Top quark mass measurements

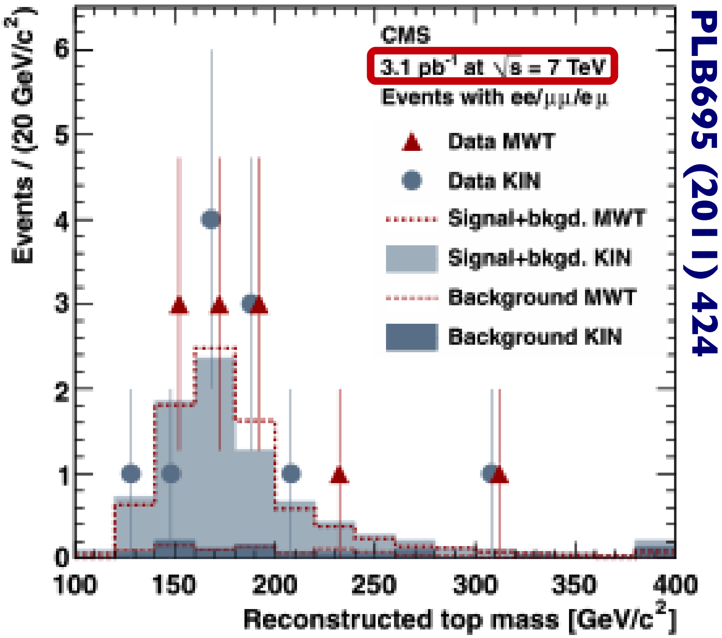
with the CMS detector at the LHC

Pedro Silva (CERN)
on behalf of the CMS Collaboration

Top Quark Physics Day
MIAPP Summer 2014 Institute program

Miro, Bleu II, 1961

Since we re-discovered the top at CMS...



PLB695 (2011) 424

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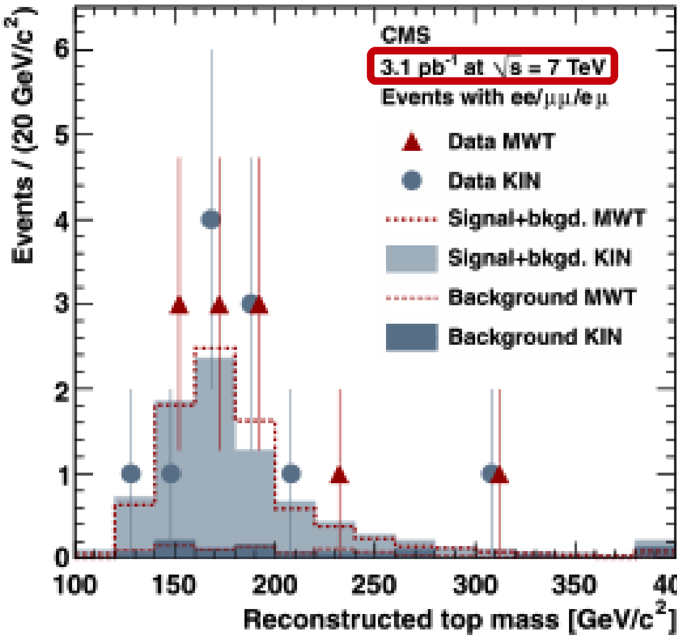

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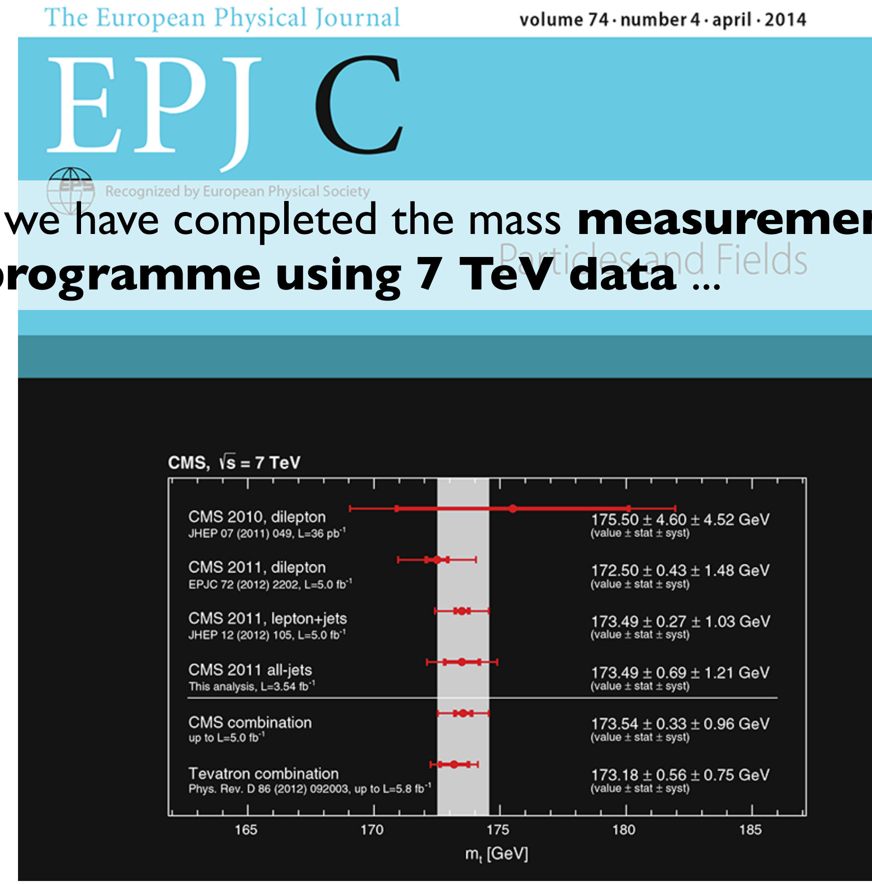

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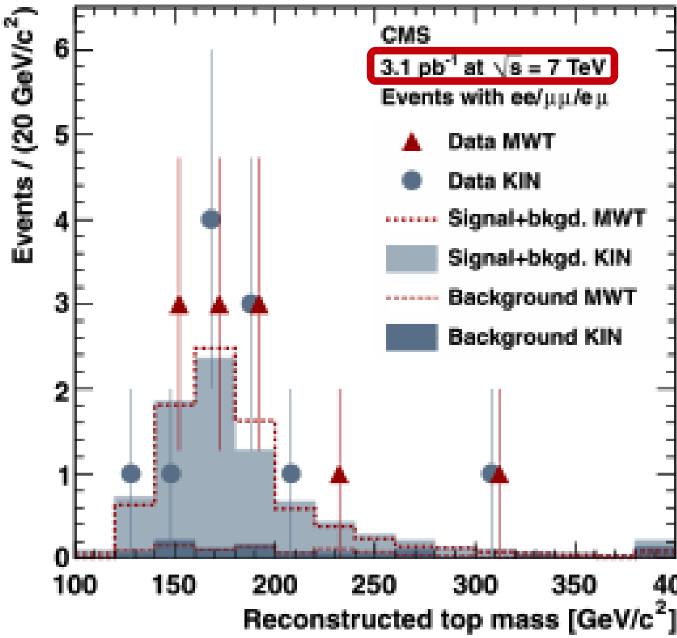

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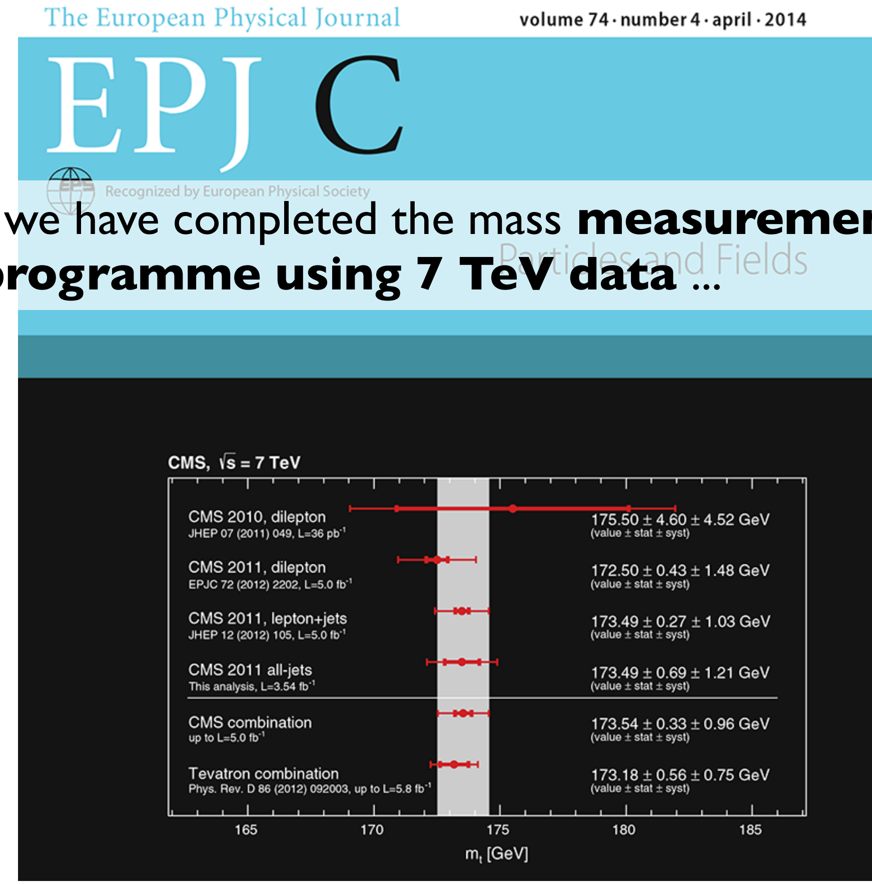

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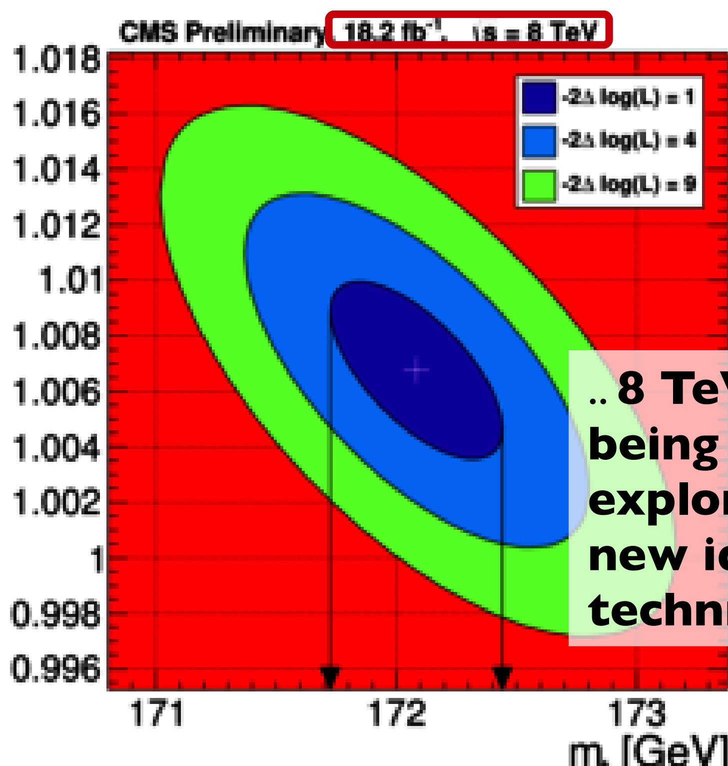

CMS PAS-TOP-14-002

.. **8 TeV data is being explored with new ideas and techniques** …

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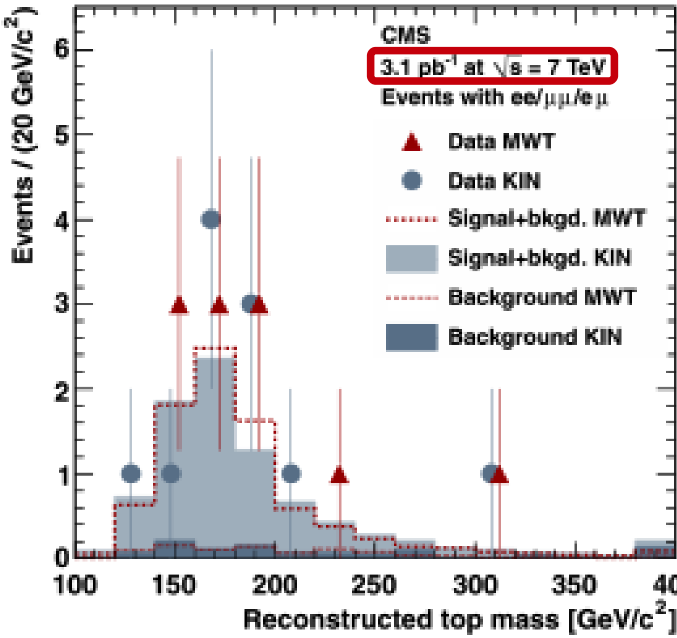

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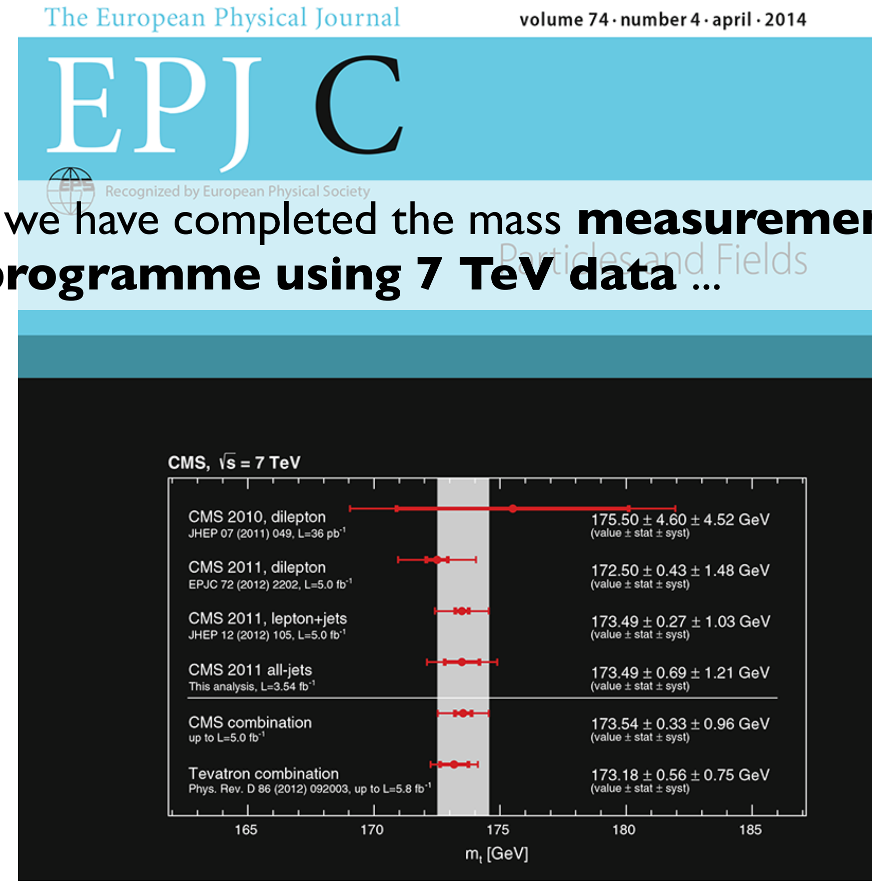

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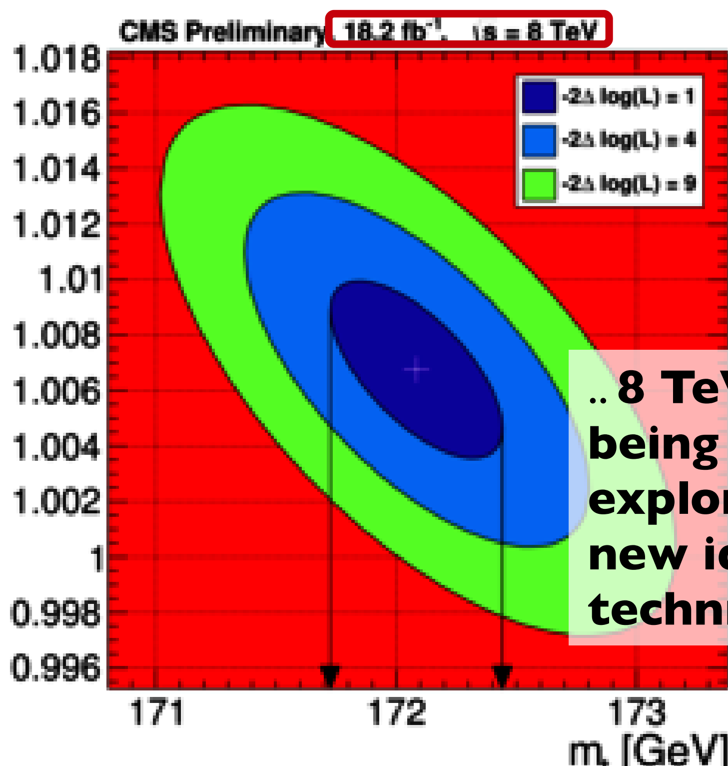

