim \frac{m}{p_T} \frac{1}{\sqrt{z(1-z)}} \sim \frac{2m}{p_T}$$

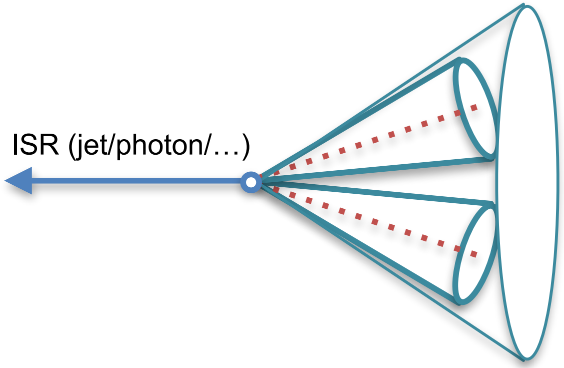
DR<1
- W with pT>150 GeV
- H with pT>250 GeV
- Top with pT>500 GeV



Heavy particles

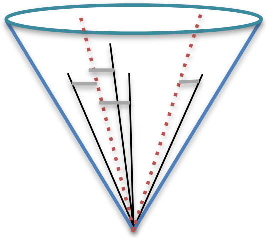


Pair production



Specific selections

How - observables and substructure approaches

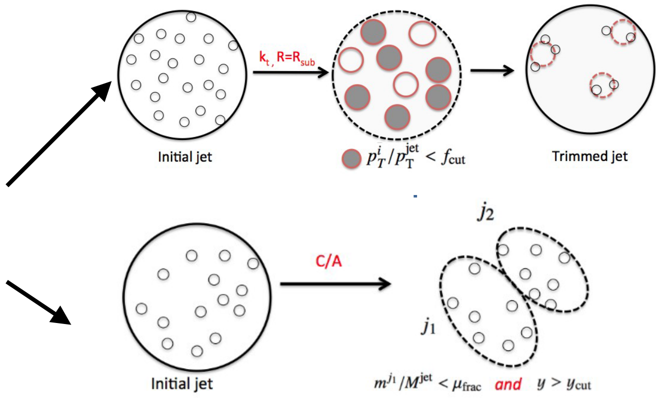


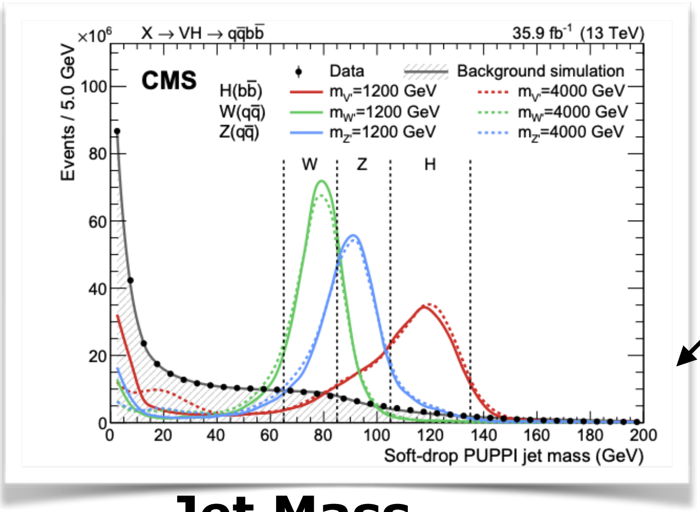
N-“subjettiness”

$$\tau_N^{(\beta)} = \frac{1}{p_t R^{\beta}} \sum_{i\in \mathrm{jet}} p_{ti} \min(\theta_{ia_1}^{\beta}, \ldots, \theta_{ia_N}^{\beta})$$

Grooming,
soft activity control
and cleaning

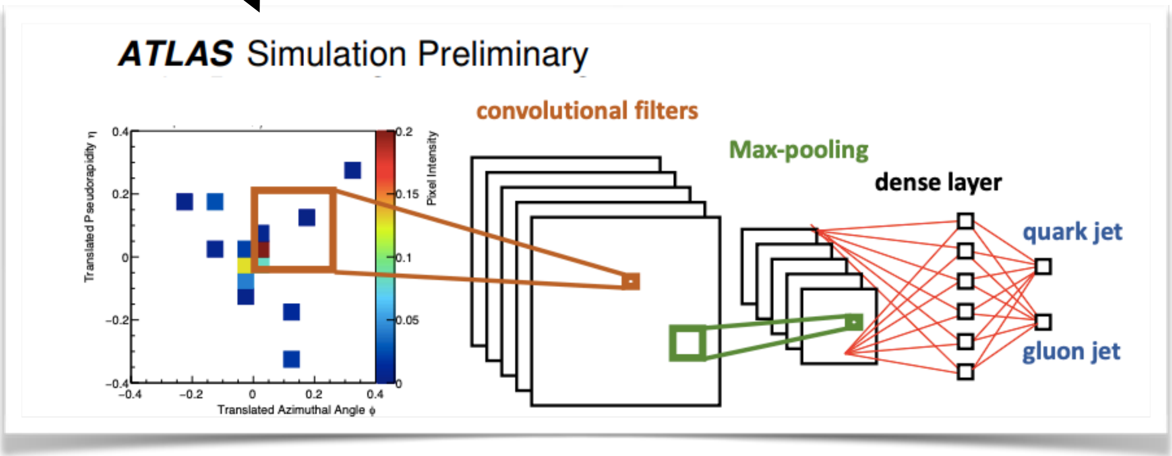
Trimming
Soft Drop





Jet Mass

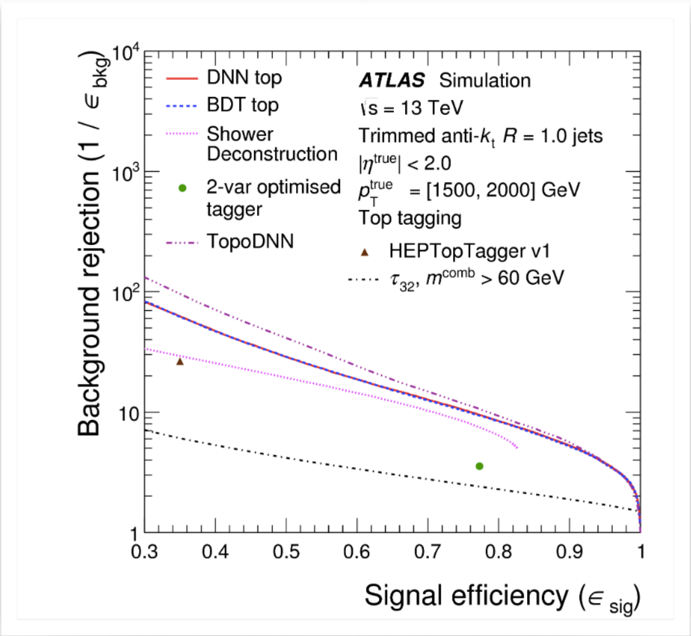
Classification

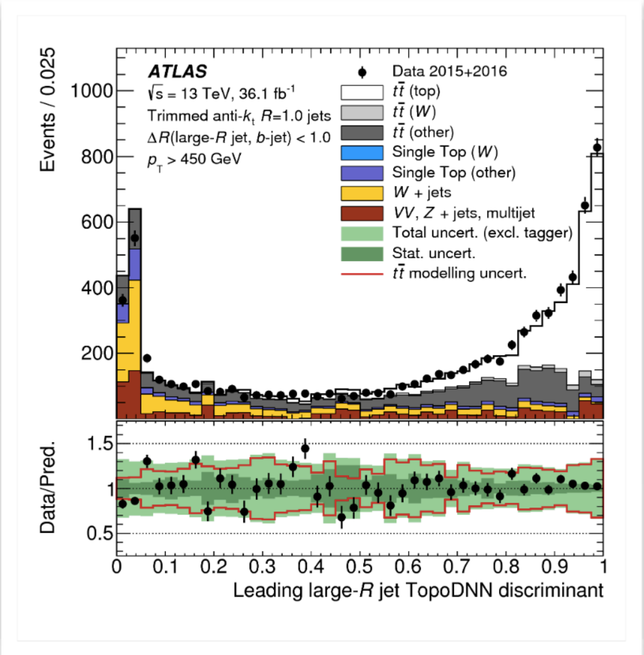


Neural Networks

How - observables and substructure approaches

ATLAS-JETM-2018-03
CMS DP-2017/027





top tagging

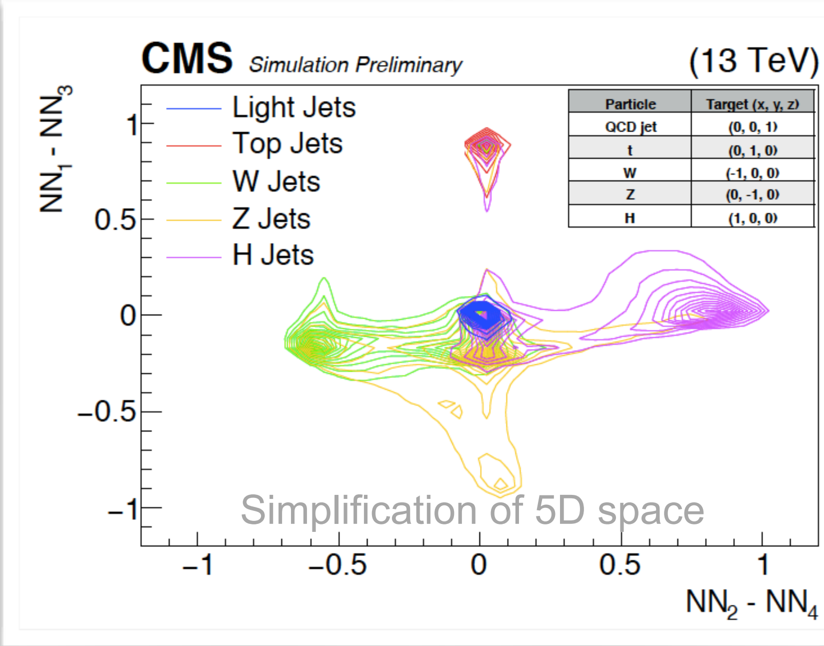
BDT and DNN
with ~10 substructure
observables as input

TopoDNN, directly uses
inputs to jet finding also

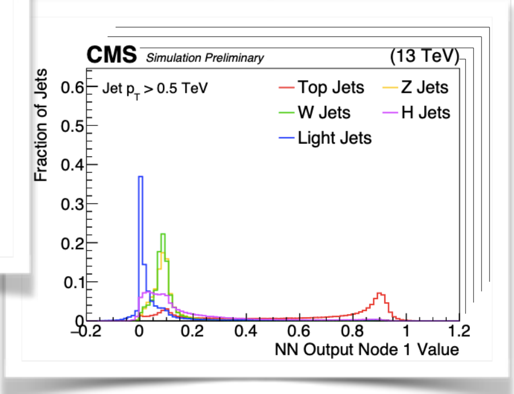
BEST
Boost Event Shape Tagger

simultaneously classify hadronic decays of boosted heavy objects and discriminate them from the light-jet background

Based on consistency test of a jet with its expected N-prong topology using hypothesized reference frames corresponding to each heavy particle mass

