Uncertainties in event generator predictions for LHC physics

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Snowmass EF05 Precision QCD Meeting,
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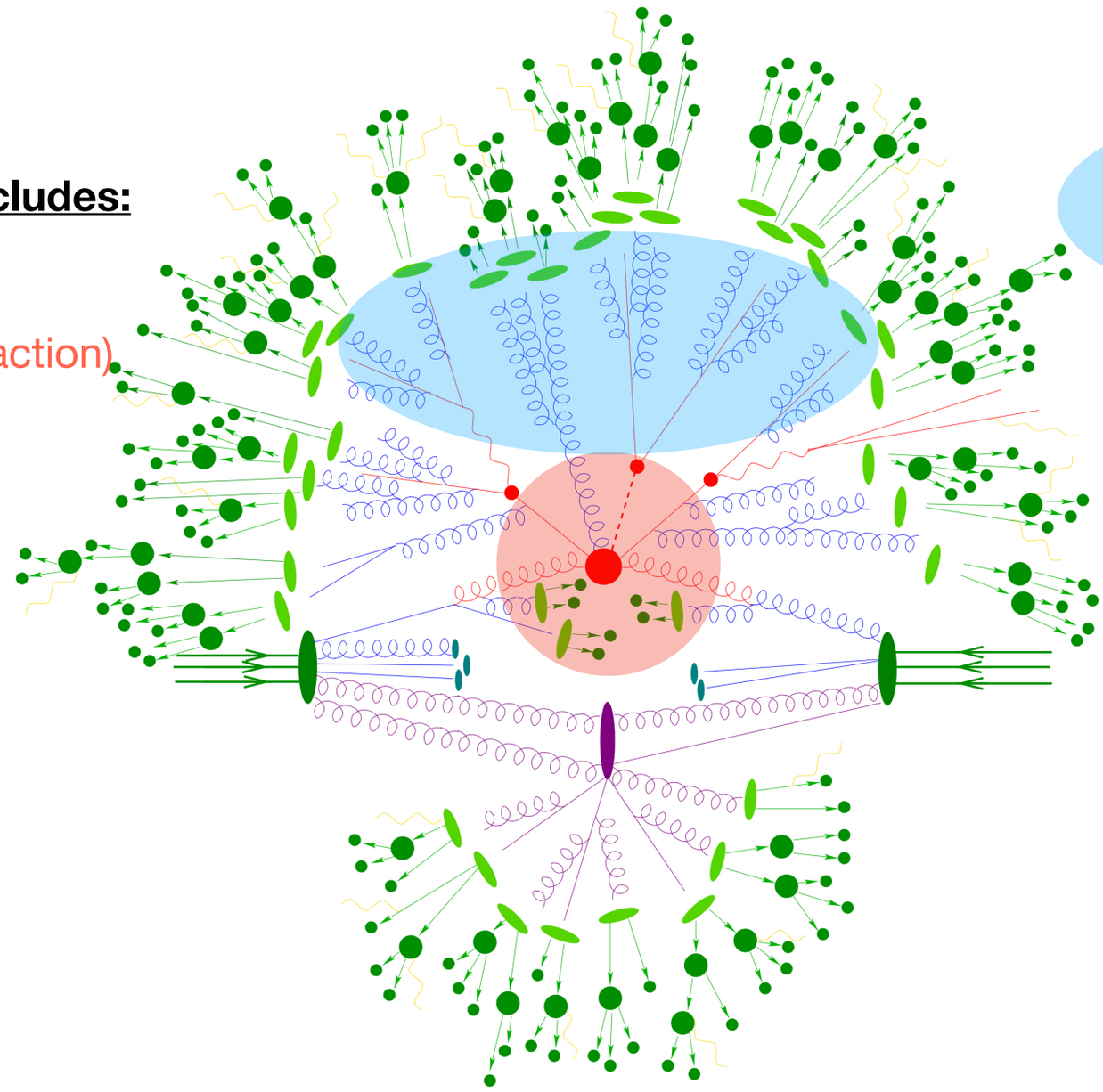
Outline of the talk

- Definition of scales in typical event
- Brief overview of fixed order calculations
- Discussion of MC uncertainties:
  - Scale variations in parton showers
  - Matrix Element (ME) - Parton Shower (PS) matching scale
  - Color reconnection
  - b-jet fragmentation
  - Flavor response
  - Decay tables
  - Underlying event
- Summary and outlook

Definition of scales in a typical event

Full event description includes:

Initial state parton shower
Signal process (hard interaction)
Final state parton shower
Fragmentation
Hadron decays
Beam remnants
Underlying event



Parton shower
$\mathcal{O}$ (1 TeV - 1 GeV)

Hard process:
$\mathcal{O}$ (1 TeV)

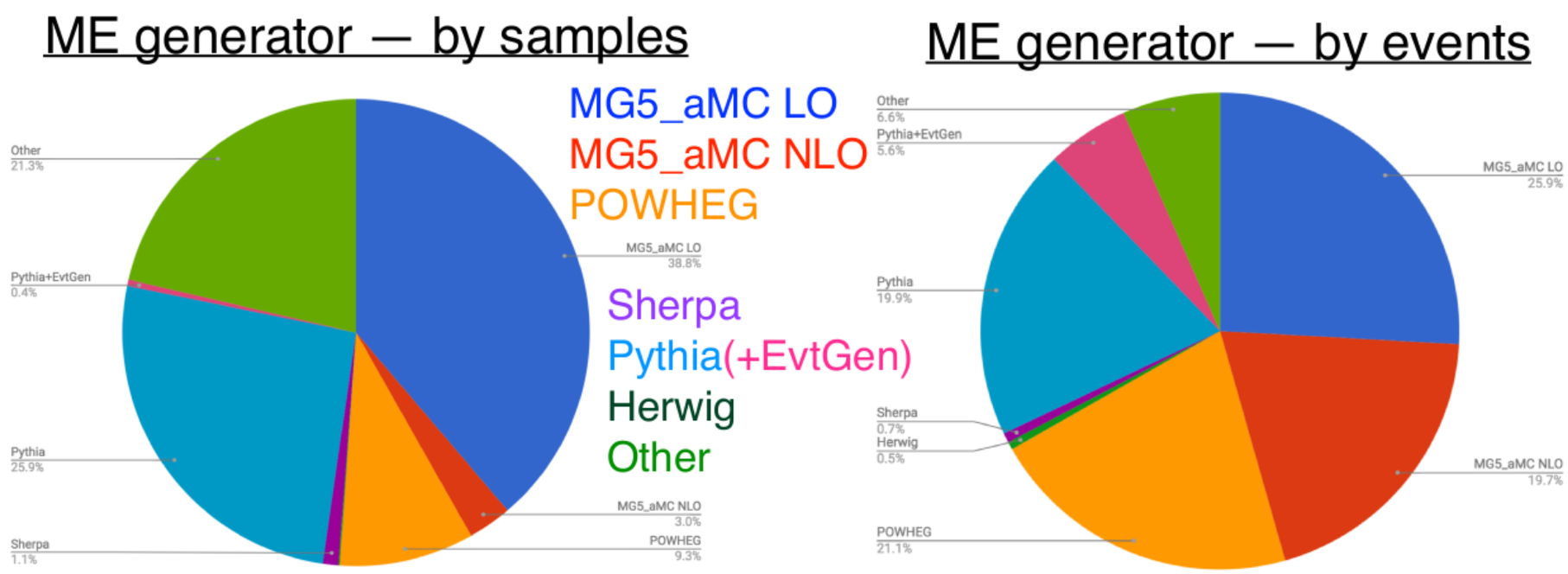
$\mathcal{O}$ (1 GeV) **$\mathcal{O}$ (1 TeV-10 GeV)** **$\mathcal{O}$ (1 TeV)** **$\mathcal{O}$ (1 TeV-10 GeV)** **$\mathcal{O}$ (1 GeV)**

non-perturbative perturbative non-perturbative

Status of fixed order generators

- NLO revolution facilitated the computation of cross section at NLO accuracy, widely used in CMS (MadLoop/ Openloops)
- Need even higher precision to match LHC data (e.g. WW cross section)
- Several methods for NNLO computation exist
  - Different approaches exist for canceling divergences, current goal to have 2 → 3 NNLO results by beginning of HL LHC (included in the Yellow Report)
- NNLO = “2-loop virtual” + “real-virtual” + “double real” (Gregory Soyez’s talk)
- Computationally intensive
- Merging/matching:
  - Defines the cusp of fixed order computation (at NNLO/NLO/LO, hard scales) and parton shower

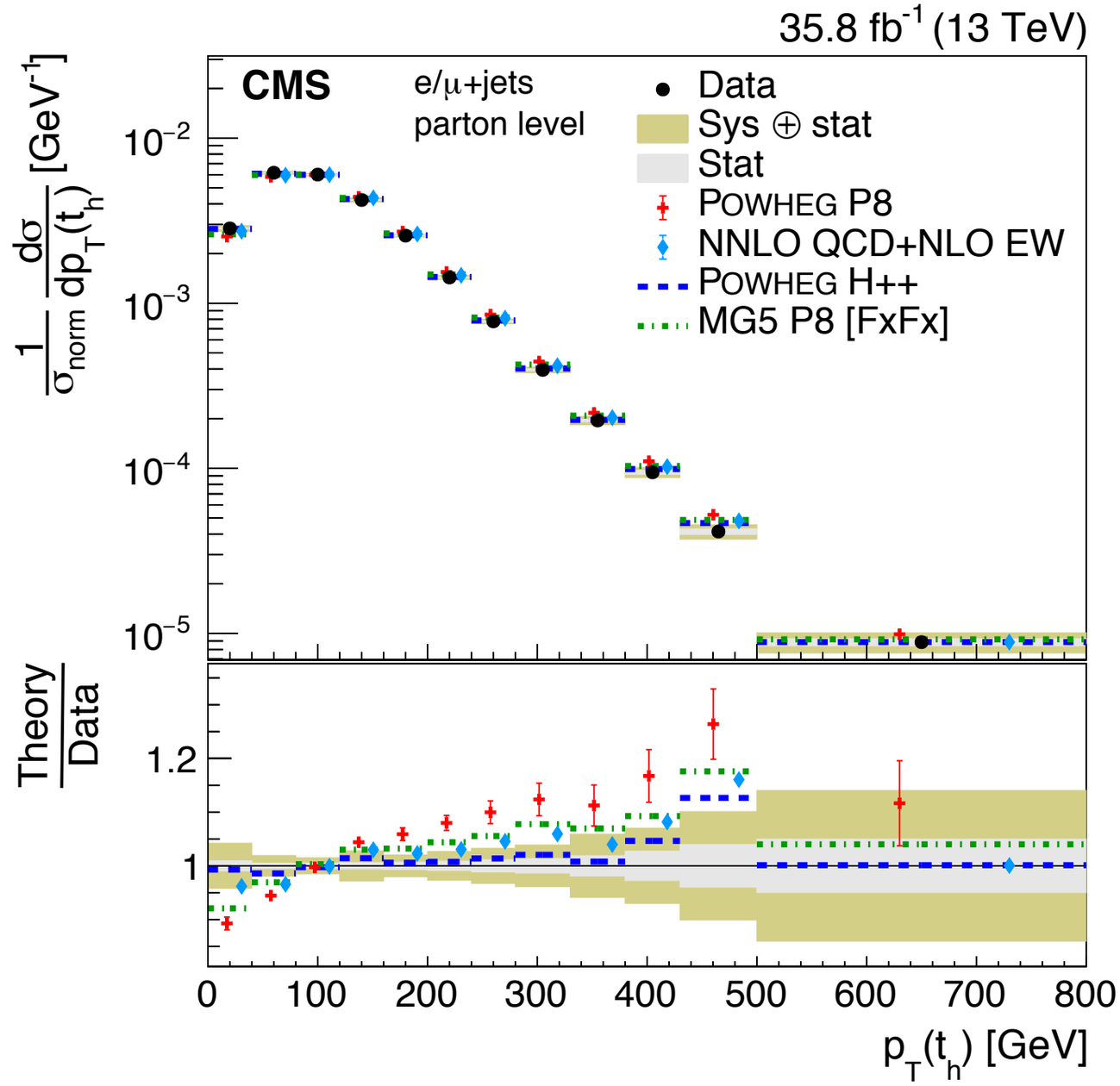
Q. Li,
A. Grohsjean



2016 sample generation

Comparison of the p_T spectra of hadronically decaying top-quarks

- Compare predictions at parton level (top quarks are defined as signal *before* decay, no phase space restriction)
- Measured p_T spectra of t_h (and t_l) softer than predicted by PYTHIA8 based parton shower models (trend *slightly* more pronounced for $0 < |y(t_h)| < 0.5$)
- <u>NNLO QCD+NLO EW</u> (m_t = 173.3 GeV) calculation **also** predicts are harder spectrum
- Rapidity (y), p_T (tt), y(tt), M(tt) distribution in agreement with data at parton level
- Particle level (computed using experimentally accessible quantities) trends more pronounced than at the parton level (albeit similar)
- <u>NNLO QCD+NLO EW</u> calculation predicts a higher-average M(tt) spectrum than observed in data



TOP-17-002

Matrix element renormalization and factorization uncertainties

- **Description:**
  - Ascertain uncertainty stemming from choice of renormalization (μ_R) and factorization (μ_F) scales
  - For a top sample, these are set to the transverse mass $m_T = \sqrt{(m_t^2 + p_T^2)}$ of the top quark, where $m_t = 172.5$ GeV
- **Prescription:**
  - Envelope computed by varying μ_R, μ_F individually and by correlating them
  - For template fits uncertainty may be taken as nuisance parameters
  - Uncertainty uncorrelated between QCD-induced (tt) and EWK-induced (single top) processes

Systematic	Scale	Variation
ME μ_R / μ_F	μ_R	↑ ↓ ↑ ↓
	μ_F	↑ ↑ ↓ ↓

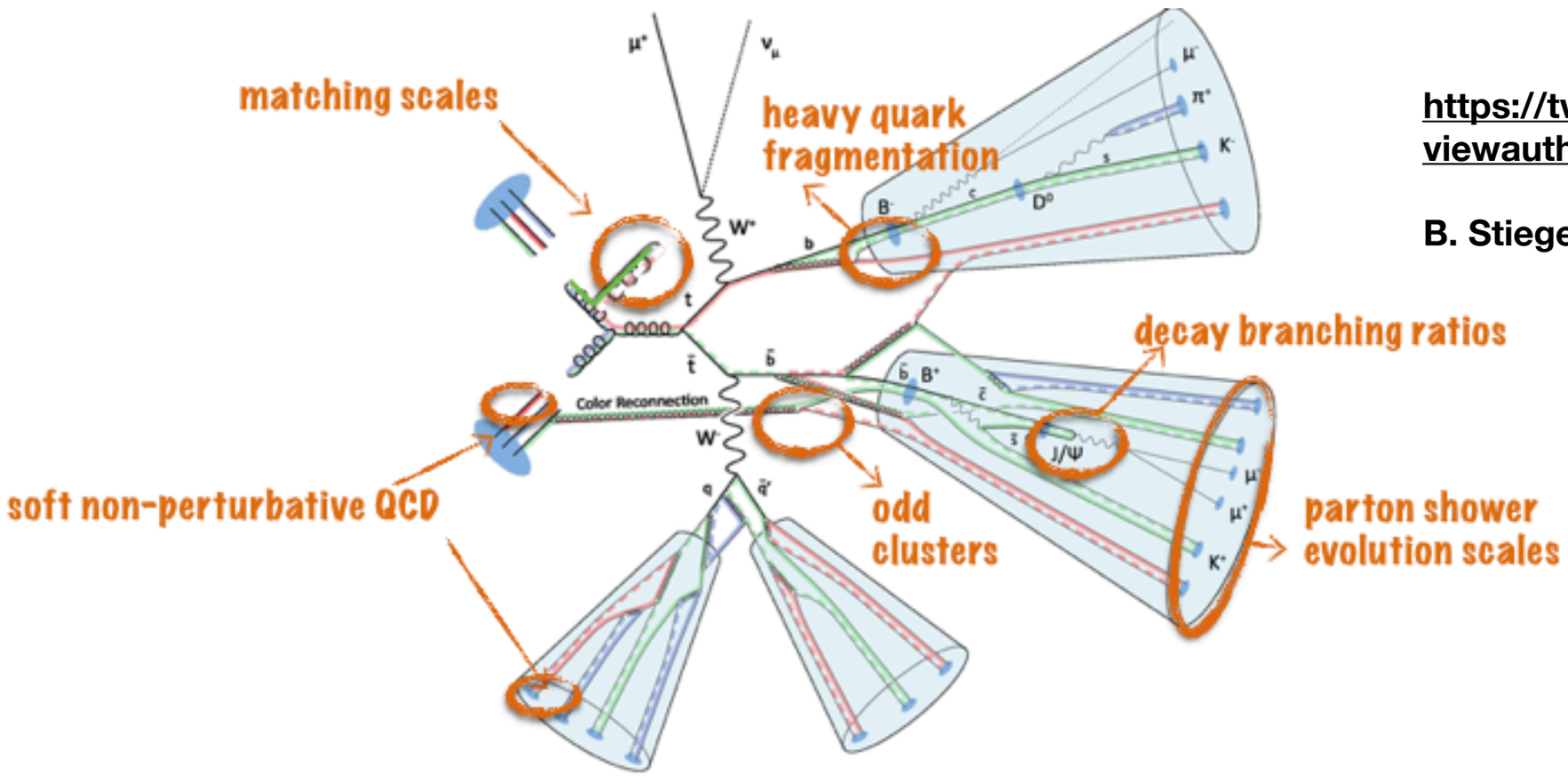
Specifically for POWHEG samples

↑ **Vary by factor of 2**

↓ **Vary by factor of 0.5**

Systematic Uncertainties in the top sector

Various sources of systematic uncertainties



https://twiki.cern.ch/twiki/bin/viewauth/CMS/TopSystematics

B. Stieger

- PYTHIA is used as default MC for modeling parton showers
- Samples with Powheg+Herwig++ and Powheg+Herwig7 produced
- Modeling differences serve as cross check, not quoted as systematic uncertainty