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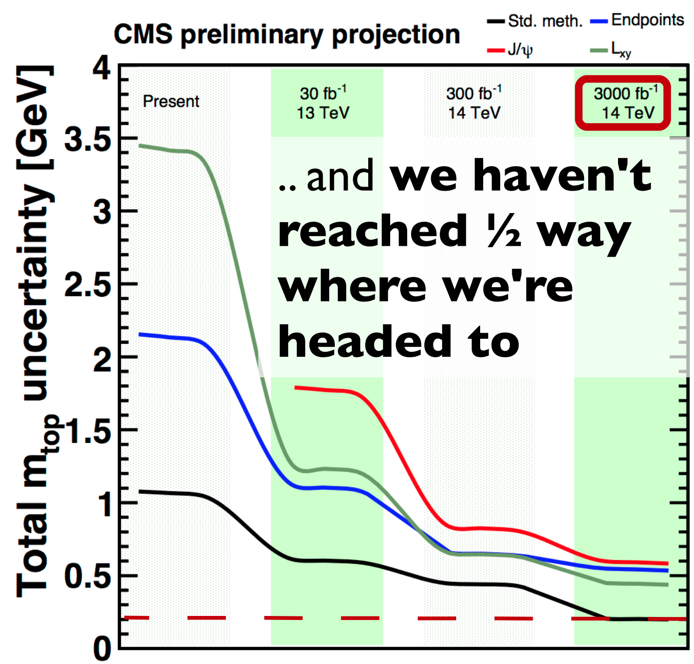
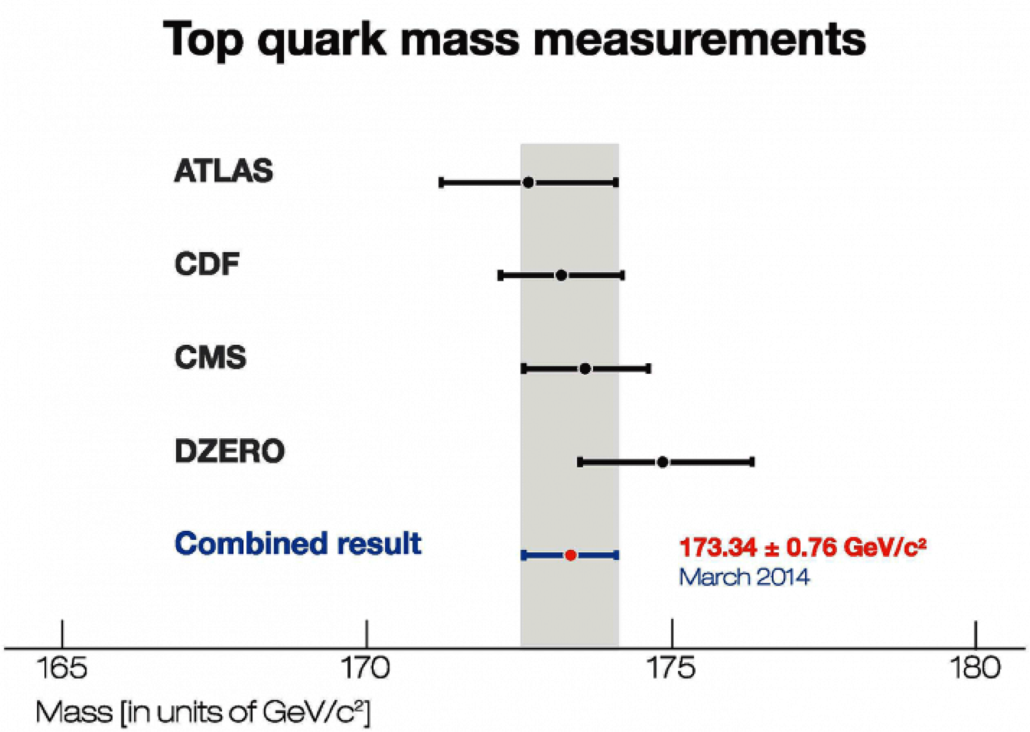


.. and **we haven't reached ½ way where we're headed to**

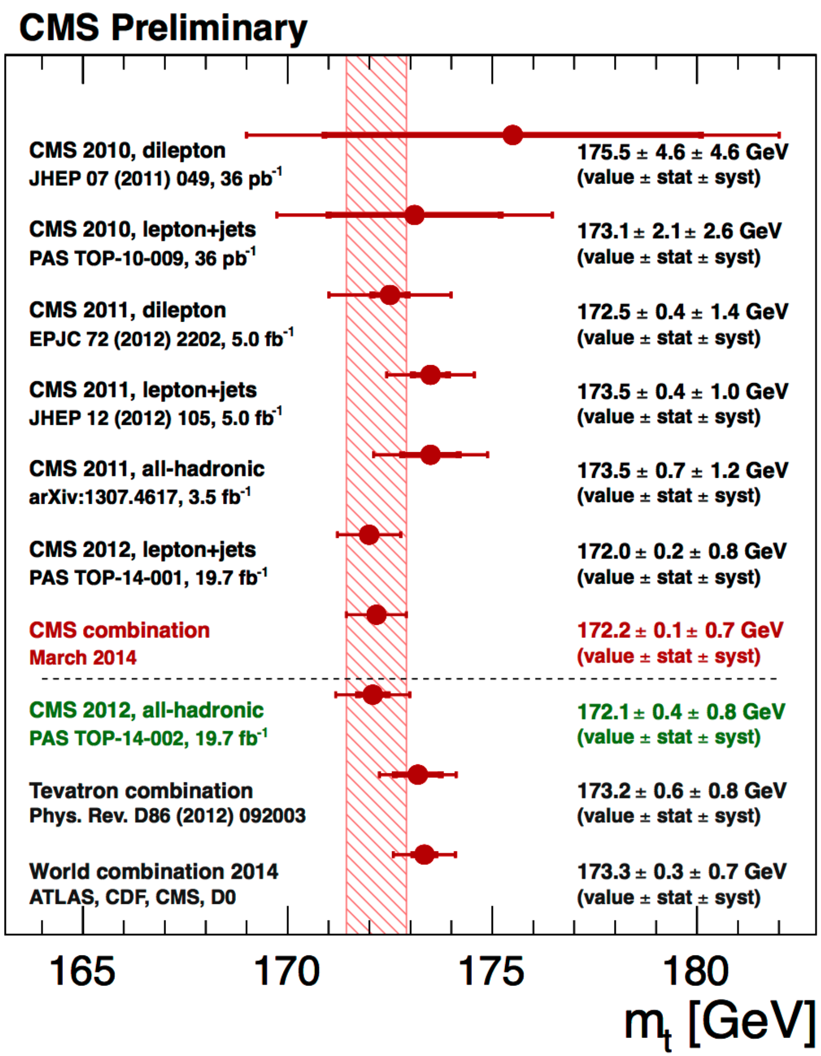
CMS PAS-FTR-13-017

Experimental status overview

- **Top mass is accurately measured**
  - 0.4% total uncertaninty on m_{top}
  - mostly from invariant mass-based methods
  - intrinsic calibration to a MC-based reference
  - consistent measurements across colliders



- **The case for CMS results**
  - most precise measurements in almost every channel
  - ~ 0.4% systematics + 0.05% statistical uncertainty



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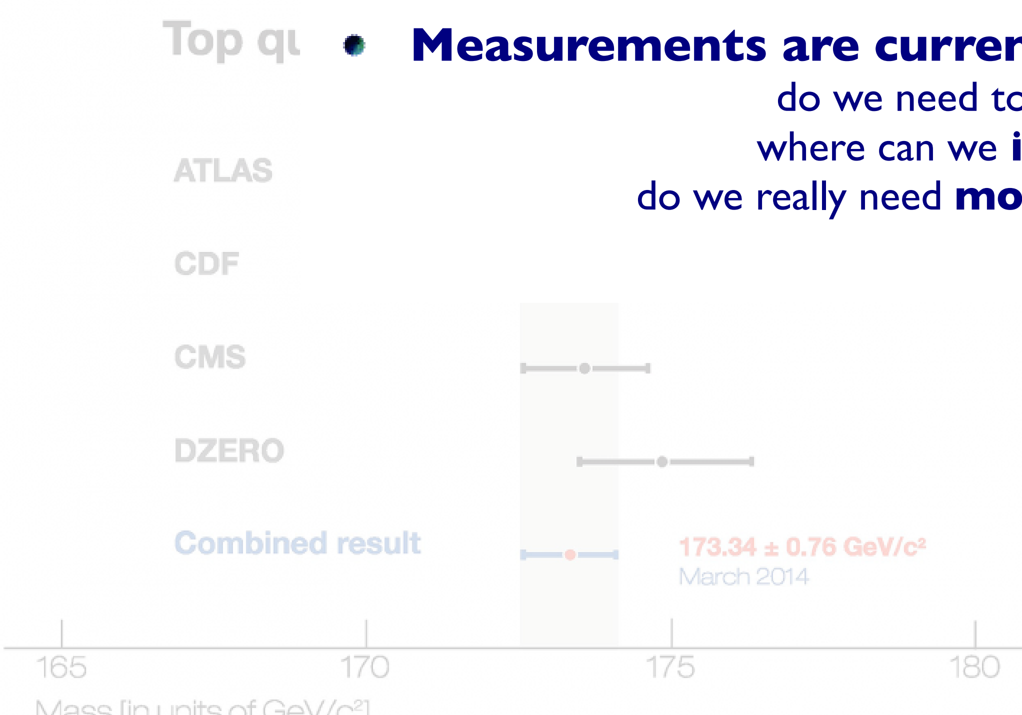
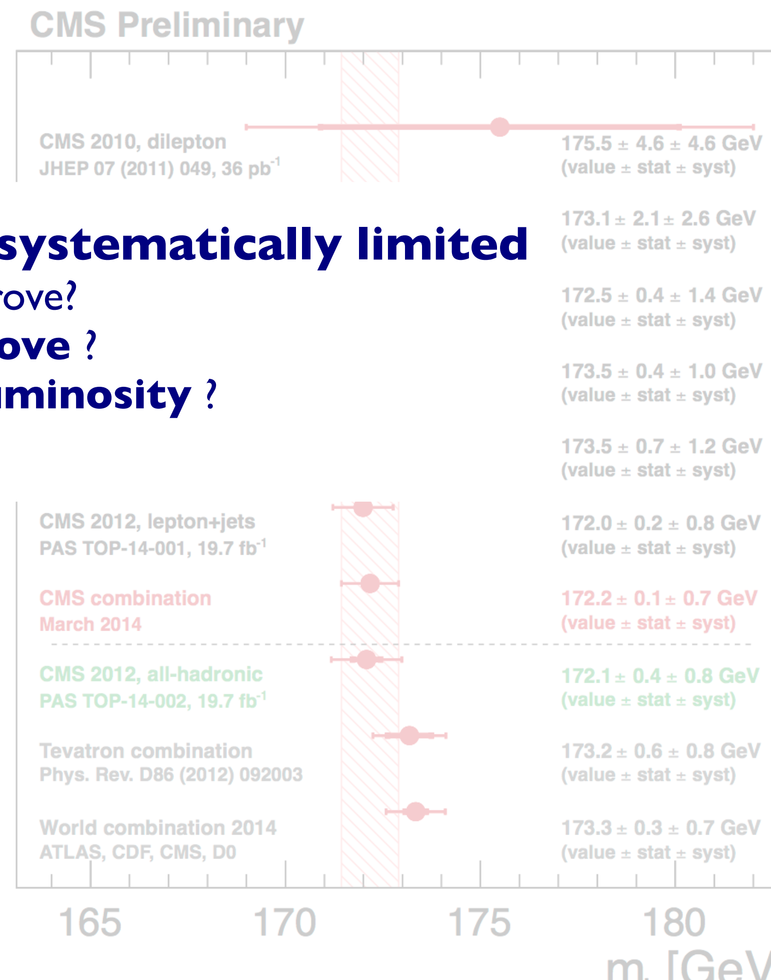




- **Measurements are currently systematically limited**

do we need to improve?

where can we **improve** ?

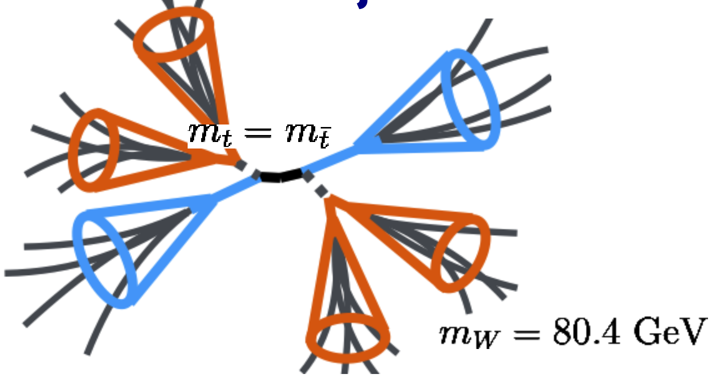
do we really need **more luminosity** ?

“Classic” measurements

- Although mostly produced from QCD the top quark evolution is dictated by EWK processes
  - Γ_t=1.4 GeV >> Λ_{QCD} : it decays before hadronizing mostly in the Wb channel
  - Γ_W=2.5 GeV >> Λ_{QCD} : the W decays before b-hadronization time scale
  - use final state products to reconstruct mass of initial particle

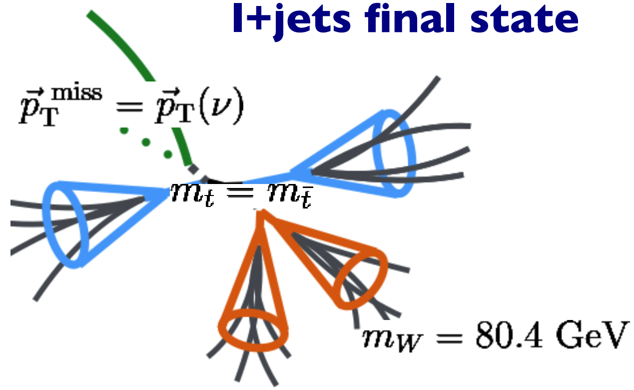
- Different **techniques** used **depending on the final state**

all jets final state



- Fully reconstructable
- Fit kinematics of 6 permutations

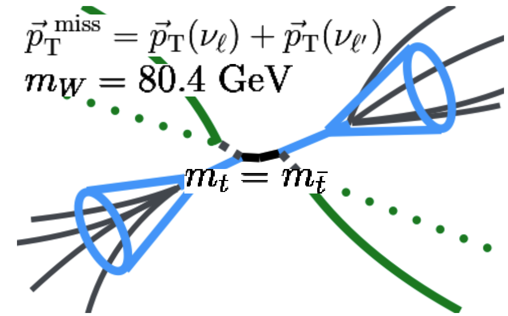
l+jets final state



- Up to 2 solutions for $p_Z(\nu)$
- Fit kinematics of 2 permutations

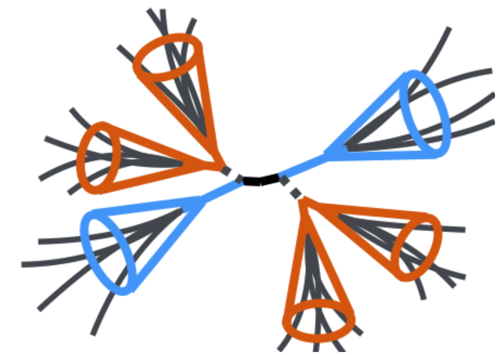
- Can fit jet energy scale in-situ by imposing $m_{jj'}=m_W$

dilepton final state



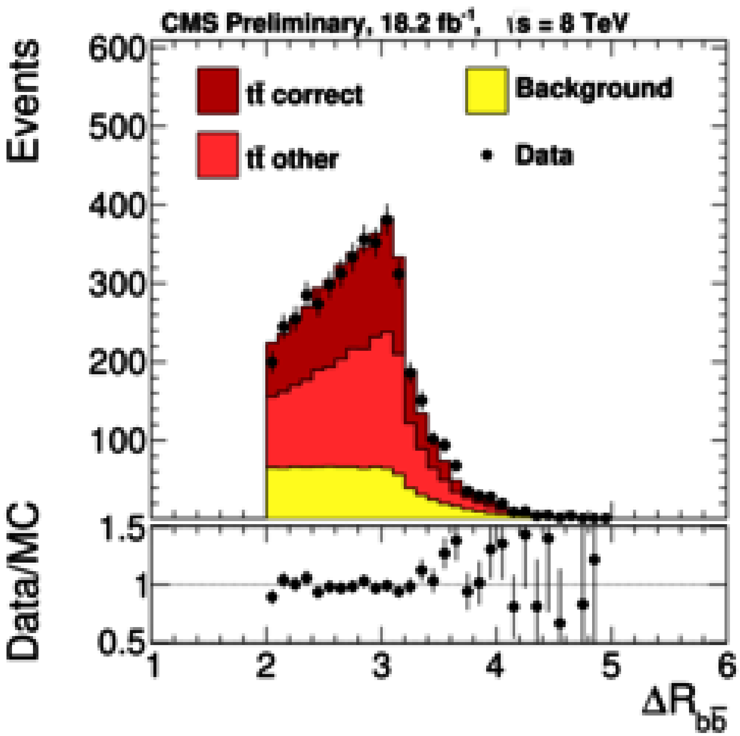
- Up to 2x4 solutions / event
- Alternatively use partial kinematics e.g. b-l system
- No b-JES fit in-situ

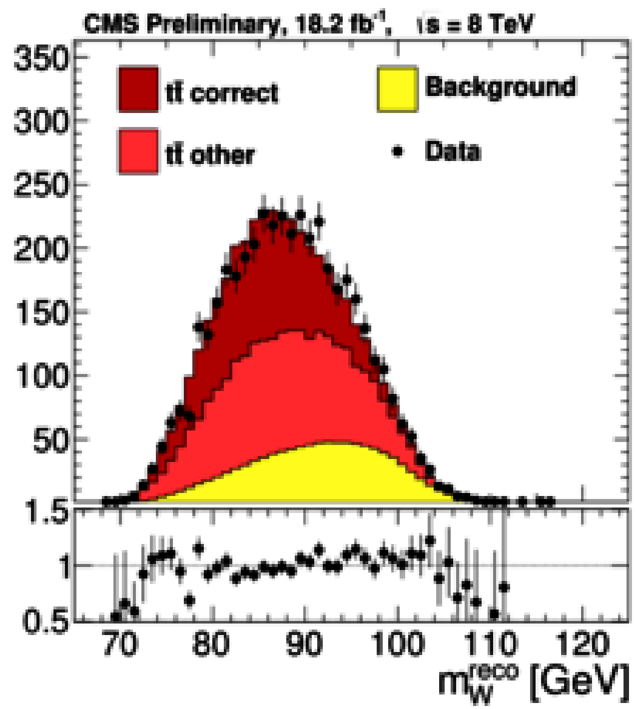
Measurement using all-jets

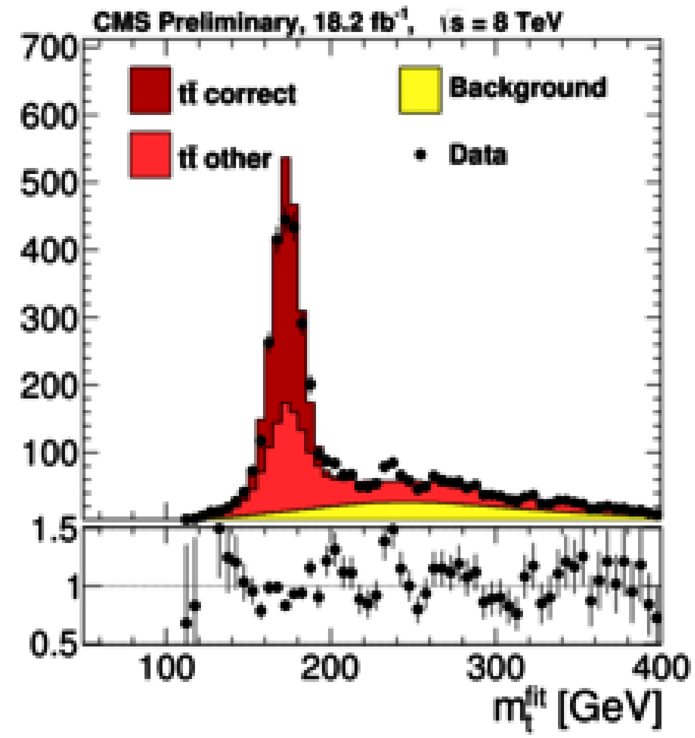


- ≥6 high-p_T jets, ≥2 b-tags and ΔR_{bb}>1.5
- Use permutation with best χ^2 and $P_{gof}(\chi^2)$>0.09, after kinematics fit

