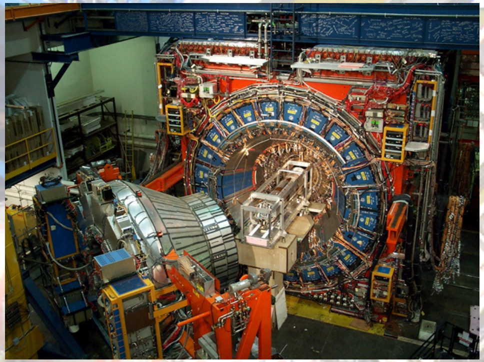
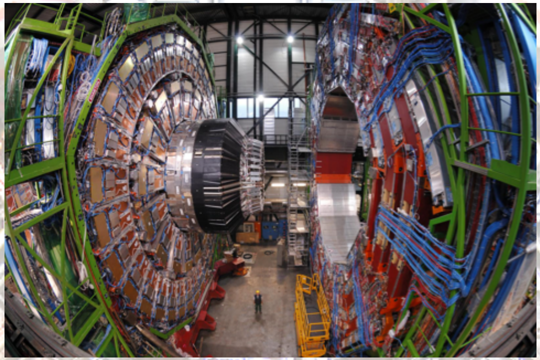
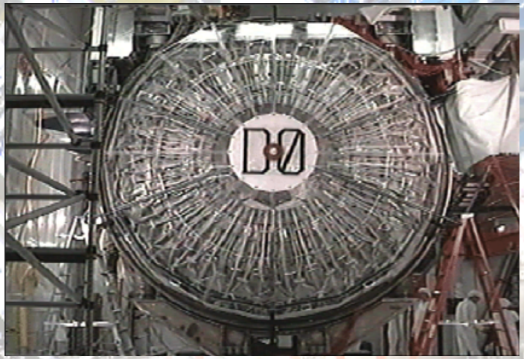