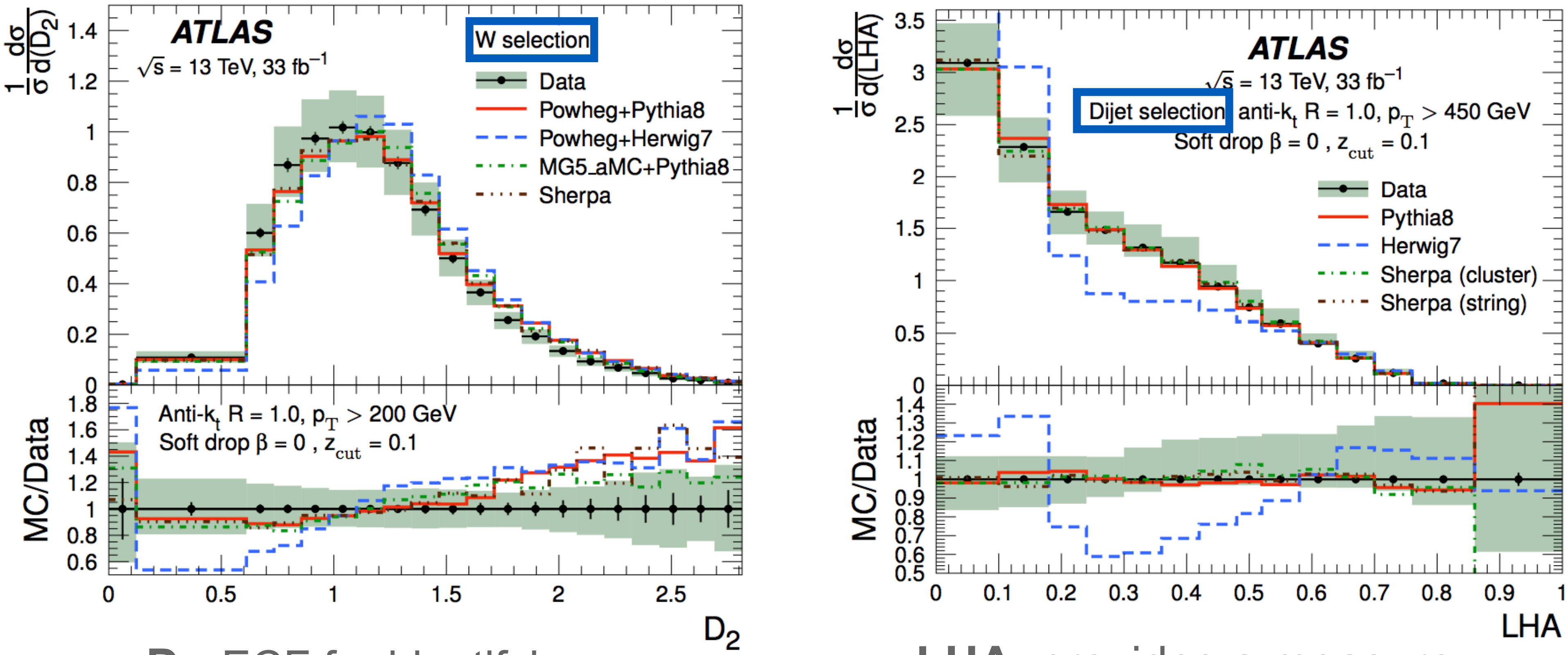


Particle	Target (x, y, z)
QCD jet	(0, 0, 1)
t	(0, 1, 0)
W	(-1, 0, 0)
Z	(0, -1, 0)
H	(1, 0, 0)



Substructures in large-R soft drop boosted jets

arXiv:1903.02942v1



D_2: ECF for identifying two-body structures

LHA: provides a measure of jet broadness

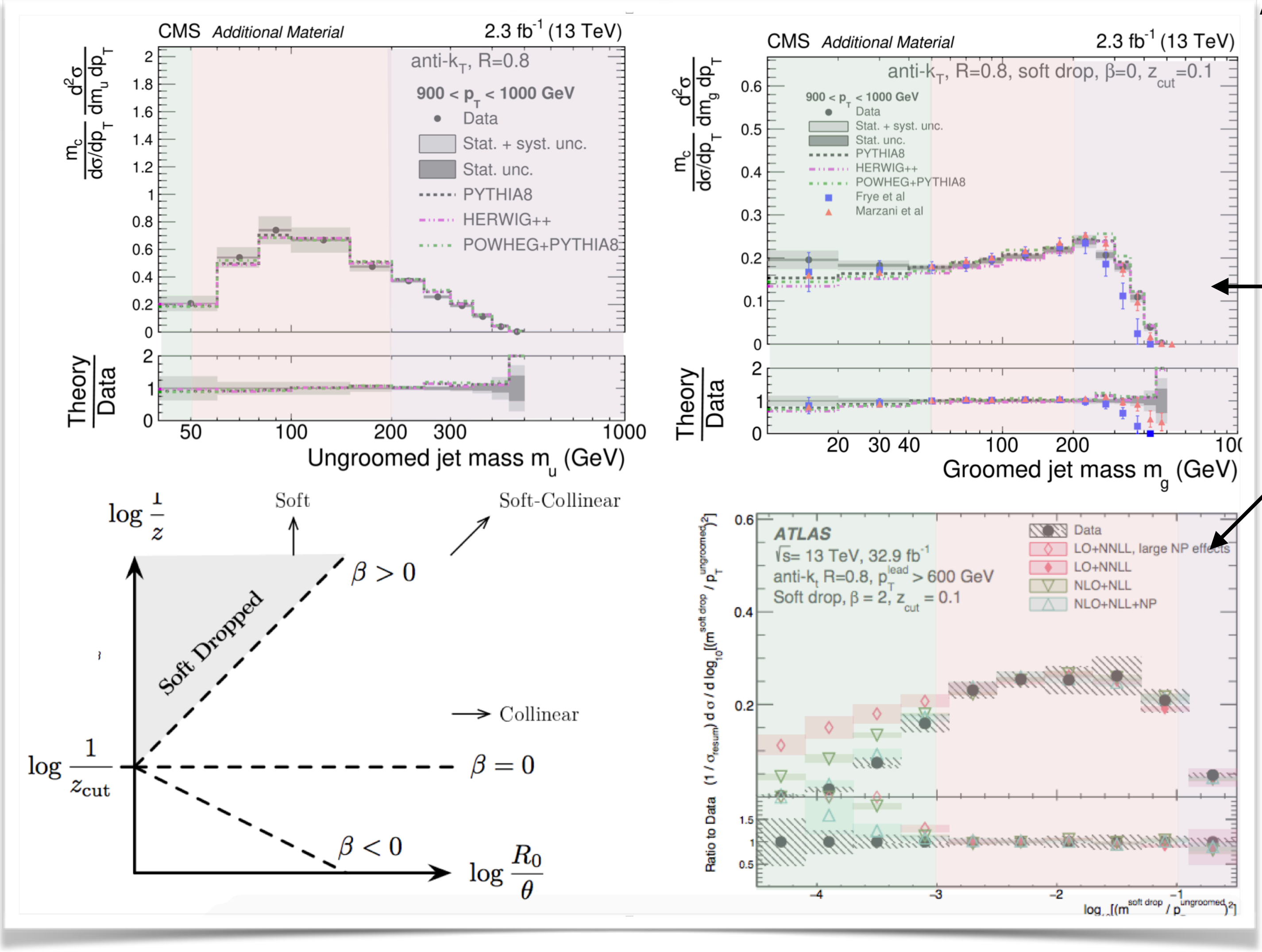
For the *W* selection, all MC predictions have a peak shifted relative to data, suggesting that the models are overestimating gluon radiation

Les Houches angularity (LHA) is compared between large-radius jets from data and MC model predictions.

For the dijet selection, all models except Herwig7 describe the data

Groomed vs ungroomed

CMS - JHEP 11 (2018) 113
ATLAS - PRL 121, 092001 (2018)



$$\frac{\min(p_{T1},p_{T2})}{p_{T1}+p_{T2}} > z_{\text{cut}}\left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

Di-jet events

pT [900,1000] GeV

pT_lead > 600 GeV

Non perturbative
Resummation
Fixed-order

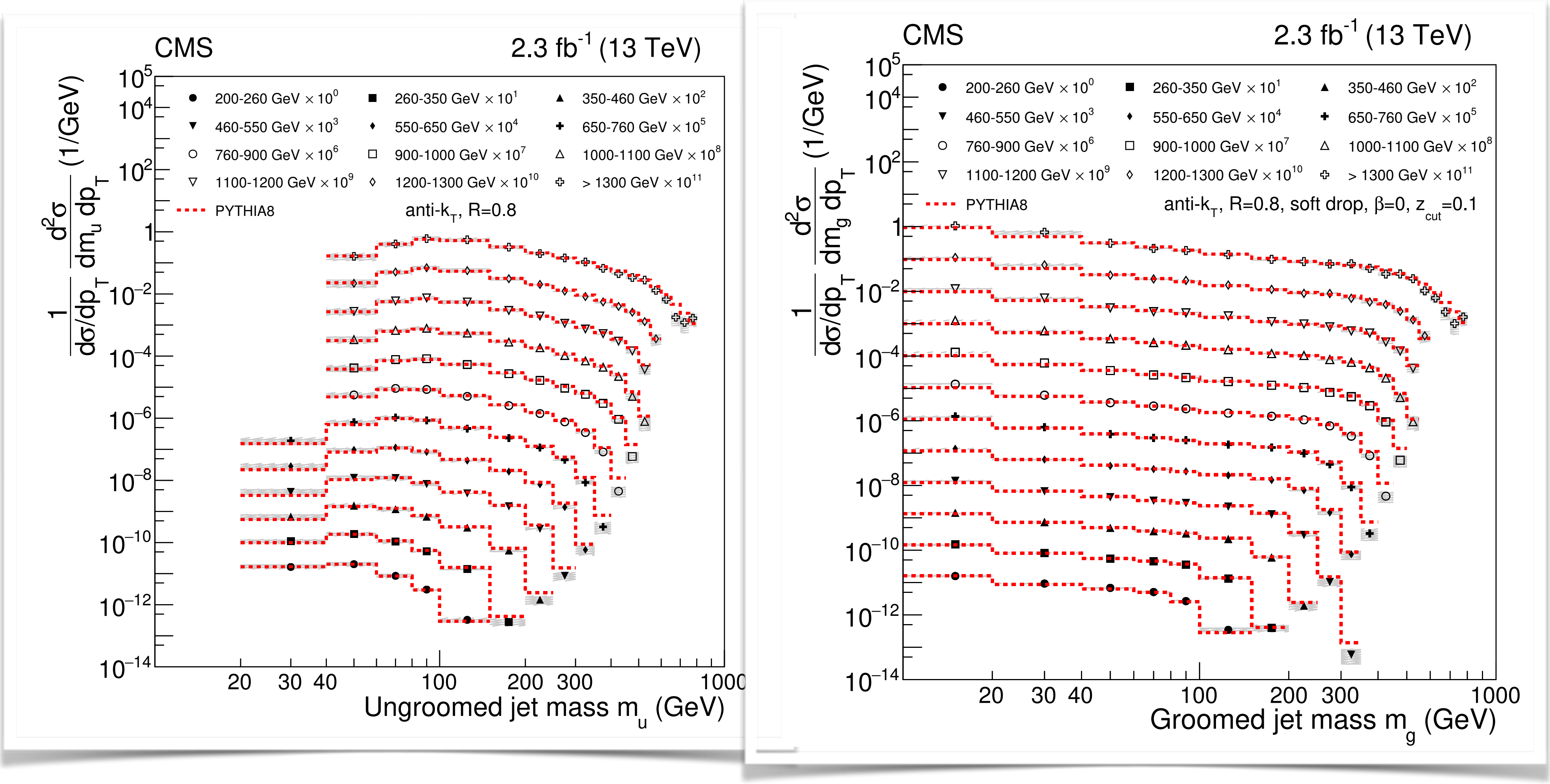
The data are compared to various theoretical predictions:

+LO prediction slightly off above the splitting threshold (m/pT>0.3), recovered by grooming

+NLO ~same behavior of LO

+LO and NLO + resumm disagree at very low masses and for $m/p_T > 0.3$

Differential jet cross section vs jet mass



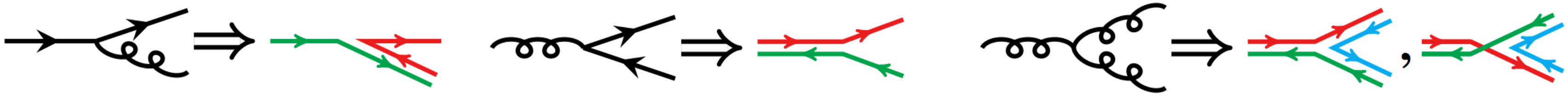
Jet mass probes high and low energy components of jet

Grooming

1) focus to probe the hard component

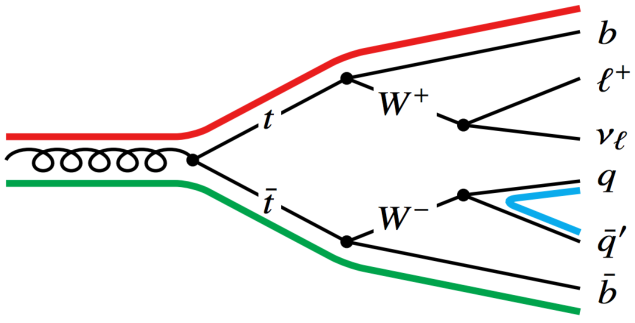
2) decrease the jet mass overall and reduce the sensitivity of the observable to details of the physics modeling and pileup effects.