- Background is modeled with an **event mixing technique**
- Use reconstructed W mass peak to constraint JES in-situ
- Parametrize m_T and m_W for different permutations and JES hypothesis







Measurement using all-jets

- 72% signal events with 45% correct permutations are expected after selection
- Ideogram method:

$$\mathcal{L}(\text{sample}|m_t,\text{JSF}) = \prod_{\text{events}} \left(\sum_{i=1}^{n} P_{\text{gof}}(i) \left(\sum_j f_j P_j(m_{t,i}^{\text{fit}}|m_t,\text{JSF}) \times P_j(m_{W,i}^{\text{reco}}|m_t,\text{JSF}) \right) \right)^{w_{\text{event}}}$$

combine all events

weight each permutation by kin. fit probability

probability of correct/wrong/un-matched permutation yielding (m_T,JSF)

pull events which have correct combinations

- Event-per-event likelihoods are combined ▶
- Extract m_t and residual jet energy scale factor
  - fractions of signal and correct permutations float freely

2D fit

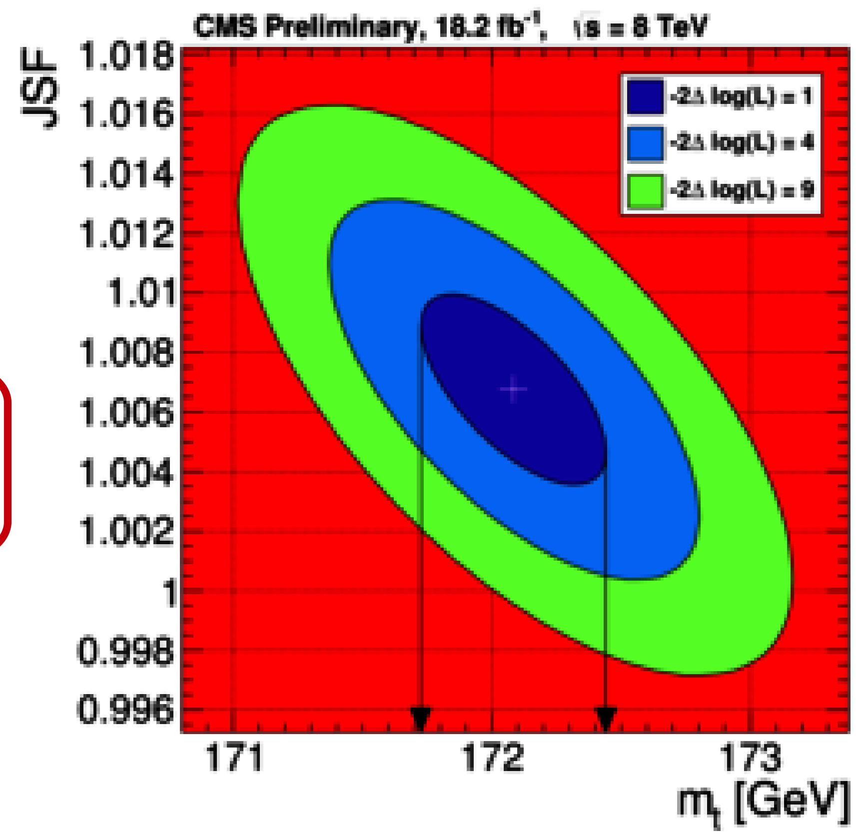
m_{top} = 172.08 ± 0.36 (stat+JSF) ± 0.83 (syst) GeV

JSF= 1.007 ± 0.003 (stat) ± 0.011 (syst)

1D fit m_{top} = 172.59 ± 0.27 (stat) ± 1.05 (syst) GeV

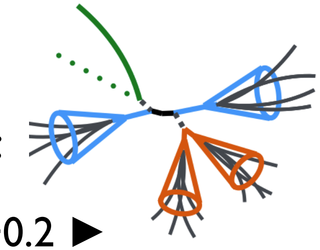
1D fit, 7 TeV, EPJC 74 (2014) 2758

m_{top} = 173.49 ± 0.69 (stat) ± 1.21 (syst) GeV

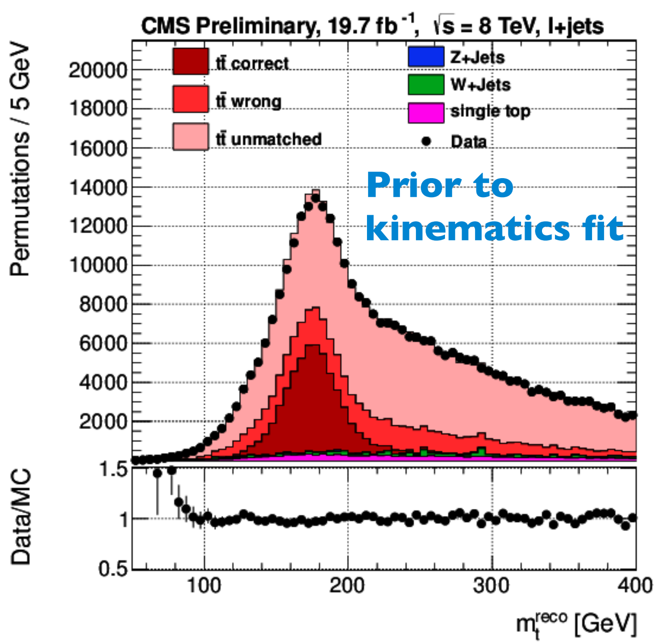


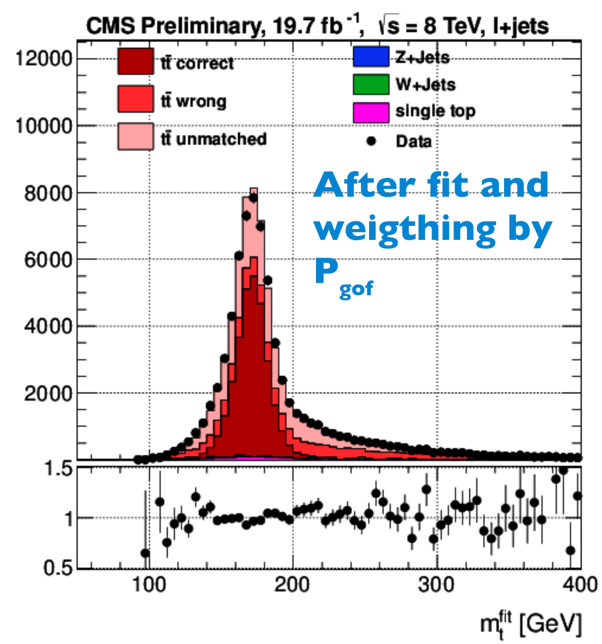
Measurement using l+jets

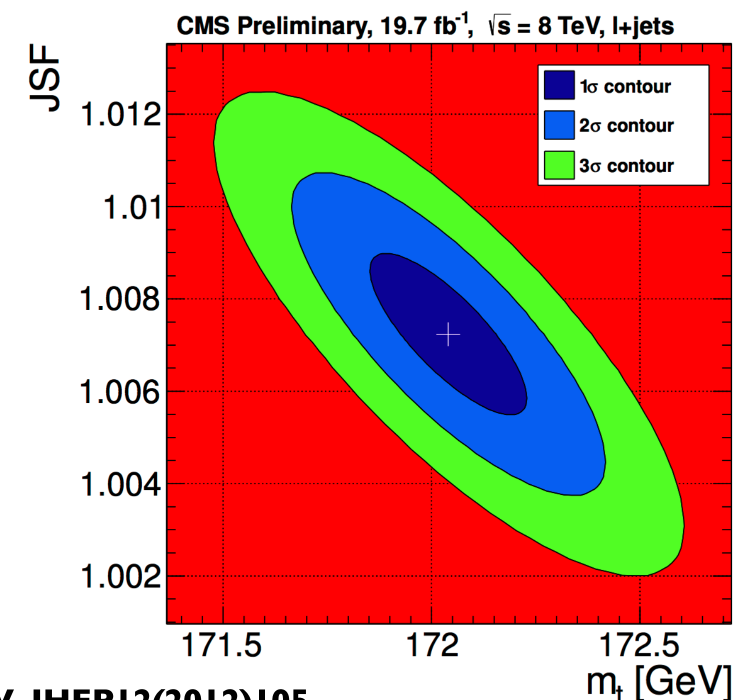
- =1 isolated lepton, ≥4 jets, ≥2 b-tags
- Similar approach to the one used in all jets:
  - perform kinematics fit and require $P_{gof}(\chi^2)>0.2$ ▶
  - apply an ideogram method after parametrizing m_t for different permutations



Permutations	Before fit	After fit, $P_{gof}>0.2$, and weight
Purity	94	96
Correct	13	44
Wrong	16	21
Un-matched	71	35







2D fit

m_{top} = 172.04 ± 0.19 (stat+JSF) ± 0.75 (syst) GeV

JSF = 1.007 ± 0.002 (stat) ± 0.012 (syst)

2D fit, 7 TeV, JHEP12(2012)105

m_{top} = 173.49 ± 0.43 (stat+JSF) ± 0.98 (syst) GeV

JSF = 0.994 ± 0.003 (stat) ± 0.008 (syst)

Systematic uncertainties

We have now a better understanding with respect to the 7 TeV analyses

Channel	ℓ+jets		All jets	
	δm_t (GeV)	δJSF	δm_t (GeV)	δJSF
Experimental uncertainties				
Fit calibration	0.10	0.001	0.06	<0.001
p_T- and η-dependent JES	0.18	0.007	0.28	0.006
Lepton energy scale	0.03	<0.001		
Missing transverse energy	0.09	0.001		
Jet energy resolution	0.26	0.004	0.10	<0.001
b-tagging	0.02	<0.001	0.02	<0.001
Pileup	0.27	0.005	0.31	0.001
Trigger			0.18	0.003
Background	0.11	0.001	0.22	0.002
Hadronization model				
Flavor-dependent JSF	0.41	0.004	0.36	0.004
b-fragmentation	0.06	0.001	0.07	0.001
Semi-leptonic B hadron decays	0.16	<0.001	0.12	<0.001
Hard scattering process model				
PDF	0.09	0.001	0.02	<0.001
Renormalization/factorization scales	0.12±0.13	0.004±0.001	0.19±0.19	0.004±0.002
ME-PS matching threshold	0.15±0.13	0.003±0.001	0.20±0.19	0.002±0.002
ME generator	0.23±0.14	0.003±0.001	0.09±0.21	0.003±0.002
Non-perturbative QCD model				
Underlying event	0.14±0.17	0.002±0.002	0.13±0.28	0.000±0.002
Colour reconnection	0.08±0.15	0.002±0.001	0.00±0.25	0.000±0.002
Total	**0.75**	**0.012**	**0.83**	**0.011**

- Similar treatment as for 7 TeV but larger statistics (data + MC) help refining syst. assessments

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- **Signal modelling is added**
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  modeling of top p_T estimated after re-weigthing simulation to observed top p_T
- **Hadronization** is the dominant uncertainty
  Pythia-based JES extrapolation: from calibrated jet flavour to other flavours
  Pythia vs Herwig differences are evaluated separately for light, gluon and b-jets
  b-fragmentation: default vs LEP
  Semi-leptonic B rates: from PDG

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b-fragmentation: default vs LEP

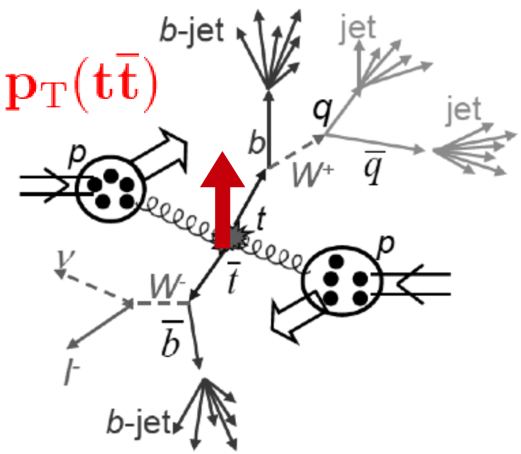
Semi-leptonic B rates: from PDG

- **Consistency cross-check of our current assessment of the hadronization uncertainty**
  String vs cluster fragmentation in Sherpa : parton-to-particle out-of-cone effects negligible in tt events
  Pythia vs Herwig (with Powheg) in top pair events: consistent effects with main estimate

m_t differential measurements

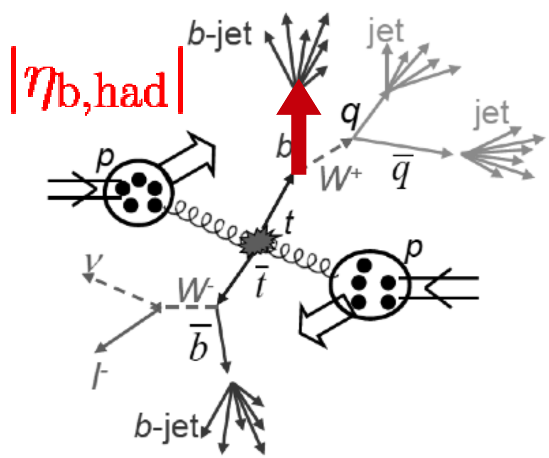
- We rely on MC-based **models of the top production and decay chain**
  - particular models for underlying event (UE), colour reconnection (CR) are taken into account
  - do these tools describe our data in the different phase space regions?
  - is our assessment of systematic uncertainties mined by casual cancellations?
  - can we find sensitivity to different components in top quark p_T, b-quark rapidity, charge, etc. ?
- Choose **representative observables which can potentiate particular effects**

Radiation effects



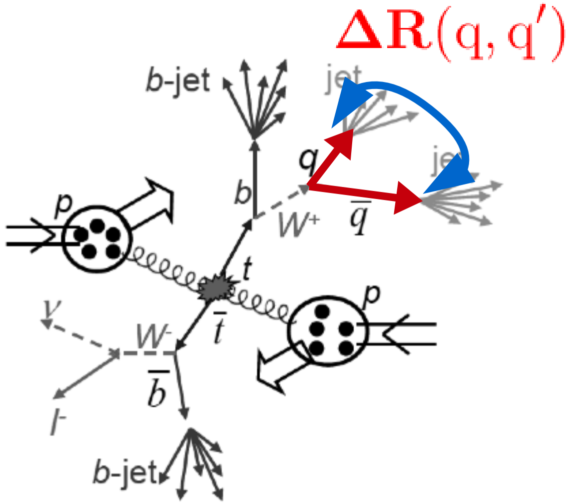
H_T $m_{t\bar{t}}$ $p_{T,t\bar{t}}$
Jet multiplicity

b-quark kinematics



$p_{T,b,had}$ $|\eta_{b,had}|$
$\Delta R_{b\bar{b}}$ $\Delta\phi_{b\bar{b}}$

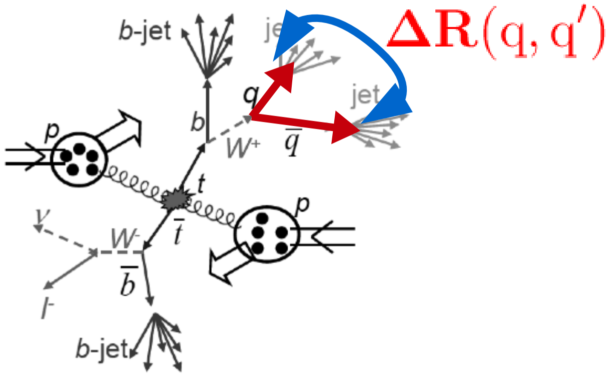
Colour reconnection

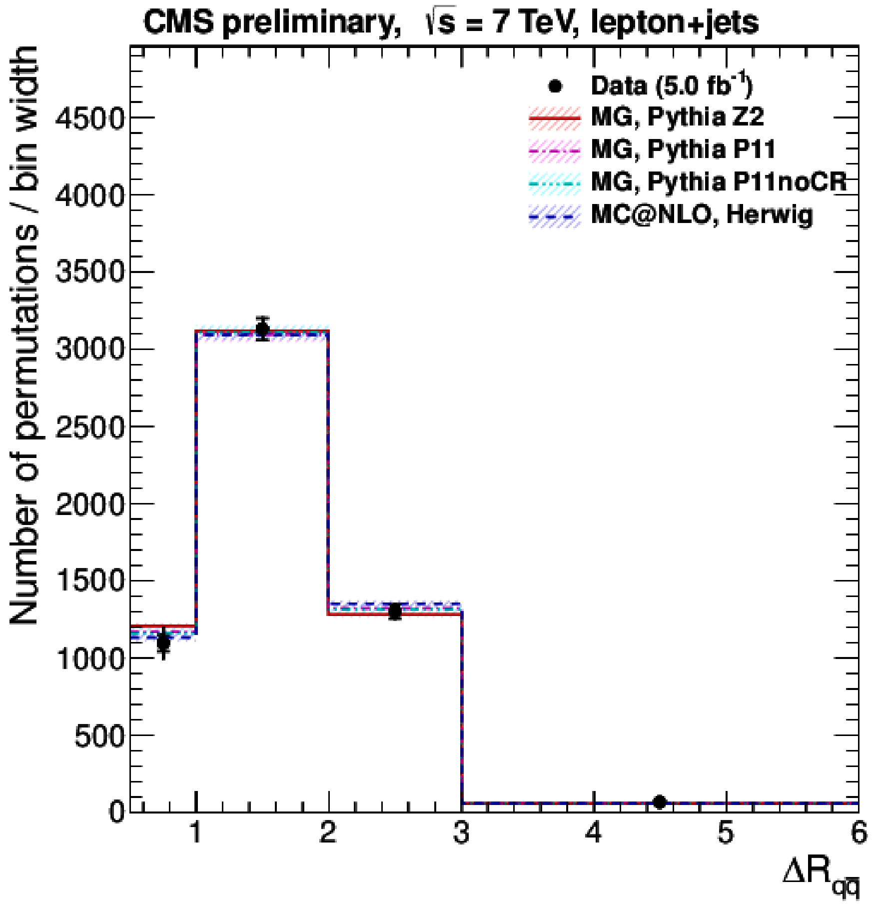


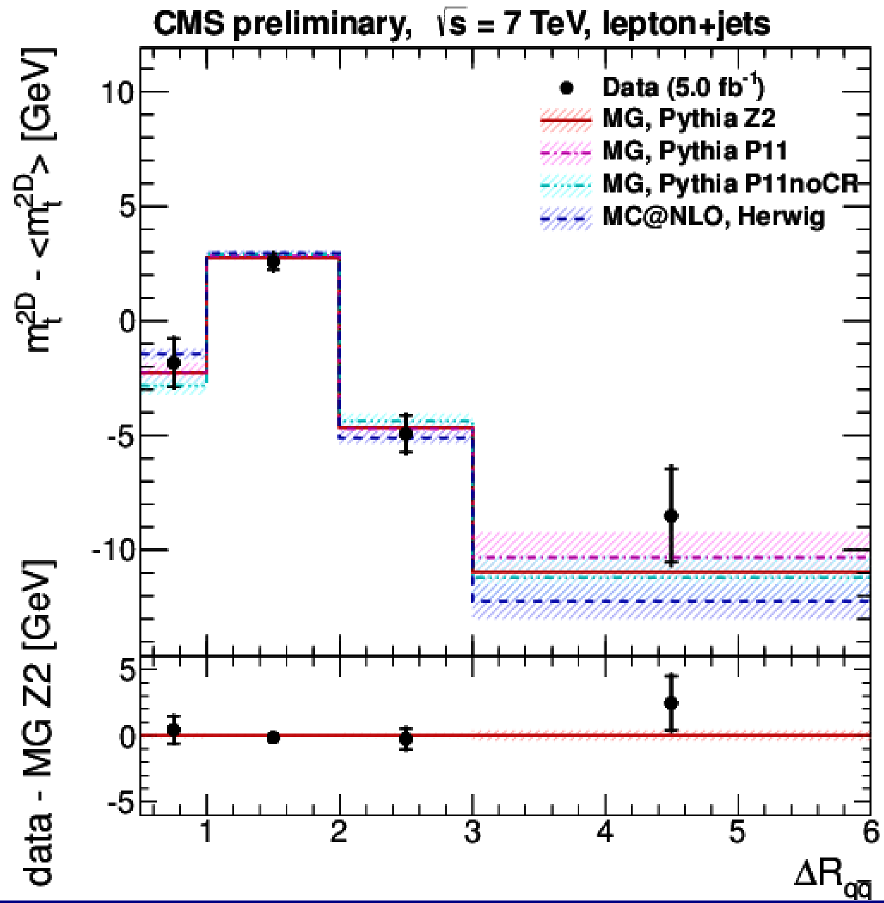
$\Delta R_{q\bar{q}}$ $\Delta\phi_{q\bar{q}}$
$p_{T,t,had}$ $|\eta_{t,had}|$