Top quark mass: breaking through the sound barrier of 0.5% precision

Oleg Brandt
University of Heidelberg
on behalf of
ATLAS, CDF, CMS, DØ

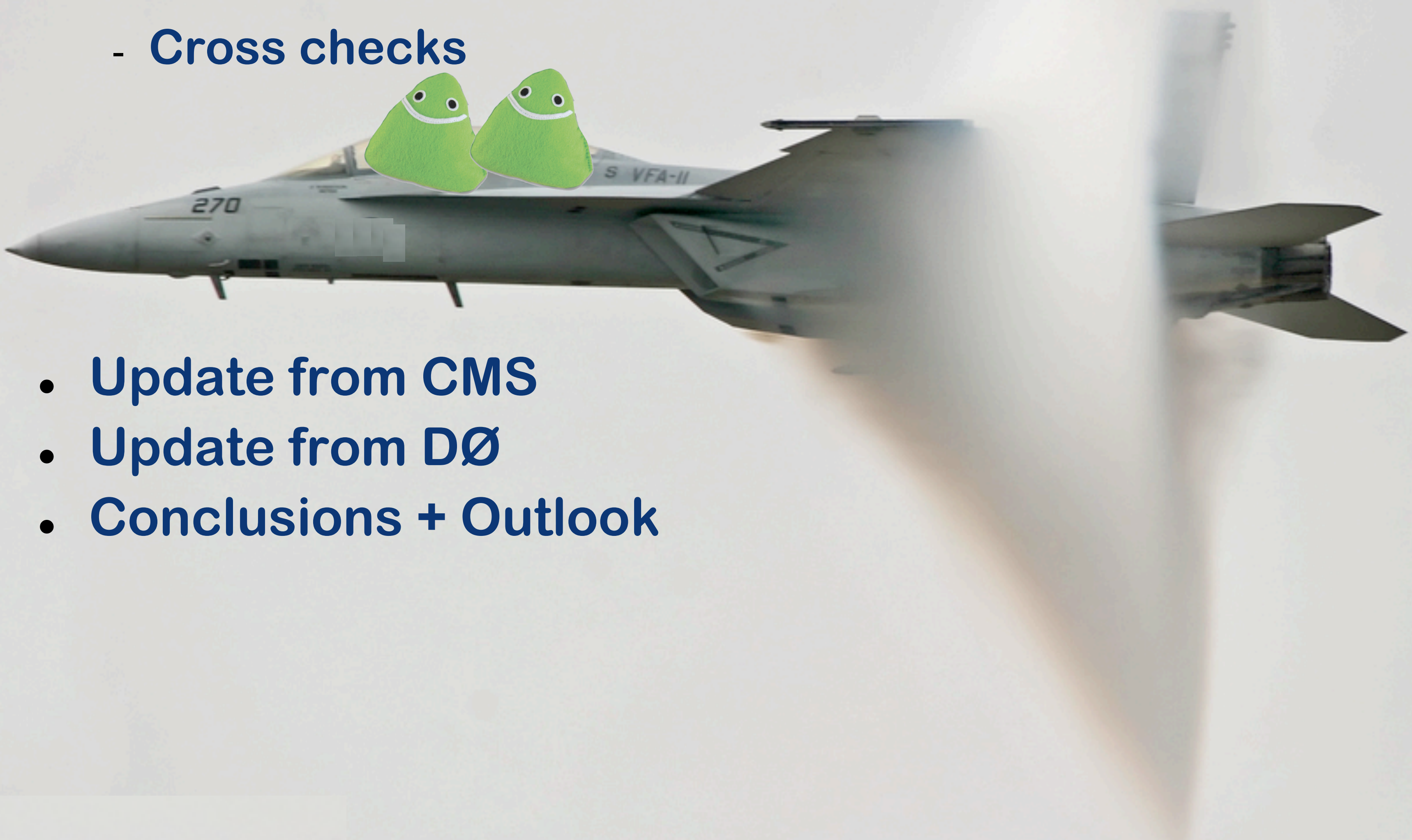
Bundesministerium für Bildung und Forschung

HGSFP

Top quark mass:

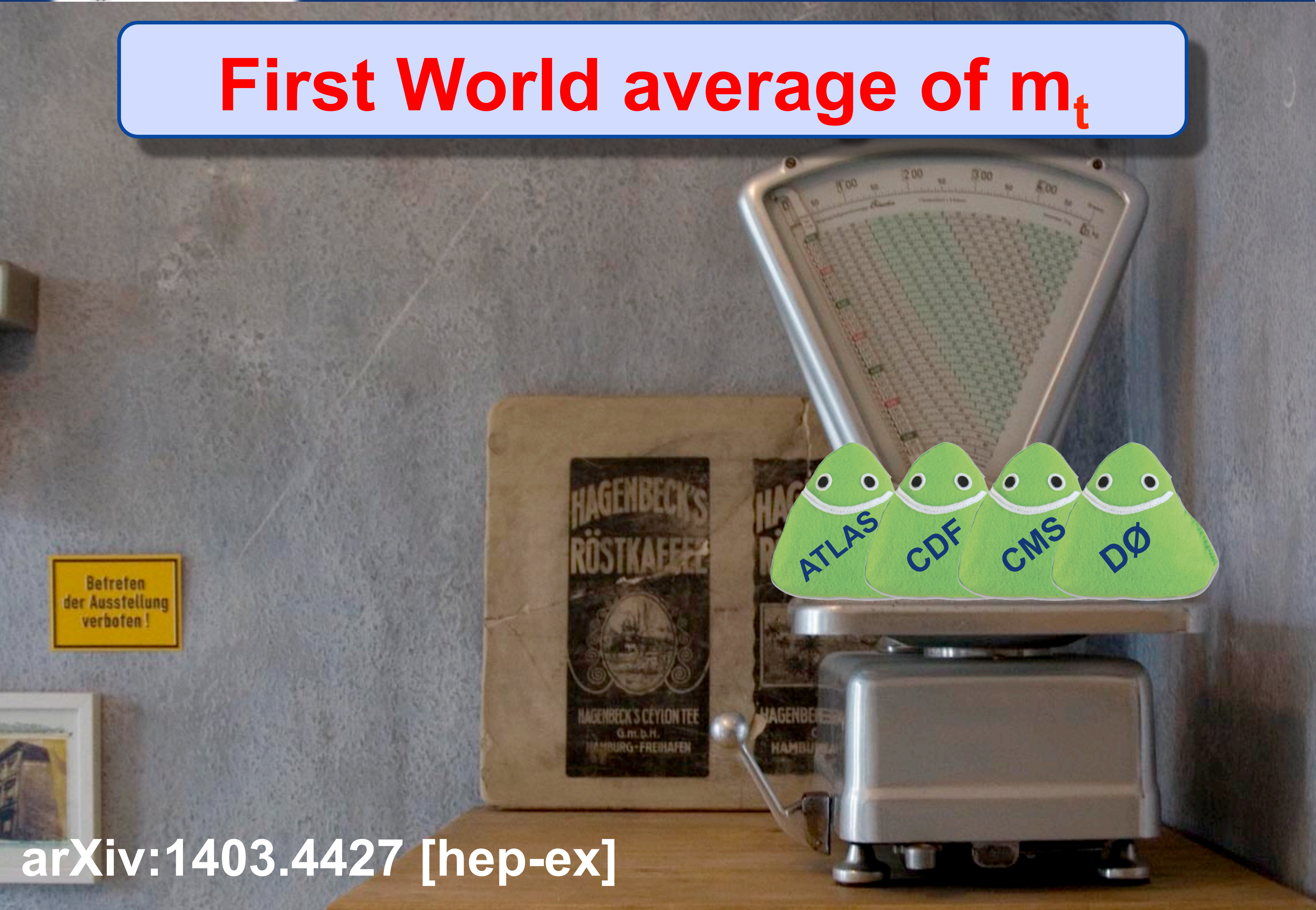
breaking through the sound barrier of 0.5% relative precision