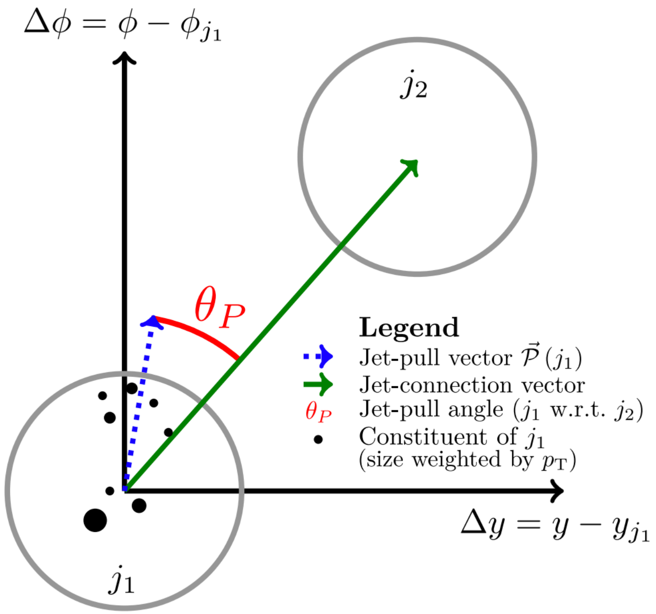
Color flow



Jet pull encodes color information

$$\vec{\mathcal{P}}(j)=\sum_{i\in j}\frac{\left|\Delta\vec{r}_i\right|\cdot p_{\mathrm{T}}^{i}}{p_{\mathrm{T}}^{j}}\,\Delta\vec{r}_i$$





Color connections affect radiation structure, kinematics (coherence) and topology (reconnection)

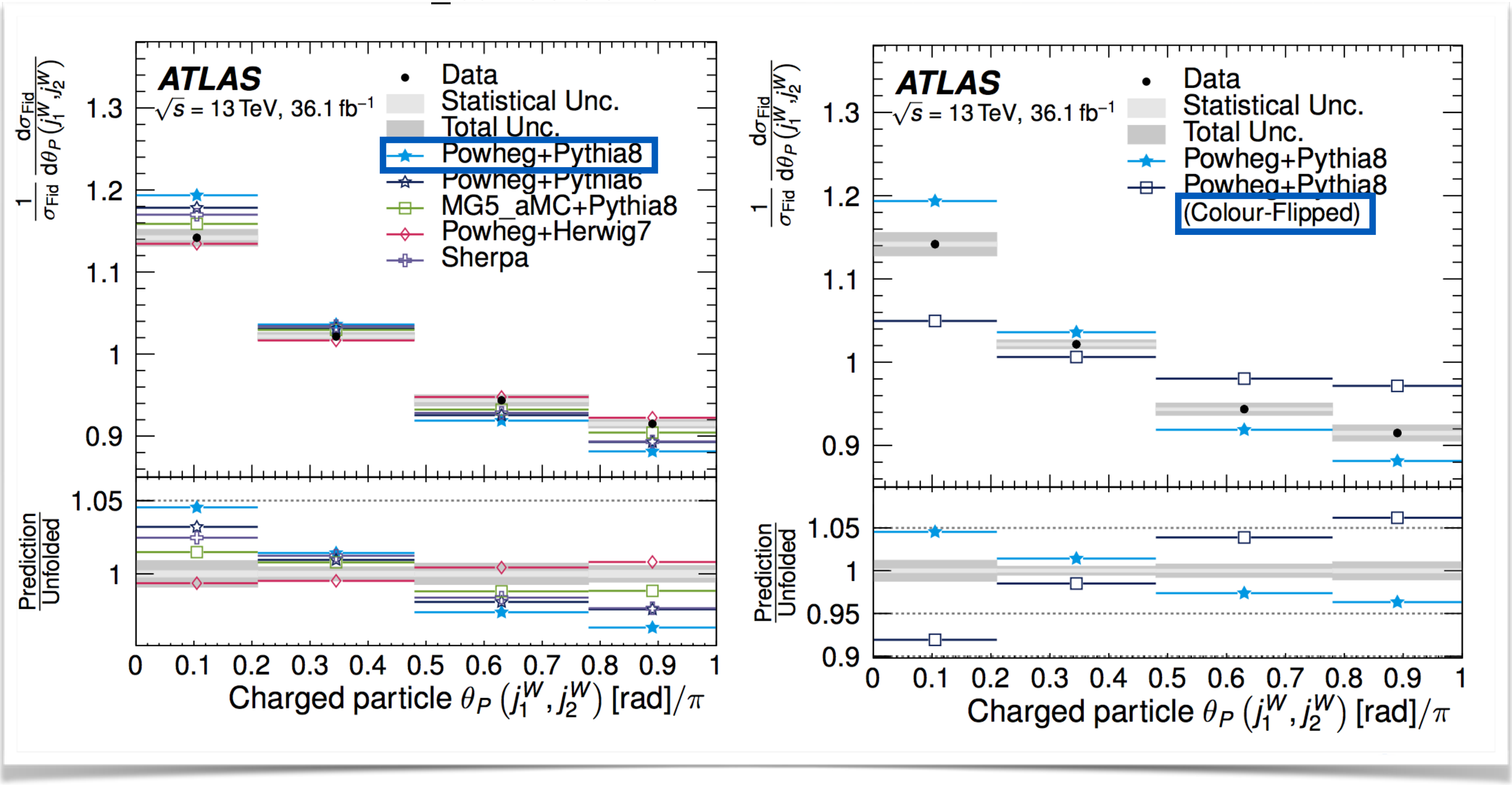
Connections are still a poorly constrained effect of QCD and require further experimental input

Potential to: distinguish between event topologies, complement the kinematic properties, help in the correct assignment of jets to a particular physical process

Color flow

Eur. Phys. J. C 78 (2018) 847

tt_bar selection



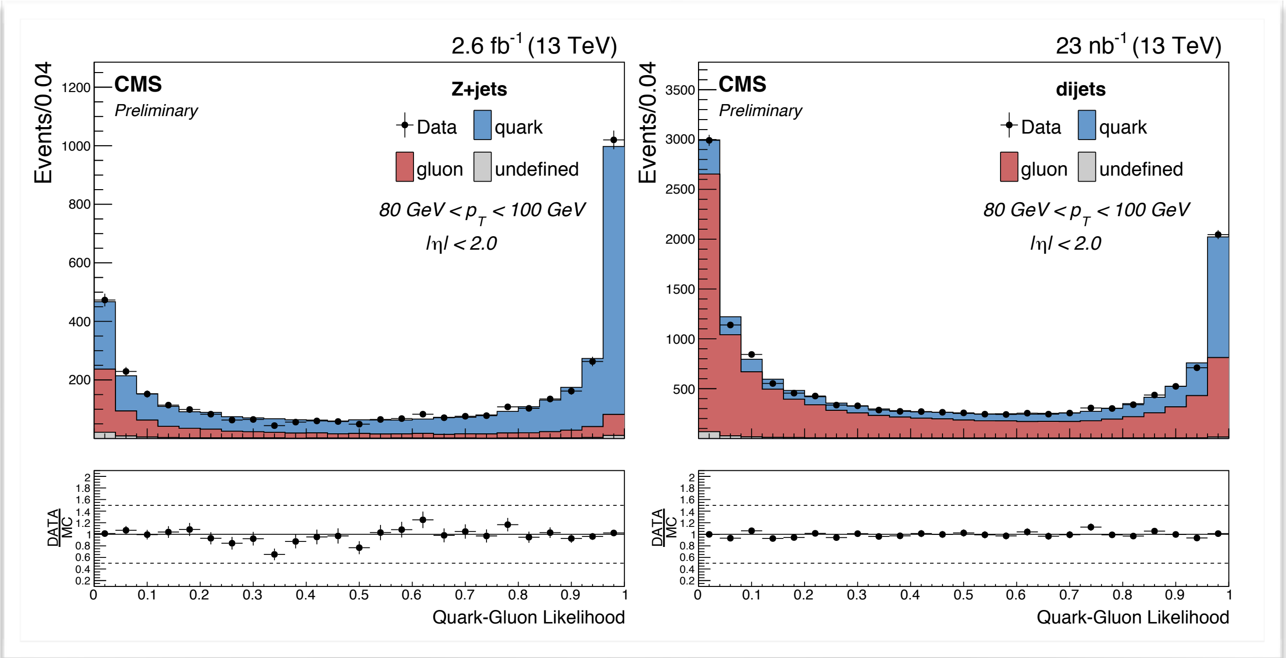
The magnitude of the jet-pull vector is poorly modelled in general, with the prediction obtained from Powheg + Herwig 7 agreeing best with data.

The default SM prediction, Powheg + Pythia 8, agrees poorly with the data. Powheg + Pythia 6 are in significantly better agreement

A model simulating an exotic flow is used (color-flipped): data favors the SM case over the exotic model

Jet-ID

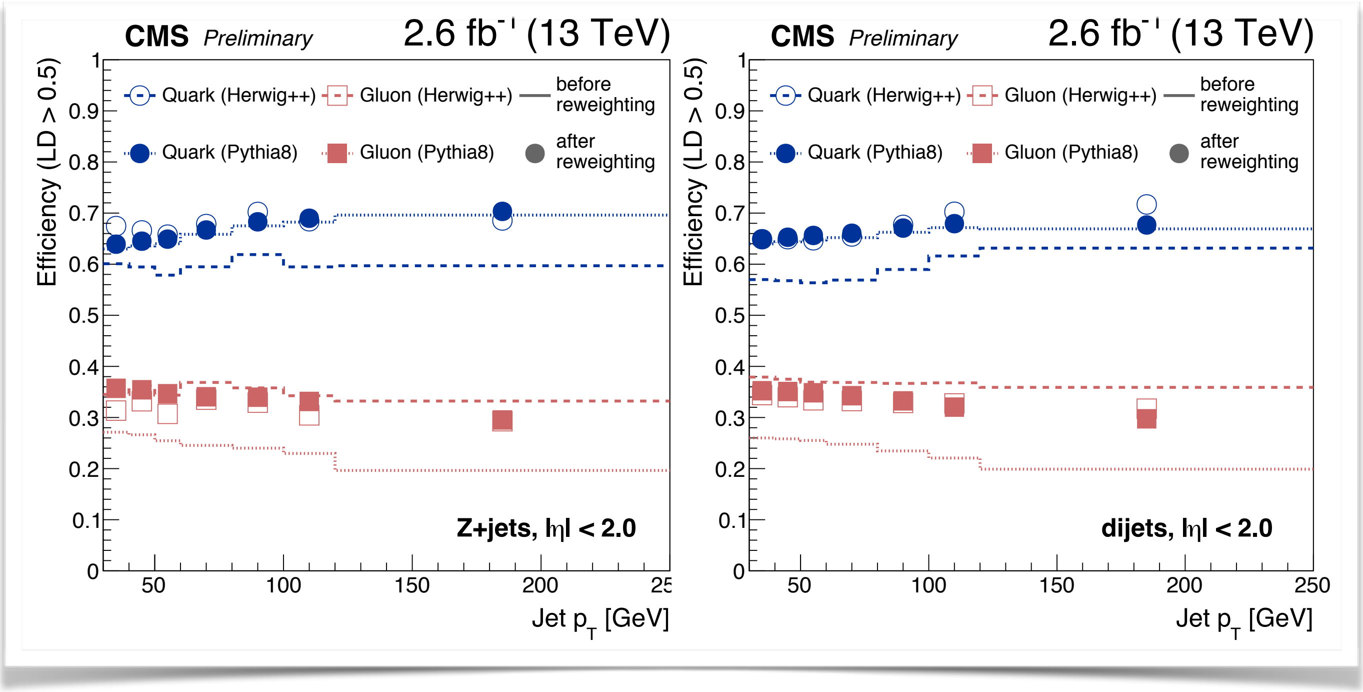
CMS-DP-2016-070



Different variables used to build the discriminator (multiplicity, minor axis, fragmentation…)