Systematic uncertainties arising from scale variations in the parton shower

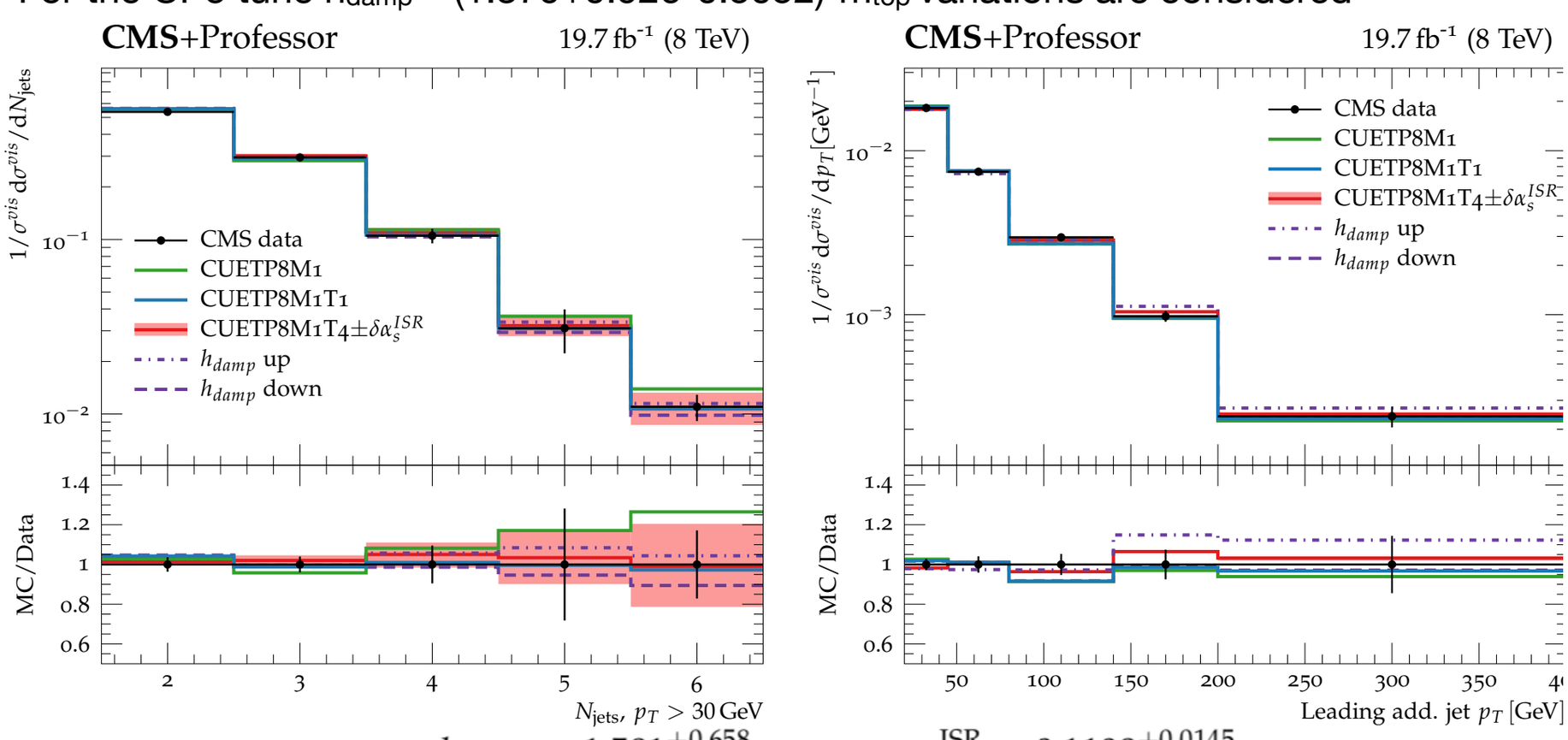
- **Description:**
  - Uncertainty arising out of the scale Q^2 at which the strong coupling constant (α_s) is evaluated
  - Estimated by varying the renormalization scale for QCD emissions in initial-state and final-state radiation (ISR and FSR)
  - Variations encompass NLO compensation terms to preserve soft gluon limit
  - Typically one of the **largest sources of systematic uncertainty**
- **Prescription:**
  - Event weights encompass these variations
    - Vary renormalization scale (μ_R) by 0.5 and 2 (code snippet)

Decorrelating systematic uncertainties arising from scale variations in the parton shower

- For template fits, need to decorrelate splittings at unrelated scales (e.g gluon splittings in ISR ($\mu_R \sim m + p_T$) and $q \rightarrow qg$ in weak decays where $\mu_R \sim m_Z$)
- Applies to ISR in the parton shower
- Scale variations for different splitting types independently (using options in PYTHIA8):
  - $g \rightarrow gg$
  - $g \rightarrow qq$
  - $q \rightarrow qg$
  - $x \rightarrow xg$ where x is b, t `UncertaintyBands:nFlavQ = 4`
- Weights corresponding to each of these variations available (code snippet)
- For a discussion on the need for NLO compensation terms ($\mathcal{O}(\alpha_s^2)$) in the soft gluon emission limit, look at M. Seidel's talk

Systematic uncertainties arising from ME-PS matching scale

- **Description:**
  - The matrix element-parton shower matching scale error is estimated by varying the h_{damp} parameter
  - The POWHEG generator scales the cross section for real emissions by a damping function $\mathbf{h_{damp}^2 / (p_T^2 + h_{damp}^2)}$ which drives the hardness of the real emission (regulates the high-pT radiation)
- **Prescription:**
  - The damping variable h_{damp} is set to 1.379*m_{top}, a value derived from data at $\sqrt{s}$ = 8 TeV in the dilepton channel using a similar ME calculation and assuming the CP5 tune
  - For the CP5 tune h_{damp} = (1.379+0.926-0.5052)*m_{top} variations are considered



$$h_{\mathrm{damp}} = 1.581^{+0.658}_{-0.585} \times m_t, \qquad \alpha_s^{\mathrm{ISR}} = 0.1108^{+0.0145}_{-0.0142}$$

TOP-16-021

CP5 plots not public yet

Systematic uncertainties arising from color reconnection

- **Description:**
  - Color reconnection reconfigures color strings after parton shower
  - Color reconnection model based on modeling of multiple parton interactions. PYTHIA8 includes:
    - **MPI-based modeling** assigns a probability to each parton pair to reconnect with a harder system high $p_T \rightarrow$ less likely to be color connected

$$P = \frac{p^2_{\mathrm{T_{Rec}}}}{p^2_{\mathrm{T_{Rec}}} + p^2_T} \qquad p^2_{\mathrm{T_{Rec}}} = R \cdot p_{T_0}$$

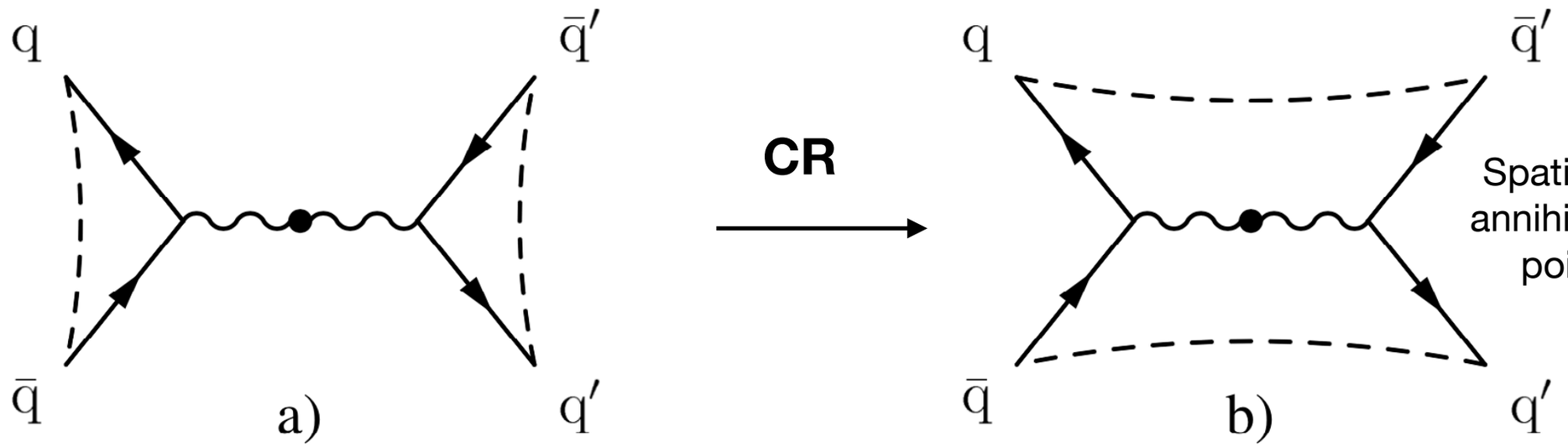
    - $p_{T_{Rec}}$ is a regularization term prevents divergence of partonic cross sections at low p_T, R is a parameter
  - **QCD inspired model** includes minimization of string length in addition to QCD color rules. Determines color-compatibility of two strings iteratively. Causally connect produced strings through a string length measure (λ)

$$\lambda = \ln\left(1 + \sqrt{2}\frac{E}{m_0}\right)$$

    - *m0* parameter determines whether a connection is favored, *E* = energy
  - **Gluon move model:** Iteratively move each final-state gluon from a "string piece" of partons to another. Naive model does not include quark reconnection, implemented by including a "flip" mechanism (move quarks as well)

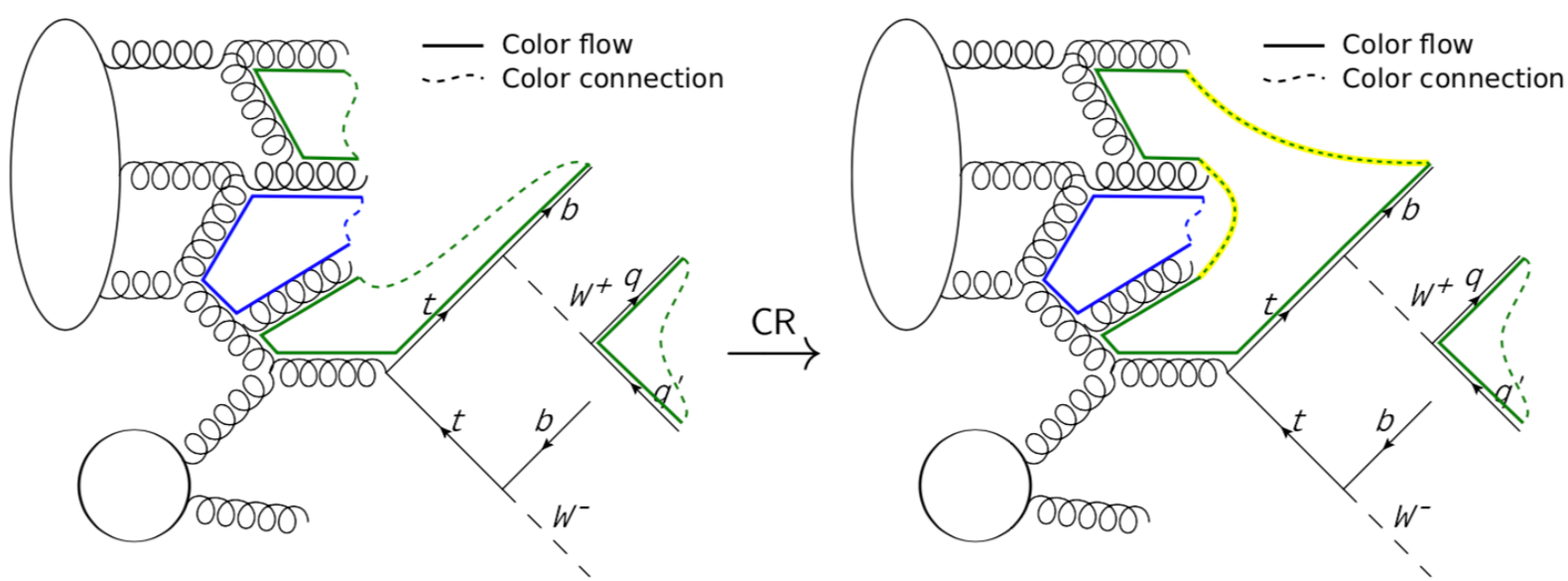
Systematic uncertainties arising from color reconnection

Original topologies **Reconnected version**



Spatial diagrams after annihilation, production point at the origin

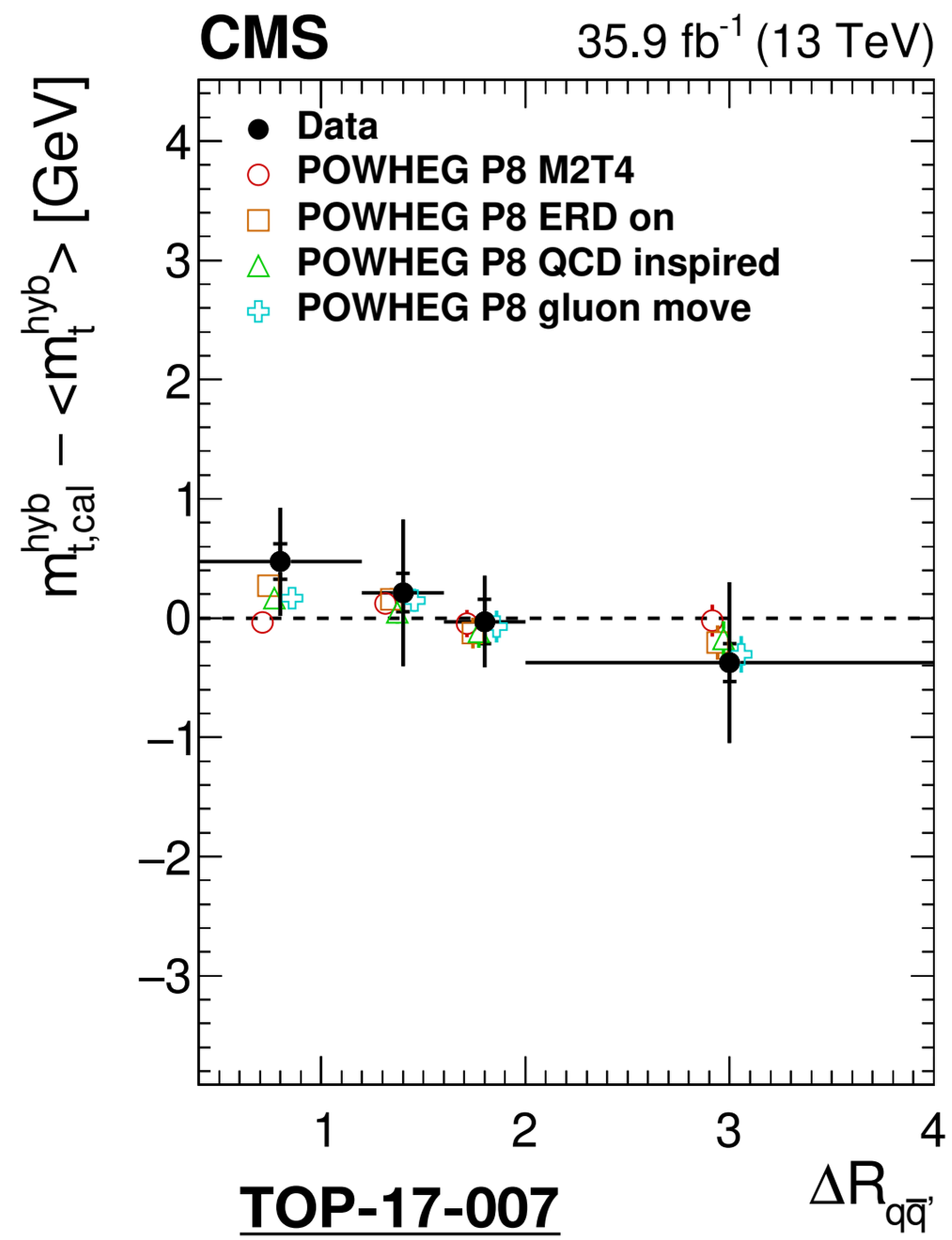
Colour Annealing — A Toy Model of Colour Reconnections: M. Sandhoff , P. Skands



M. Seidel

Systematic uncertainties arising from color reconnection

- **Prescription:**
  - Analyzers advised to implement all three models of color reconnection (CR):
    - MPI based tune with early resonance decays on (ERDon), ‘`PartonLevel:earlyResDec = on`’ (`Early Resonance Decay = off` (on): top quark (decay products) can color reconnect to other partons)
    - QCD-inspired (CR1): code snippet
    - Gluon move (CR2): code snippet
  - Largest difference between these variations w.r.t the nominal is used to assess the uncertainty
  - CR tunes correlated with underlying event (UE) tunes: need to quantify this uncertainty since UE parameters simultaneously tunes with CR model parameters



Spatial separation between light quarks

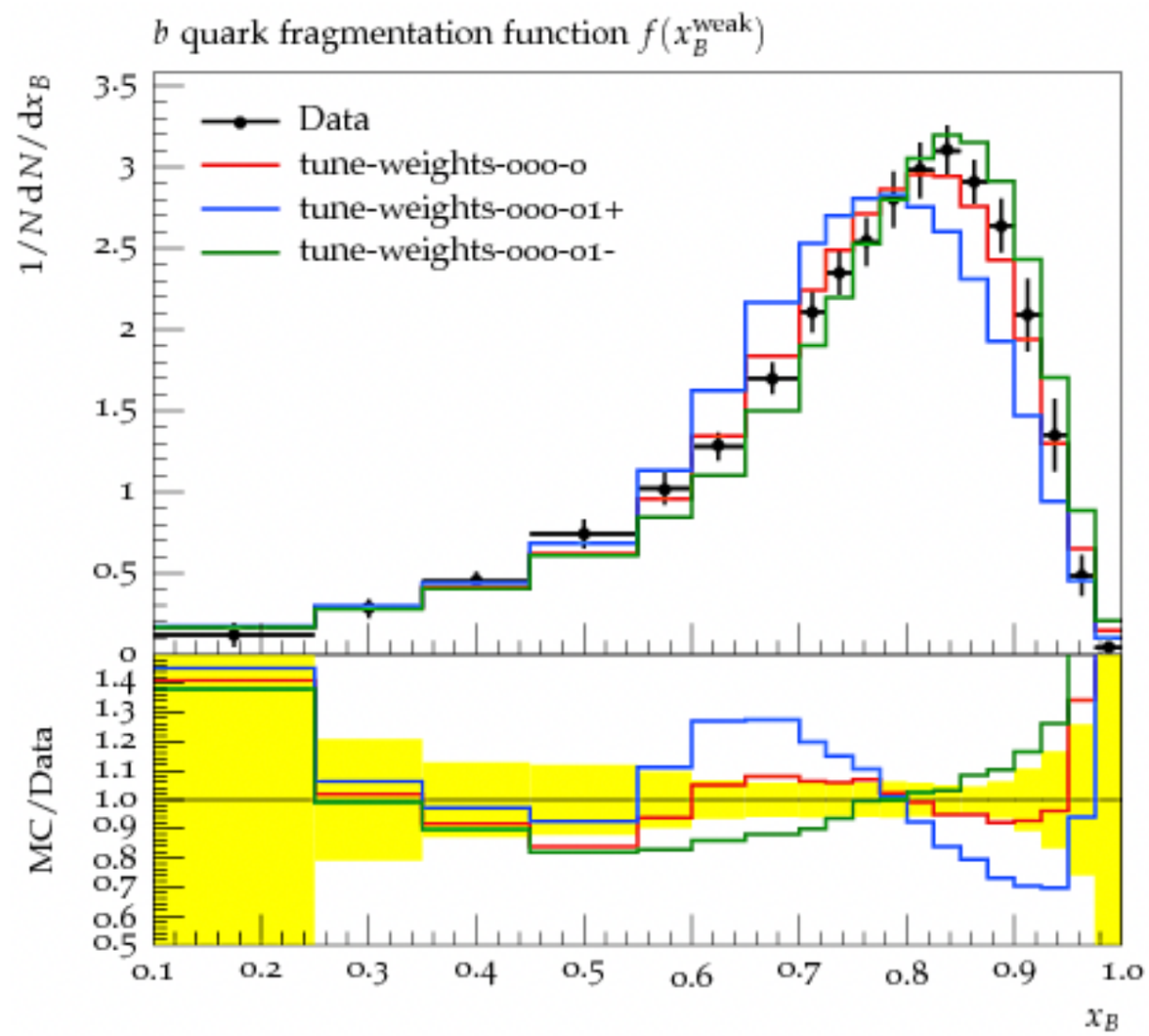
Systematic uncertainties arising from b-fragmentation