- (Motivation)
- First World Average
  - Inputs + procedure
  - Combined result
  - Cross checks



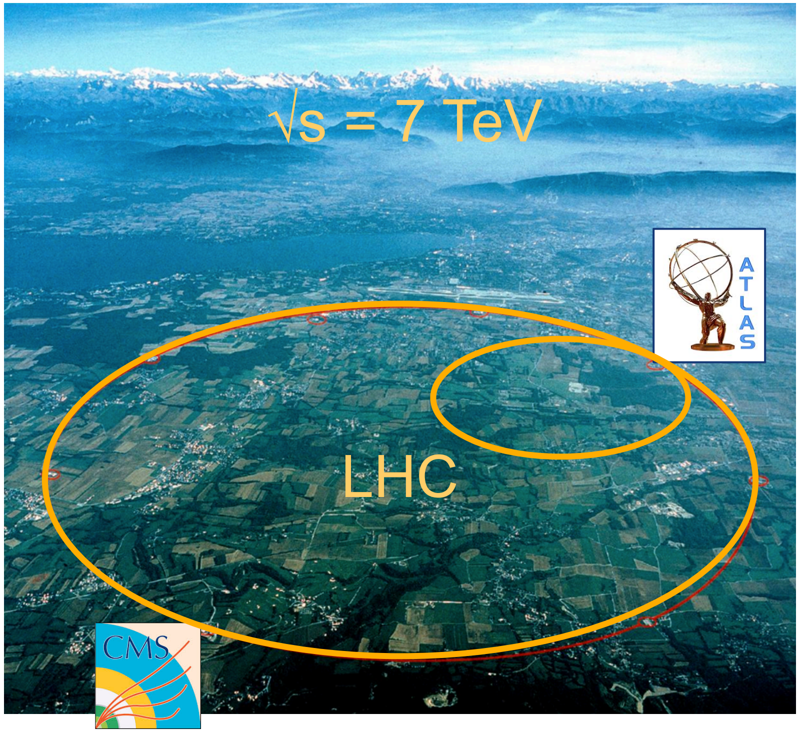
- Update from CMS
- Update from DØ
- Conclusions + Outlook