Z+jets

Dijet



Reweighting:

good performances on both parton shower models

selection efficiencies after the reweighting are very close for both generators

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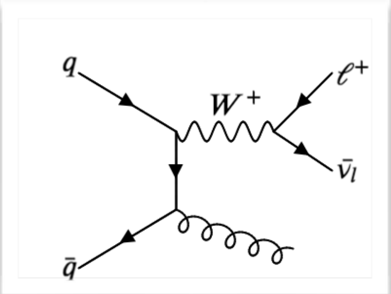
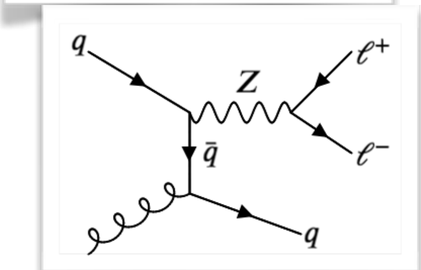
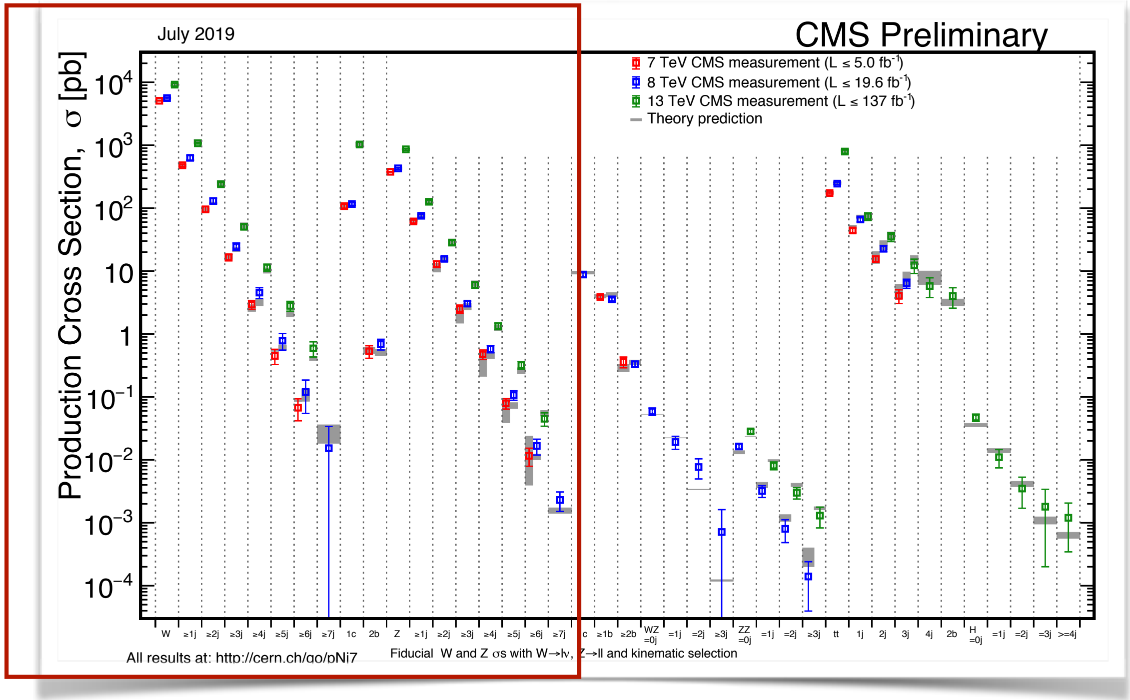
Vector boson + jets







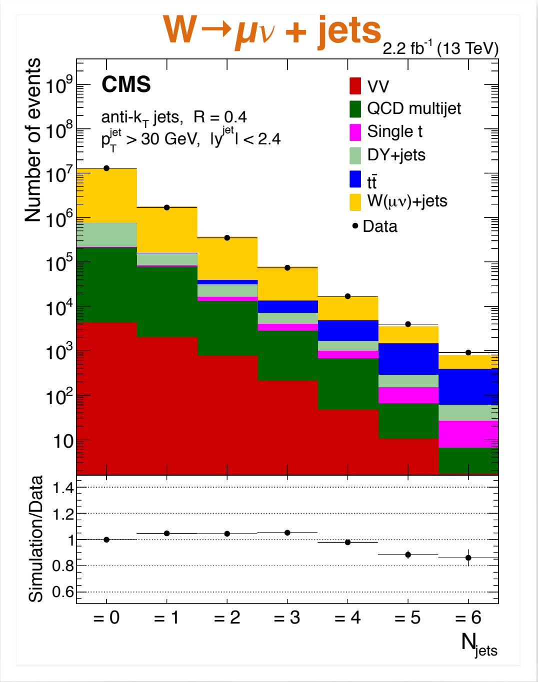
Vector boson production associated with jets:

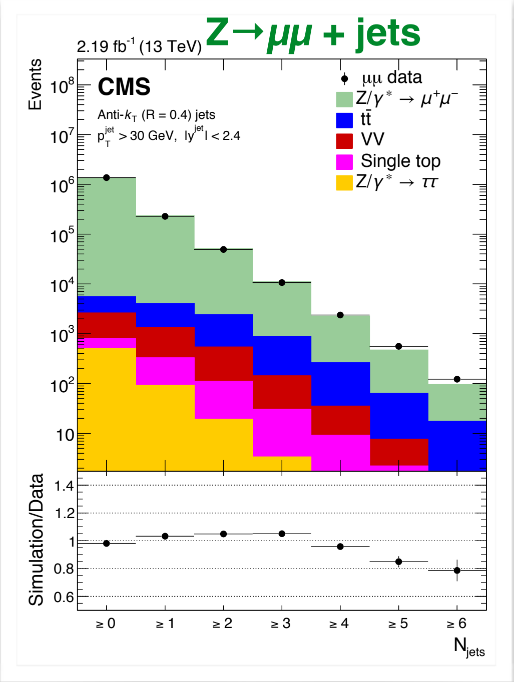
Precise tests of perturbative QCD

Sensitive to parton distribution functions (PDFs) in proton: gluon and sea-quarks PDF
 presence of jets increases parton momentum fraction (x) and energy scale (Q^2) ranges
 potential to improve the understanding of PDFs

Important background for the Standard Model processes and for searches of new physics

Vector boson + jets


W→μν + jets


Z→μμ + jets

13 TeV, 2.19 fb^{-1}

mu (W) or mu+ele (Z) channels

Main background from tt

Dominant systematics:
- Jet energy scale (1–25%)
- Jet energy resolution (1%)
- Measured efficiency (1-4%)

Theoretical predictions and model used:

LOMG_aMC →

MC multileg LO ME+PS: MadGraph5_aMC@NLO generator
- k_T- MLM merging scheme
- interfaced with PYTHIA8 using NNPDF2.3 (LO) and NNPDF3 (LO)
- up to N = 0..4 jets in the final state

NLOMG_aMCFxFx →

MC multileg NLO ME+PS: MadGraph5_aMC@NLO generator
- FXFX jet merging scheme
- interfaced with PYTHIA8 using NNPDF2.3 (LO) and NNPDF3 (NLO)
- NLO accuracy for N = 0,1,2 partons and LO accuracy for N = 3, 4

GE →

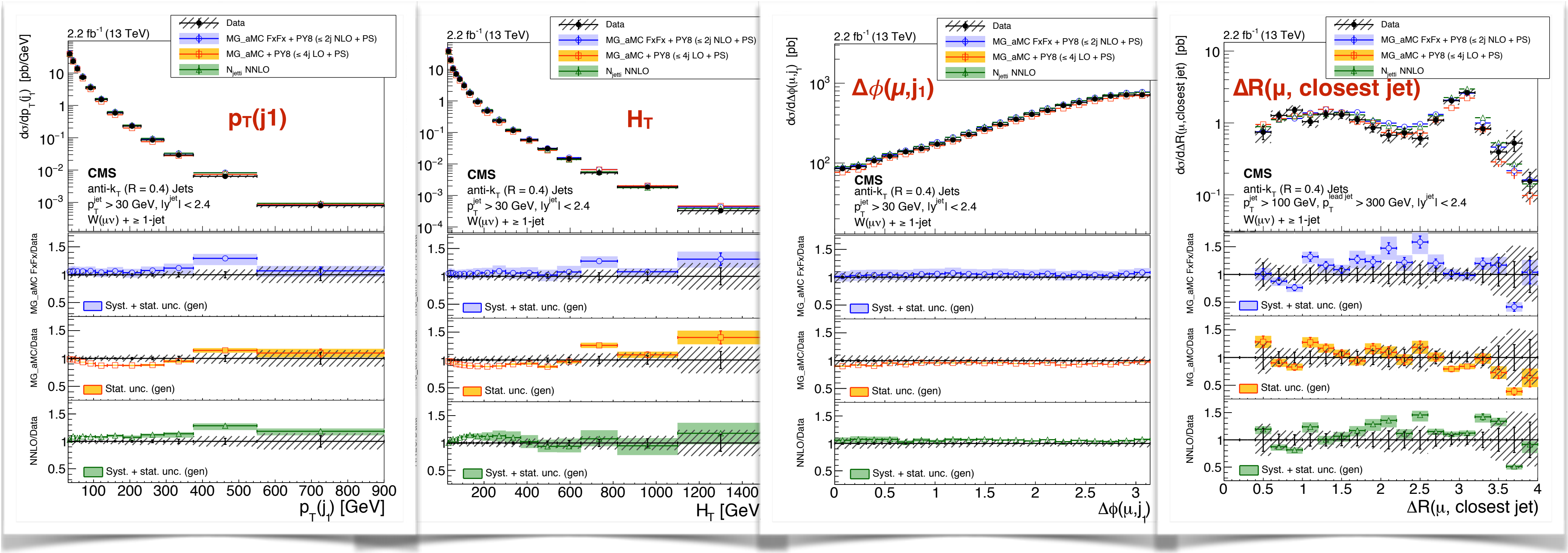
NNLO+NNLL: Geneva1.0-RC2 MC using PDF4LHC15 (**for Z**)
- combined with PS and HAD provided by PYTHIA8

Njetti NNLO →

Fixed-order NNLO calculations for V+1jet
- N-jettiness subtraction scheme using CT14
- non perturbative correction from MadGraph5_aMC@NLO+ PYTHIA8

W + jets

PRD 96 (2017) 072005



Differential cross sections (up to 4 jets)

pT, |y| of the leading jet

HT: the scalar pT sum of the jets

Δϕ(μ,j): azimuthal correlation between the muon and the leading jet

ΔR(μ, closest jet): angular distance between the muon and the closest jet

General: fairly good agreement with data within the uncertainties

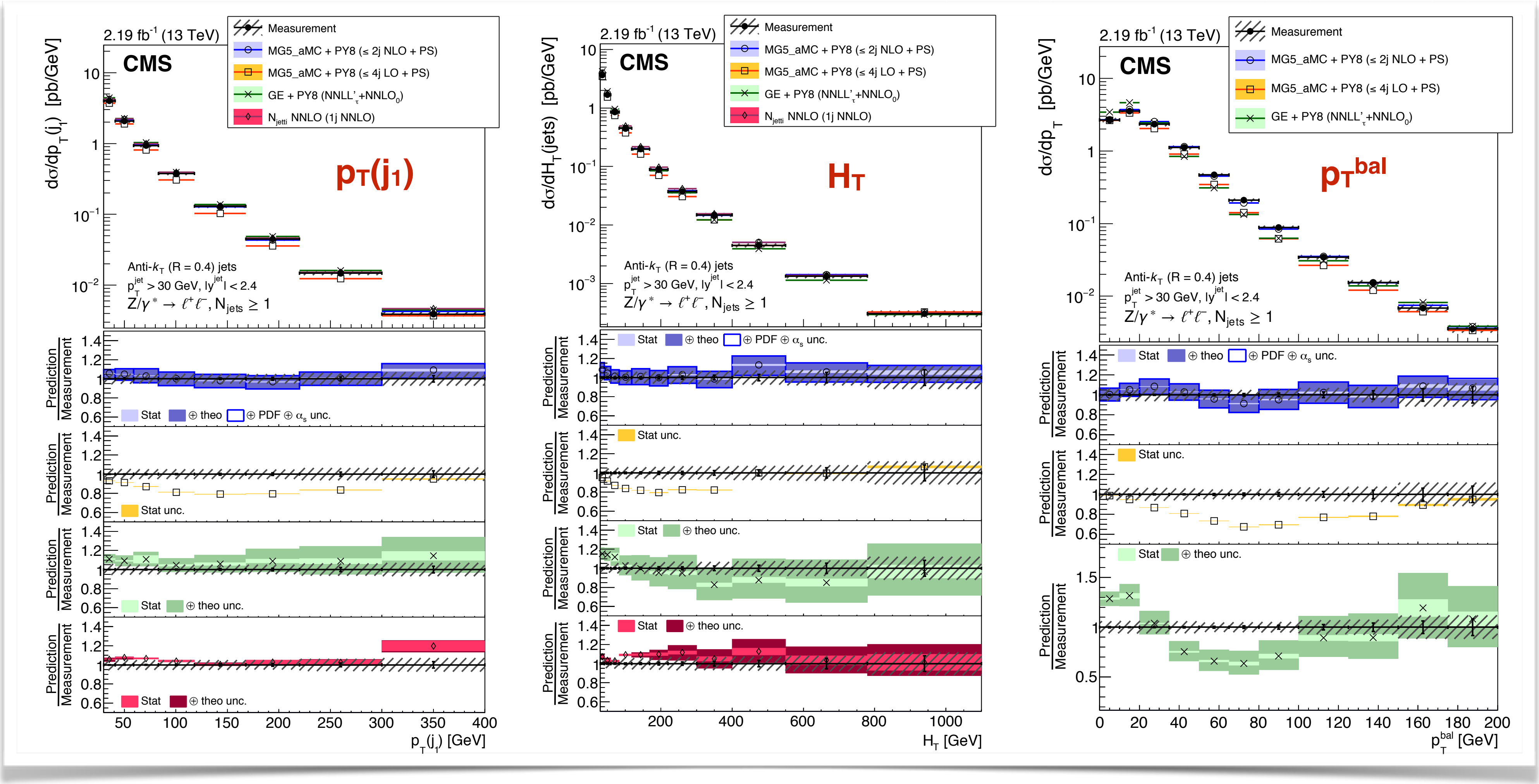
LO MG_aMC: underestimates the data at low jet pT, low HT and high DR