- **Description:**
  - b-fragmentation refers to the momentum transfer from the b-quark to the B hadron

$$f(z) \propto \frac{1}{z^{1+r\cdot bm_\perp^2}}(1-z)^a \exp\left(\frac{-bm_\perp^2}{z}\right)$$

$$m_\perp^2 = E^2 - p_z^2 \qquad r(r_b, r_c) \in [0,1]$$

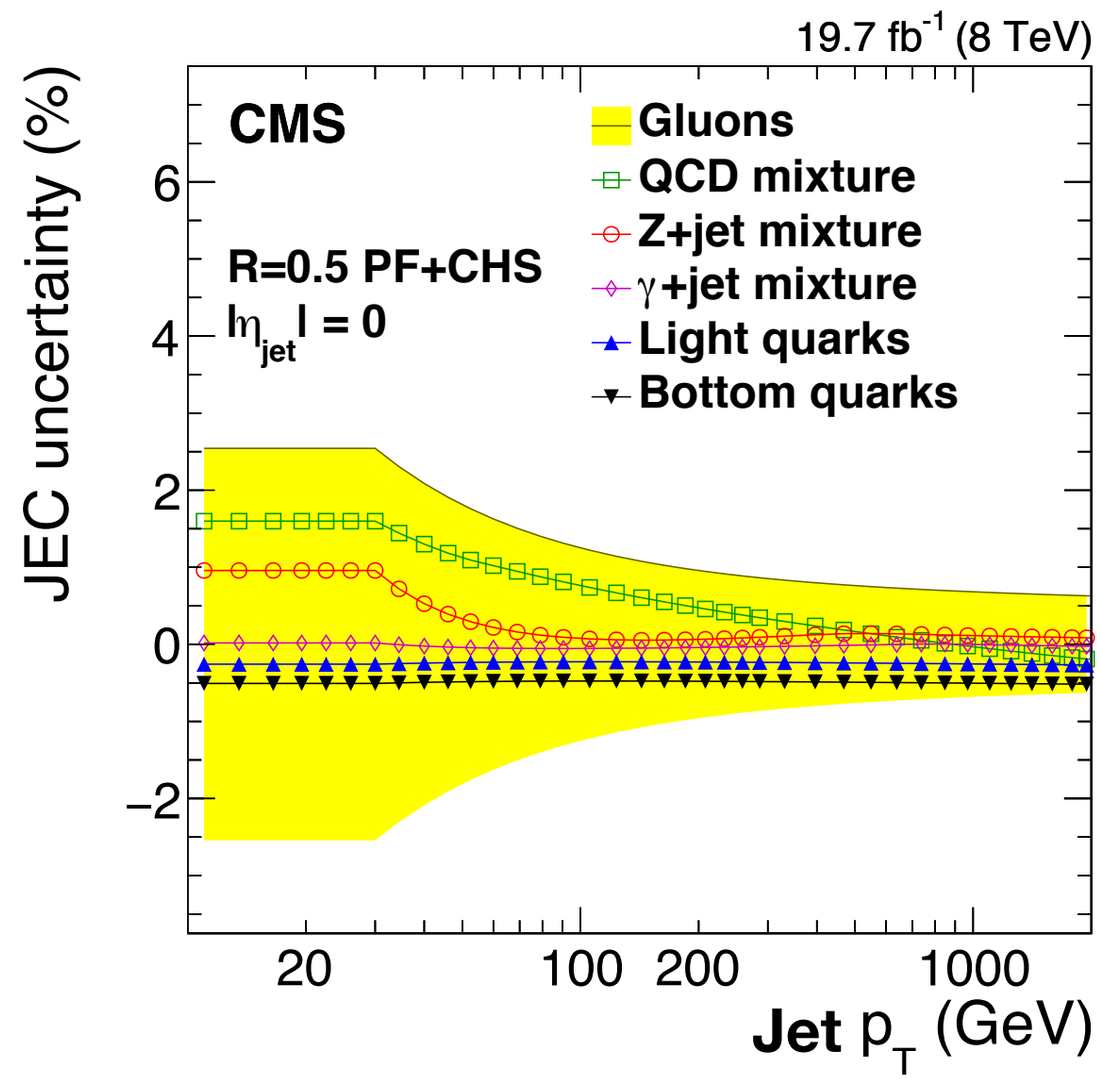
  - Tuned using LEP/SLD data
  - Fragmentation function of heavy quarks includes Bowler modification to the Lund string model and is set to 0.895 (r_b) (CUETP8M2T4 tune) with variations between (0.184 - 0.197) w.r.t the default value



- **Prescription:**
  - Top mass measurements in Run I applied the following reweighting to the transfer function to encompass effects on kinematics of b-jets: $x_b = p_T(B)/p_T(\text{b-jet})$

Systematic uncertainties arising from flavor response

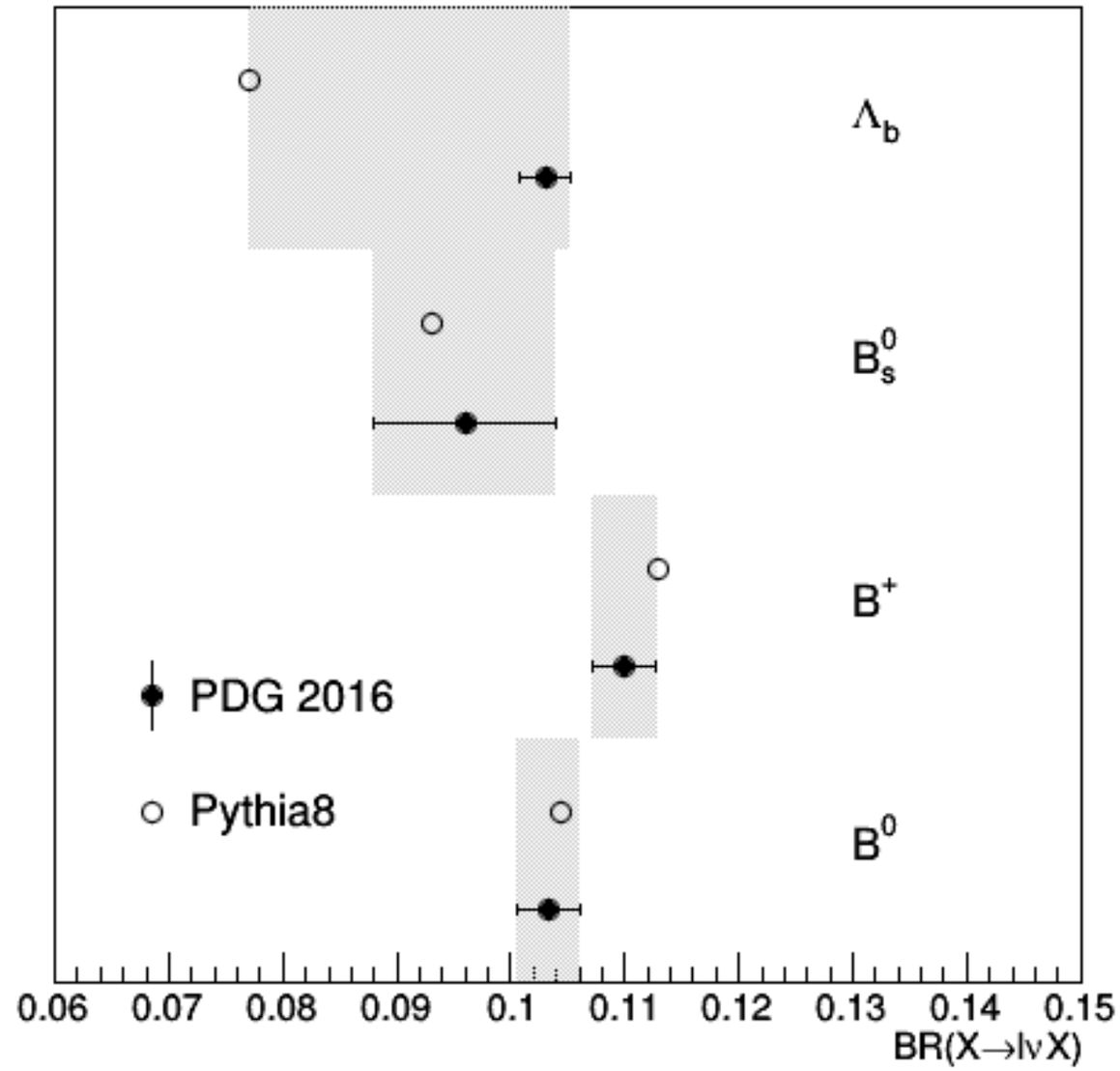
- **Description:**
  - Applicable to analyses sensitive to different jet responses for gluon, light quarks, c and b-quarks
  - Response refers to detector level response which can vary based on generator level descriptions
  - Uncertainties assessed after jet energy corrections have been applied
  - Data is replaced with HERWIG and miscalibration of each flavor checked in HERWIG wrt to the default PYTHIA description
  - For b-jets, Z+b has been used for cross checks
- **Prescription:**
  - The parton flavor truth information is used to vary the jet energy corrections for each of the 4 flavors (g, q, c, b)
  - Uncertainty based on the difference in yields from these variations



JME-13-004

Systematic uncertainties arising from decay tables

- **Description:**
  - The semi-leptonic branching ratio of B hadrons may significantly change the b jet energy response
  - Can lead to a shift in the visible b-jet energy
- **Prescription:**
  - The b-jets are reweighted based on variations of the BRs using the generator level truth information
  - Uncertainty assigned based on envelope of PYTHIA8 and PDG value for semil-leptonic B-hadron decays



Description of the underlying event (UE)

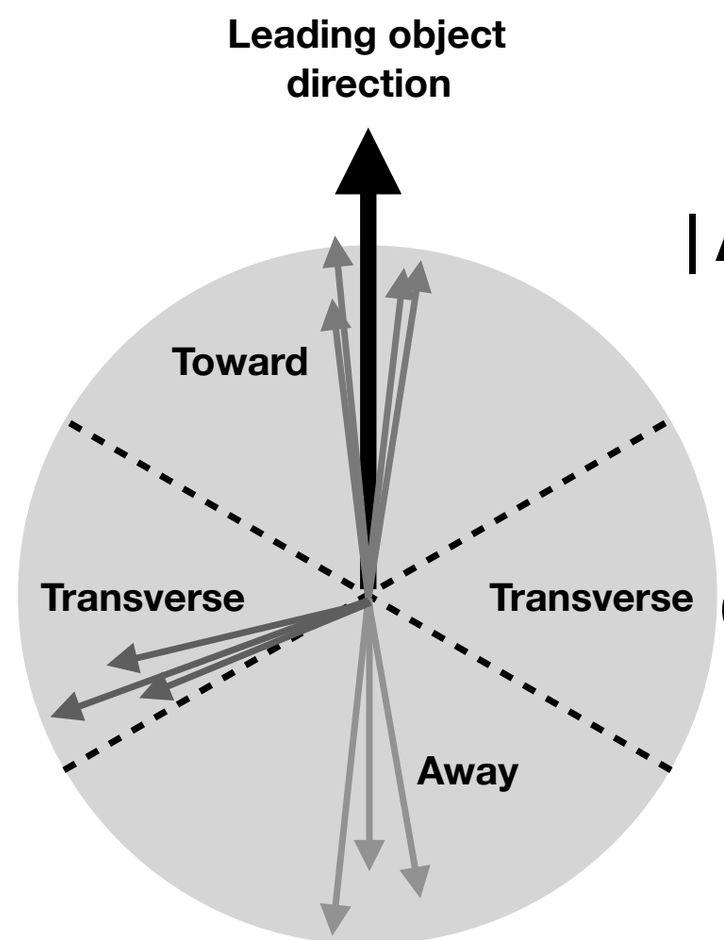
[Slight detour]

- UE defined as activity not associated with particles originating from the hard scatter of two partons. Generally studied in events that contain a hard scattering with pT ≳ 2 GeV

Leading object defined on an event-by-event basis

Φ regions relative to the leading object that are sensitive to the underlying event

Azimuthal separation between charged particles and leading object $\Delta\Phi = \Phi - \Phi_{max}$ used to define sensitive regions



$|\Delta\Phi| \leq 60^0$

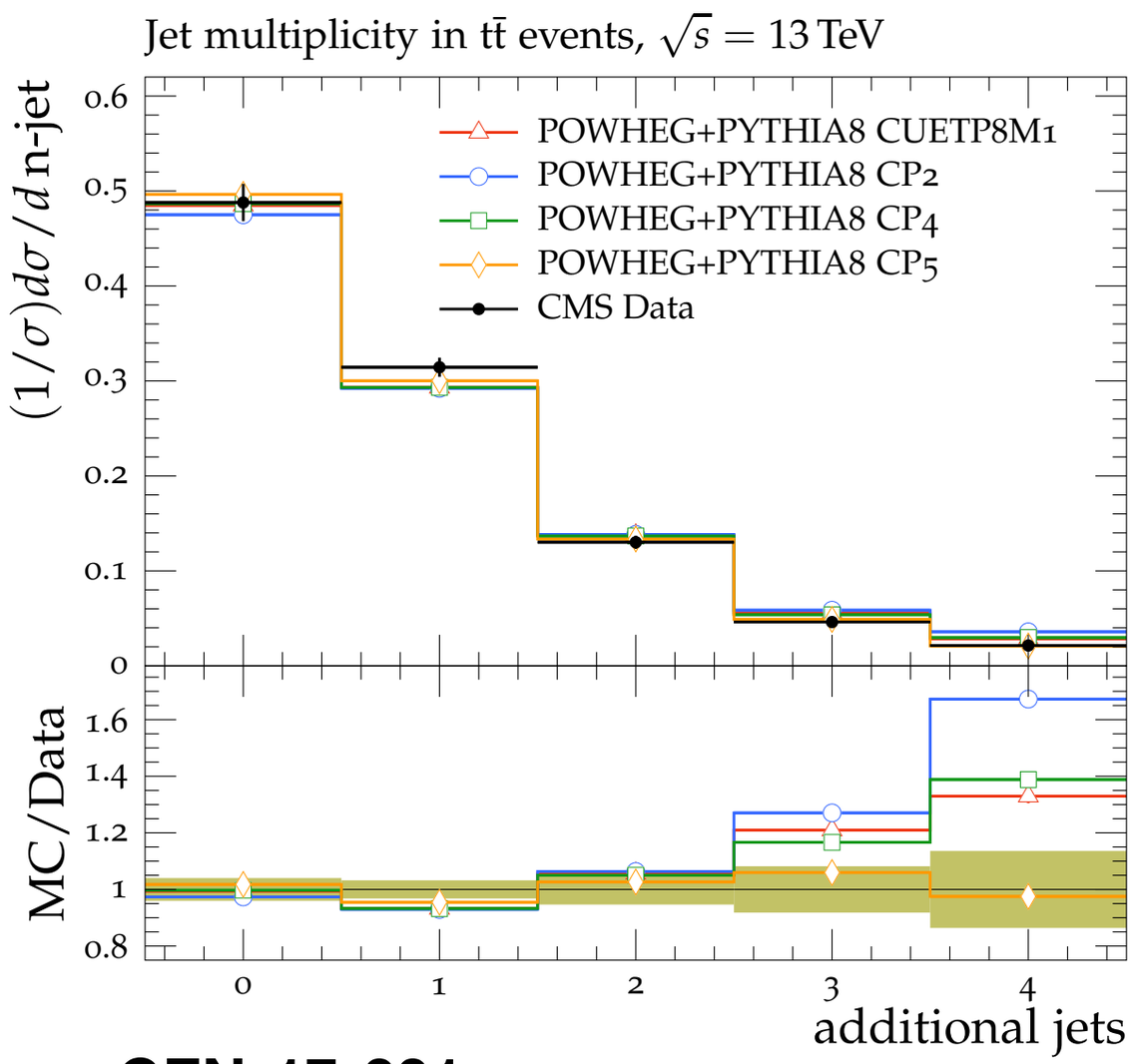
$60^0 < |\Delta\Phi| \leq 120^0$

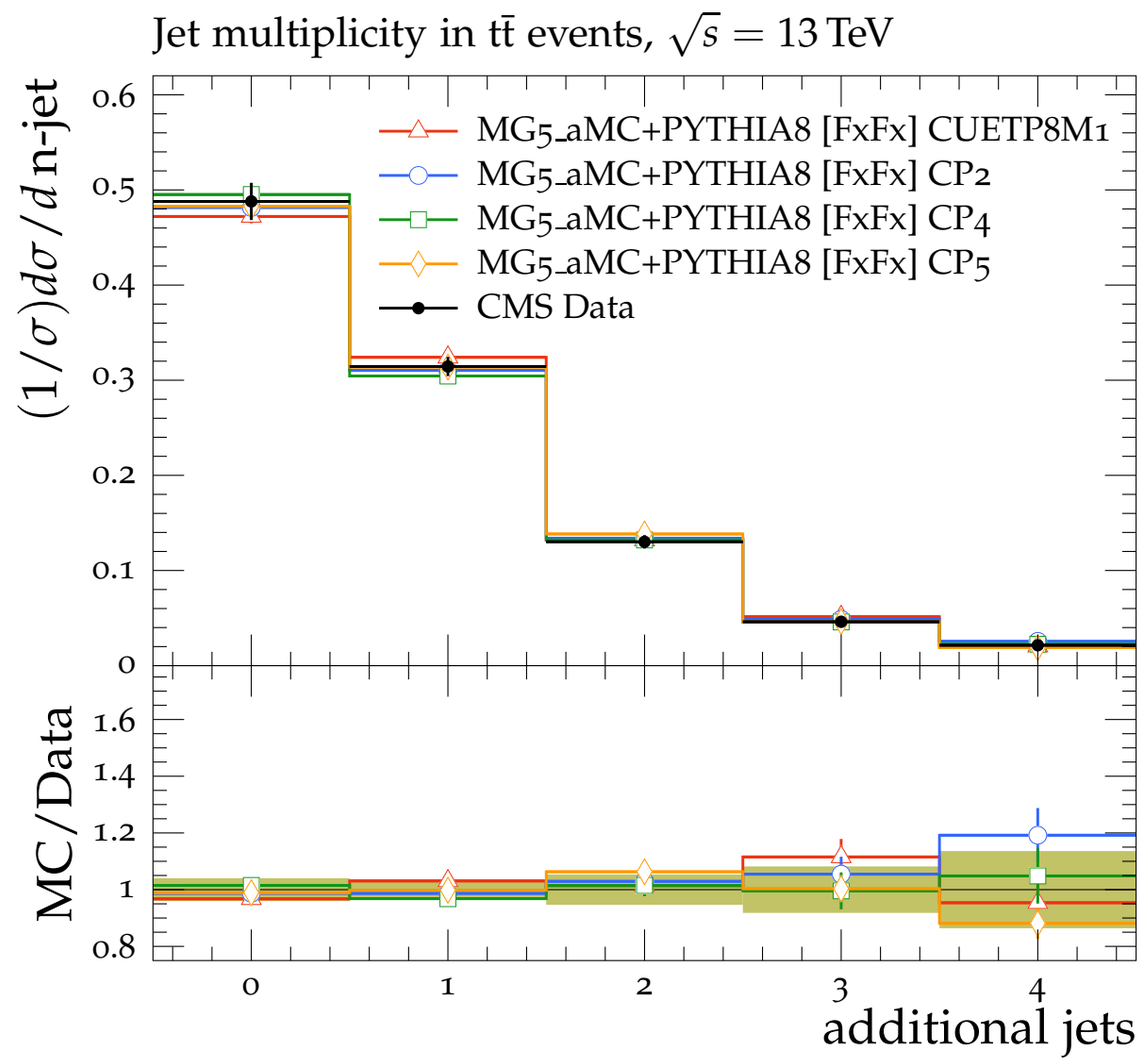
$|\Delta\Phi| < 120^0$

Validation of the underlying event (UE) tunes in top events

[Slight detour]