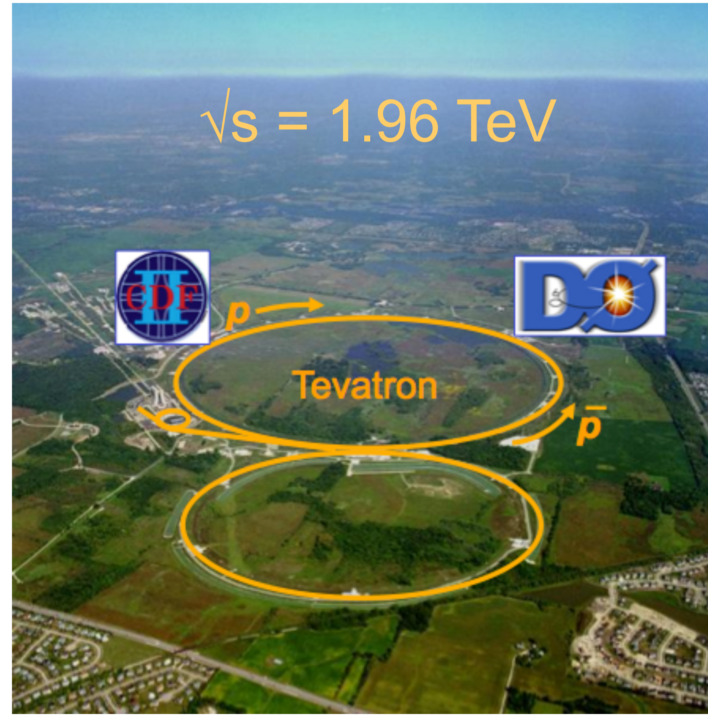
First World average of m_t



arXiv:1403.4427 [hep-ex]

World average: input measurements





arXiv:1403.4427 [hep-ex]

- **ATLAS:**
  - ATLAS-CONF-2013-046 [l+jets, 4.7 fb^{-1}]
  - ATLAS-CONF-2013-077 [dilepton, 4.7 fb^{-1}]
- **CMS**
  - JHEP 12 (2012) 105 [l+jets, 4.9 fb^{-1}]
  - EPJC 72 (2012) 2202 [dilepton, 4.9 fb^{-1}]
  - EPJC 74 (2014) 2758 [all-jets, 3.5 fb^{-1}]
- **CDF:**
  - PRL 109, 152003 (2012) [l+jets, 8.7 fb^{-1}]
  - PRD 83, 111101(R) (2011) [dilepton, 5.6 fb^{-1}]
  - PLB 714, 24 (2012) [all-jets, 5.8 fb^{-1}]
  - PRD 88, 011101 (2013) [$\not{E}_T$+jets, 8.7 fb^{-1}]
- **DØ:**
  - PRD 84, 032004 (2011) [l+jets, 3.6 fb^{-1}]
  - PRD 86, 051103 (2012) [dilepton 5.4 fb^{-1}]

World average: input measurements

Experiment	$t\bar{t}$ final state	$\mathcal{L}_{int}$ [fb^{-1}]	m_{top} ± (stat.) ± (syst.) [GeV]	Total uncertainty on m_{top} [GeV] ([%])	Reference
CDF	l+jets	8.7	172.85 ± 0.52 ± 0.99	1.12 (0.65)	[8]
	dilepton	5.6	170.28 ± 1.95 ± 3.13	3.69 (2.17)	[9]
	all jets	5.8	172.47 ± 1.43 ± 1.41	2.01 (1.16)	[10]
	E_T^{miss}+jets	8.7	173.93 ± 1.26 ± 1.36	1.85 (1.07)	[11]
D0	l+jets	3.6	174.94 ± 0.83 ± 1.25	1.50 (0.86)	[12]
	dilepton	5.3	174.00 ± 2.36 ± 1.49	2.79 (1.60)	[13]
ATLAS	l+jets	4.7	172.31 ± 0.23 ± 1.53	1.55 (0.90)	[14]
	dilepton	4.7	173.09 ± 0.64 ± 1.50	1.63 (0.94)	[15]
CMS	l+jets	4.9	173.49 ± 0.27 ± 1.03	1.06 (0.61)	[16]
	dilepton	4.9	172.50 ± 0.43 ± 1.46	1.52 (0.88)	[17]
	all jets	3.5	173.49 ± 0.69 ± 1.23	1.41 (0.81)	[18]