Njetti NNLO: best agreement for W ≥1jet

NLO MG_aMC FxFx: good agreement

Z + jets

Eur. Phys. J. C 78 (2018) 965



Differential cross sections (up to 6 jets)

pTofZ

jet kinematics: **pT , y, HT** (up to 3 jets)

pTbal: balance between the Z boson and jet transverse momenta

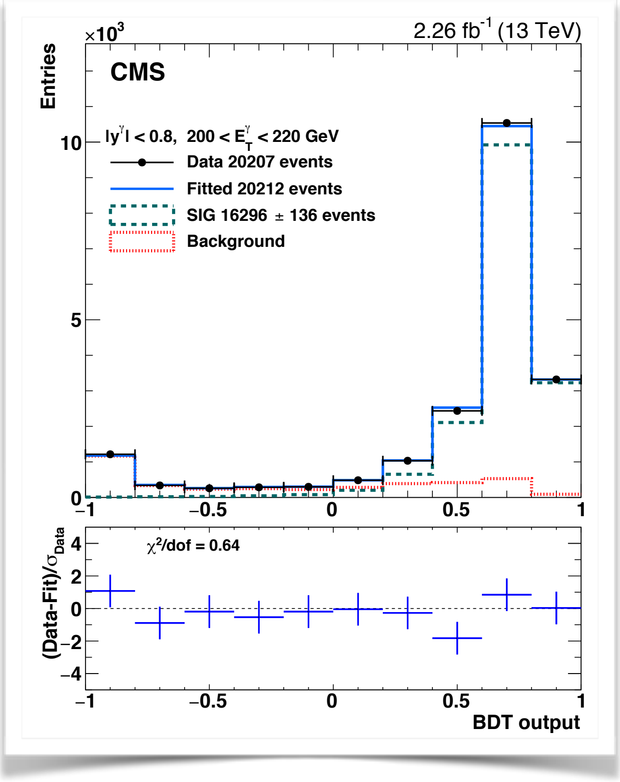
NLO MG5_aMC and **Njetty NNLO**: the best description

GENEVA: good agreement for the 1st jet

LO MG5_aMC: underestimates the data

γ + jets

Eur. Phys. J. C 79 (2019) 20



Signal extraction:

BDT based on photon (kinematic + shower shape) variables

Signal BDT template: γ+jets MC (Pythia8), validated with Z→ee, Z→μμ

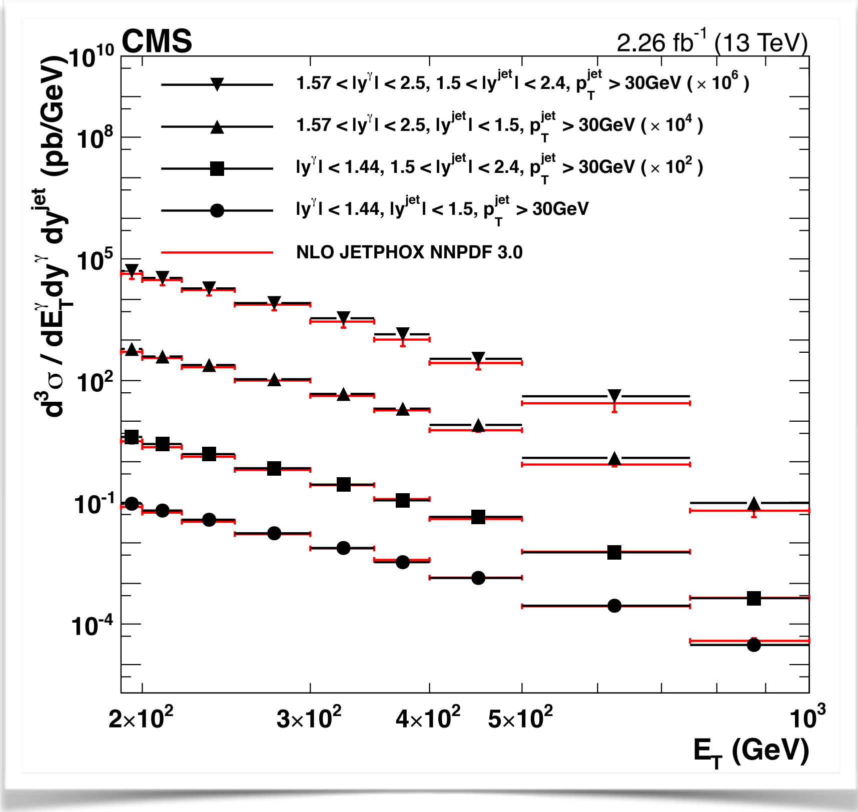
Theoretical predictions:

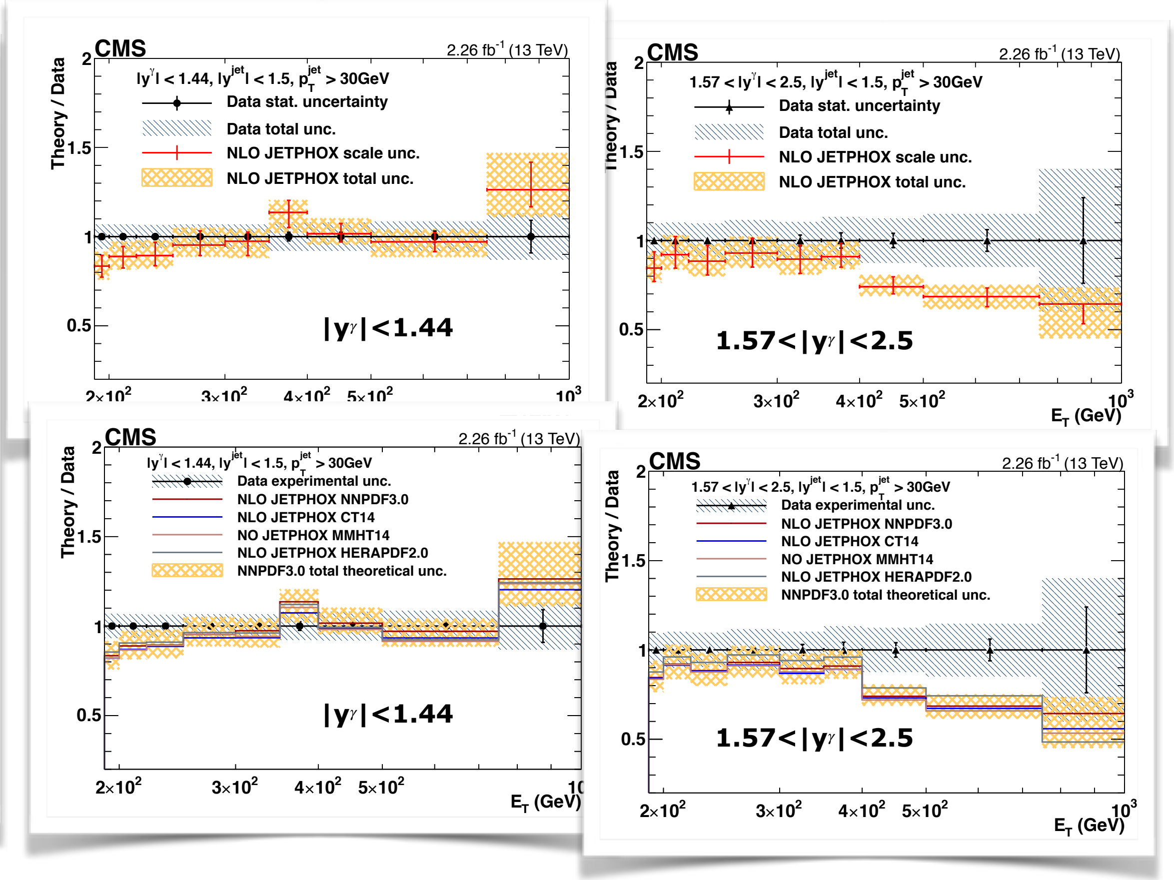
NLO: JETPHOX 1.3.1 generator, NNPDF3.0 PDFs and the Bourhis-Fontannaz-Guillet (BFG) set II parton fragmentation functions

photon ET used as the scale

total uncertainty includes the scale, PDF, αS, and underlying event and parton shower uncertainties

γ + jets





Comparison with NLO pQCD calculations:

- in two photon rapidity (and two jet rapidity bins - not shown)
- extended the photon ET range up to 1 TeV

1) Agreement with statistical and systematic uncertainties

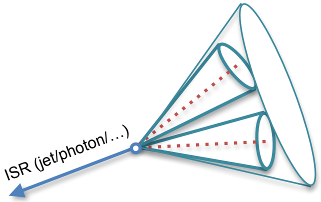
2) Low to middle range in photon ET: the experimental uncertainties are smaller or comparable to theoretical uncertainties

3) PDF sets: differences are small and within the theoretical uncertainties estimated with NNPDF3.0

1) **Inclusive jet productions**
2) **Jet substructure**
3) **V+jets**
4) **Some highlights**
5) **Double Parton Scattering**

γ + Di-jets

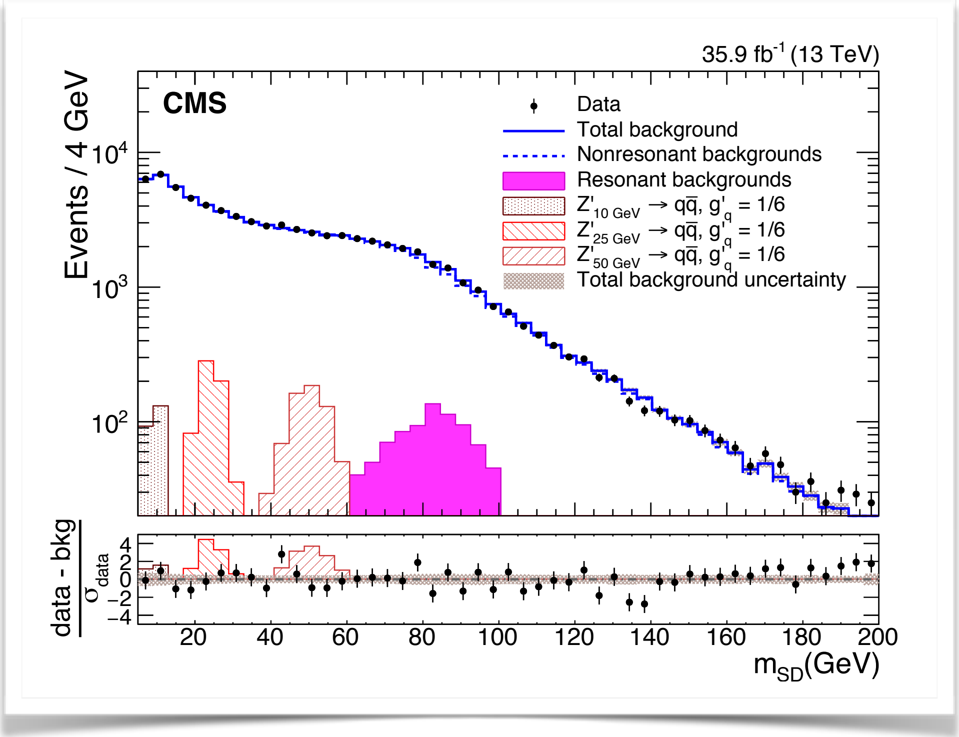
CMS - arXiv:1905.10331v1
ATLAS - Phys. Lett. B 795 (2019) 56