- Description of CMS tt data with new PYTHIA 8 tunes
- ME configurations use NNPDF3.1 NNLO PDF with $\alpha_s(m_Z) = 0.118$ and $m_{top} = 172.5$ GeV
- h_{damp} is set to $1.379 * m_{top}$

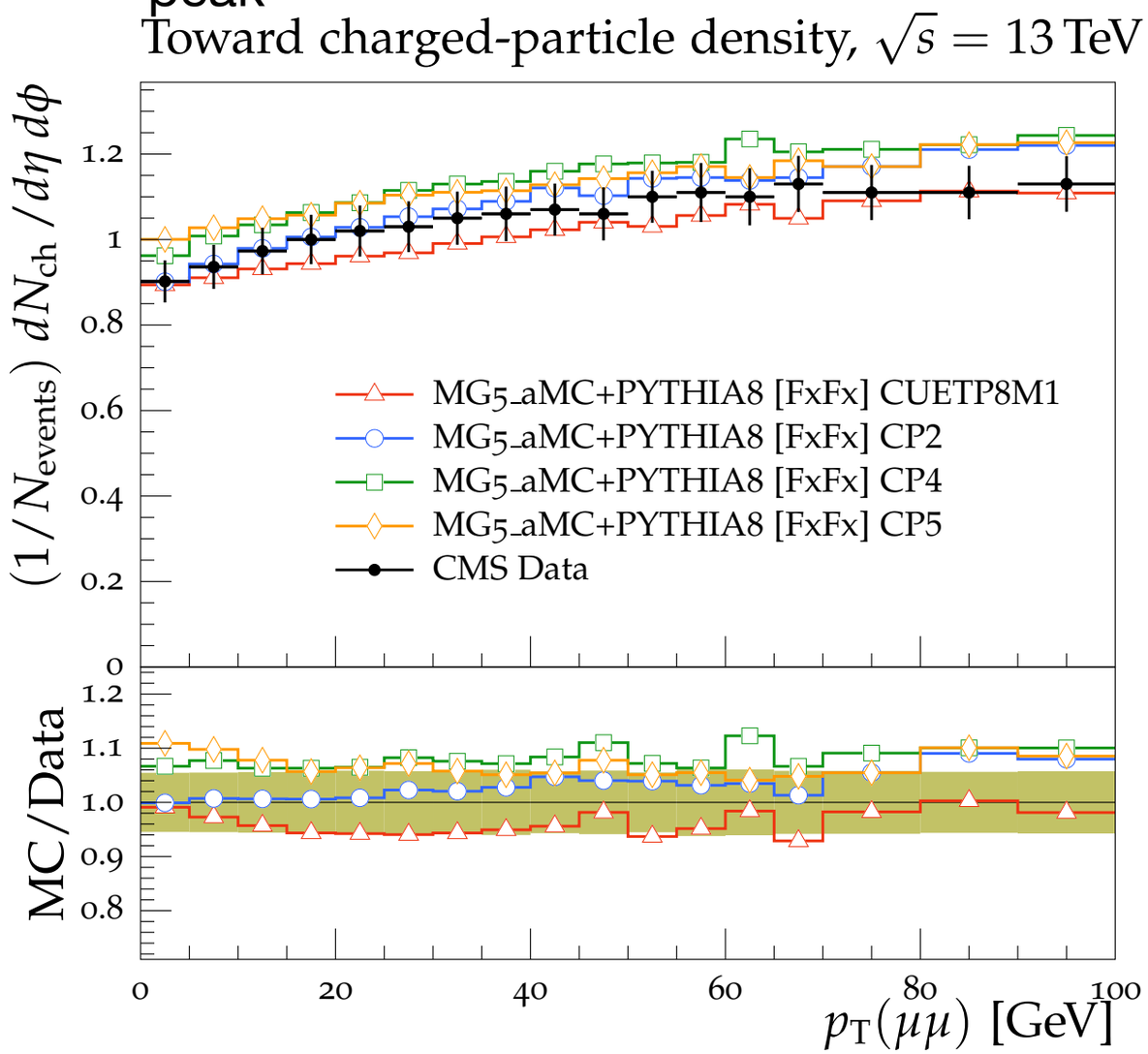


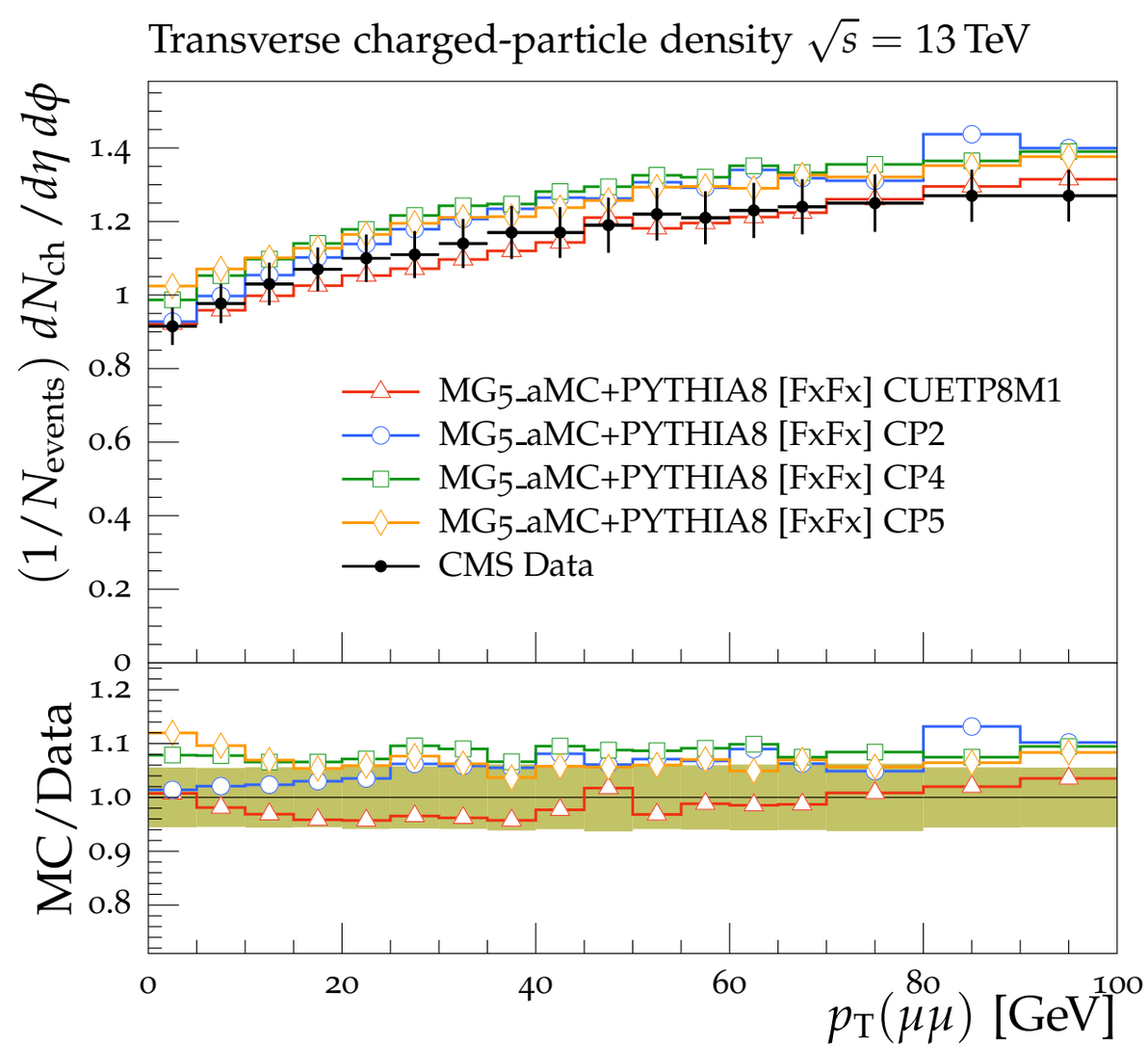


GEN-17-001

Modeling of the underlying event (UE) in Z+jets events

- Validation of UE tunes in events with a Z-boson
- In Drell-Yan events events studied in invariant mass window of 81-101 GeV around the Z-peak





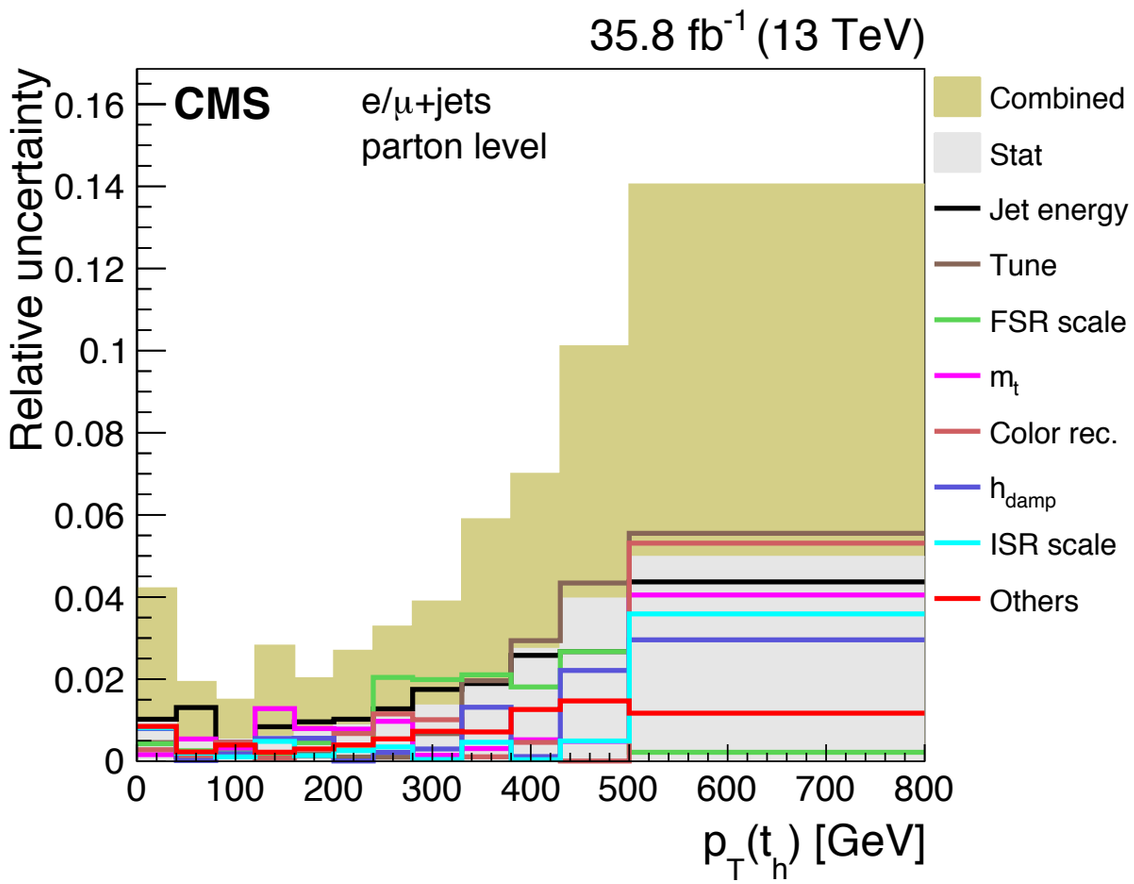
GEN-17-001

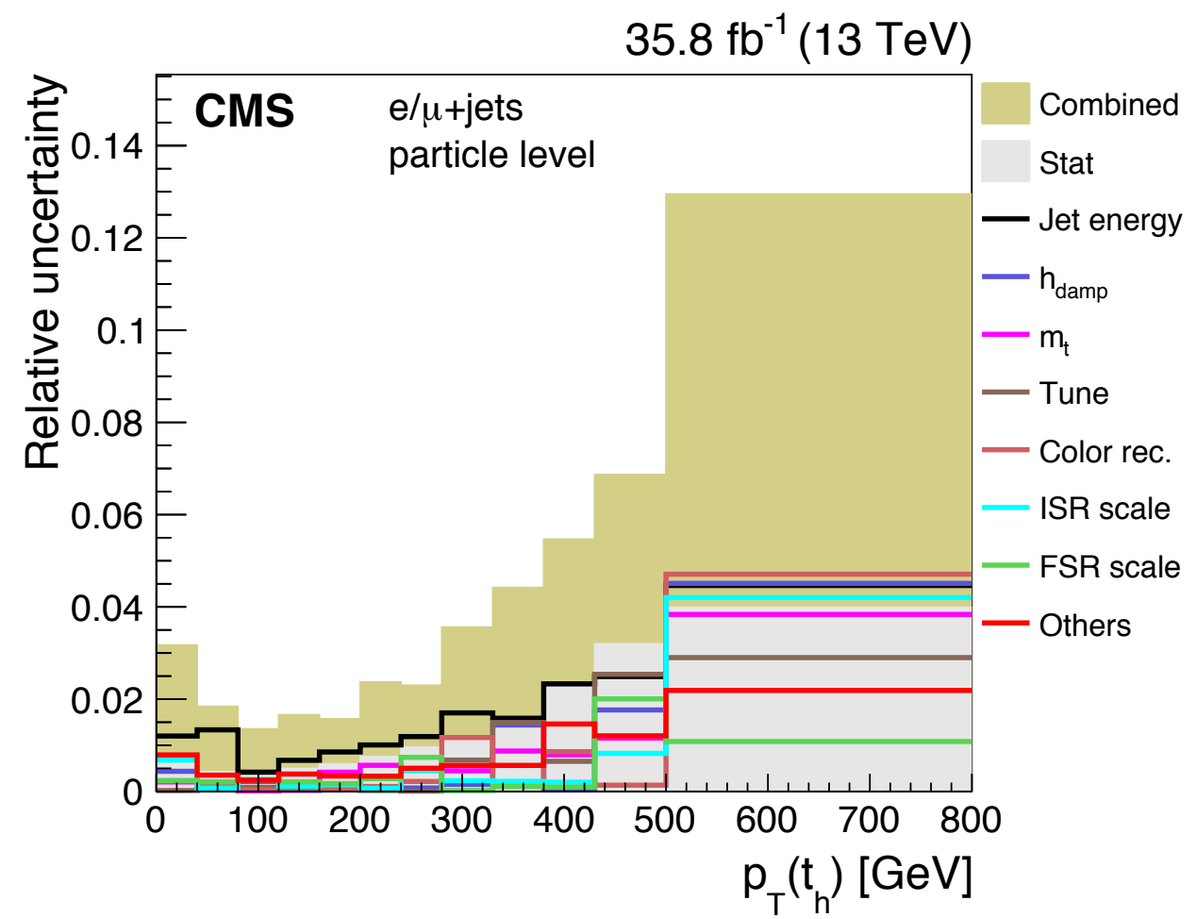
Systematic uncertainties arising from the modeling of the underlying event (UE)

- **Description:**
  - To study the differences between the nominal CP5 tune and the up/down variations of the CP5 tune
  - Implemented in dedicated MC samples quoted as the UE uncertainty
- **Prescription:**
  - The variations of the tune described in GEN-17-001 and can be found in the following code snippets:
    - Nominal: code snippet
    - Up: code snippet
    - Down: code snippet
  - Uncertainty is correlated across years and processes

Relative contribution of the uncertainties

- Uncertainties assessed by prescriptions outlined on previous slides
- h_{damp} is set to 1.58*M_{top} (data set corresponds to 2016 data taking which included CUETP8M2T4 tune)