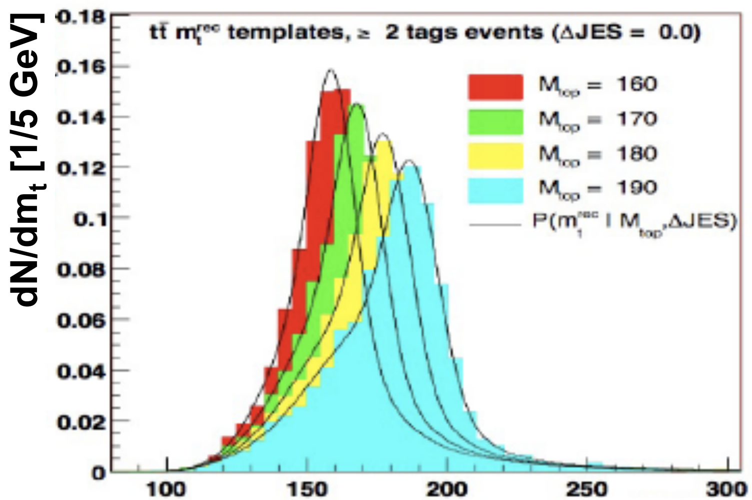
Disclaimer: above measurements are done with "traditional" techniques, which offer the highest precision → m_{top}^{MC} is measured; assume $m_{top}^{MC} = m_{top}^{pole}$

- **ATLAS:**
  - ATLAS-CONF-2013-046 [l+jets, 4.7 fb^{-1}]
  - ATLAS-CONF-2013-077 [dilepton, 4.7 fb^{-1}]
- **CMS**
  - JHEP 12 (2012) 105 [l+jets, 4.9 fb^{-1}]
  - EPJC 72 (2012) 2202 [dilepton, 4.9 fb^{-1}]
  - EPJC 74 (2014) 2758 [all-jets, 3.5 fb^{-1}]
- **CDF:**
  - PRL 109, 152003 (2012) [l+jets, 8.7 fb^{-1}]
  - PRD 83, 111101(R) (2011) [dilepton, 5.6 fb^{-1}]
  - PLB 714, 24 (2012) [all-jets, 5.8 fb^{-1}]
  - PRD 88, 011101 (2013) [$\not{E}_T$+jets, 8.7 fb^{-1}]
- **DØ:**
  - PRD 84, 032004 (2011) [l+jets, 3.6 fb^{-1}]
  - PRD 86, 051103 (2012) [dilepton 5.4 fb^{-1}]

"Traditional" measurement techniques

Template method:

- Exploit dependence of m_t on kinematic observables
  - Form templates using MC
  - Maximise consistence of templates with data given m_t



- Advantages:
  - Robust and straight-forward
- Drawback:
  - Sub-optimal sensitivity

Matrix element method:

- Directly calculate the event probability as:

$$P_{\mathrm{evt}}(m_{\mathrm{top}}) \propto f P_{\mathrm{sig}}(m_{\mathrm{top}}) + (1-f) P_{\mathrm{bgr}}$$