Select events with photon p_T > 200 GeV

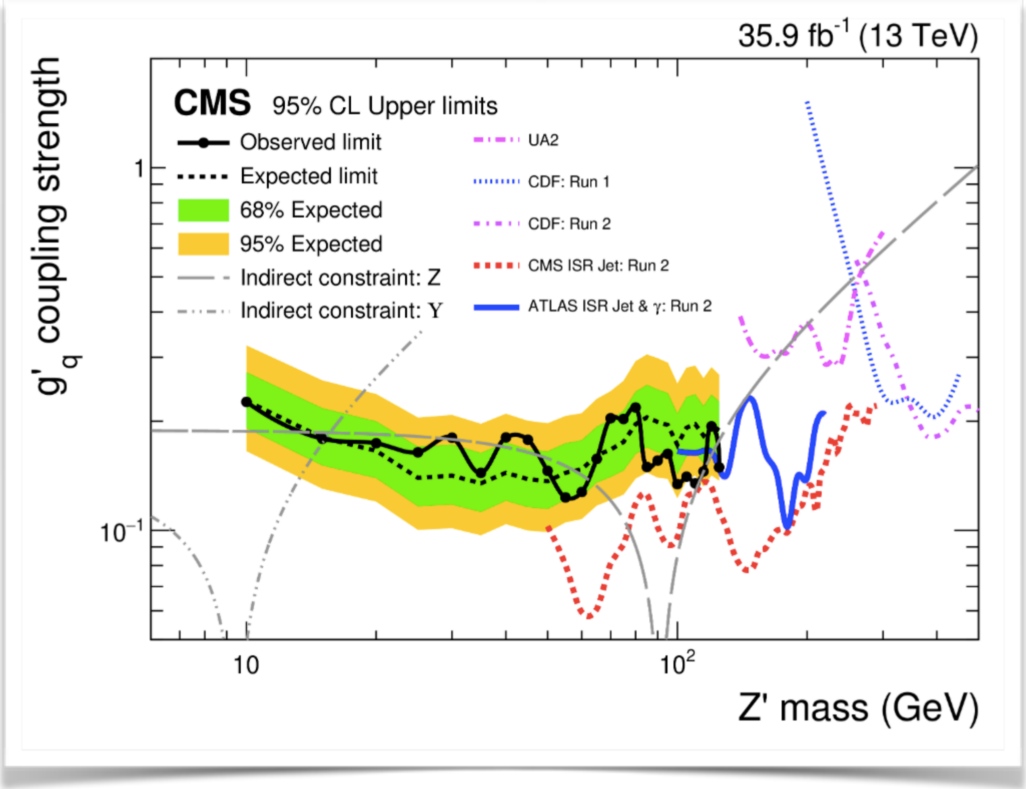
Soft-drop groomed anti-k_T R = 0.8 jet

Variable N^1_2 used to suppress background - combination of energy correlation functions



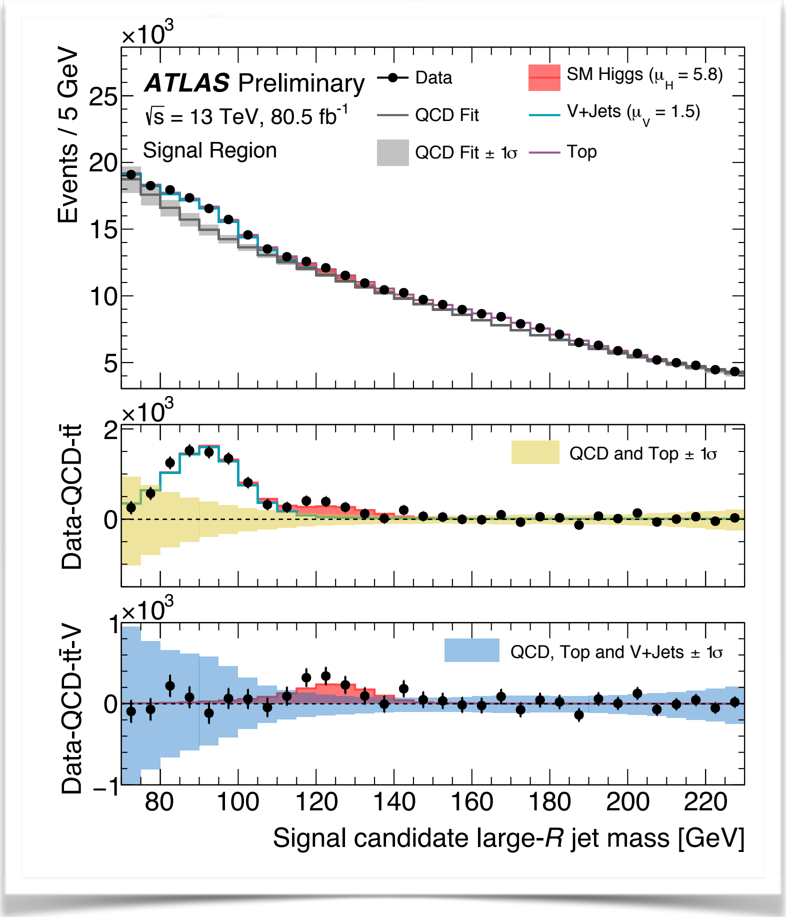
Data agree well with SM prediction

No evidence for resonance with mass from 10 to 125 GeV



Di-Bjet resonances

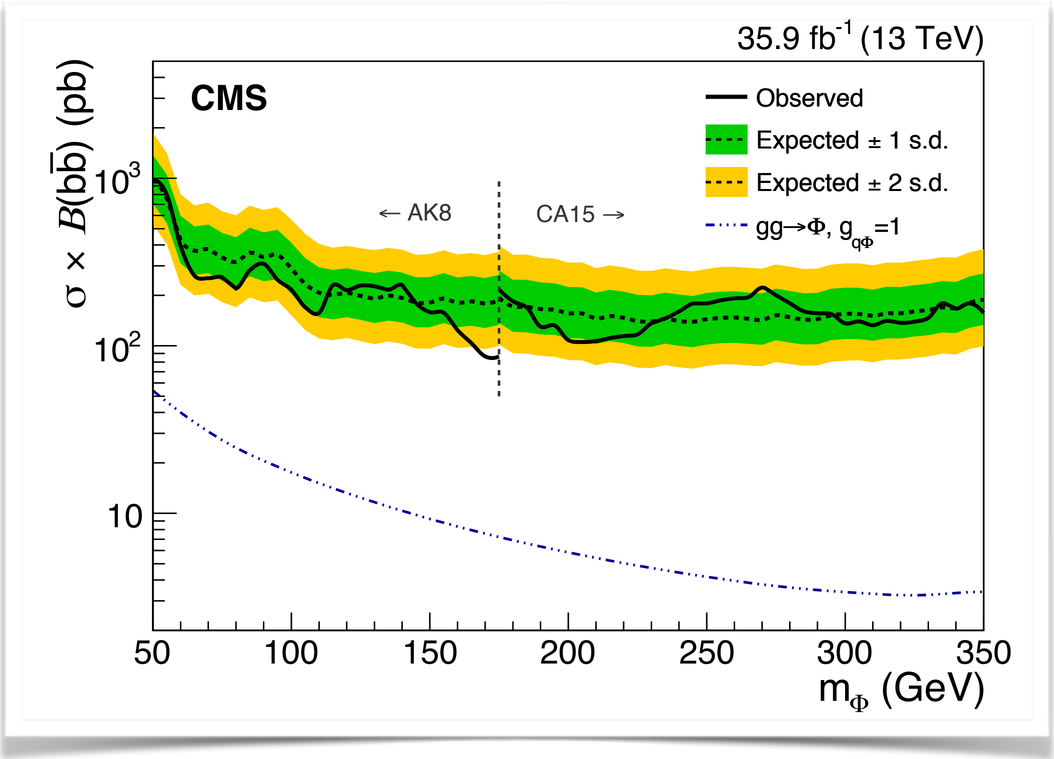
ATLAS-CONF-2018-052
CMS - Phys. Rev. D 99, 012005



Trimmed R = 1.0 jets based on TopoClusters

Jet mass combine calorimeter and track measurements

Track-based approach to tag jets potentially originating from B-mesons (b-tagged)



Soft-drop groomed Anti-kT R=0.8 (CA R=1.5) jets for low (high) resonance masses

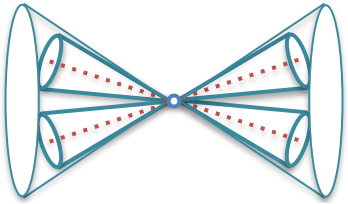
Uses DDT N^1_2

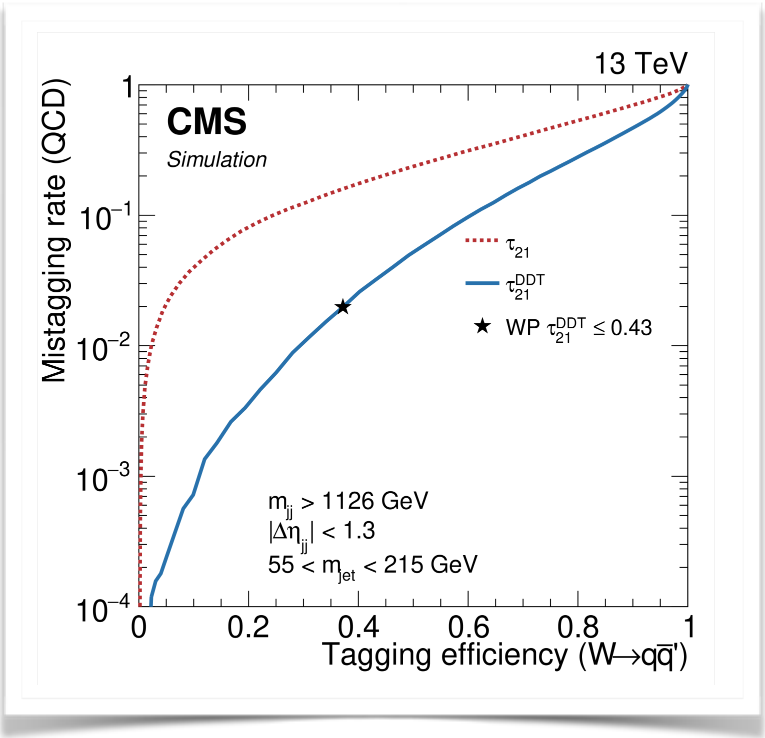
Dedicated double-b tagger (subjet b-tagging)

Data agree with SM prediction

Di-boson search

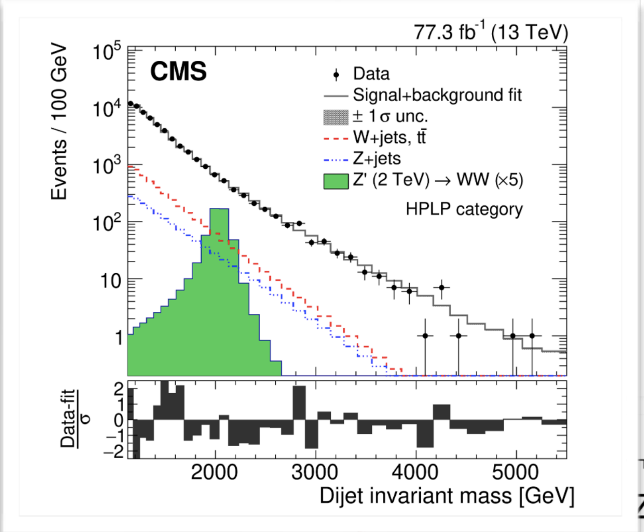
arXiv:1906.05977

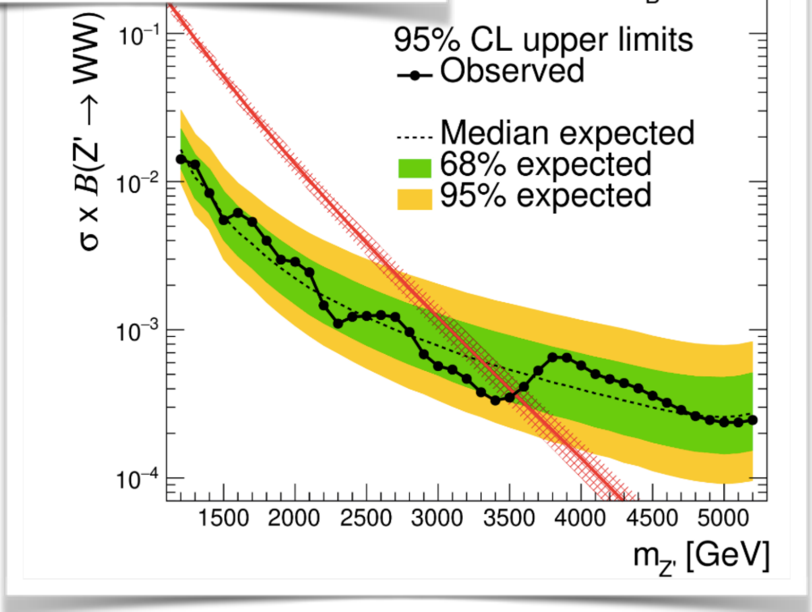




R = 0.8 jets with PUPPI pileup mitigation, groomed with soft drop

Tagging based on DDT N-subjettiness ratio τ_{21}





77 fb^{-1} of 13 TeV, 3D fit of m_{JJ} and both jet masses

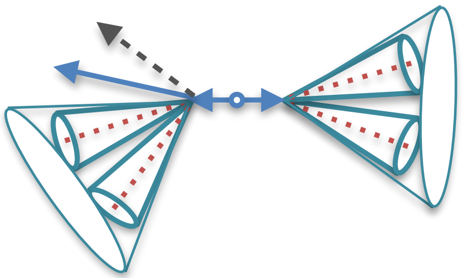
No significant excess above background estimation observed