Strategy for differential measurements

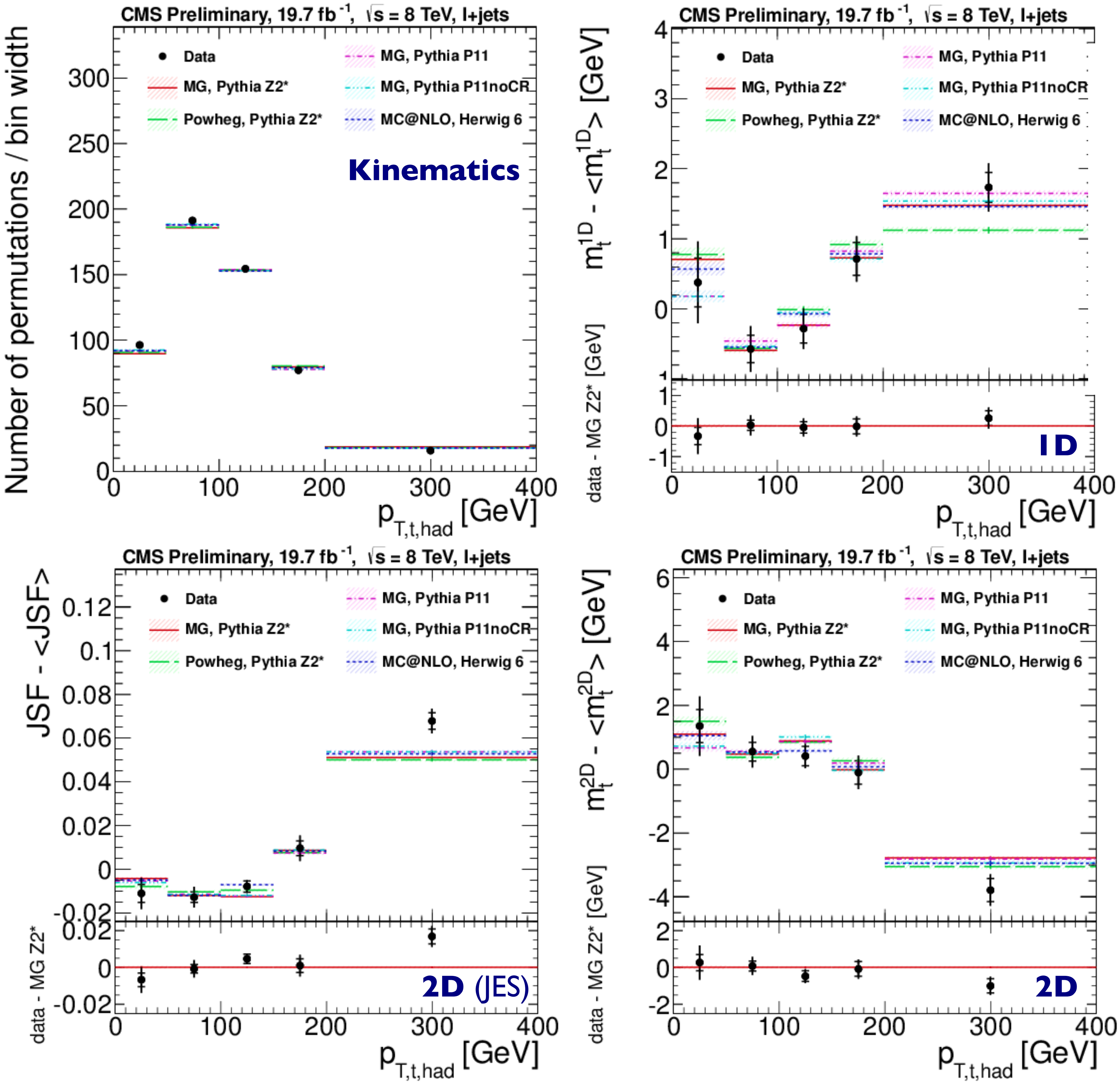
- **Study performed using golden l+jet channel**
  - **Categorize** permutations according to kinematics
  - Fit (m_t, JES) in data and MC ensembles
  - **Compare expected and observed biases** (double differences)







p_T(t had.)


CMS Preliminary, 19.7 fb⁻¹, √s = 8 TeV, l+jets
Data
MG, Pythia Z2*
Powheg, Pythia Z2*
MG, Pythia P11
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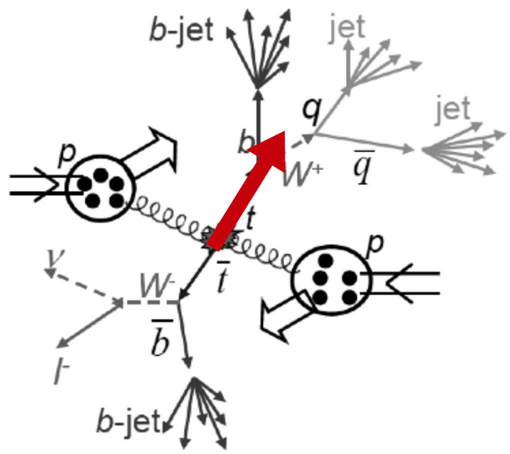
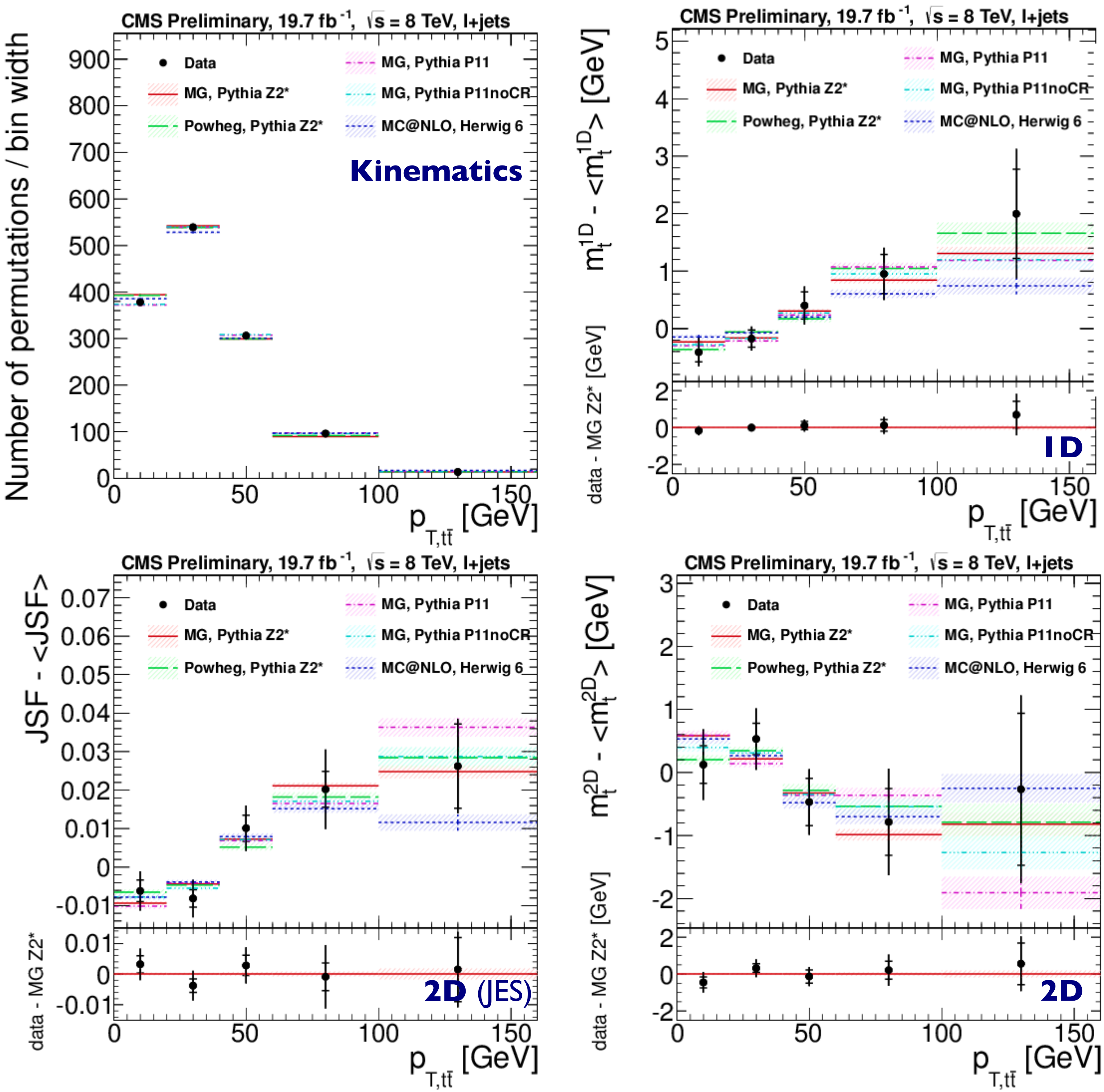
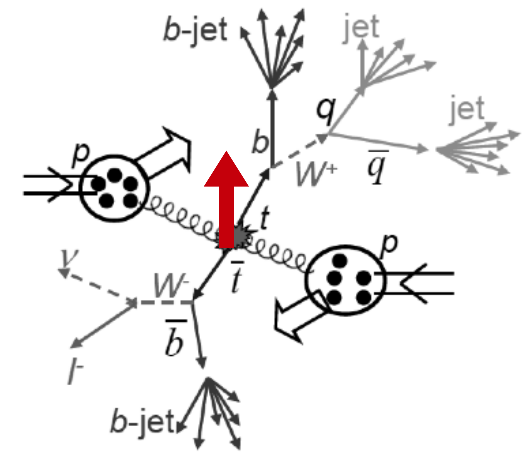
Kinematics
Number of permutations / bin width
p_T,t,had [GeV]
m_t^1D - <m_t^1D> [GeV]
data - MG Z2* [GeV]
1D
JSF - <JSF>
data - MG Z2*
2D (JES)
m_t^2D - <m_t^2D> [GeV]
2D


b-jet
jet
jet
q
b
W+
q̄
p
t
p
ν
W-
t̄
b̄
l-
b-jet

$\mathbf{p_T(t\bar{t})}$





Conclusions extracted from differential measurements

The top mass observable is used as a probe of the top quark event anatomy

- **No significant deviation** is found with respect to nominal calibration (Madgraph+Pythia6 Z2*)
- The extracted top mass is stable in all corners of phase space and for all models considered

Effect	Observable	m_t^{1D} χ^2 7 TeV	m_t^{1D} χ^2 8 TeV	JES χ^2 7 TeV	JES χ^2 8 TeV	m_t^{2D} χ^2 7 TeV	m_t^{2D} χ^2 8 TeV	ndof
Colour reconnection	$\Delta R_{q\bar{q}}$	1.01	2.87	3.41	3.66	1.49	0.83	3
	$\Delta\phi_{q\bar{q}}$	2.31	-	2.18	-	2.89	-	3
	$p_{T,t,had}$	9.40	0.89	7.83	12.03	2.89	5.76	4
	$\lvert\eta_{T,t,had}\rvert$	0.41	5.56	3.33	1.22	3.17	1.14	3
Radiation effects	H_T	3.18	6.19	1.19	9.18	2.24	7.54	4
	$m_{t\bar{t}}$	2.52	2.16	2.98	4.69	2.25	3.22	4/5
	$p_{T,t\bar{t}}$	3.39	1.02	1.67	1.22	2.18	1.33	4
	Jet mult.	1.47	4.24	2.00	0.10	1.56	1.16	2
b-quark kinematics	$p_{T,b,had}$	0.81	2.57	2.35	5.80	2.17	2.17	4
	$\lvert\eta_{T,b,had}\rvert$	2.64	1.15	0.30	0.08	0.48	0.72	2
	$\Delta R_{b\bar{b}}$	4.87	0.37	2.61	1.63	8.01	1.77	3
	$\Delta\phi_{b\bar{b}}$	2.87	-	3.86	-	6.86	-	3
"EWK" kinematics	$p_{T,q,had}$	-	4.04	-	8.39	-	1.28	4
	$\lvert\eta_{T,W,had}\rvert$	-	3.36	-	3.79	-	6.27	2
	$p_{T,q,had}$	-	1.59	-	8.06	-	1.60	4
	$\lvert\eta_{T,W,had}\rvert$	-	1.41	-	1.09	-	1.35	3
χ^2/ndof		68.68/78 (p-val=0.77) at 7 TeV 93.67/94 (p-val=0.49) at 8 TeV						

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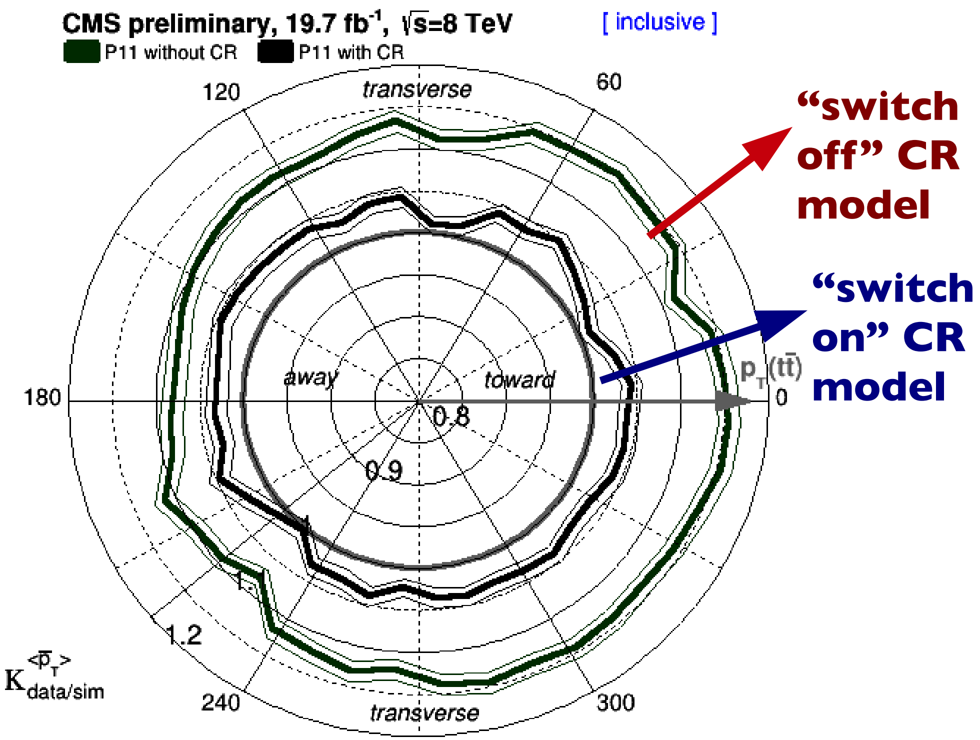
- **With more statistics** (i.e. LHC Run II and beyond)
  - establish robustness of top mass result in more detail and with better precision
  - tune models in-situ using data or simply exclude extreme models
  - use method to compare "our" favorite MC tool to well-defined QCD calculations (cf. arXiv:1405.4781)

Testing our modelling of the signal

- **Non-perturbative QCD effects**
  - can be measured in-situ from UE studies
  - compare different models: identify extreme cases
- e.g. the data/MC ratio of the average p_T/ particle
  - characterize as function of p_T(tt), $\Delta\varphi$(tt)
  - Provides evidence of CR in tt events!