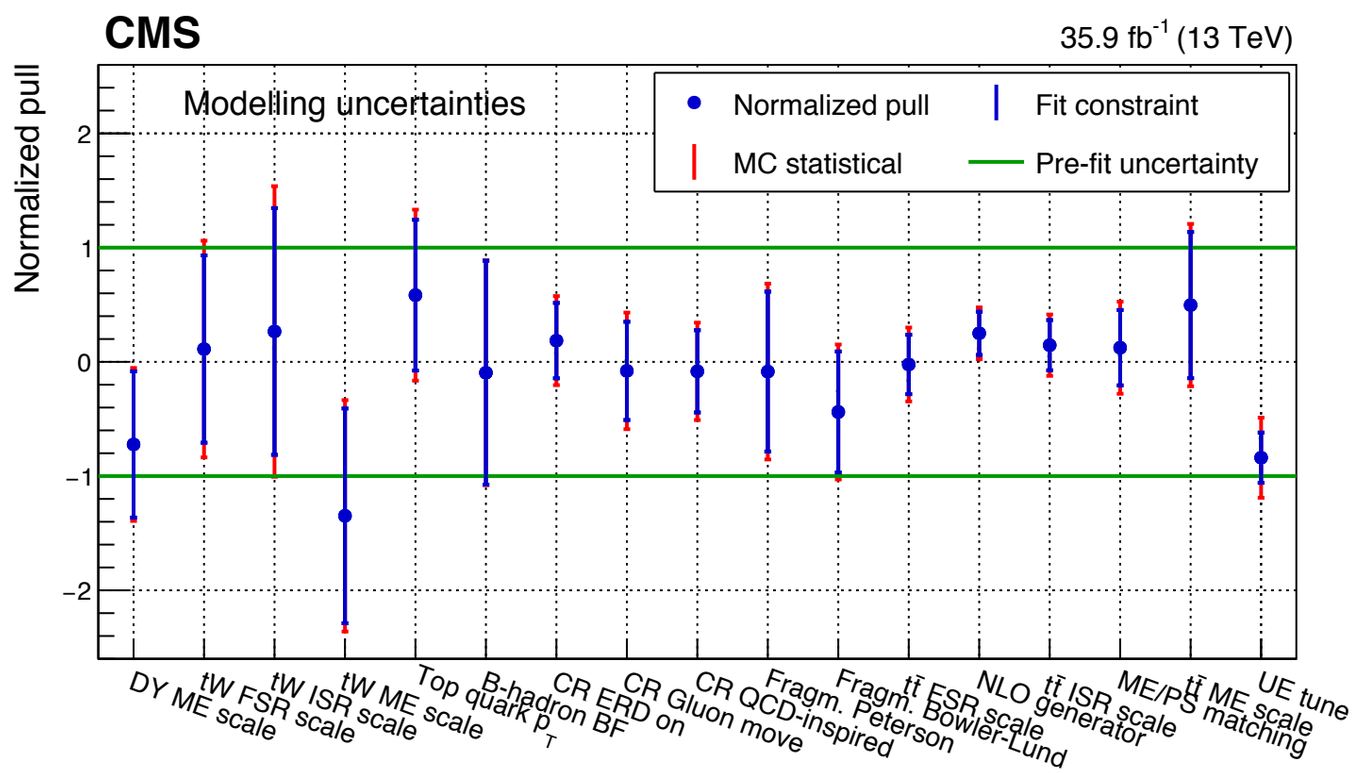


Measurement of differential cross sections for the production of top quark pairs and of additional jets in lepton+jets channel

TOP-17-002

Relative contribution of the uncertainties

Simultaneous measurement of the top quark mass (m_t) and cross section (σ_{tt}) in dilepton top events



TOP-17-001

Does not show the effect of variation of the top p_T directly; shows the uncertainty in the unfolding

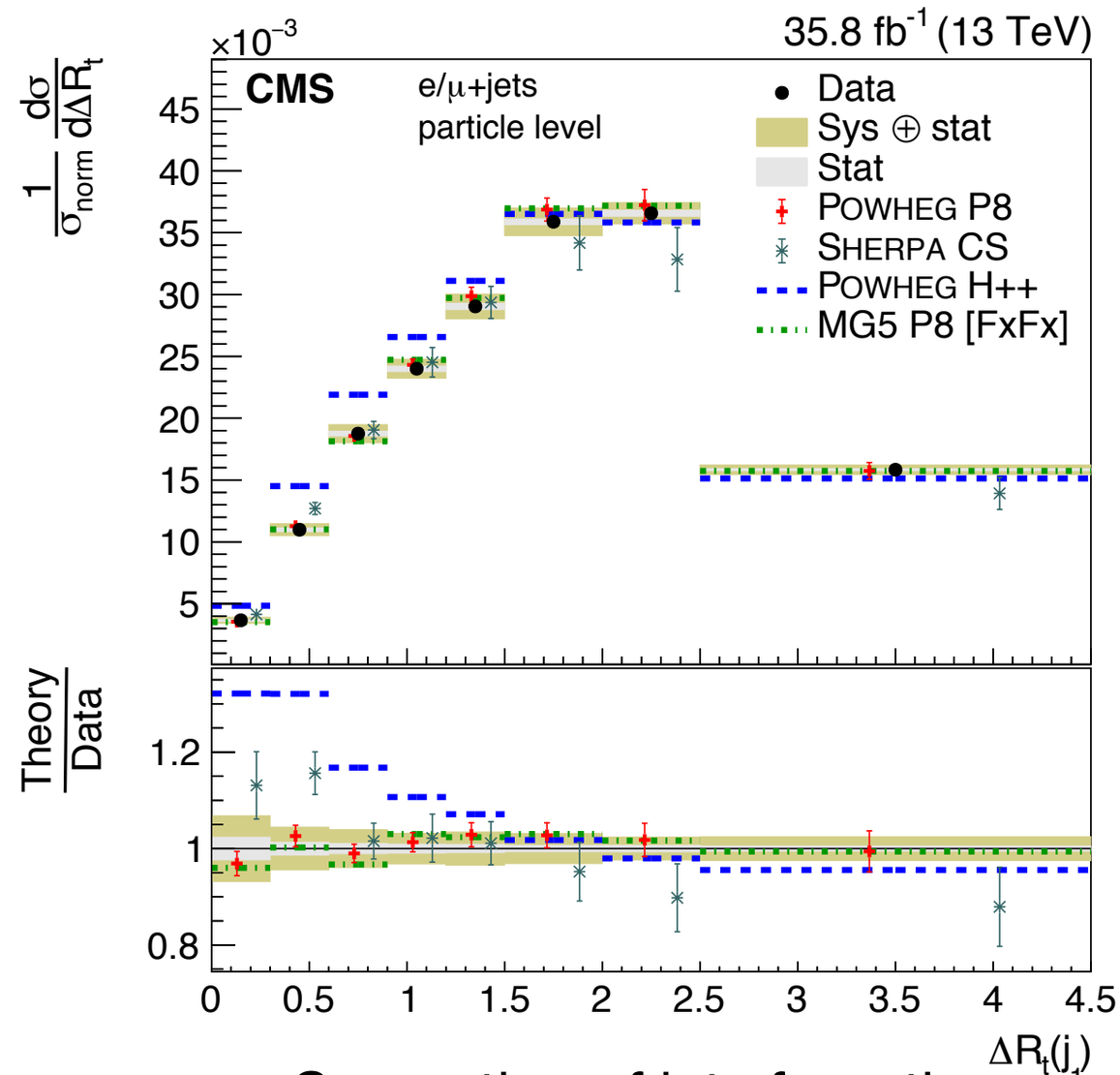
Measurement of the top mass in all-jets final state and combination with lepton+jets channel

	δm_t^{hyb} [GeV] all-jets	ℓ+jets	combination
Experimental uncertainties			
Method calibration	0.06	0.05	0.03
JEC (quad. sum)	0.15	0.18	0.17
– Intercalibration	−0.04	+0.04	+0.04
– MPFInSitu	+0.08	+0.07	+0.07
– Uncorrelated	+0.12	+0.16	+0.15
Jet energy resolution	−0.04	−0.12	−0.10
b tagging	0.02	0.03	0.02
Pileup	−0.04	−0.05	−0.05
All-jets background	0.07	–	0.01
All-jets trigger	+0.02	–	+0.01
ℓ+jets background	–	+0.02	−0.01
Modeling uncertainties			
JEC flavor (linear sum)	−0.34	−0.39	−0.37
– light quarks (uds)	+0.07	+0.06	+0.07
– charm	+0.02	+0.01	+0.02
– bottom	−0.29	−0.32	−0.31
– gluon	−0.13	−0.15	−0.15
b jet modeling (quad. sum)	0.09	0.12	0.06
– b frag. Bowler–Lund	−0.07	−0.05	−0.05
– b frag. Peterson	−0.05	+0.04	−0.02
– semileptonic b hadron decays	−0.03	+0.10	−0.04
PDF	0.01	0.02	0.01
Ren. and fact. scales	0.04	0.01	0.01
ME/PS matching	+0.24	−0.07	+0.07
ME generator	–	+0.20	+0.21
ISR PS scale	+0.14	+0.07	+0.07
FSR PS scale	+0.18	+0.13	+0.12
Top quark p_T	+0.03	−0.01	−0.01
Underlying event	+0.17	−0.07	−0.06
Early resonance decays	+0.24	−0.07	−0.07
CR modeling (max. shift)	−0.36	+0.31	+0.33
– "gluon move" (ERD on)	+0.32	+0.31	+0.33
– "QCD inspired" (ERD on)	−0.36	−0.13	−0.14
Total systematic	0.70	0.62	0.61
Statistical (expected)	0.20	0.08	0.07
Total (expected)	0.72	0.63	0.61

TOP-17-008

Summary and outlook

- Presented a brief overview of MC uncertainties accounted for in precision analyses
- Includes description and studies of tunes, underlying event modeling
- The relative contribution of uncertainties discussed
- <u>**Next steps/wish list?**</u>
  - **Understand performance of POWHEG+HERWIG++ that overestimates the radiation of additional jets close to the jets in the tt system**
  - **Next to leading log (NLL) parton shower description?**



Separation of jets from the closest top quark

Additional Material

Use of Monte Carlo Generators in CMS

1) For theorists to get an idea of what the relevant questions are in current and future experiments. For example
   a) are perturbative scale uncertainties dominant or sub-dominant? QCD vs EW?
   b) how are parton shower resummation uncertainties estimated? how important are they?
   c) how do you deal with uncertainties related to heavy flavor or more generally identified particle production?
   d) how are hadronization uncertainties assessed? how important are they when parton shower is treated separately?
   c) what are the most problematic analyses when it comes to MC uncertainties?
   d) ...

2) For experimentalists to get an idea what we realistically can achieve, based on solid theory. For example
   a) reduction of perturbative uncertainties within the foreseeable future, based on current pQCD technology
   b) improvements on resummation, both analytic and parton shower, and what impact to expect from this
   c) calculation / simulation of heavy flavor / identified particle production and related uncertainties
   d) uncertainties in hadronization models and how to assess them without playing herwig vs PYTHIA
   e) ...

Status of fixed order generators: Merging and matching scales

- Defines the cusp of fixed order computation (at NNLO/NLO/LO, hard scales) and parton shower

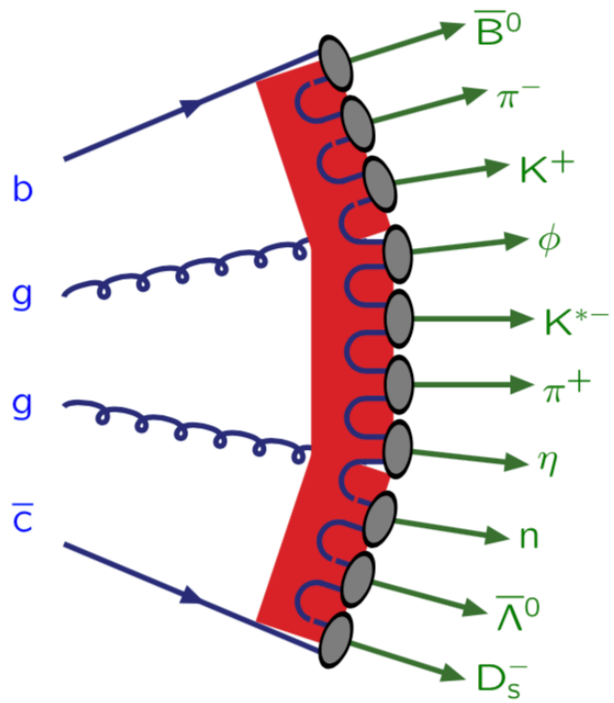
Recent progress:

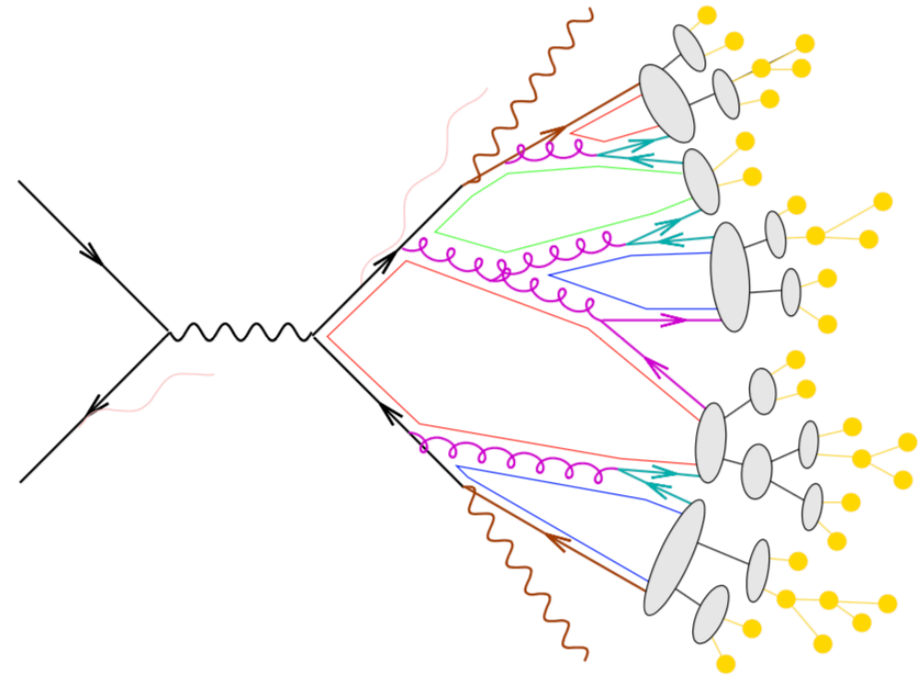
- NNLO matching for colour-singlet production
  - $\text{MiNNLO}_{\text{PS}}$: POWHEG framework, no reweighting [Monni,Nason,Re,Wiesemann,Zanderighi,19]
  - GenEvA: SCET-based [Bauer,Tackmann,Thaler,08]
  - UNLOPS: SHERPA framework [Höche,Prestel,14]
- uncertainty assessment: e.g. [Gellersen, Prestel, 20]

Challenges: *pp* processes with light jets

HERWIG vs. PYTHIA

String vs. Cluster





program	PYTHIA	HERWIG
model	string	cluster
energy–momentum picture	powerful	simple
	predictive	unpredictive
parameters	few	many
flavour composition	messy	simple
	unpredictive	in-between
parameters	many	few

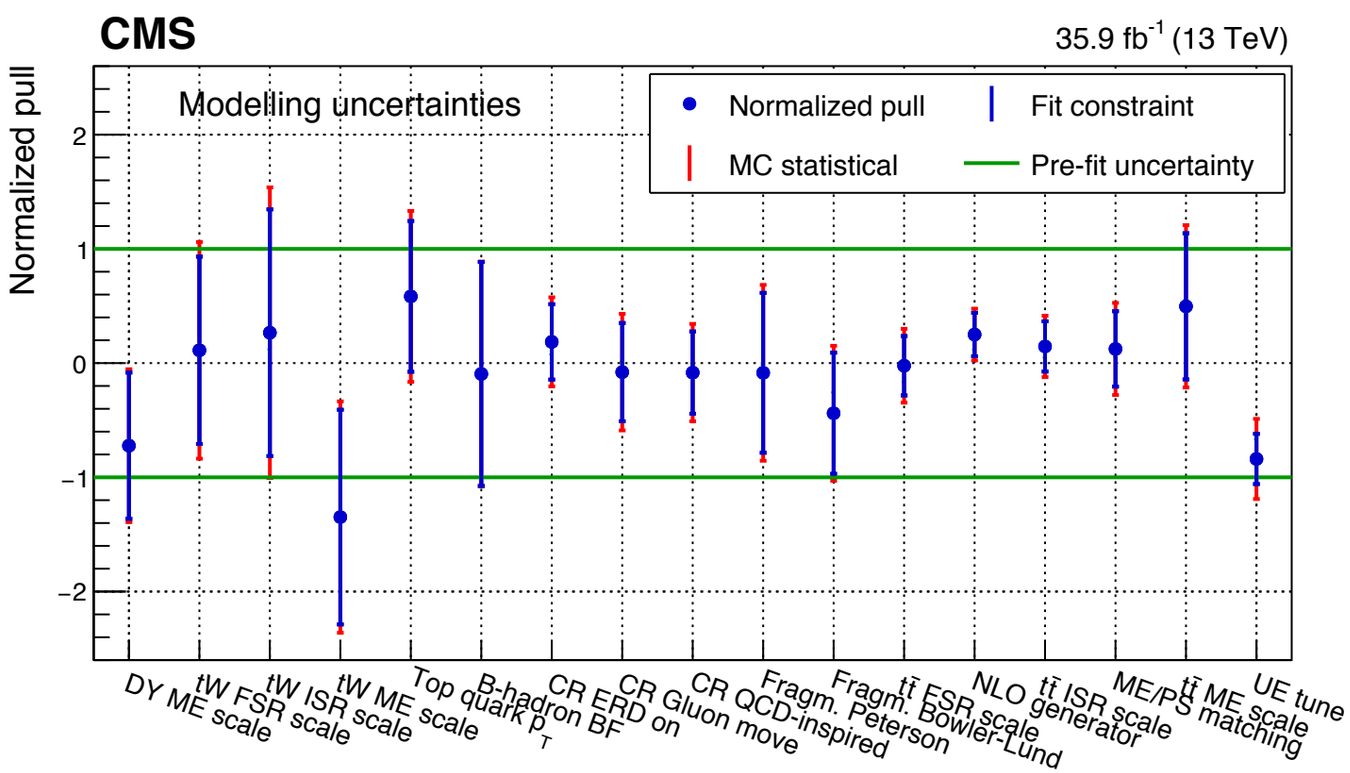
Search for heavy Higgs bosons decaying to a top quark pair

https://arxiv.org/abs/1908.01115

Uncertainty (# of parameters)	Type	Affected process	Correlation
Jet p_T scale (19)	shape	All	All
Jet p_T resolution	shape	All	All
Unclustered p_T^{miss}	shape	All	All
btagging heavy-flavor jets	shape	All	All
btagging light-flavor jets	shape	All	All
Pileup	shape	All	All
Electron identification	shape	All	All
Muon identification	shape	All	All
Single-electron trigger	shape	All	e, $\ell\ell$
Single-muon trigger	shape	All	μ, $\ell\ell$
Luminosity calibration	norm.	All	All
Renorm. scale SM $t\bar{t}$	shape	SM $t\bar{t}$	All
Fact. scale SM $t\bar{t}$	shape	SM $t\bar{t}$	All
Parton shower FSR $t\bar{t}$	shape	SM $t\bar{t}$	All
h_{damp}	shape	SM $t\bar{t}$	All
Top quark mass	shape	SM $t\bar{t}$	All
Top quark p_T (2)	shape	SM $t\bar{t}$	All
PDF (3)	shape	SM $t\bar{t}$	All
Renorm. scale res. signal	shape	Resonant signal	All
Renorm. scale int. signal	shape	Interference signal	All
Fact. scale res. signal	shape	Resonant signal	All
Fact. scale int. signal	shape	Interference signal	All
SM $t\bar{t}$ norm.	norm.	SM $t\bar{t}$	All
Single top t channel norm.	norm.	Single top t channel	ℓ
Single top s channel norm.	norm.	Single top s channel	ℓ
Single top tW channel norm.	norm.	Single top tW channel	All
W + jets norm.	norm.	W + jets	ℓ
Z/γ^* + jets norm.	norm.	Z/γ^* + jets	ℓ
Z/γ^* + jets norm. from data	norm.	Z/γ^* + jets	$\ell\ell$
Diboson norm.	norm.	Diboson	All
$t\bar{t}V$ norm.	norm.	$t\bar{t}V$	All
QCD multijet norm. from data, e	norm.	QCD multijet	e
QCD multijet norm. from data, μ	norm.	QCD multijet	μ
MC statistical uncertainty (365)	shape	All	No