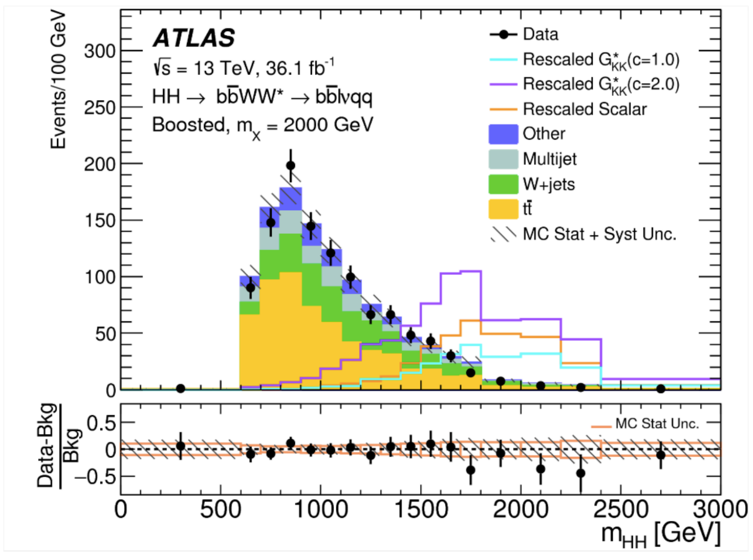
Exclusions on e.g. the mass of a new heavy boson reach up to 3.8 TeV

Data agree with SM prediction

Di-Higgs search

ATLAS - JHEP 04 (2019) 092
CMS - arXiv:1904.04193



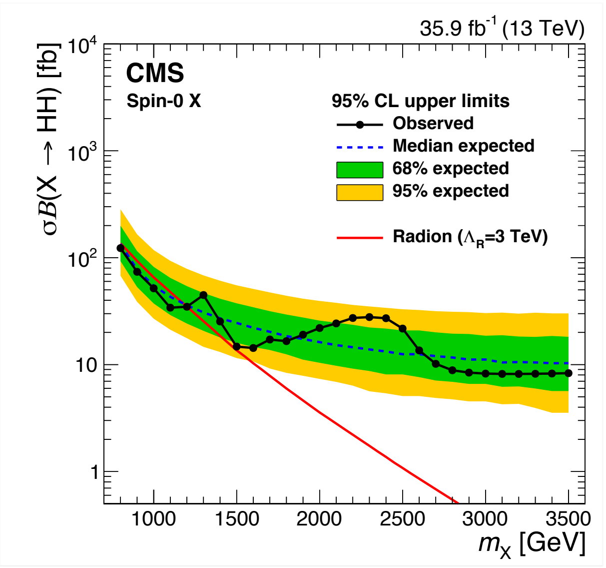


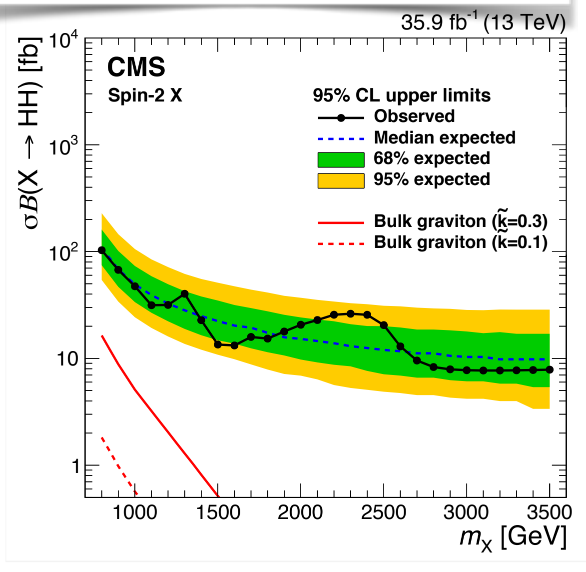
Heavy particle X decaying into two 125 GeV Higgs bosons

X -> HH -> WW*bb

Use of mass and N-subjettiness ratios

Added challenge: Use of lepton for event selection - can overlap with large-R jet

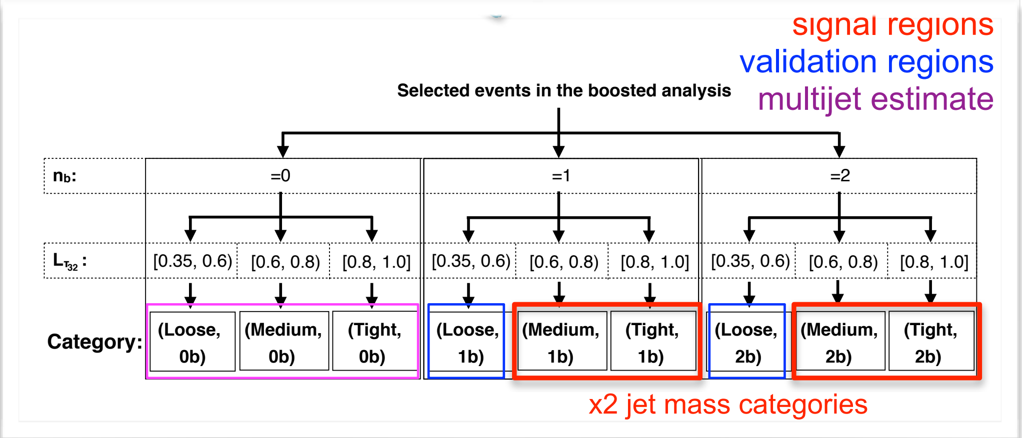




Data agree with SM prediction

Di-top search

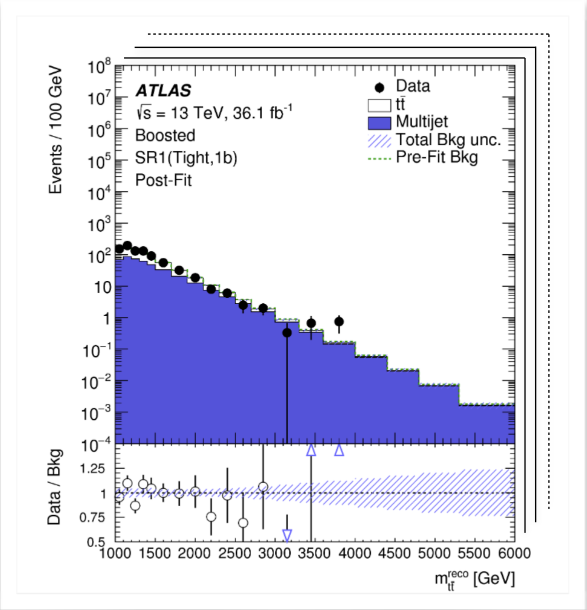
Phys. Rev. D 99 (2019) 092004

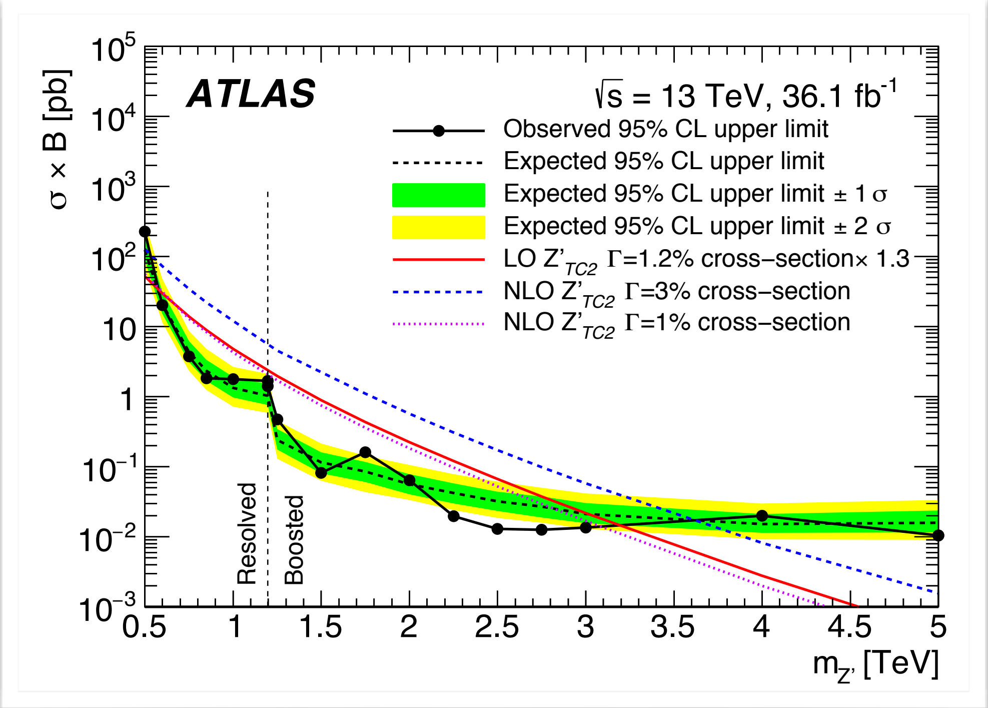


Selection on:

- jet mass
- N-subjettiness ratio τ_{32}
- b-tagged R=0.2 track jets

τ_{32} of both top candidates combined into likelihood $L_{\tau_{32}}$





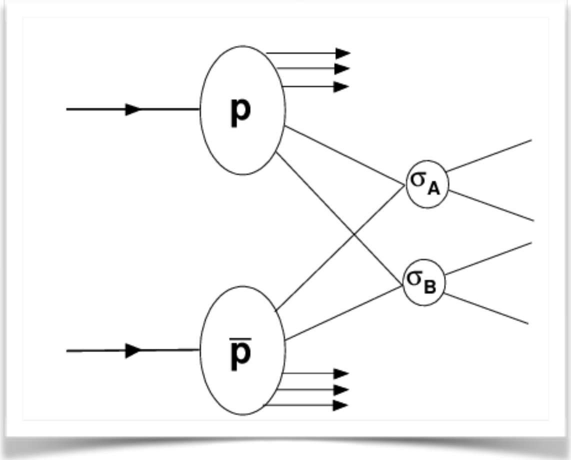
Data agree with SM prediction

1) **Inclusive jet productions**
2) **Jet substructure**
3) **V+jets**
4) **Some highlights**
5) **Double Parton Scattering**

Double Parton Scattering

CMS-PAS-SMP-18-015

Double parton scattering in a pp collision
 - an insight in hadron structure and an irreducible background to searches



Double-parton distribution

$$\frac{d\sigma_{DPS}}{dx_A dx_B dx'_A dx'_B} = m\hat{\sigma}_A\hat{\sigma}_B \int d^2\boldsymbol{y}\, F(x_A, x_B, \boldsymbol{y}) F(x'_A, x'_B, \boldsymbol{y})$$