CMS PAS-TOP-13-007

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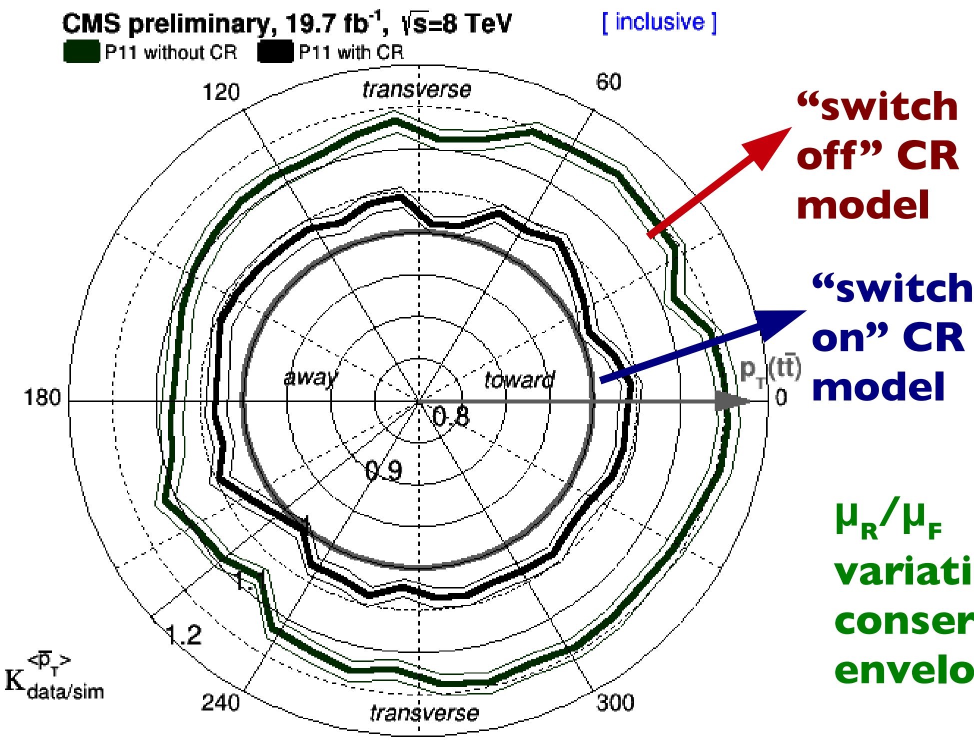
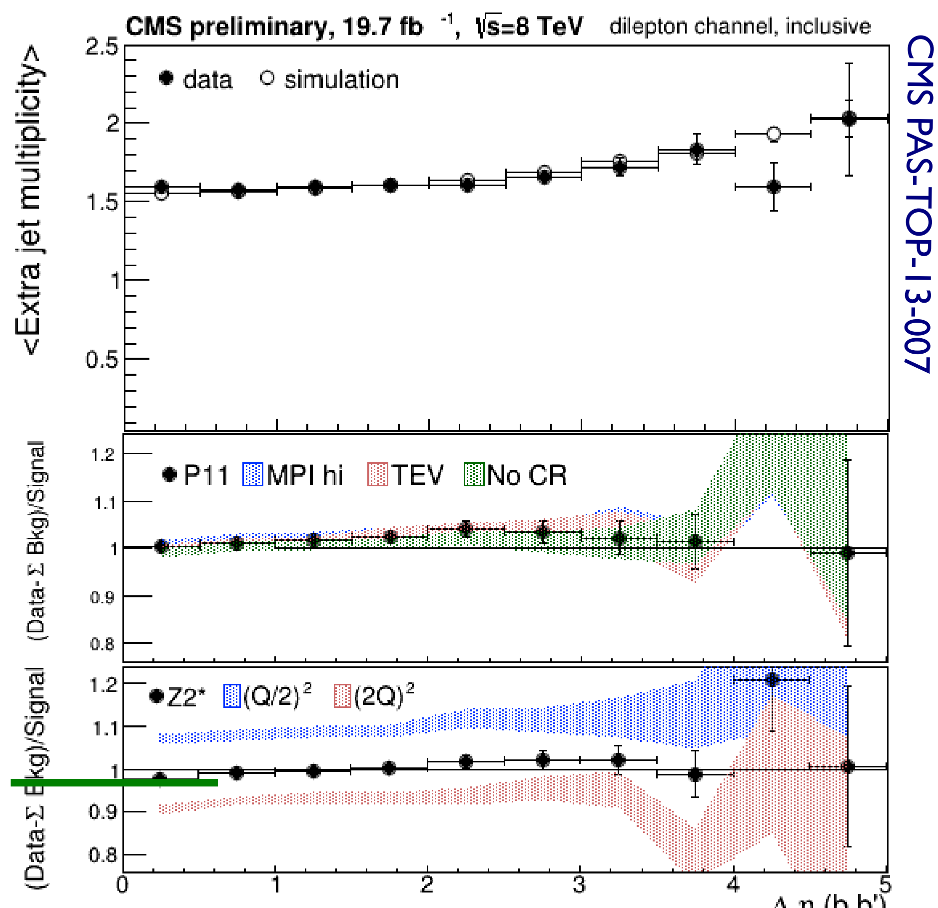


CMS PAS-TOP-13-007

- **ISR/FSR** effects
  - modelled from μ_R/μ_F and ME-PS matching
  - measure differential cross-section: N_{jets}, H_T, gap fractions, …
- e.g. extra jet multiplicity as function of $\Delta\eta(b,b')$



μ_R/μ_F variation is a conservative envelope

CMS PAS-TOP-13-007

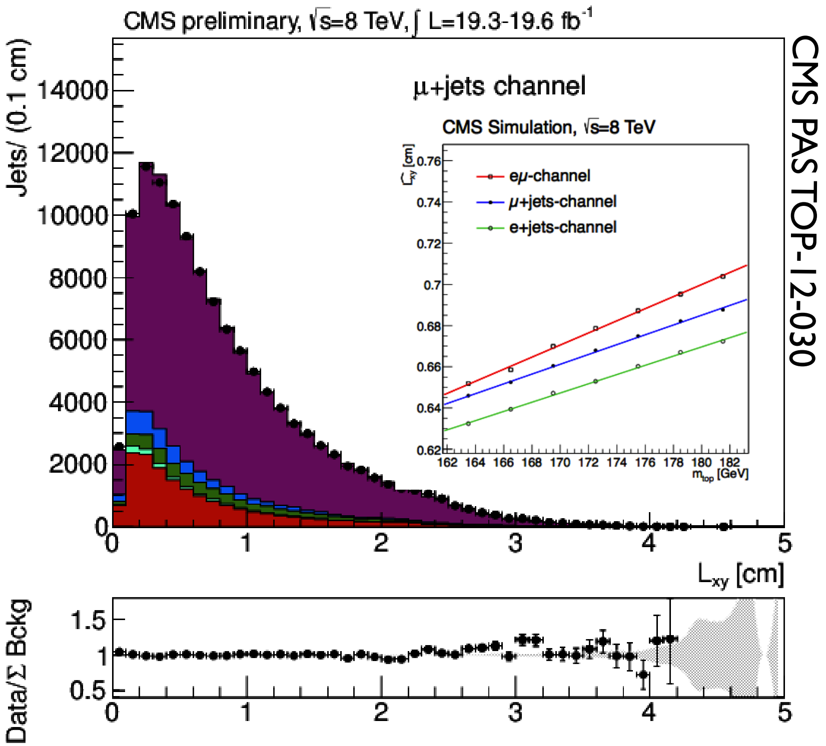
Alternative methods

Reduce specific systematics using robust observables: typically require high statistics

B-hadron lifetime technique

m_{top} = 173.5 ± 1.5 (stat) ± 1.3 (syst) ± 2.6 ($p_{T(t)}$) GeV

- Pioneered by CDF
- No JES uncertainty
- Sensitive to fragmentation and top p_T
- would benefit from theory developments



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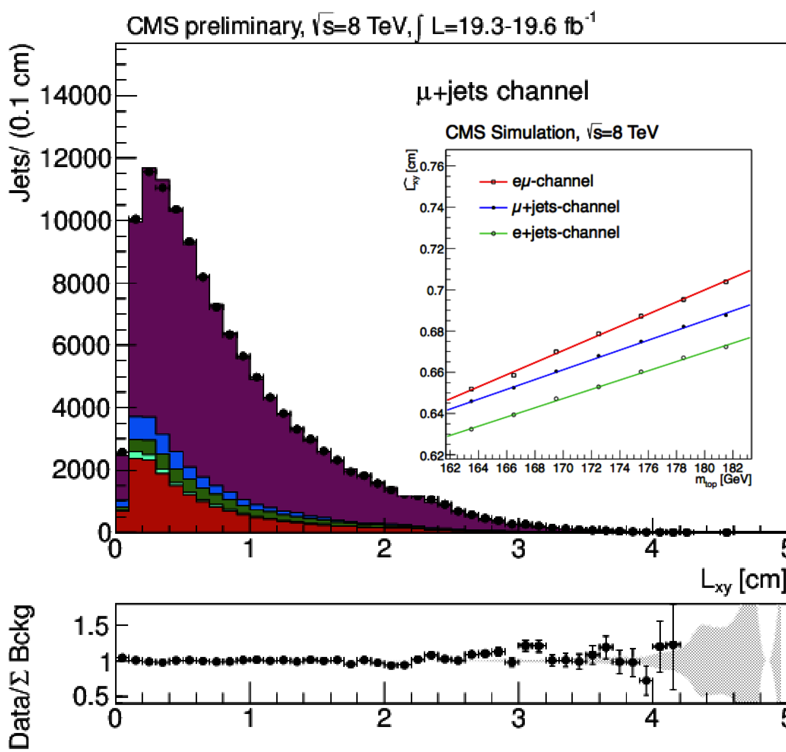
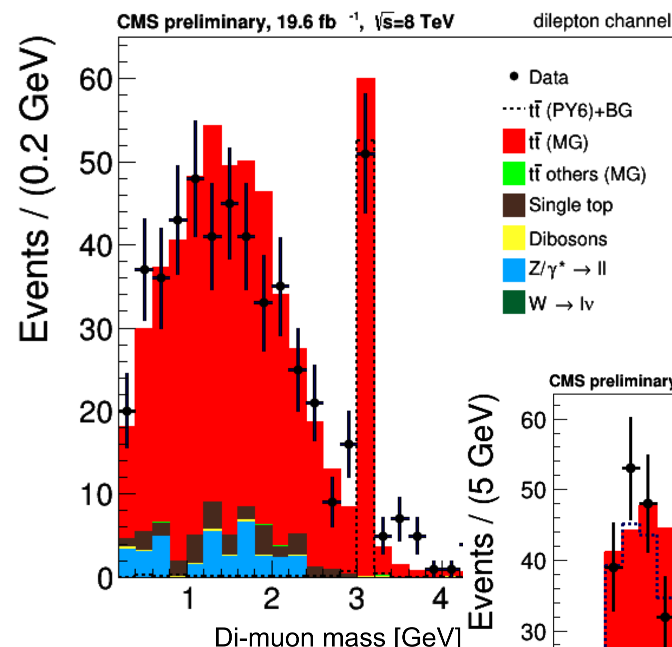
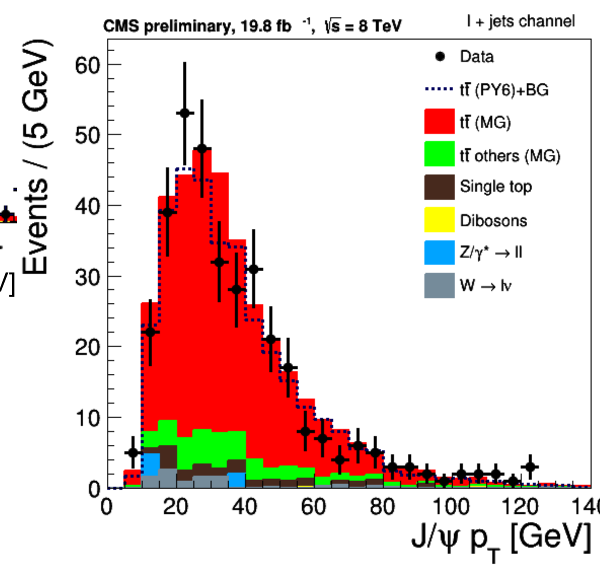


J/ψ method

- first observation of J/ψ production in tt events!
- preliminary fragmentation/hadronization studies
- in the future: use M(J/ψ,l) to reconstruct m_t



CMS PAS-TOP-13-007



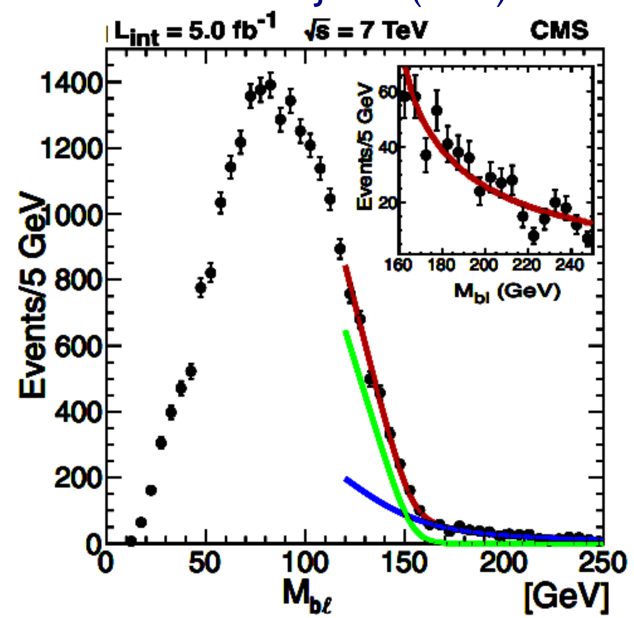
Resolving the ambiguity in interpreting $m_t^{exp.}$

- Explore **endpoint** for the spectrum of variables which:
  - are suited to analyze events with symmetric 3 body decays
  - factorize event-by-event boost of the tt system
- Use M(l,b) and M_{T2}-variants JHEP 0903 (2009) 143 PRL 107 (2011) 061801
- **Compare directly with LO expectations**

m_{top} = 173.9 ± 0.9 (stat) +1.7/-2.1(syst) GeV

  - main uncertainties: jet energy scale, QCD effects and fit choices

EPJC 73 (2013) 2494



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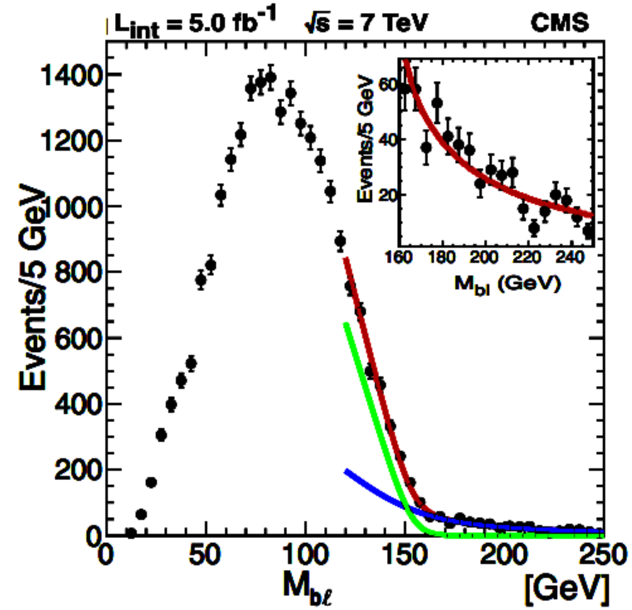
EPJC 73 (2013) 2494



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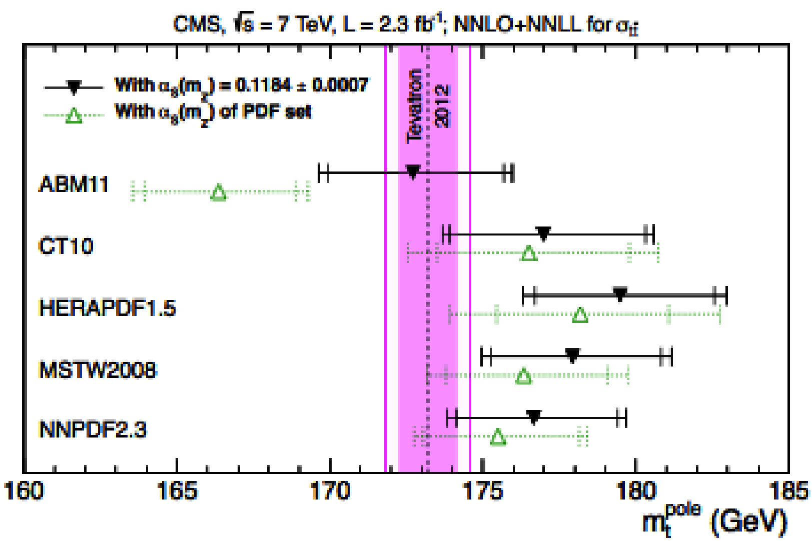
PLB 728 (2013) 496



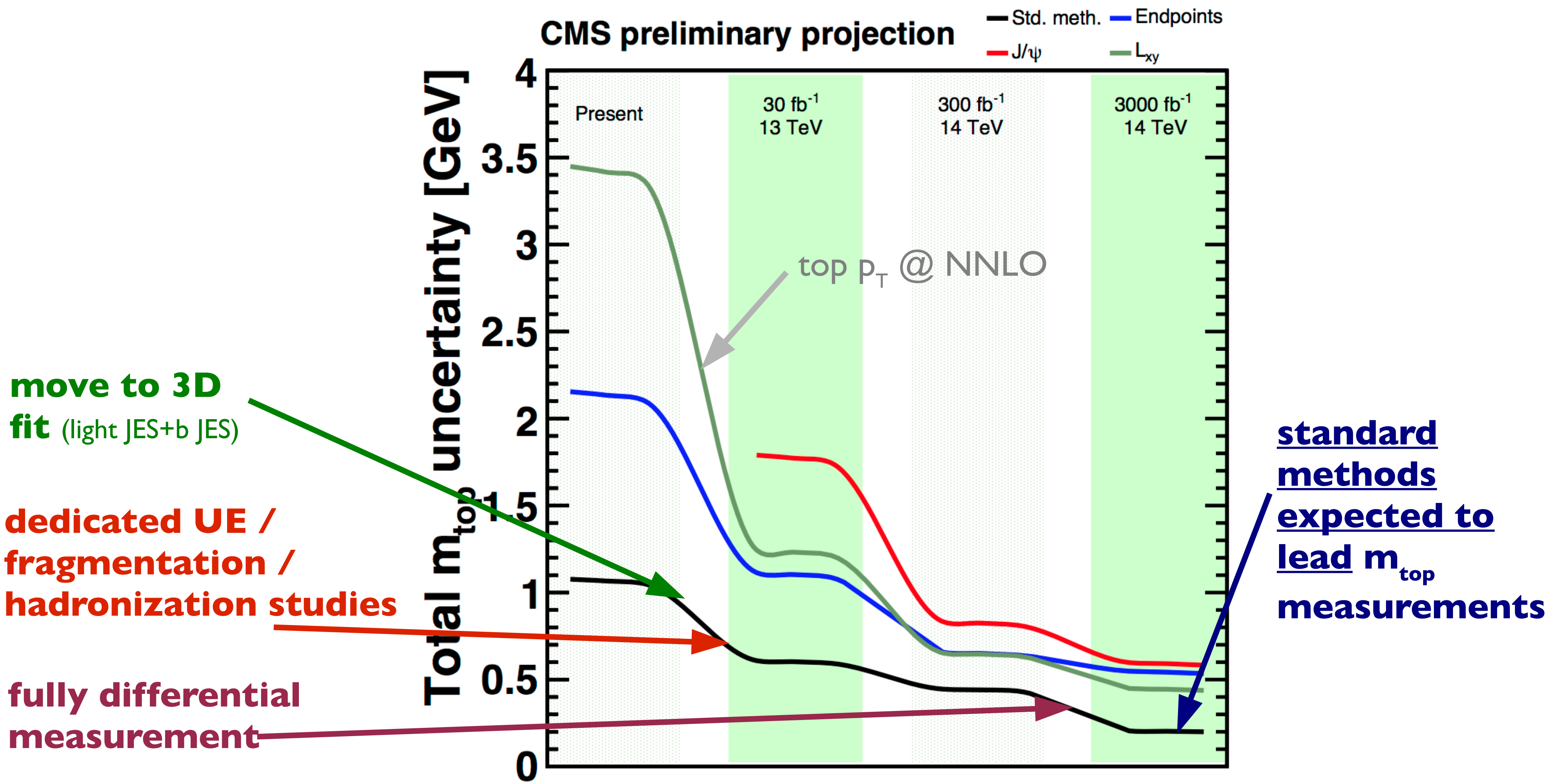
- Extrapolate **m_T^{pole} from cross section**
- Needs careful choice of cuts for cross section measurement
  - minimize acc. dependency on m_T and signal model systematics
- First NNLO+NNLL determination of m_T^{pole}

$$m_{top} = 176.7\ +3.0\ /\ -2.8\ \ GeV$$ using NNPDF2.3

- α_S determination is also possible after fixing m_t^{pole}
- In both cases compare with different PDF predictions

Top mass @ CMS: quo vadis?