Relative contribution of the uncertainties

- Simultaneous measurement of the top quark mass (m_t) and cross section (σ_{tt}) in dilepton top events

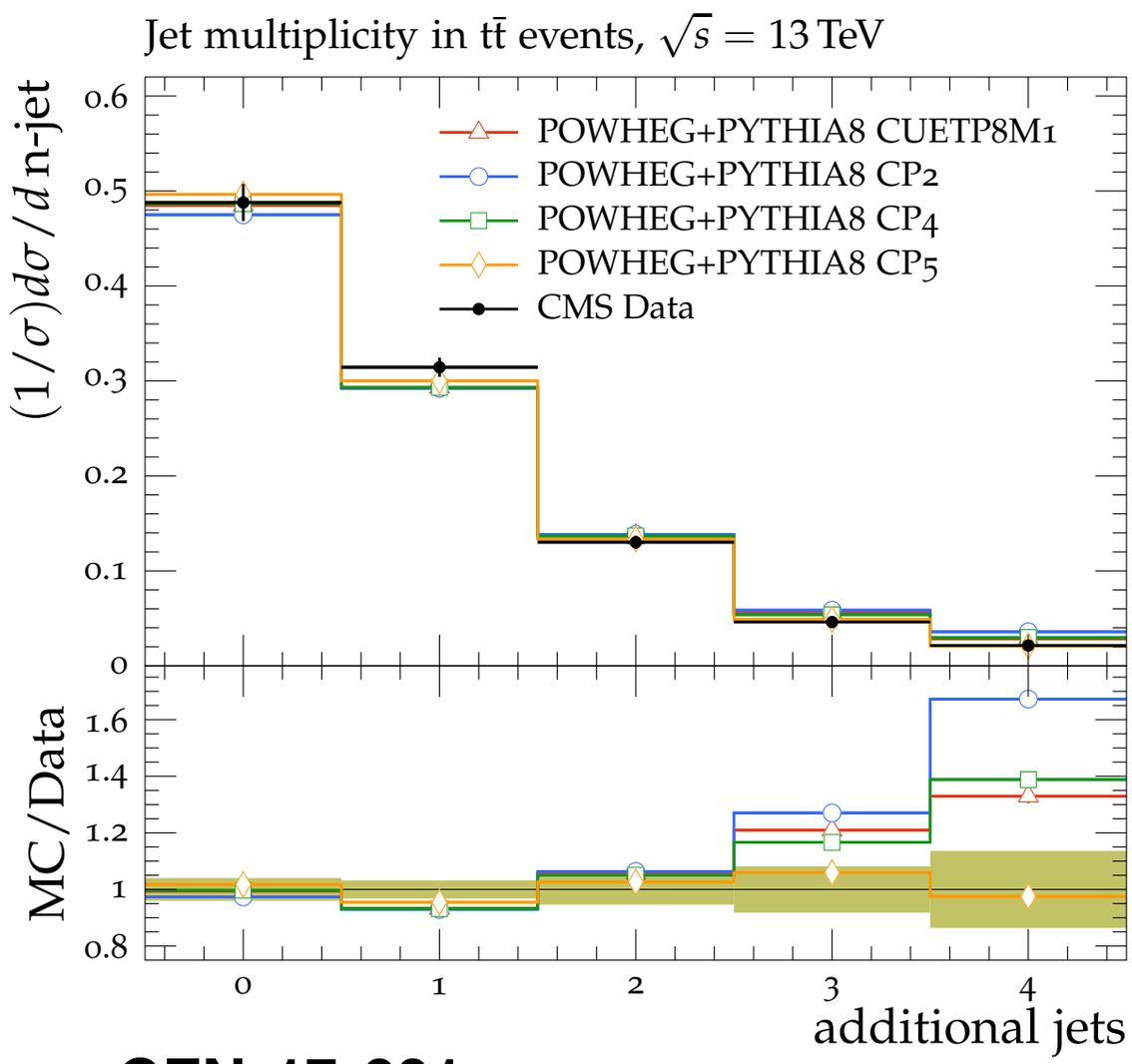


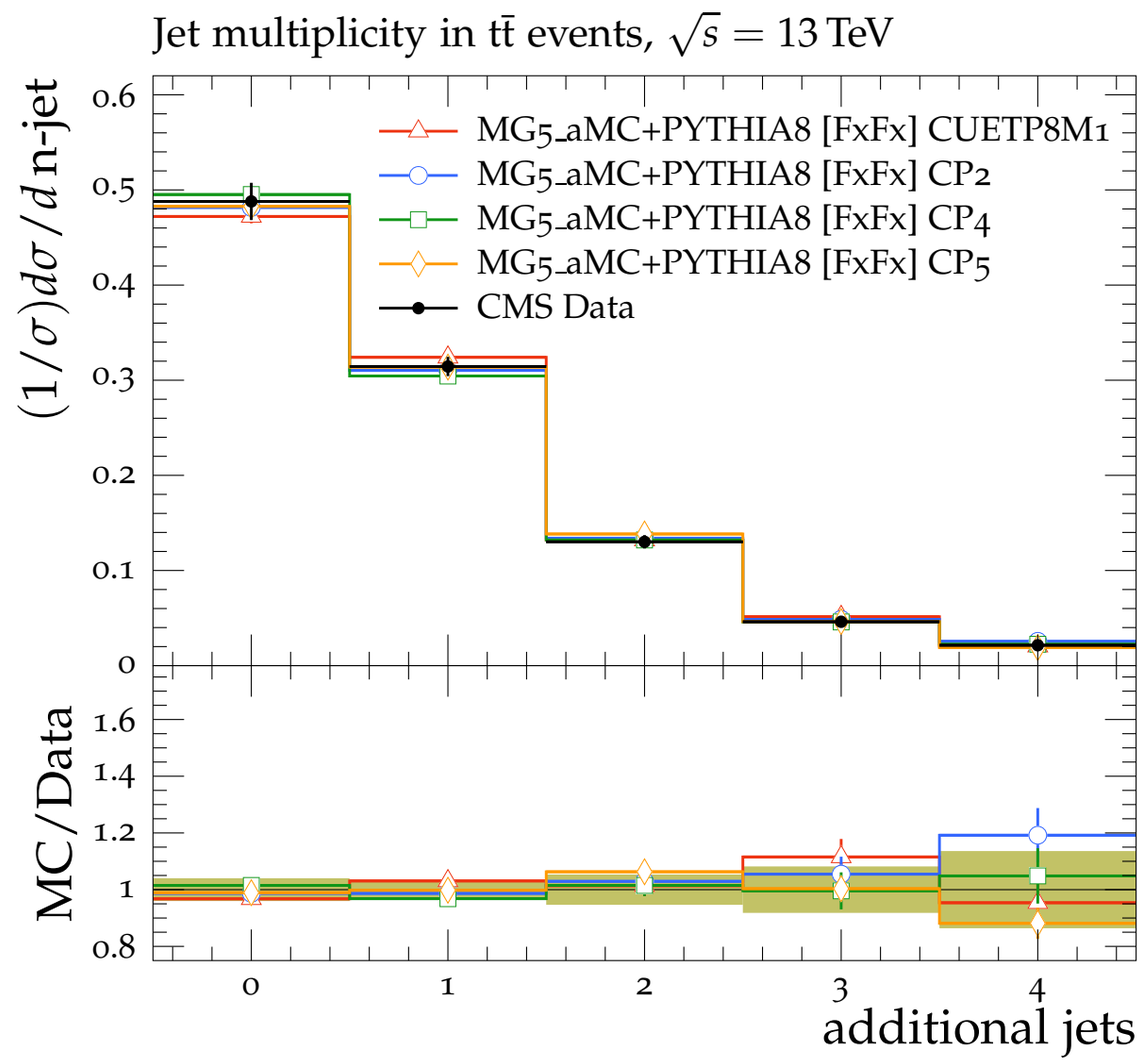
Source	Uncertainty [%]
Trigger	0.4
Lepton ident./isolation	2.2
Muon momentum scale	0.2
Electron momentum scale	0.2
Jet energy scale	0.7
Jet energy resolution	0.5
b tagging	0.3
Pileup	0.3
$t\bar{t}$ ME scale	0.5
tW ME scale	0.7
DY ME scale	0.2
NLO generator	1.2
PDF	1.1
m_t^{MC}	0.4
Top quark p_T	0.5
ME/PS matching	0.2
UE tune	0.3
$t\bar{t}$ ISR scale	0.4
tW ISR scale	0.4
$t\bar{t}$ FSR scale	1.1
tW FSR scale	0.2
b quark fragmentation	1.0
b hadron BF	0.2
Colour reconnection	0.4
DY background	0.8
tW background	1.1
Diboson background	0.3
W+jets background	0.3
$t\bar{t}$ background	0.2
Statistical	0.2
Integrated luminosity	2.5
MC statistical	1.2
Total $\sigma_{t\bar{t}}^{vis}$ uncertainty	4.2
Extrapolation uncertainties	
$t\bar{t}$ ME scale	$\mp^{0.4}_{<0.1}$
PDF	$\pm^{0.8}_{0.6}$
Top quark p_T	$\pm^{0.2}_{0.3}$
$t\bar{t}$ ISR scale	$\mp^{0.2}_{<0.1}$
$t\bar{t}$ FSR scale	± 0.1
UE tune	<0.1
m_t^{MC}	$\mp^{0.2}_{0.3}$
Total $\sigma_{t\bar{t}}$ uncertainty	$^{+4.3}_{-4.2}$

TOP-17-001

Systematic uncertainties arising from the modeling of the underlying event (UE)

- **Prescription:**
  - The differences between the nominal CP5 tune and the up/down variations of the CP5 tune implemented in dedicated MC samples quoted as the UE uncertainty





GEN-17-001

Description of underlying event tunes

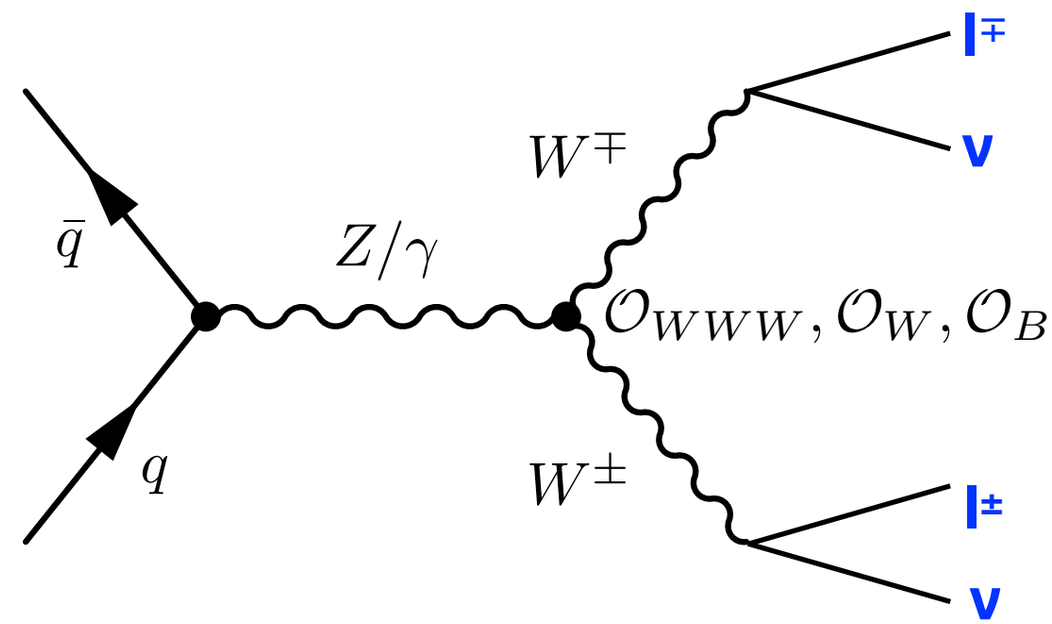
The settings, used in the determination of the new CMS PYTHIA8 UE tunes, are as follows:

- Tune CP1 uses the NNPDF3.1 PDF set at LO, with α_S values used for the simulation of MPI, hard scattering, FSR, and ISR equal to, respectively, 0.13, 0.13, 0.1365, and 0.1365, and running according to an LO evolution.
- Tune CP2 is a slight variation with respect to CP1, uses the NNPDF3.1 PDF set at LO, with α_S values used for the simulation of MPI, hard scattering, FSR, and ISR contributions equal to 0.13, and running according to an LO evolution.
- Tune CP3 uses the NNPDF3.1 PDF set at NLO, with α_S values used for the simulation of MPI, hard scattering, FSR, and ISR contributions equal to 0.118, and running according to an NLO evolution.
- Tune CP4 uses the NNPDF3.1 PDF set at NNLO, with α_S values used for the simulation of MPI, hard scattering, FSR, and ISR contributions equal to 0.118, and running according to an NLO evolution.
- Tune CP5 has the same settings as CP4, but with the ISR emissions ordered according to rapidity.

GEN-17-001

Precision Physics with Multibosons (W^+W^-)

- Diboson production, **W^+W^-**, occurs at the LHC via **s-channel, t-channel (dominant)**, sub-dominant $gg \rightarrow W^+W^-$
- Allows for **precise tests of the SM**
- Important **background** in many **New Physics (NP) searches**
- **Pursued in both CMS and ATLAS**



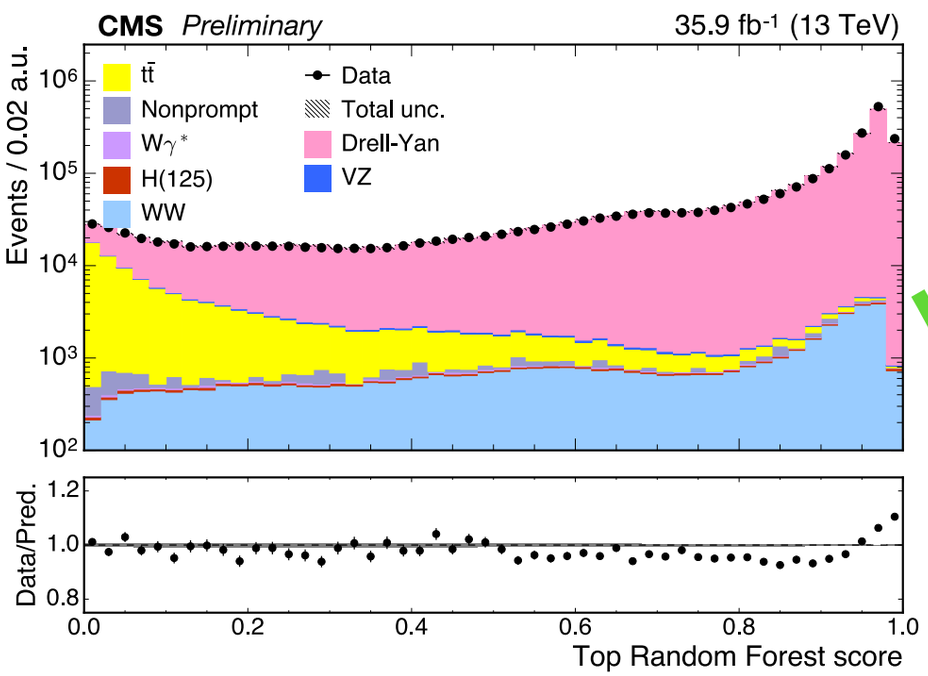
- **<u>ATLAS:</u> Cut based analysis in 0 jet bin**
- **<u>CMS:</u> Two different complementary search strategies** designed to reduce top and Drell-Yan backgrounds explored:
  - **sequential cut based analysis (in 0 and 1 jet bins)**
  - **Random forest classifier** trained on simulated events (incl. $n_{jet} \geq 2$)

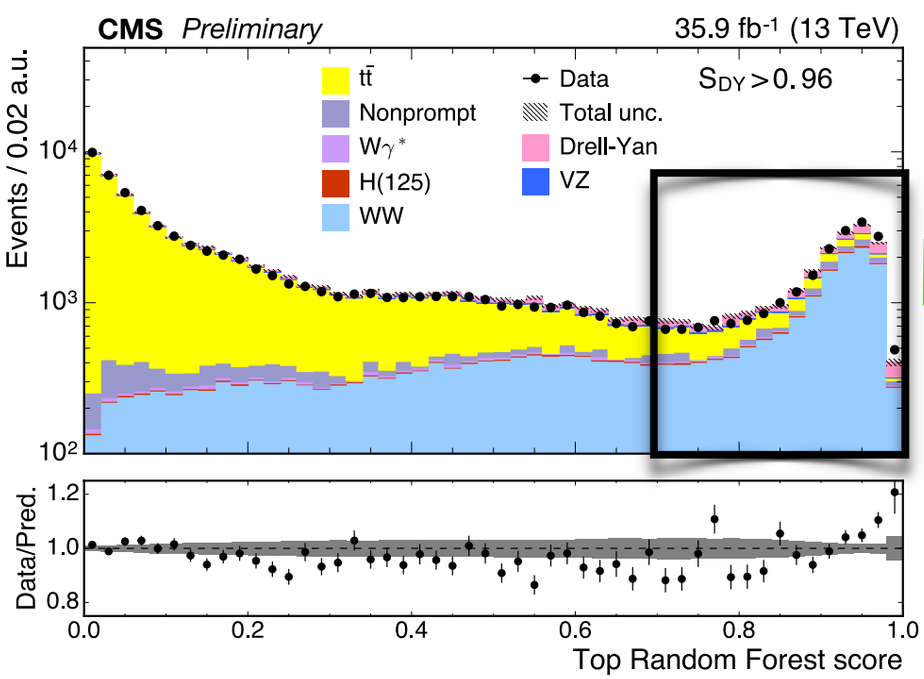
s-channel process could acquire contributions from higher dimensional operators