Dpdf are factorized
G(y) is the transverse Dpdf

$$F(x_A, x_B, \boldsymbol{y}) = f(x_A) f(x_B) G(\boldsymbol{y})$$

$$\frac{d\sigma_{DPS}}{dx_A dx_B dx'_A dx'_B} = m \cdot \hat{\sigma}_A f(x_A) f(x'_A) \cdot \hat{\sigma}_B f(x_B) f(x'_B) \cdot \int d^2\boldsymbol{y}\, G(\boldsymbol{y})$$

$$\frac{d\sigma_{DPS}}{dx_1 dx_2 dx'_1 dx'_2} = \frac{m}{\sigma_{eff}} \frac{d\sigma_1}{dx_1 dx'_1} \frac{d\sigma_2}{dx_2 dx'_2} \qquad \frac{1}{\sigma_{eff}} = \int d^2\boldsymbol{y} G(\boldsymbol{y})$$

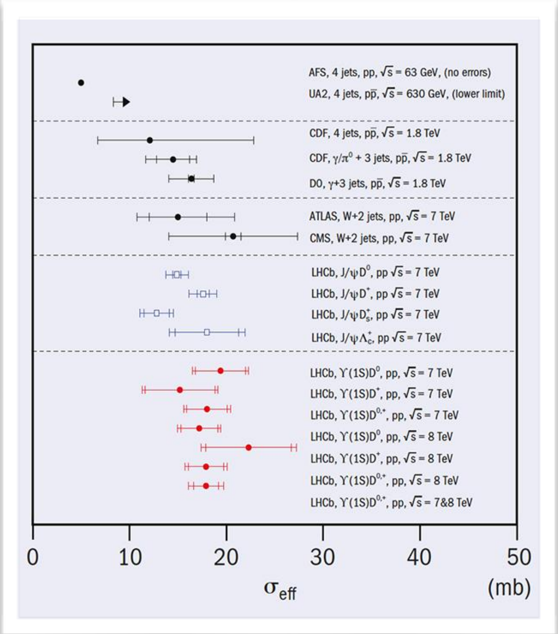
DPS is usually suppressed with respect to a corresponding SPS production

σ_{eff} is independent on the final state

σ_{eff} is an insight in the transverse hadron structure, allowing access to:

+ 3D structure of the proton
+ direct measurement of partons correlations

DPS in same sign W pair



σ_{eff} measurment:

Exploiting different topologies arising from correlations in SPS processes

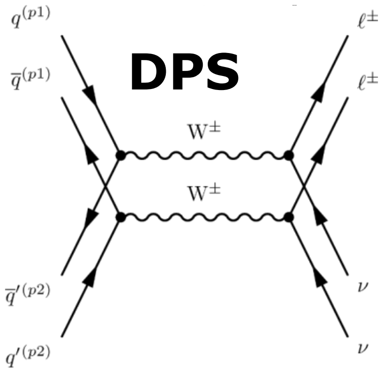
Several measurement exists from past experiment, LHC and in different final state

Large uncertainty mostly due to model-dependent extraction

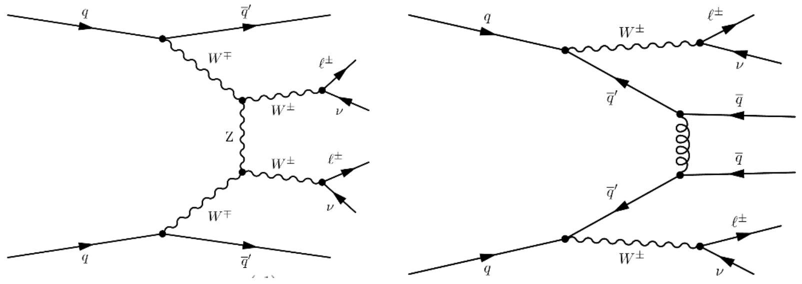
Same sign W production:

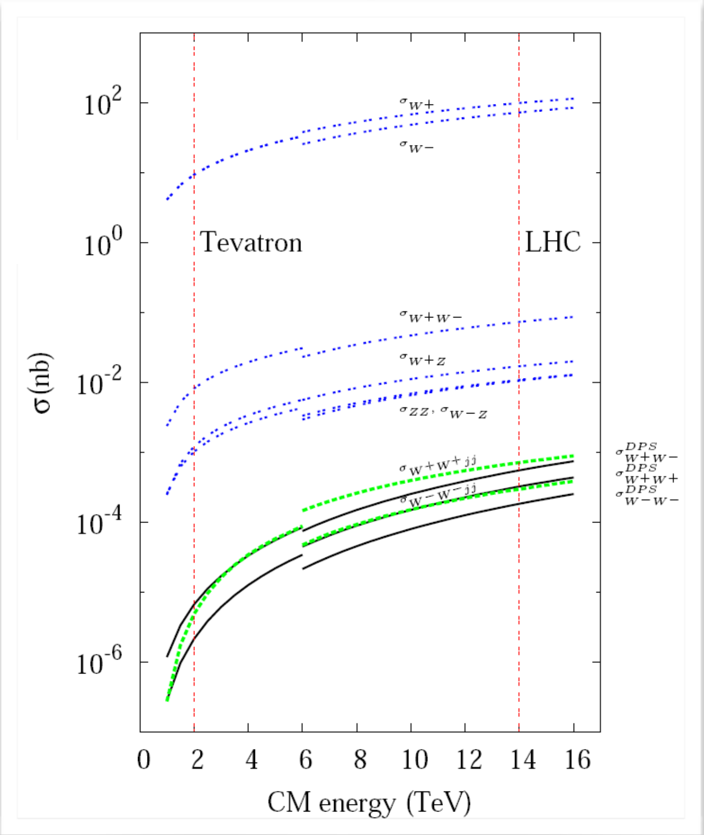
- SPS largely suppressed, x-sec ~DPS
- Very clear final state if leptonic

DPS



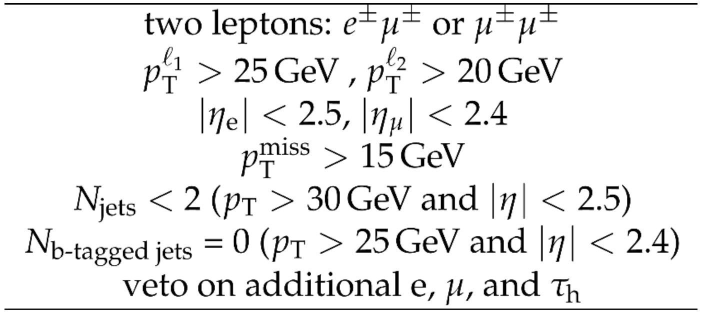
SPS





DPS in same sign W pair

- p_T^{l1} and p_T^{l2}
- E_T^{miss}
- M_{T2}^{ll}
- $m_T(l_1, l_2)$
- $m_T(l_1, E_T^{miss})$
- $\Delta\varphi(l_1, l_2)$
- $\Delta\varphi(l_1, E_T^{miss})$
- $\Delta\varphi(l_1 l_2, l_2)$
- $\eta_1 \cdot \eta_2$
- $|\eta_1 + \eta_2|$

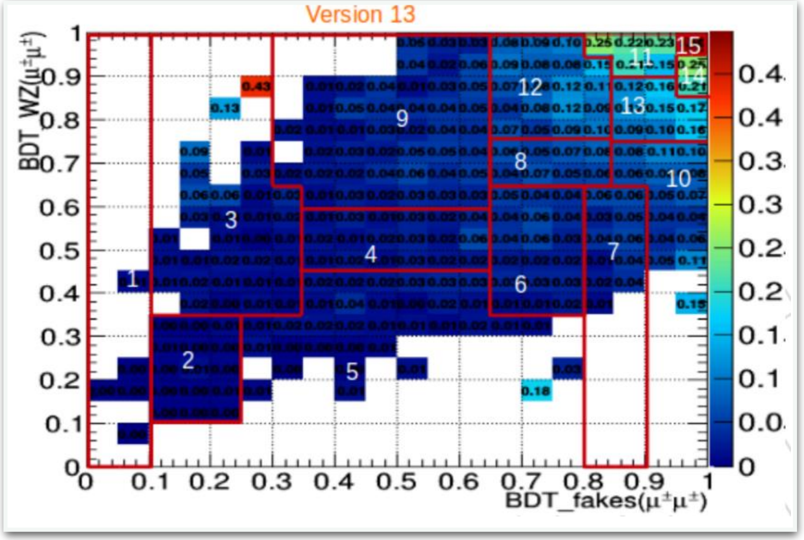


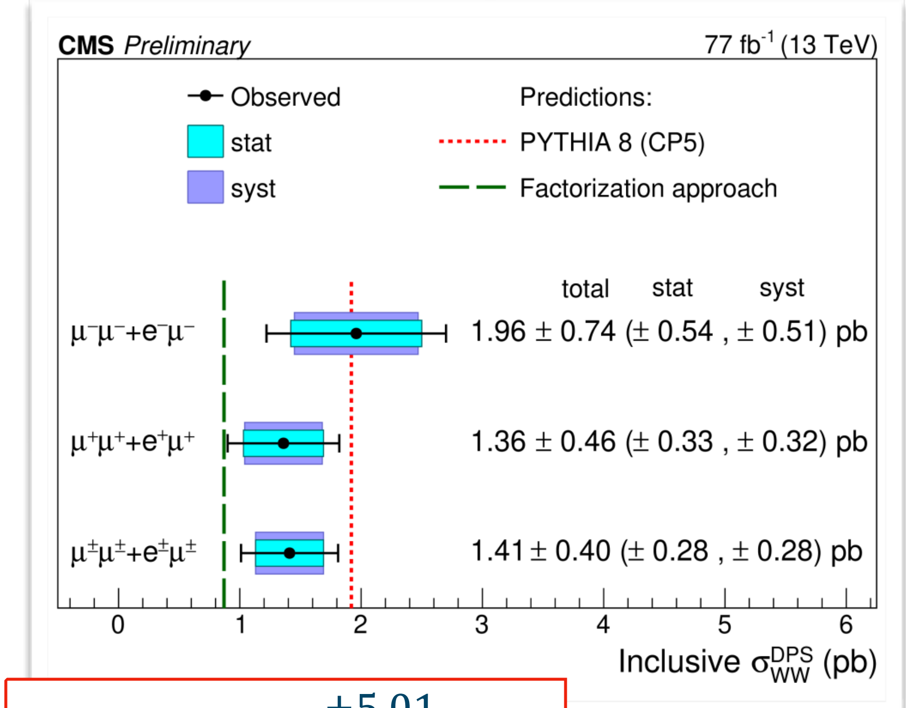
two leptons: $e^{\pm}\mu^{\pm}$ or $\mu^{\pm}\mu^{\pm}$
$p_{\mathrm{T}}^{\ell_1} > 25\,\mathrm{GeV}$, $p_{\mathrm{T}}^{\ell_2} > 20\,\mathrm{GeV}$
$|\eta_{\mathrm{e}}| < 2.5$, $|\eta_{\mu}| < 2.4$
$p_{\mathrm{T}}^{\mathrm{miss}} > 15\,\mathrm{GeV}$
$N_{\text{jets}} < 2$ ($p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 2.5$)
$N_{\text{b-tagged jets}} = 0$ ($p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $|\eta| < 2.4$)
veto on additional e, μ, and τ_{h}

MVA based on BDT technique to enhance signal sensitivity

- 2 BDTs trained
- WZ background
- Fake lepton background

- Same variables used in both BDTs
- The BDTs determine a 2D distribution





σ_{eff} is $12{,}67^{+5{,}01}_{-2{,}92}$ mb

Summary

- **Several differential cross sections provided by ATLAS and CMS collaborations**
  - Covering different centre-of-mass energies
  - Many observables are studied and compared to the theoretical predictions

- **Boosted objects play an important role in many ATLAS and CMS analyses**
  - Both experiments established performant default procedures to utilize jet substructure
  - Searches often re-optimise or adapt techniques
  - Typical use-cases are di-boson, -top, -higgs resonance searches, plus cascade decays
  - Increasing importance of boosted objects and substructure techniques with rising mass targets

- **Theoretical calculations reached NNLO precision for V+1jet and NLO for 4/5 jets, overall good agreement with data**

- **Double Parton Scattering is an unavoidable process to take into account for any search and is expected to play an important role for proton structure understanding**

- **Measurements provide valuable input for a better understanding of**
  - Perturbative QCD
  - SM predictions
  - PDFs of the proton

- **No evidence of physics beyond the Standard Model at the LHC yet**

- **Much to look forward to**
  - Majority of current results use a fraction of recorded Run-2 data
  - Substructure tools and techniques are continuously refined

Thanks to the organizers for the kind invitation