- Projections made as a roadmap towards HL-LHC based on flagship measurements @ the LHC
  - improved fitting techniques. dedicated signal modeling studies
  - to be accompanied with improvements from theory



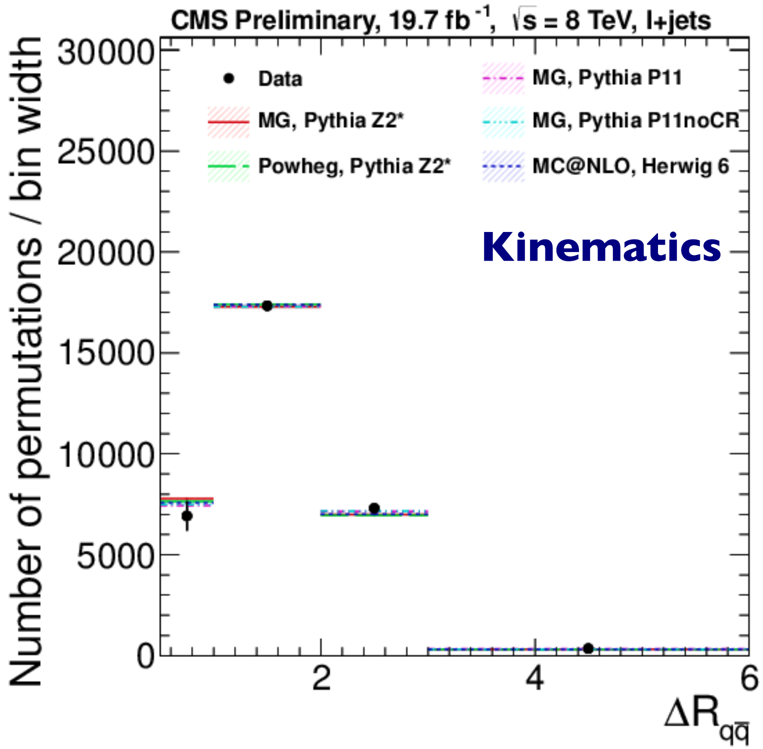
Conclusions

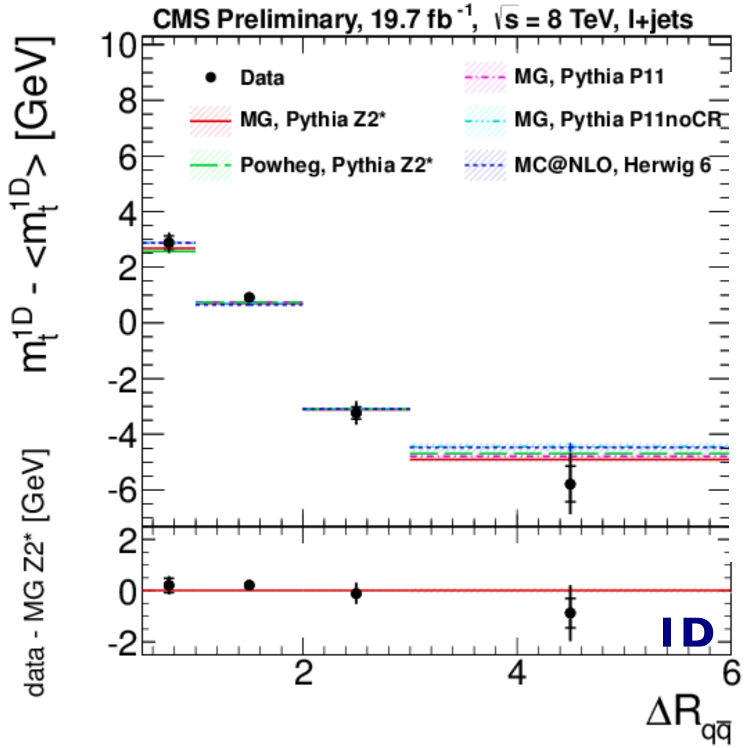
- **Rich m_{top} measurement programme at CMS**
  - fundamental SM parameter and window to new physics
  - 7 TeV programme fully published, moving to full 8 TeV dataset
- **"Classic" mass measurements adopt the MC definition of m_{top}**
  - σ=0.4% m_{top} ~ 4 Λ_{QCD} !
  - inclusive phase-space calibration is performed
  - robustness tested against different theory models and experimental uncertainties
- **Data can be used to image in finer detail a top quark event**
  - differential measurements do not reveal significant biases for different variables
  - UE studies show that a colour reconnection model is needed to describe top pair events in data
- **Alternative methods** can further help:
  - robust against specific systematics
  - clarify interpretation of classic measurements
- **Higher statistics is crucial: expect great benefits from 300 fb^{-1} and 3000 fb^{-1}**

Ultimate experimental precision 200 MeV ~ Λ_{QCD} may be possible

Backup

$\Delta R(q, q')$


CMS Preliminary, 19.7 fb^{-1}, $\sqrt{s}$ = 8 TeV, l+jets
Data
MG, Pythia Z2*
Powheg, Pythia Z2*
MG, Pythia P11
MG, Pythia P11noCR
MC@NLO, Herwig 6
Kinematics
Number of permutations / bin width
$\Delta R_{q\bar{q}}$


CMS Preliminary, 19.7 fb^{-1}, $\sqrt{s}$ = 8 TeV, l+jets
Data
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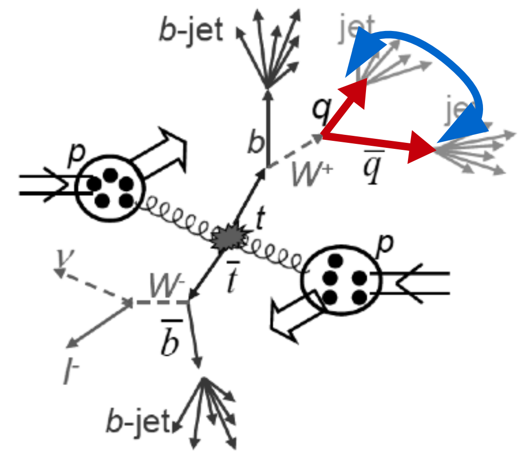
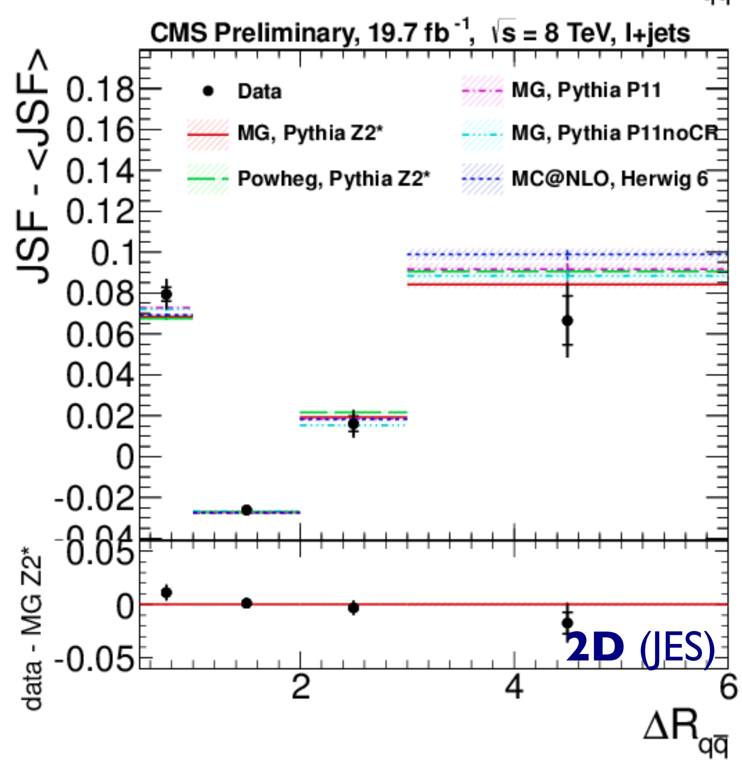
Powheg, Pythia Z2*
MG, Pythia P11
MG, Pythia P11noCR
MC@NLO, Herwig 6
m_t^{1D} - $<m_t^{1D}>$ [GeV]
data - MG Z2* [GeV]
1D
$\Delta R_{q\bar{q}}$


b-jet
jet
jet
q
$\bar{q}$
b
W^+
p
t
$\bar{t}$
p
ν
W^-
$\bar{b}$
l^-
b-jet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MG, Pythia Z2*
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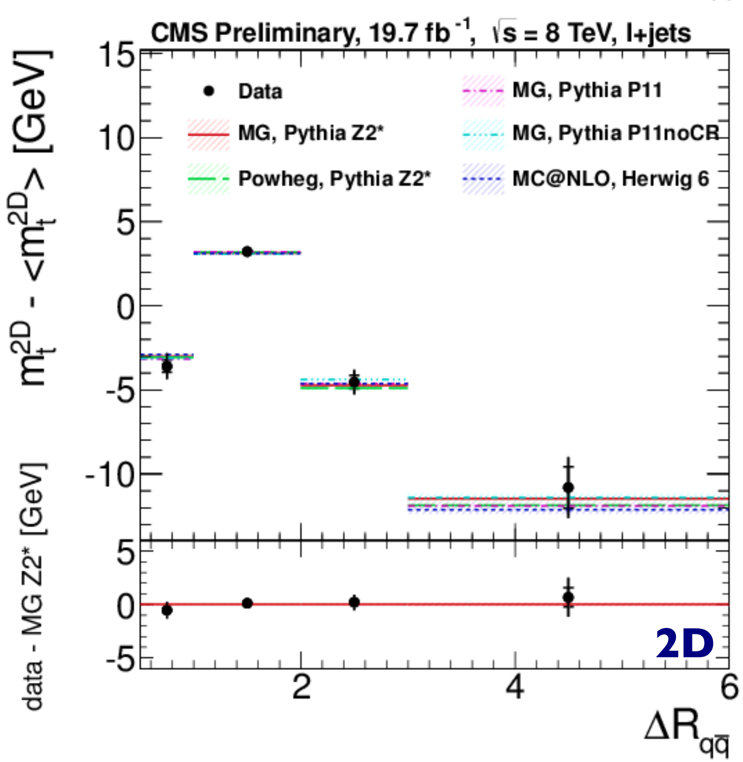
MG, Pythia P11noCR
MC@NLO, Herwig 6
JSF - <JSF>
data - MG Z2*
2D (JES)
$\Delta R_{q\bar{q}}$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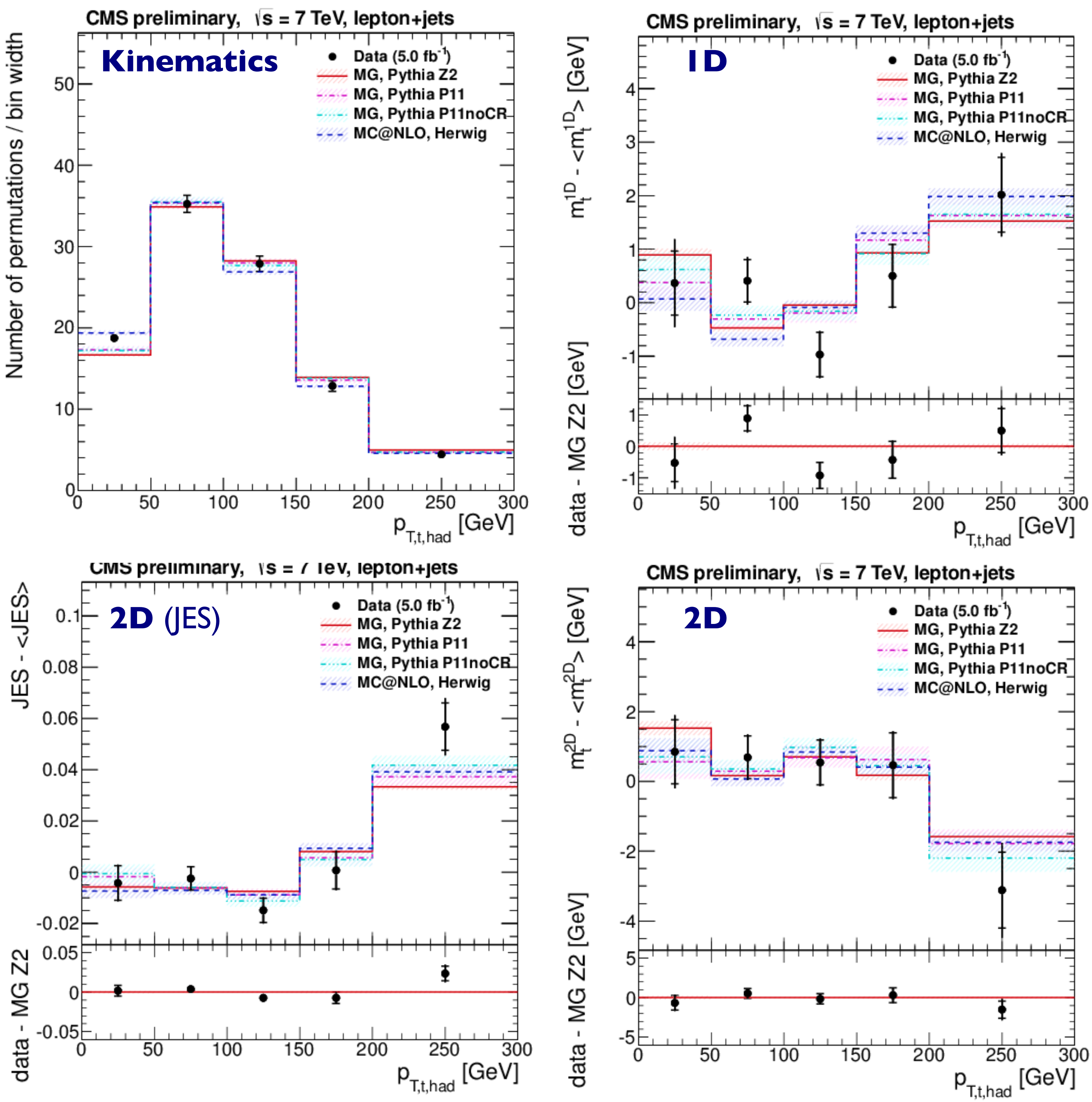
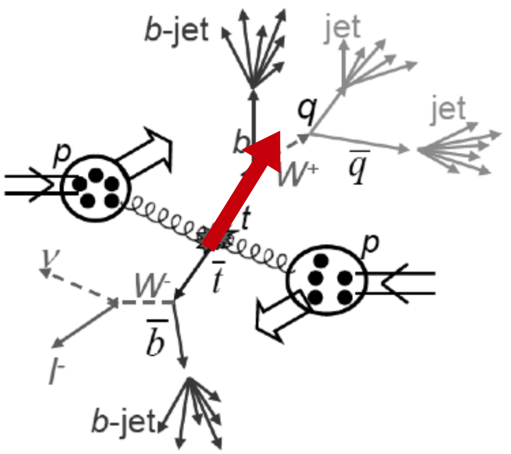
MG, Pythia P11noCR
MC@NLO, Herwig 6
m_t^{2D} - $<m_t^{2D}>$ [GeV]
data - MG Z2* [GeV]
2D
$\Delta R_{q\bar{q}}$

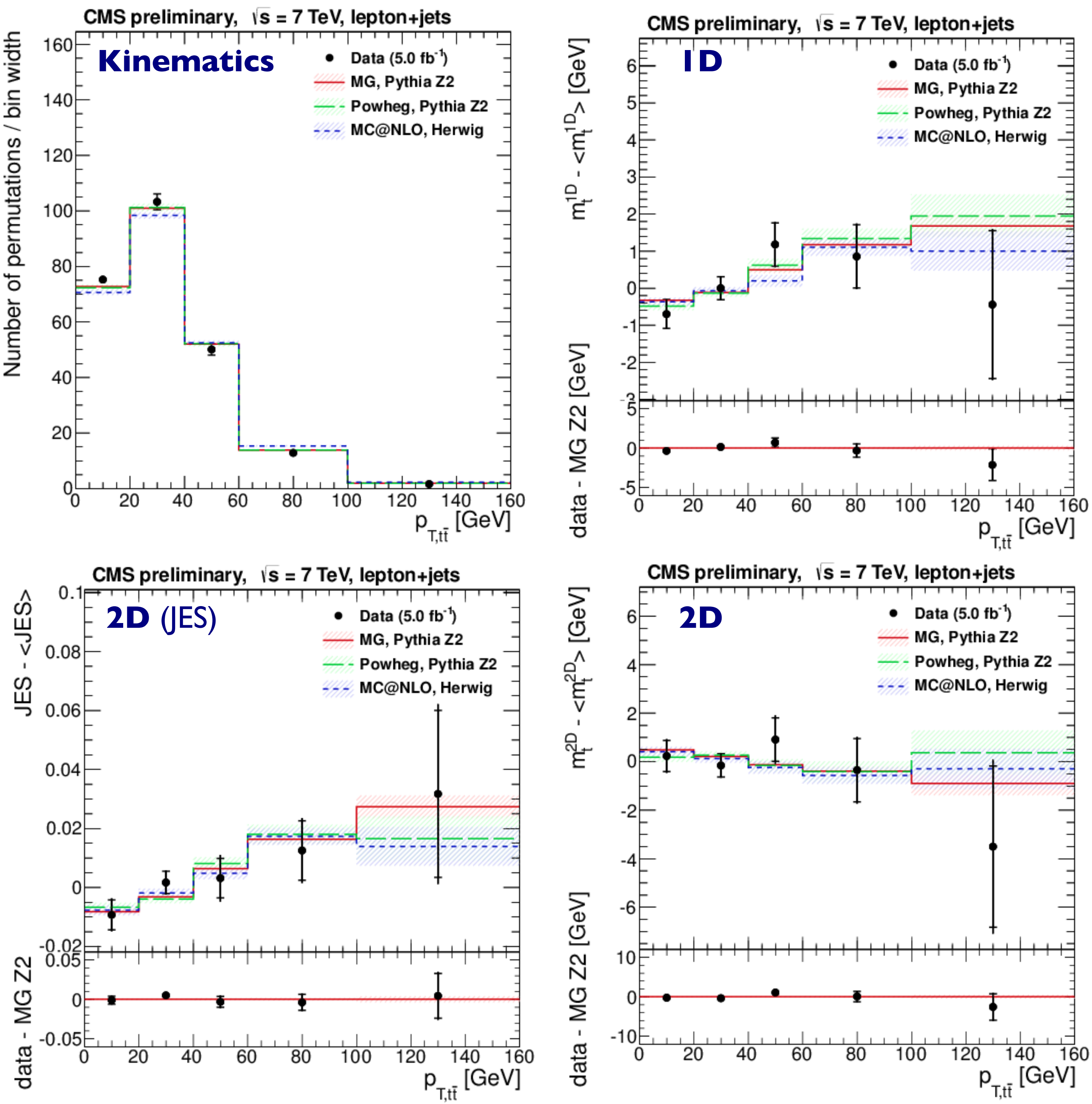
p_T(t had.)