Analysis performed in oppositely charged leptonic final state

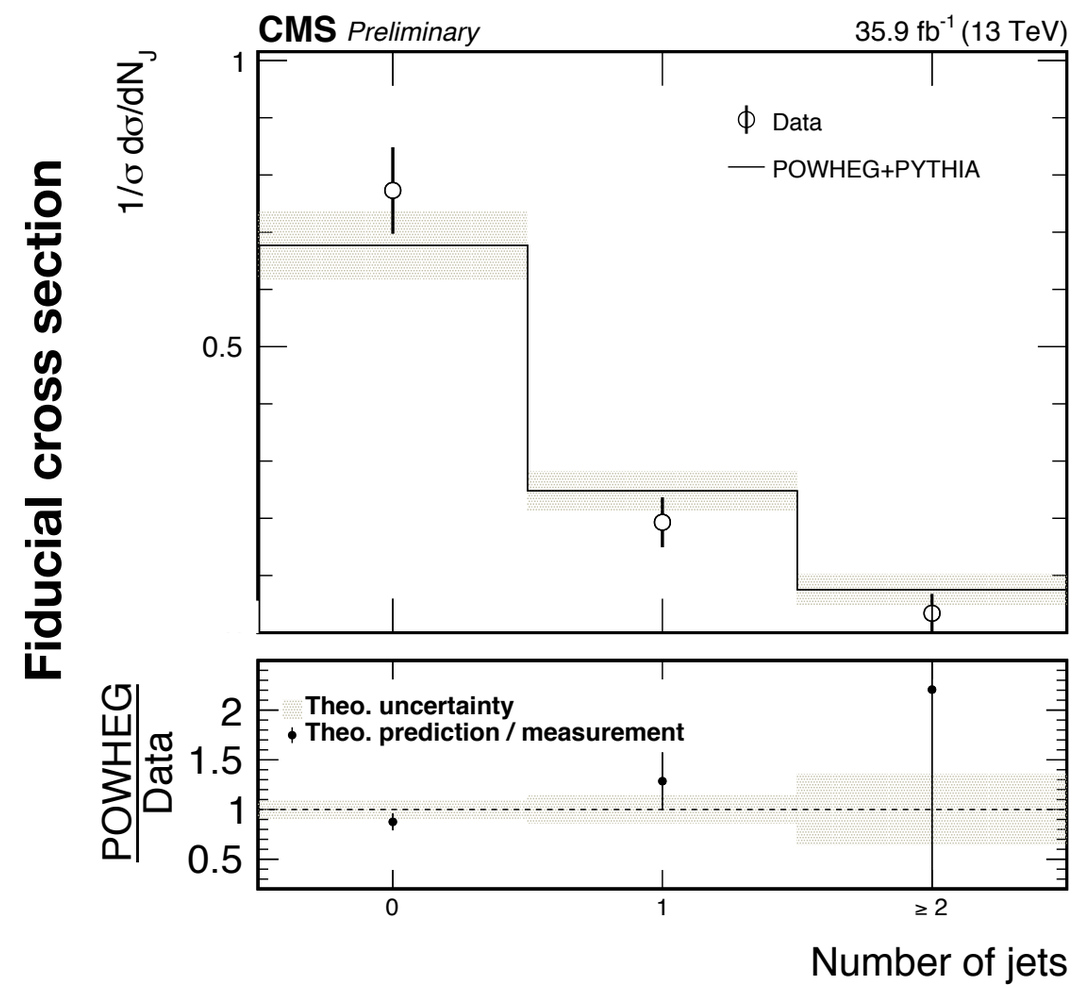
Higgs → W^+W^- considered:
- background (CMS)
- signal (ATLAS)

Using the Random Forest Discriminator





- Background contributions reduced by using novel method:
  - **Random Forest discriminator**
- Independently trained **collection of binary decision trees**
- Score defined as combination of **decisions of each tree**
- **Uses all jet categories**



Systematic Uncertainties

Theoretical Uncertainties

- Event selection in jet binned category (**cut based analysis**): sensitive to higher order QCD corrections
- Ascertained by varying factorization and renormalization scales (in some cases pT- resummation technique used)
- Additional theoretical uncertainties arise from α_s, PDFs

Total cross section:

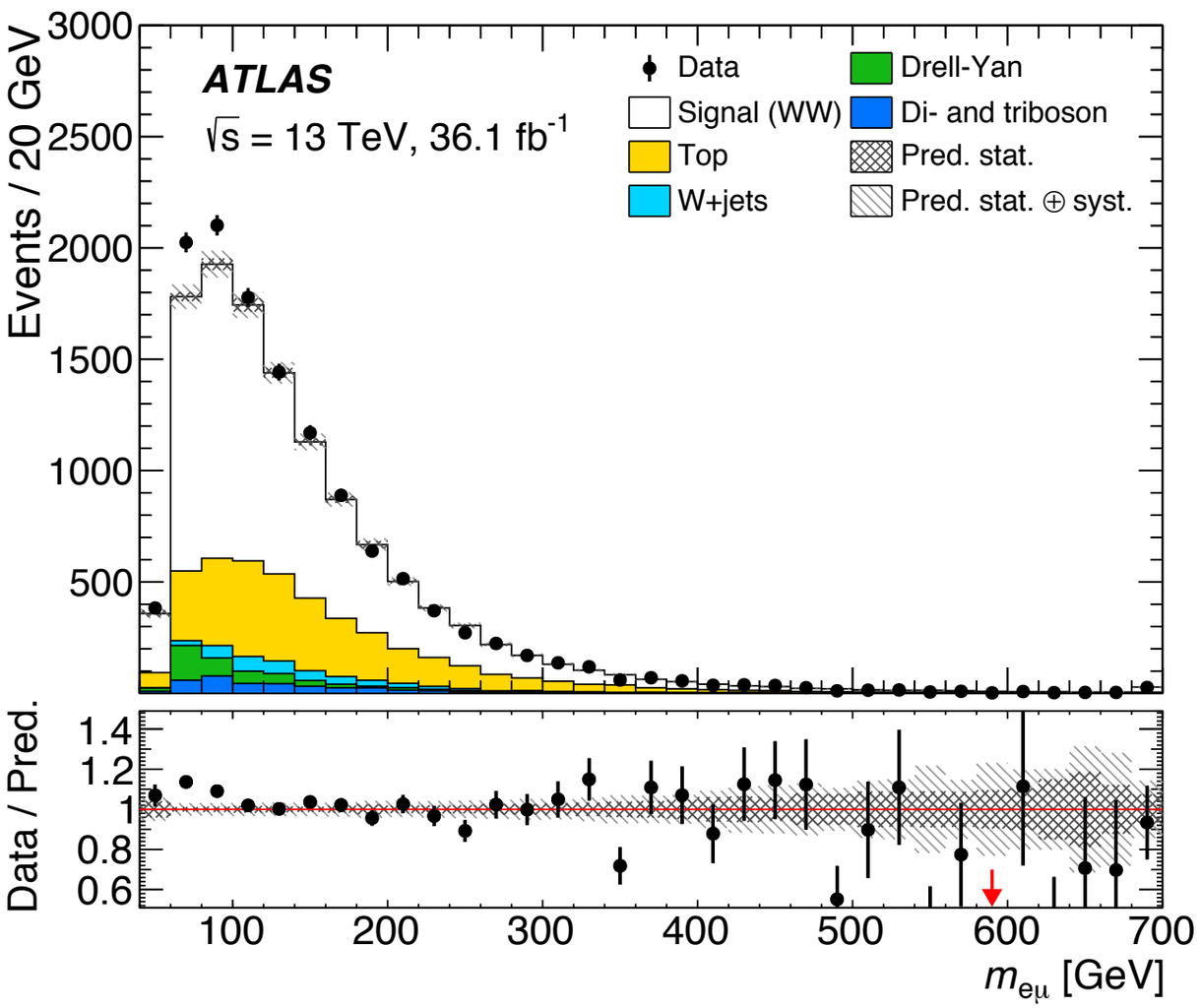
σ = 117.6 ± 1.4 (stat) ± 5.5 (syst) ± 1.9 (theo) ± 3.2 (lumi) pb

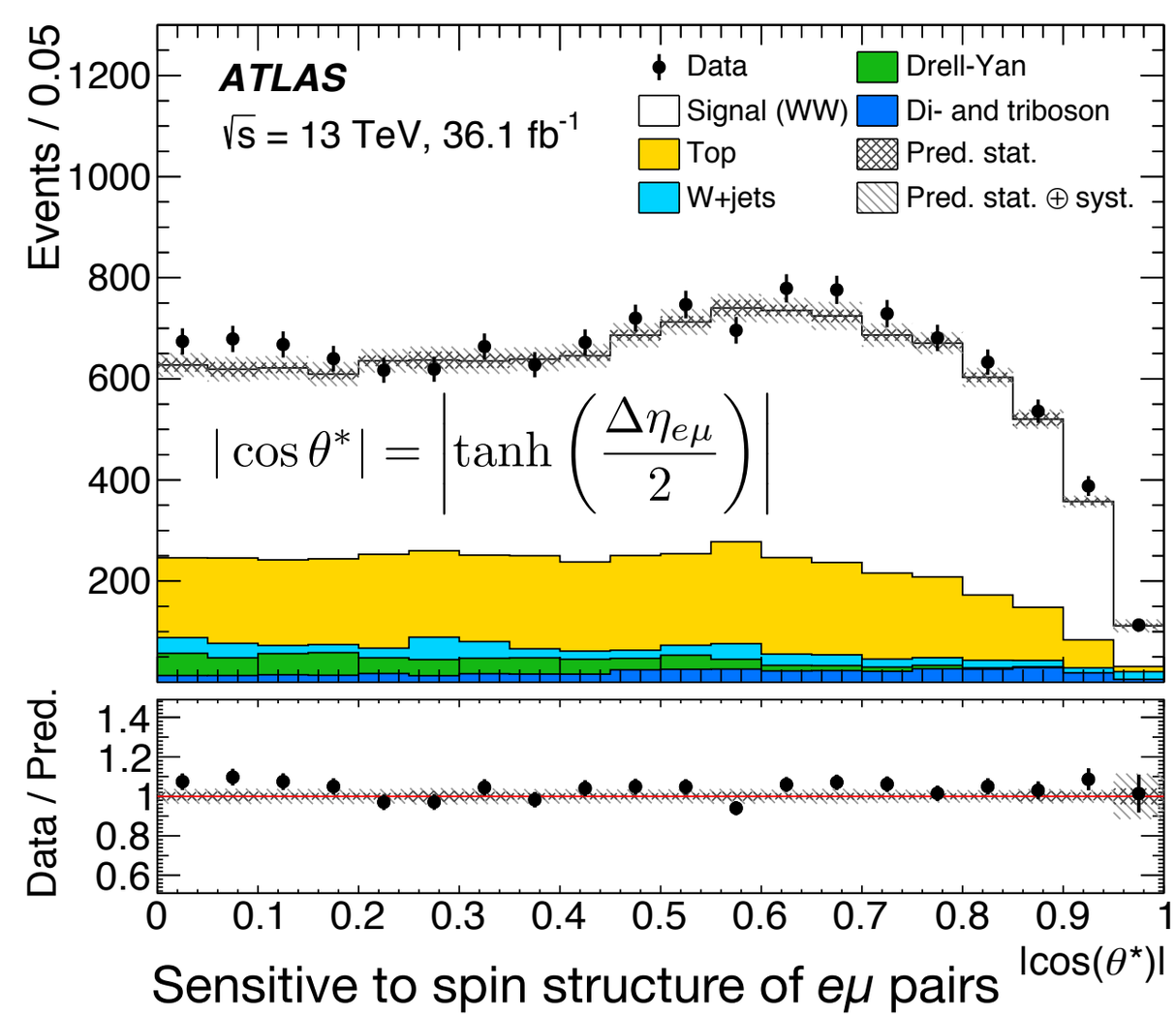
σ_{NNLO} = 118.7 + 3.0 -2.6 pb

Uncertainty source	(%)
Statistical uncertainty	1.2
$t\bar{t}$ normalization	2.0
Drell-Yan normalization	1.4
$W\gamma^*$ normalization	0.4
Nonprompt leptons normalization	1.9
Lepton efficiencies	2.1
b-tagging (b/c)	0.4
b-tagging (light)	1.0
Jet energy scale and resolution	2.3
Pileup	0.4
Simulation and data control regions sample size	1.0
Total experimental systematic uncertainty	4.6
QCD factorization and renormalization scales	0.4
Higher-order QCD corrections and p_T^{WW} distribution	1.4
PDFs	0.4
Underlying event modeling	0.5
Total theoretical systematic uncertainty	1.6
Luminosity	2.7
Total uncertainty	5.7

Precision Physics with Multibosons (W^+W^-)

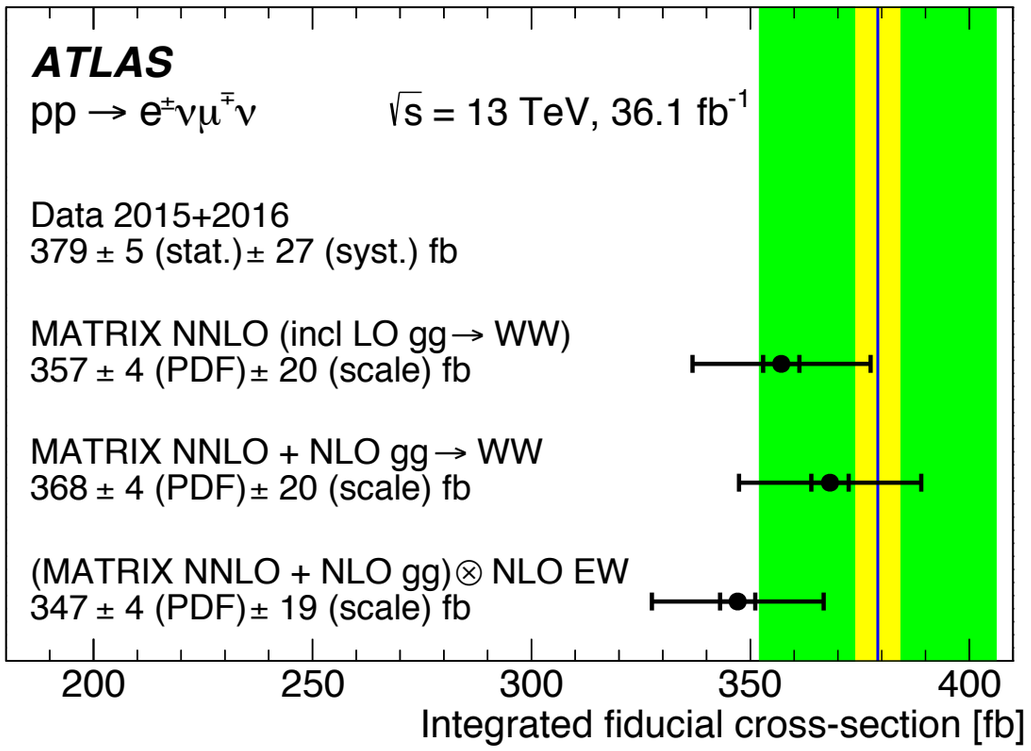
- $W^{\pm}W^{\mp} \rightarrow e^{\pm}\nu\mu^{\mp}\nu$ decay studied, with jet vet, includes b-veto
- Fiducial cross section computed (definition on slide 19)





Sensitive to spin structure of $e\mu$ pairs

Systematic Uncertainties



Total cross section:

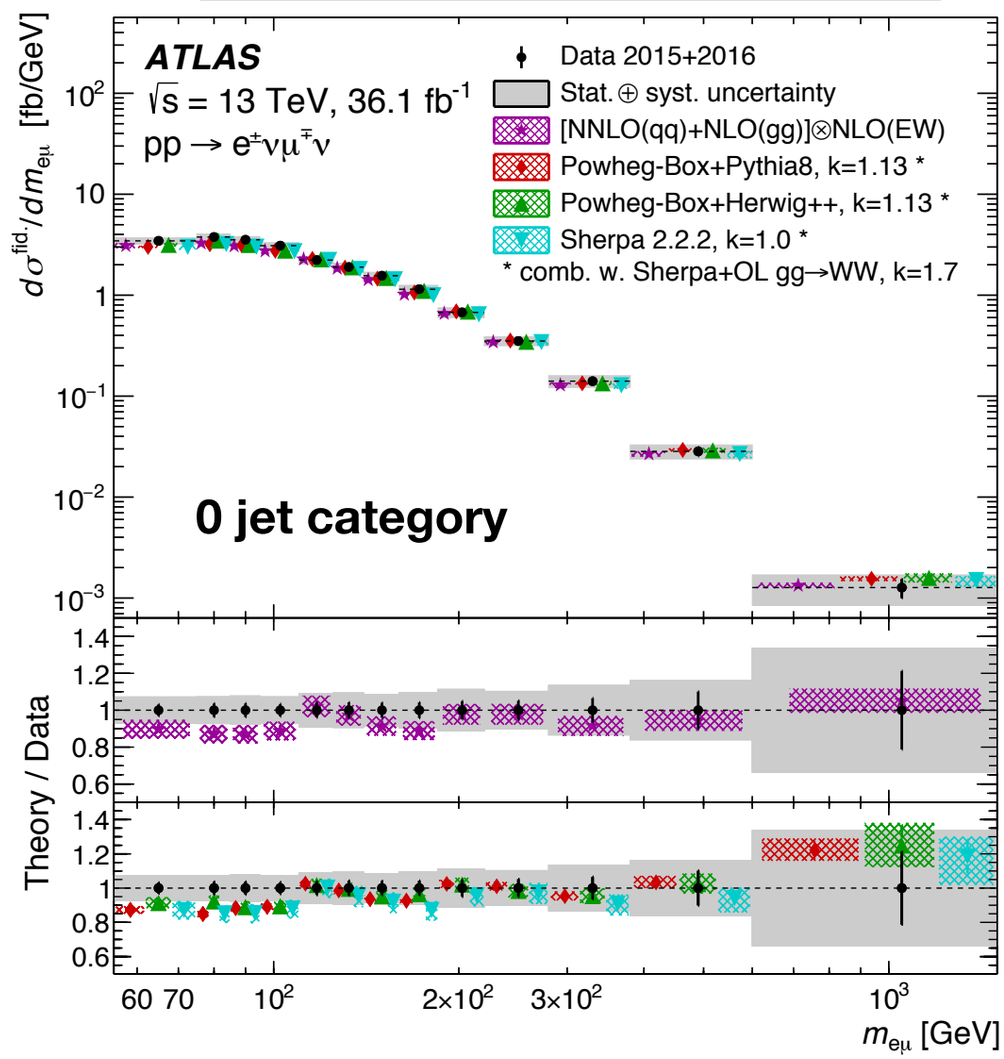
σ_{fid} = 379.1 ± 5.0 (stat) ± 25.4 (syst) ± 8.0 (lumi) fb