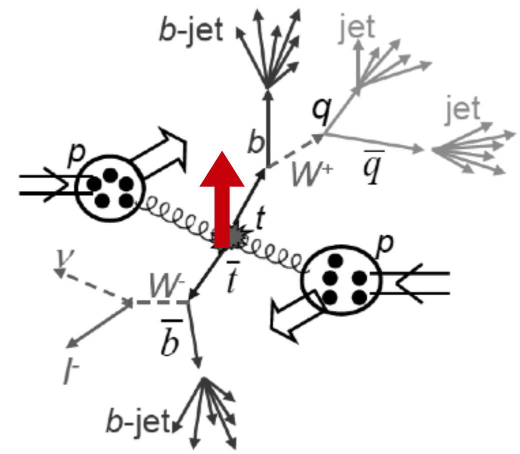
CMS preliminary, √s = 7 TeV, lepton+jets
Kinematics
Data (5.0 fb⁻¹)
MG, Pythia Z2
MG, Pythia P11
MG, Pythia P11noCR
MC@NLO, Herwig
Number of permutations / bin width
p_T,t,had [GeV]
1D
m_t^1D - <m_t^1D> [GeV]
data - MG Z2 [GeV]
2D (JES)
JES - <JES>
data - MG Z2
2D
m_t^2D - <m_t^2D> [GeV]



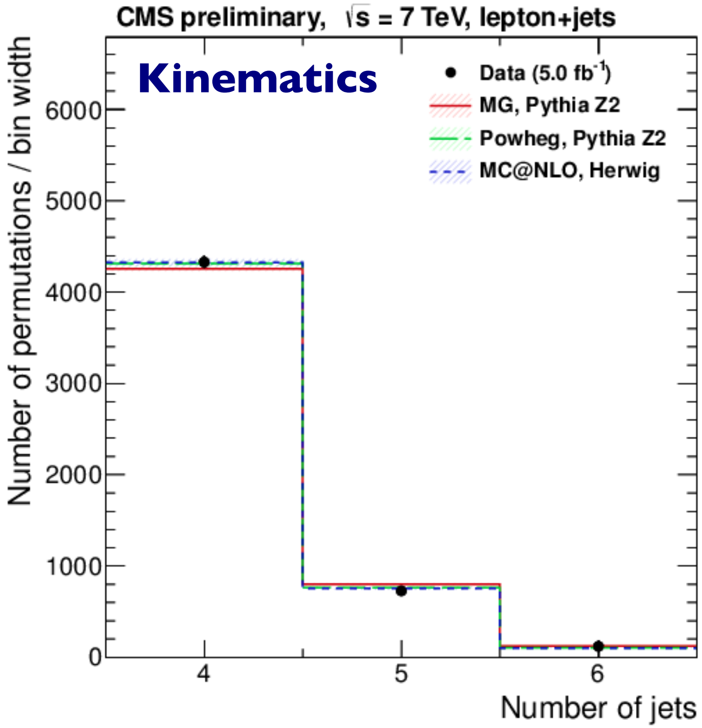
b-jet
jet
q
jet
p
b
W+
q̄
t
t̄
p
ν
W-
b̄
l-
b-jet


CMS preliminary, √s = 7 TeV, lepton+jets
Kinematics
Data (5.0 fb-1)
MG, Pythia Z2
Powheg, Pythia Z2
MC@NLO, Herwig
Number of permutations / bin width
p_T,tt̄ [GeV]
1D
m_t^{1D} - <m_t^{1D}> [GeV]
data - MG Z2 [GeV]
2D (JES)
JES - <JES>
data - MG Z2
2D
m_t^{2D} - <m_t^{2D}> [GeV]

$p_T(t\bar{t})$


b-jet
jet
q
jet
p
b
W+
q̄
t
p
ν
W-
t̄
b̄
l-
b-jet

N(jets)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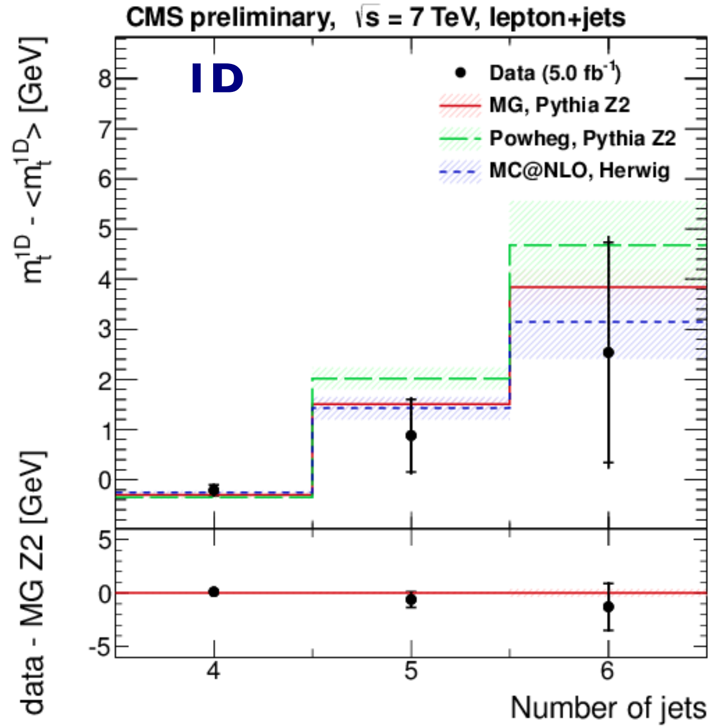
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1D
Data (5.0 fb⁻¹)
MG, Pythia Z2
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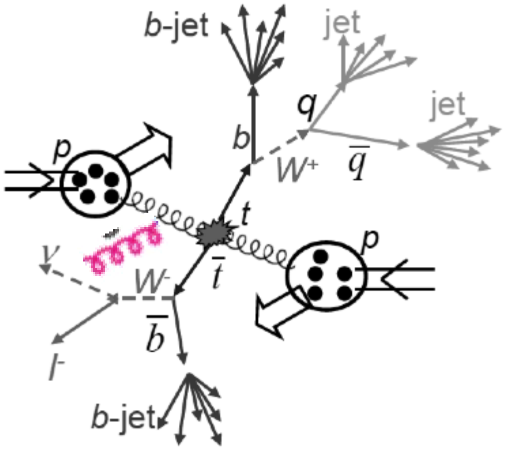
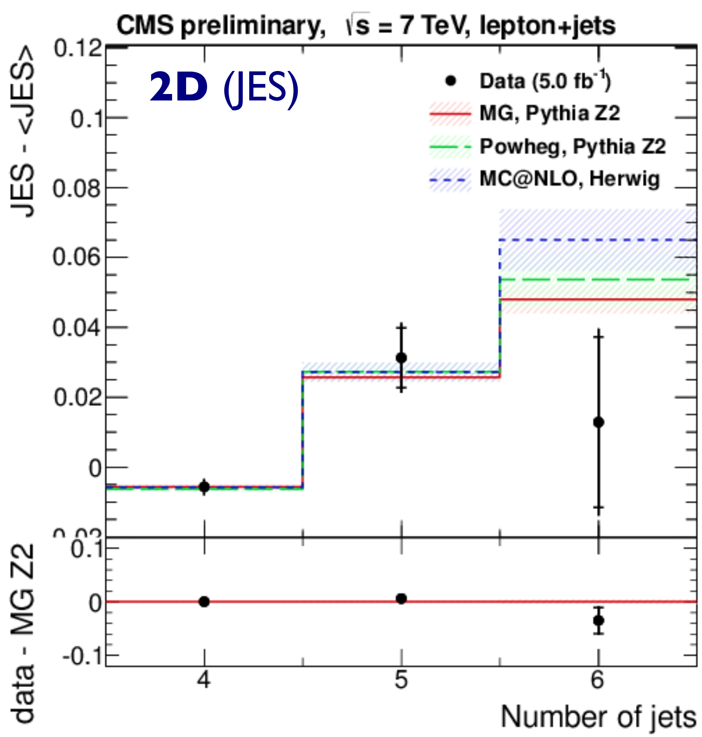
m_t^1D - <m_t^1D> [GeV]
data - MG Z2 [GeV]
Number of jets


b-jet
jet
jet
q
b
W+
q̄
p
t
t̄
ν
W-
b̄
l-
p
b-jet


CMS preliminary, √s = 7 TeV, lepton+jets
2D (JES)
Data (5.0 fb⁻¹)
MG, Pythia Z2
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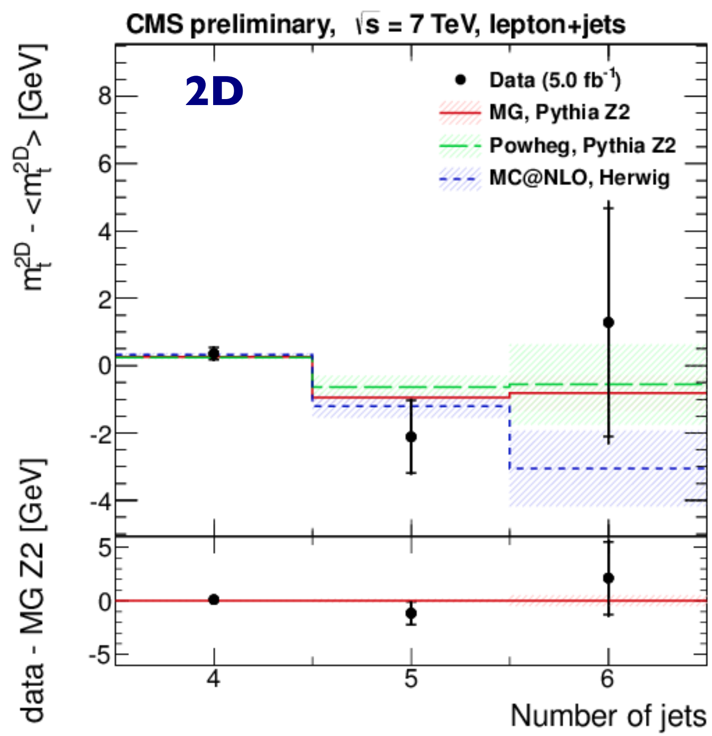
JES - <JES>
data - MG Z2
Number of jets


CMS preliminary, √s = 7 TeV, lepton+jets
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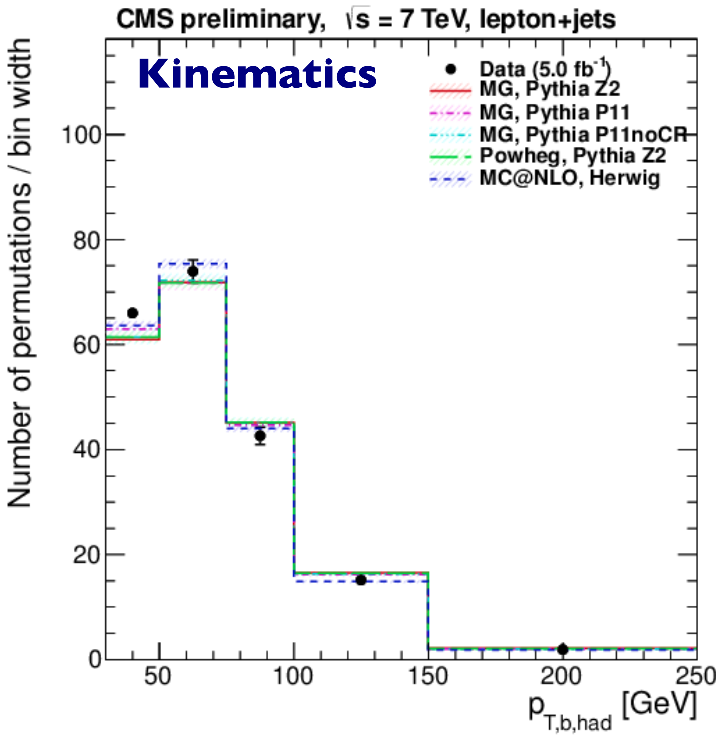
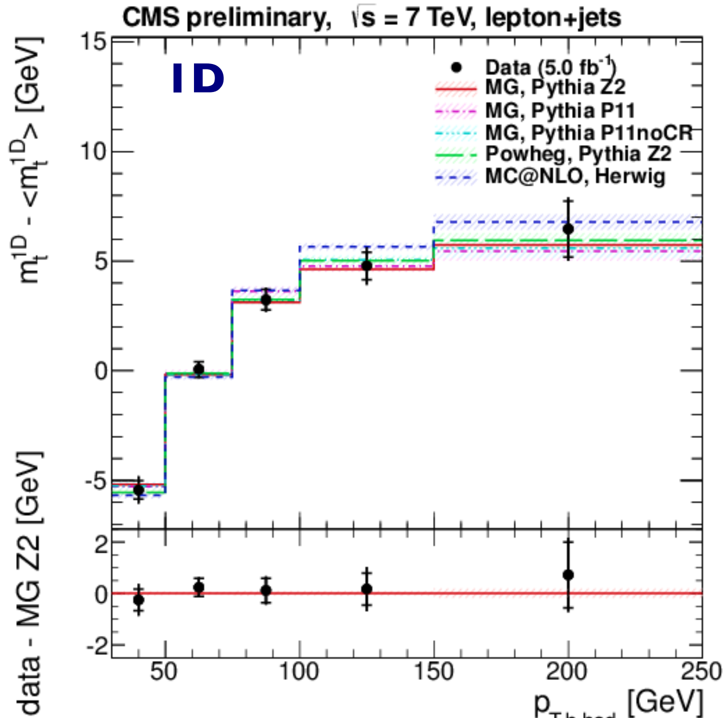
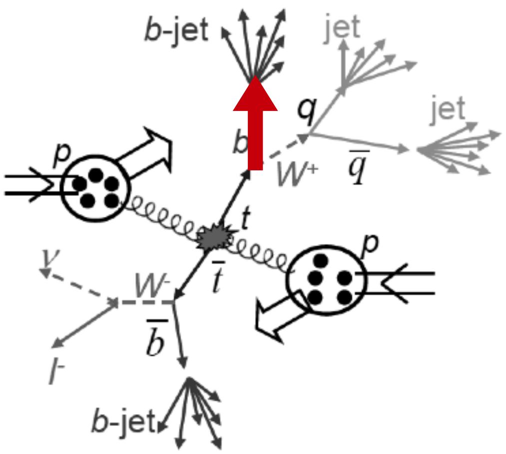
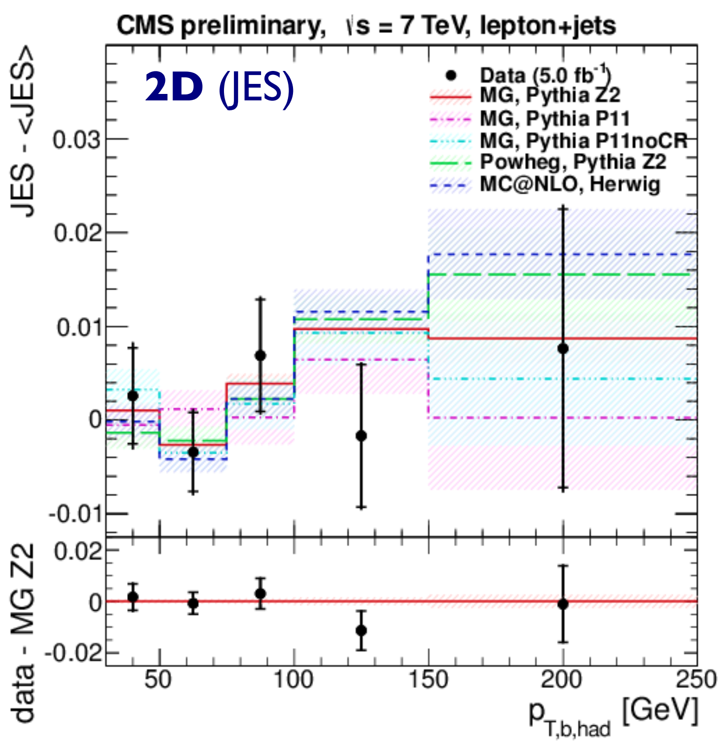
Data (5.0 fb⁻¹)
MG, Pythia Z2
Powheg, Pythia Z2
MC@NLO, Herwig
m_t^2D - <m_t^2D> [GeV]
data - MG Z2 [GeV]
Number of jets

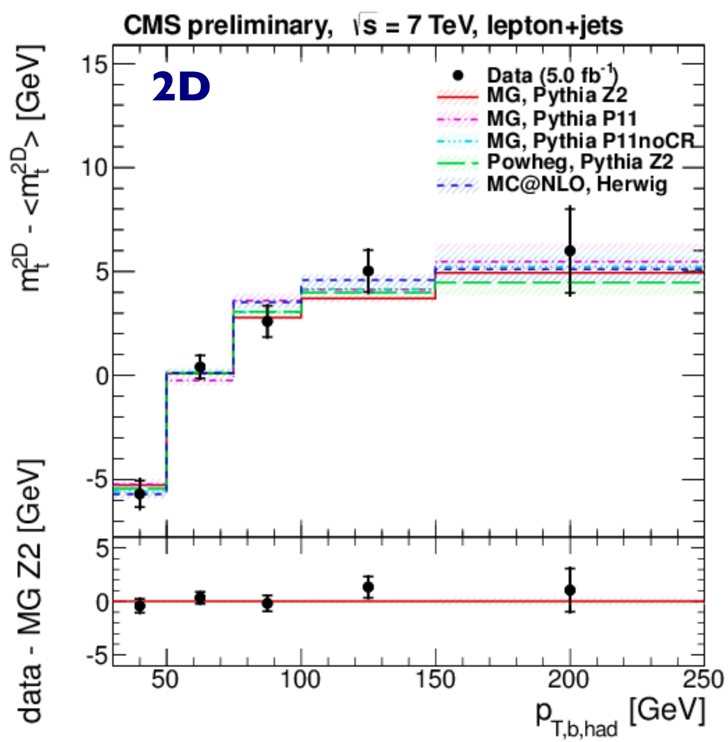
p_T(b had.)