Systematic uncertainties associated with fiducial cross section:

Uncertainty source	Uncertainty [%]
Electron	0.7
Muon	0.9
Jets	3.0
b-tagging	3.4
$E_{\mathrm{T}}^{\mathrm{miss,track}}$	0.4
Pile-up	1.6
W+jets background modelling	3.1
Top-quark background modelling	2.6
Other background modelling	1.3
Unfolding, incl. signal MC stat. uncertainty	1.4
PDF+scale	0.1
Systematic uncertainty	6.7
Statistical uncertainty	1.3
Luminosity uncertainty	2.1
Total uncertainty	7.1

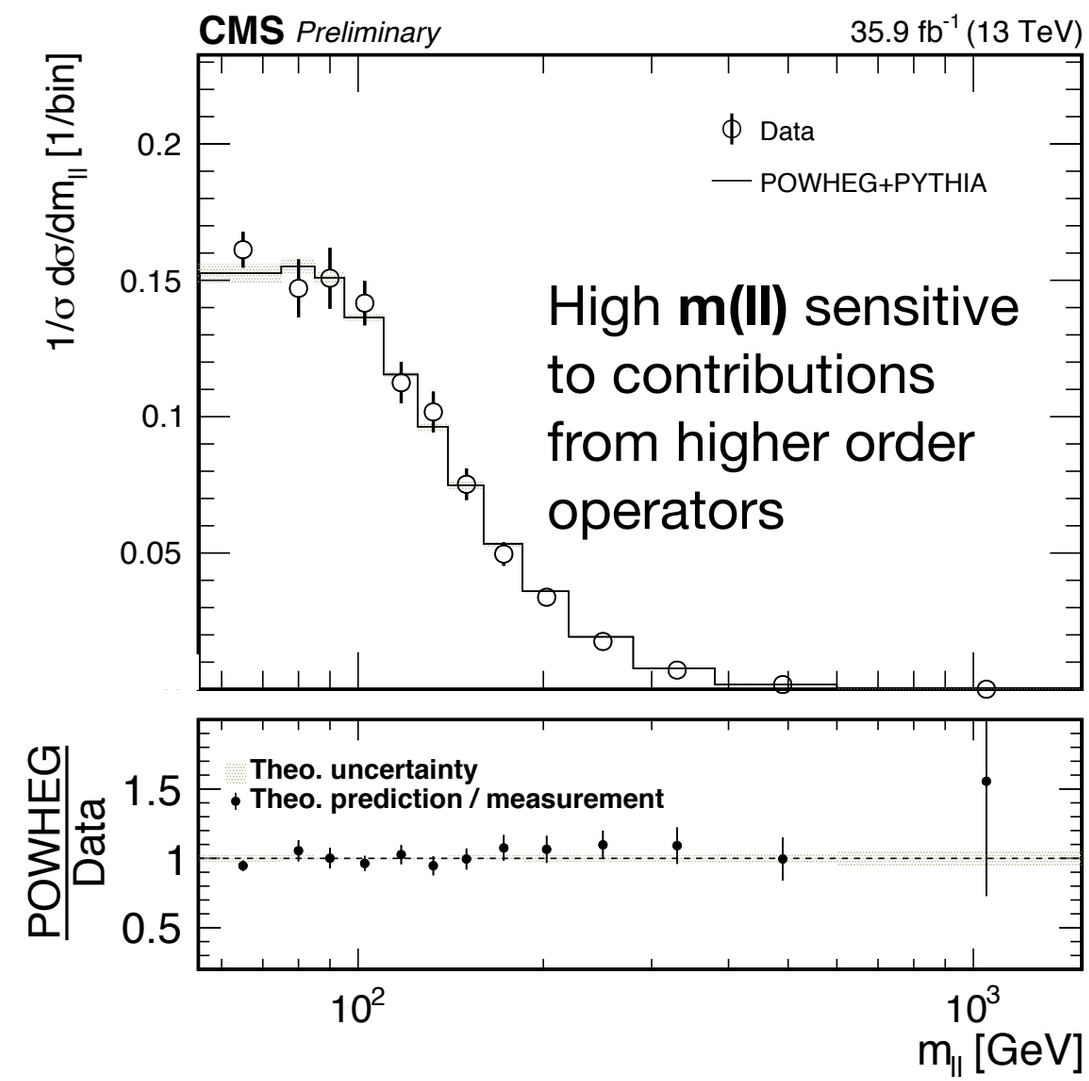
Differential cross sections

Fiducial selection requirements		
p_T^{ℓ}	>	27 GeV
$\lvert\eta^{\ell}\rvert$	<	2.5
$m_{e\mu}$	>	55 GeV
$p_T^{e\mu}$	>	30 GeV
E_T^{miss}	>	20 GeV
No jets with p_T	>	35 GeV, $\lvert\eta\rvert < 4.5$



Fiducial cross section computed in:

m(ll) > 20 GeV, p_T(ll) > 30 GeV and p_T(miss) > 20 GeV



EFT Interpretation

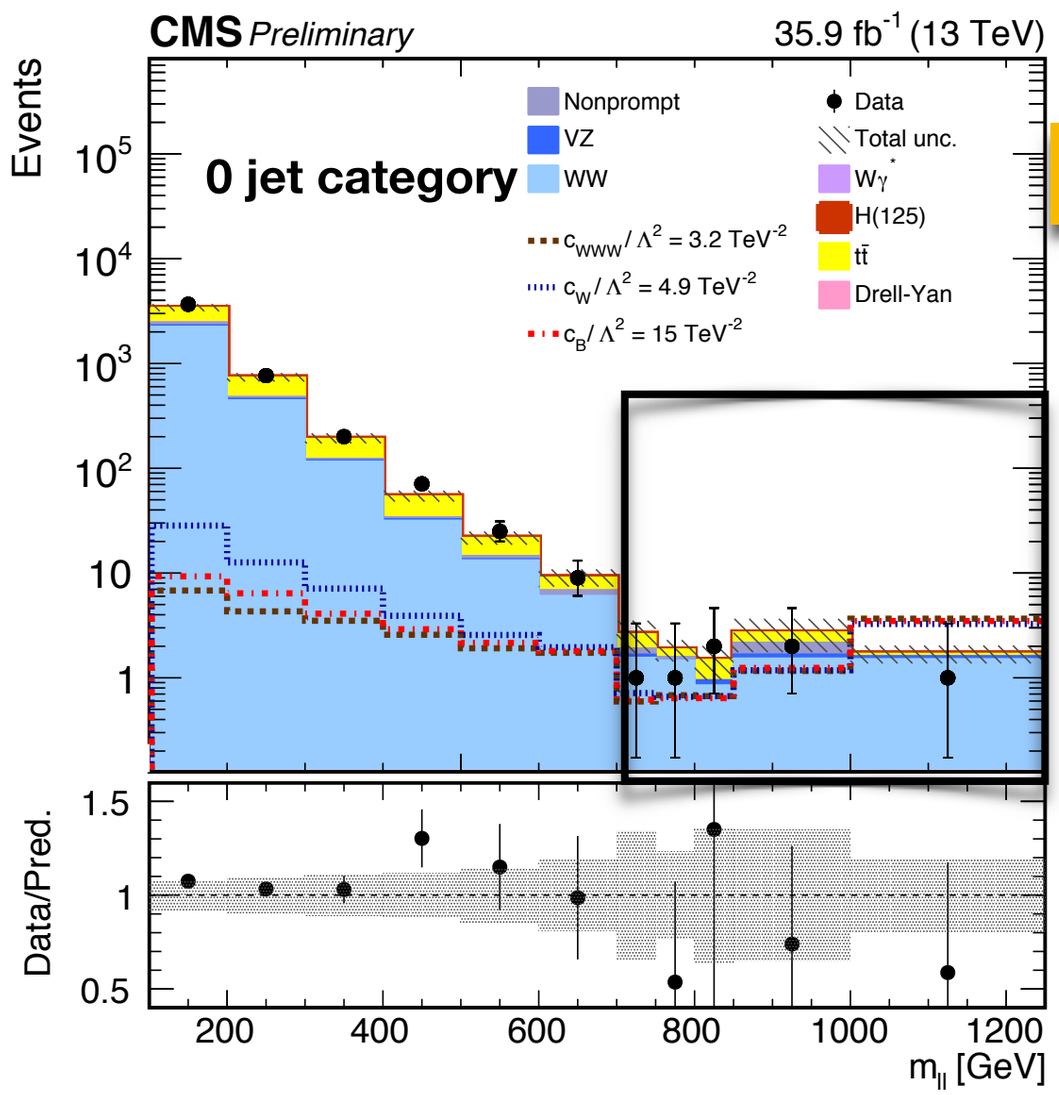
- **Limits set on Wilson coefficients associated with CP conserving operators:**

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}]$$

$$\mathcal{O}_W = (\mathcal{D}_\mu\Phi)^\dagger W^{\mu\nu}(\mathcal{D}_\nu\Phi) \qquad \mathcal{O}_B = (\mathcal{D}_\mu\Phi)^\dagger B^{\mu\nu}(\mathcal{D}_\nu\Phi)$$

CP conserving

CP non-conserving



ATLAS

Parameter	Observed 95% CL [TeV^{-2}]	Expected 95% CL [TeV^{-2}]
c_{WWW}/Λ^2	[−3.4 , 3.3]	[−3.0 , 3.0]
c_W/Λ^2	[−7.4 , 4.1]	[−6.4 , 5.1]
c_B/Λ^2	[−21 , 18]	[−18 , 17]
$c_{\tilde{W}WW}/\Lambda^2$	[−1.6 , 1.6]	[−1.5 , 1.5]
$c_{\tilde{W}}/\Lambda^2$	[−76 , 76]	[−91 , 91]

CMS

Coefficients (TeV^{-2})	68% CL interval		95% CL interval	
	expected	observed	expected	observed
c_{WWW}/Λ^2	$[-1.78, 1.82]$	$[-0.93, 0.99]$	$[-2.67, 2.71]$	$[-1.78, 1.84]$
c_W/Λ^2	$[-3.67, 2.68]$	$[-2.03, 1.33]$	$[-5.28, 4.22]$	$[-3.56, 2.78]$
c_B/Λ^2	$[-9.45, 8.40]$	$[-5.14, 4.30]$	$[-13.9, 12.8]$	$[-9.35, 8.46]$

EFT Interpretation

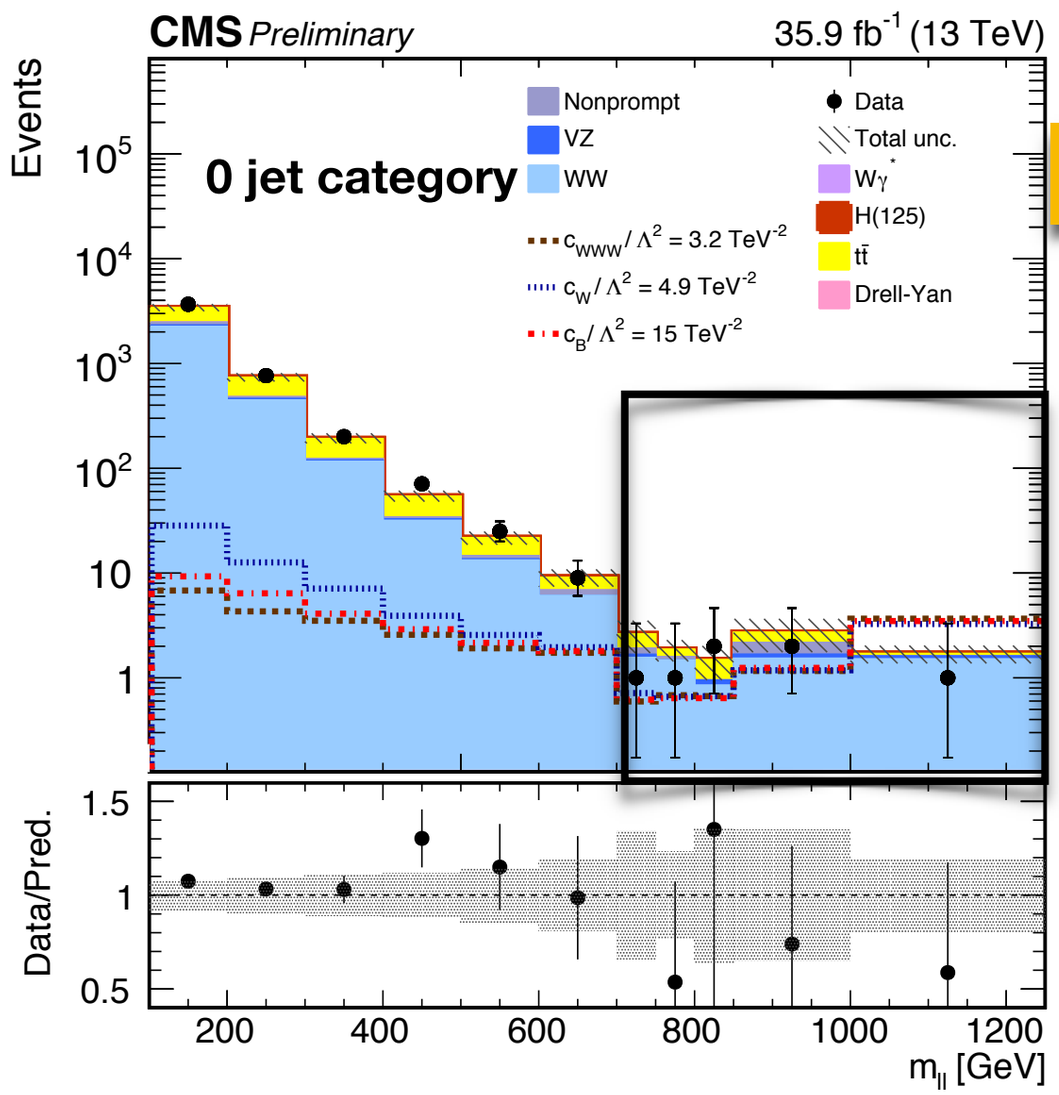
- **Limits set on Wilson coefficients associated with CP conserving operators:**

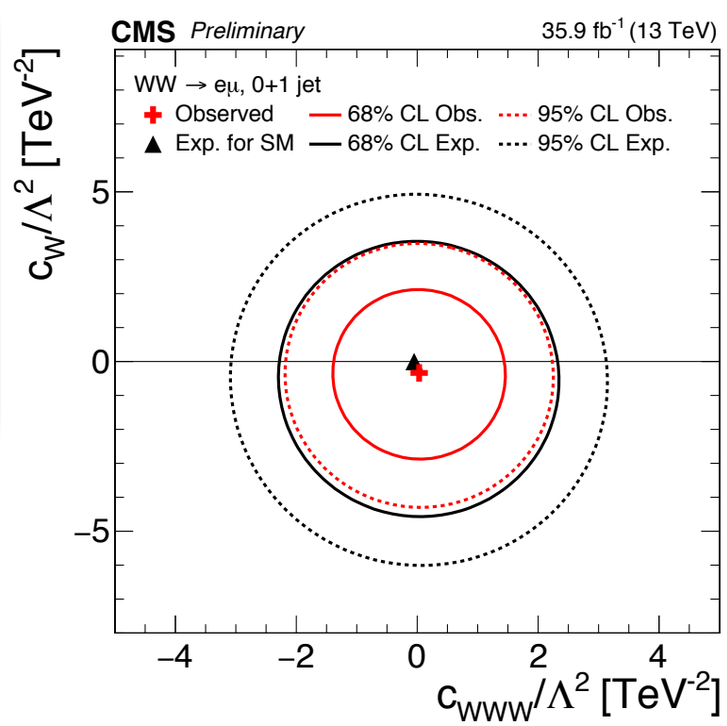
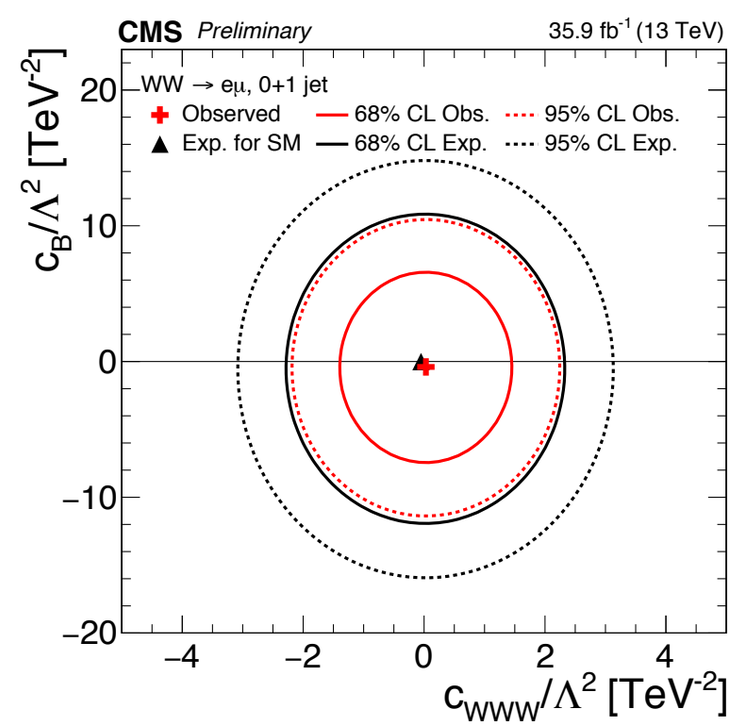
$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}]$$

$$\mathcal{O}_W = (\mathcal{D}_\mu\Phi)^\dagger W^{\mu\nu}(\mathcal{D}_\nu\Phi) \qquad \mathcal{O}_B = (\mathcal{D}_\mu\Phi)^\dagger B^{\mu\nu}(\mathcal{D}_\nu\Phi)$$

CP conserving

CP non-conserving



ATLAS

Parameter	Observed 95% CL [TeV^{-2}]	Expected 95% CL [TeV^{-2}]
c_{WWW}/Λ^2	[−3.4 , 3.3]	[−3.0 , 3.0]
c_W/Λ^2	[−7.4 , 4.1]	[−6.4 , 5.1]
c_B/Λ^2	[−21 , 18]	[−18 , 17]
$c_{\tilde{W}WW}/\Lambda^2$	[−1.6 , 1.6]	[−1.5 , 1.5]
$c_{\tilde{W}}/\Lambda^2$	[−76 , 76]	[−91 , 91]