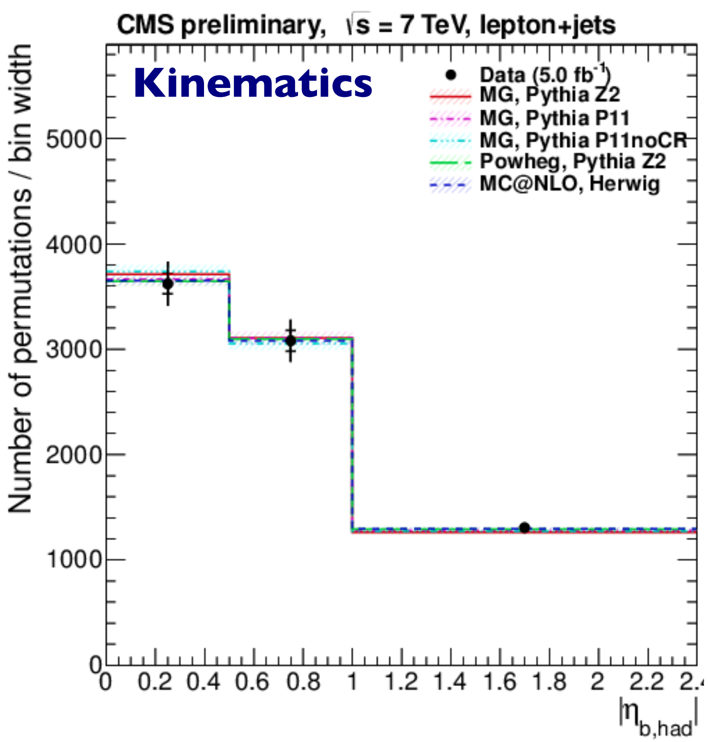

CMS preliminary, √s = 7 TeV, lepton+jets
Kinematics
Data (5.0 fb⁻¹)
MG, Pythia Z2
MG, Pythia P11
MG, Pythia P11noCR
Powheg, Pythia Z2
MC@NLO, Herwig
Number of permutations / bin width
p_T,b,had [GeV]

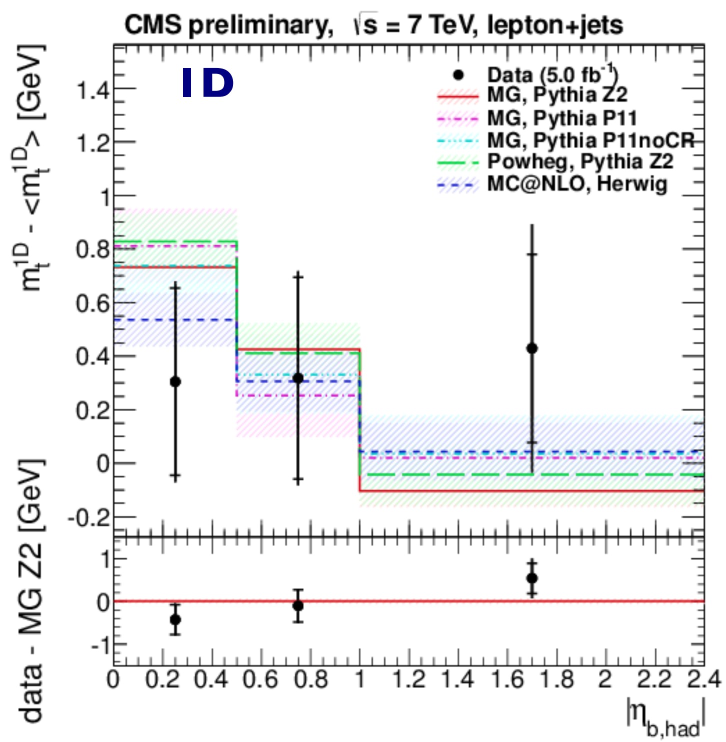

CMS preliminary, √s = 7 TeV, lepton+jets
1D
Data (5.0 fb⁻¹)
MG, Pythia Z2
MG, Pythia P11
MG, Pythia P11noCR
Powheg, Pythia Z2
MC@NLO, Herwig
m_t^1D - <m_t^1D> [GeV]
data - MG Z2 [GeV]
p_T,b,had [GeV]

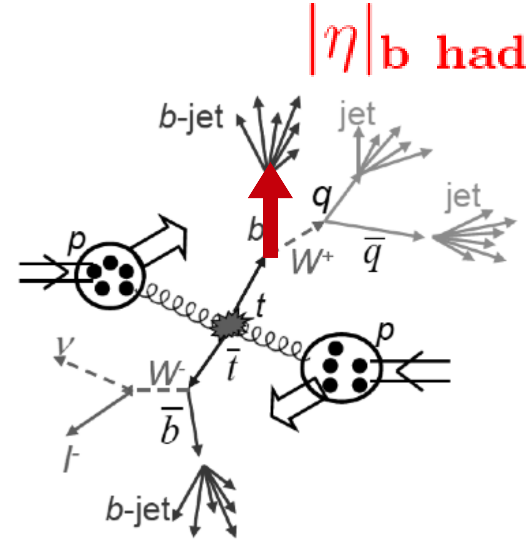

b-jet
jet
q
b
W+
q̄
t
p
t̄
W-
b̄
ν
l-
b-jet

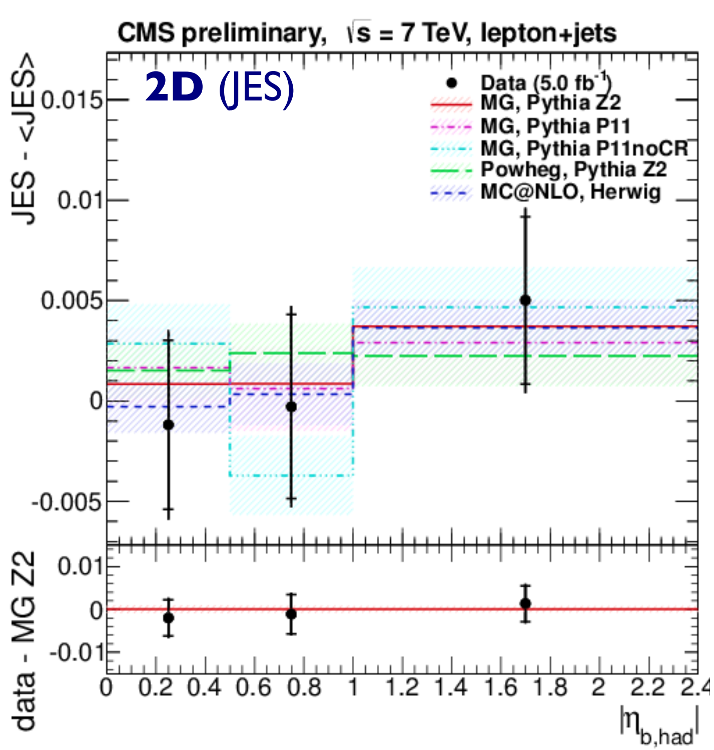

CMS preliminary, √s = 7 TeV, lepton+jets
2D (JES)
Data (5.0 fb⁻¹)
MG, Pythia Z2
MG, Pythia P11
MG, Pythia P11noCR
Powheg, Pythia Z2
MC@NLO, Herwig
JES - <JES>
data - MG Z2
p_T,b,had [GeV]

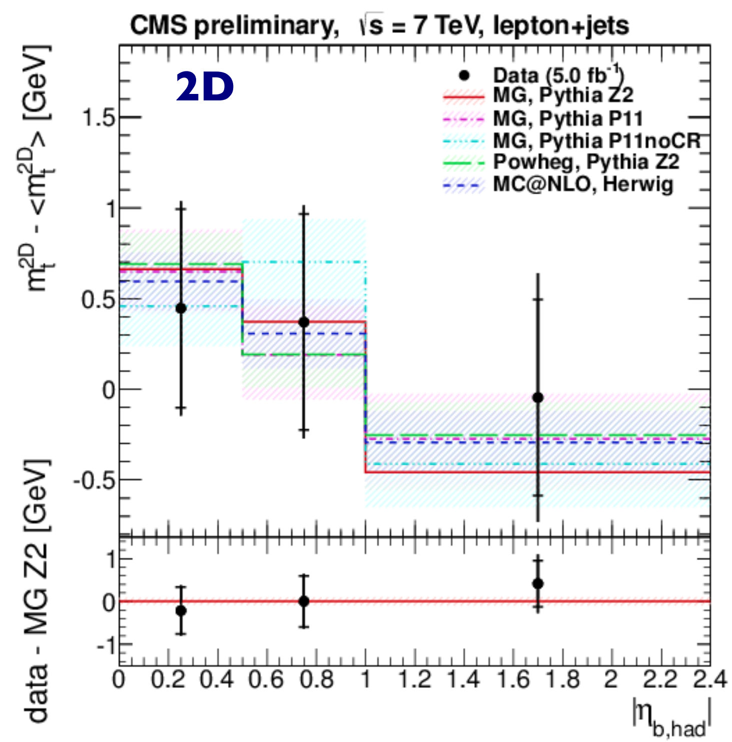

CMS preliminary, √s = 7 TeV, lepton+jets
2D
Data (5.0 fb⁻¹)
MG, Pythia Z2
MG, Pythia P11
MG, Pythia P11noCR
Powheg, Pythia Z2
MC@NLO, Herwig
m_t^2D - <m_t^2D> [GeV]
data - MG Z2 [GeV]
p_T,b,had [GeV]


CMS preliminary, √s = 7 TeV, lepton+jets
Kinematics
Data (5.0 fb⁻¹)
MG, Pythia Z2
MG, Pythia P11
MG, Pythia P11noCR
Powheg, Pythia Z2
MC@NLO, Herwig
Number of permutations / bin width
|η_b,had|

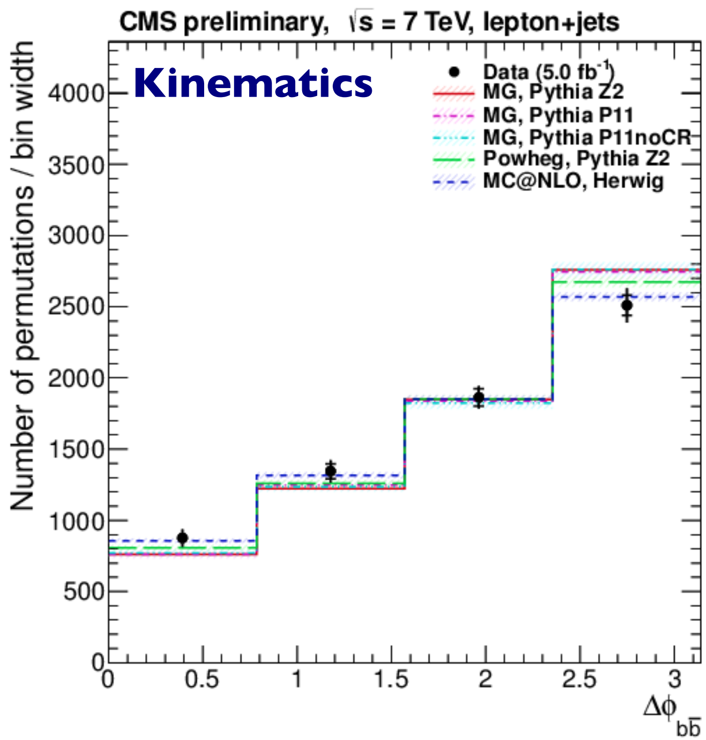

CMS preliminary, √s = 7 TeV, lepton+jets
1D
Data (5.0 fb⁻¹)
MG, Pythia Z2
MG, Pythia P11
MG, Pythia P11noCR
Powheg, Pythia Z2
MC@NLO, Herwig
m_t^1D - <m_t^1D> [GeV]
data - MG Z2 [GeV]
|η_b,had|

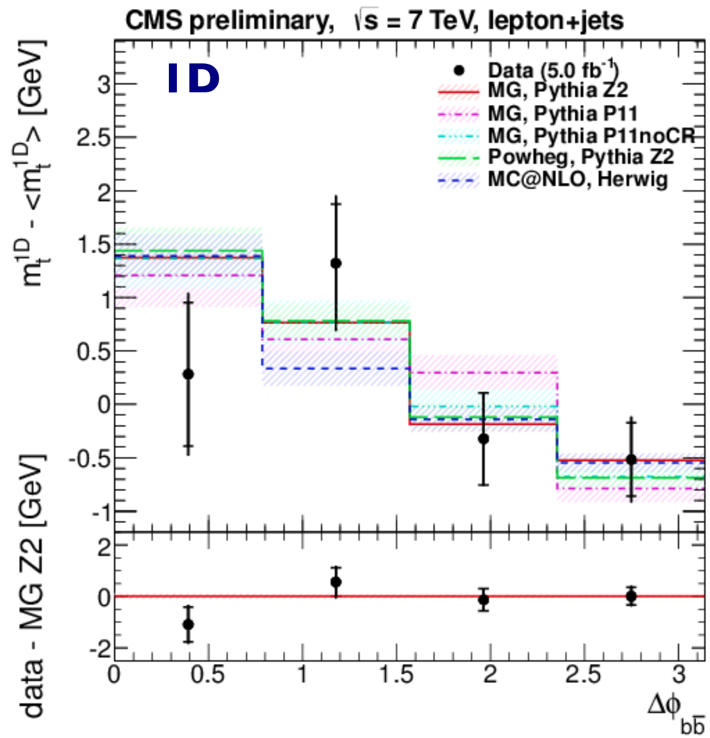

|η|b had
b-jet
jet
q
jet
b
W+
q̄
p
t
p
ν
W-
t̄
b̄
l-
b-jet

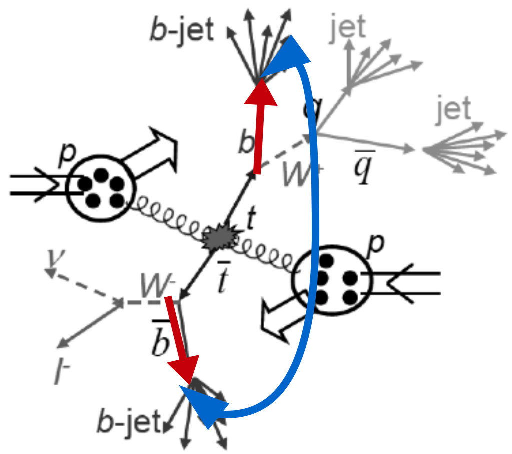

CMS preliminary, √s = 7 TeV, lepton+jets
2D (JES)
Data (5.0 fb⁻¹)
MG, Pythia Z2
MG, Pythia P11
MG, Pythia P11noCR
Powheg, Pythia Z2
MC@NLO, Herwig
JES - <JES>
data - MG Z2
|η_b,had|

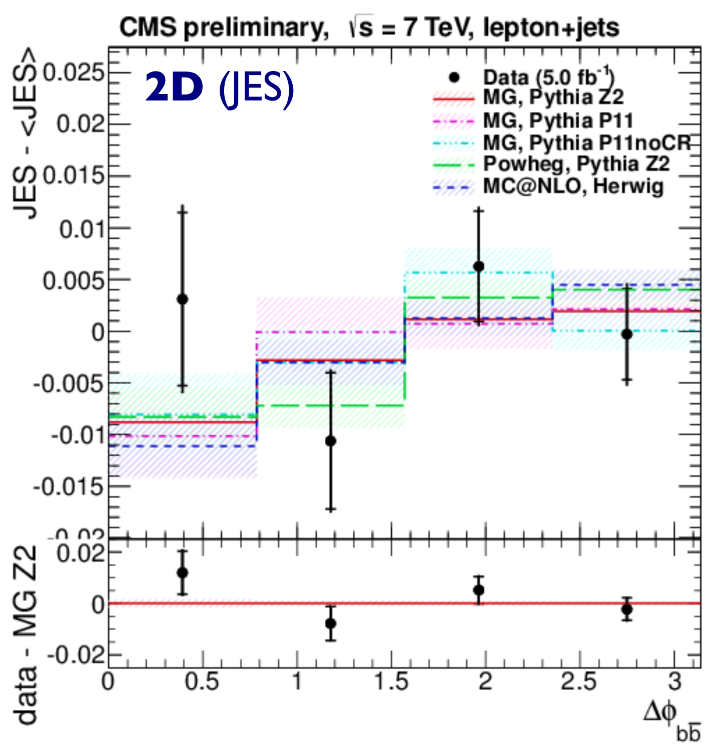

CMS preliminary, √s = 7 TeV, lepton+jets
2D
Data (5.0 fb⁻¹)
MG, Pythia Z2
MG, Pythia P11
MG, Pythia P11noCR
Powheg, Pythia Z2
MC@NLO, Herwig
m_t^2D - <m_t^2D> [GeV]
data - MG Z2 [GeV]
|η_b,had|

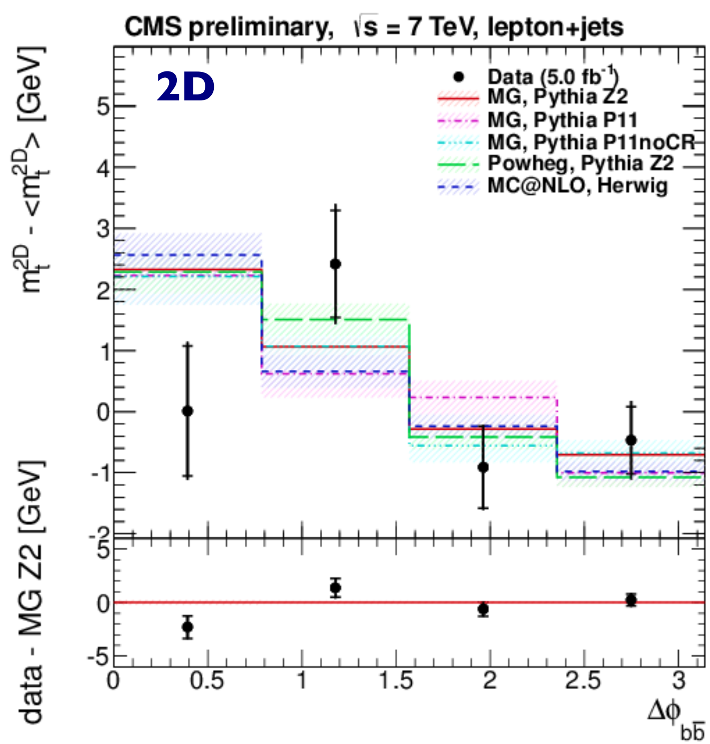
$\Delta\phi(b\bar{b})$











UE studies in ttbar events

- Data/MC ratio of the average p_T per charged particle
  - Compare ratio with two Perugia11 variations: with and without colour reconnection
  - Evolve comparison as function of the number of extra jets in the event