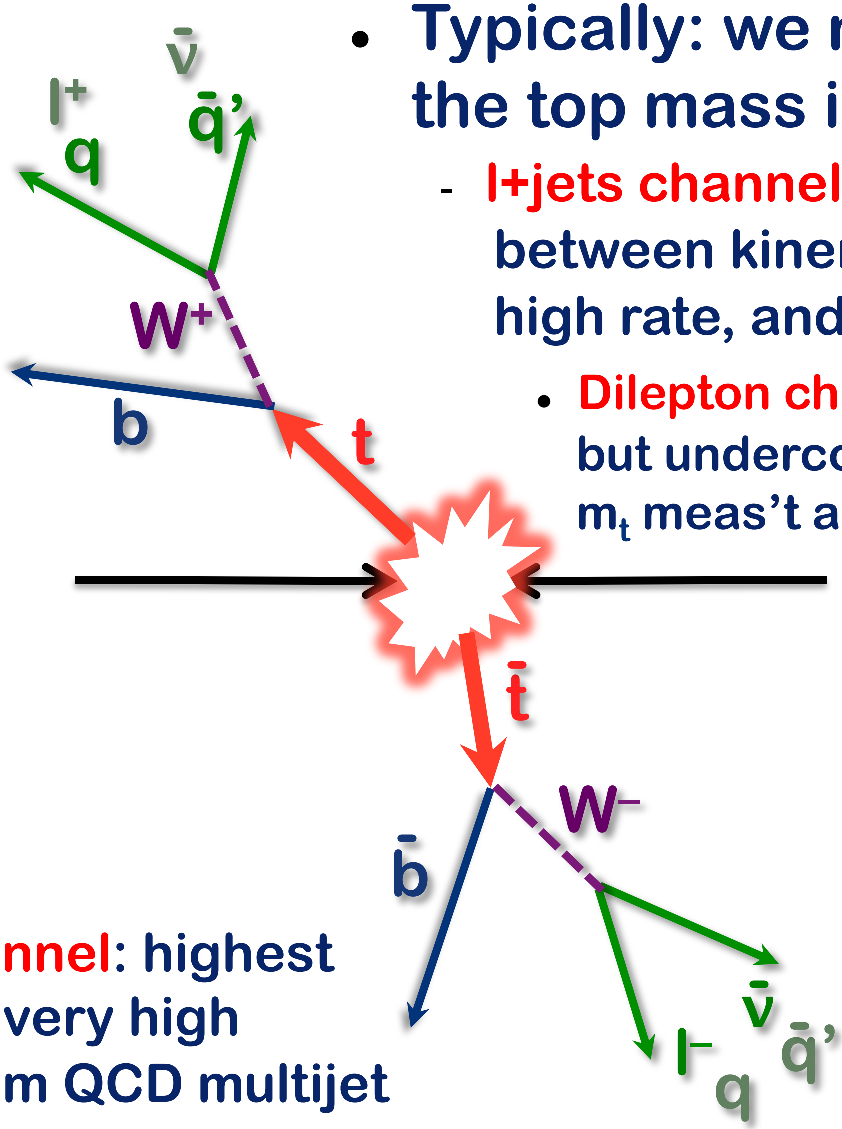
$$P_{\mathrm{sig}}(m_{\mathrm{top}}) \propto \int \ldots \mathrm{d}\sigma_{t\bar{t}}(m_{\mathrm{top}})$$

$$\mathrm{d}\sigma_{t\bar{t}} \propto |\mathcal{M}_{t\bar{t}}|^2 (m_{\mathrm{top}})$$

- Advantages:
  - Use full 4-vectors → maximal use of statistical information
  - Theory assumptions
- Drawback:
  - Computationally intensive
  - Theory assumptions

Definition of decay channels

- Typically: we measure the top mass in tt events:
  - **l+jets channel**: good compromise between kinematic reconstruction, high rate, and backgrounds
    - **Dilepton channel**: low backgrounds, but underconstrained kinematics for m_t meas't and low rate



- **All-hadronic channel**: highest branching ratio, very high backgrounds from QCD multijet production

Combination methodology

- The combination is performed using BLUE:
  - BLUE: Best Linear Unbiased Estimate
    - Obtain best unbiased estimate via linear combination of input measurements by minimising the total uncertainty on the combined result
  - Assume uncertainties are Gaussian
  - Use categories of uncertainties that are uncorrelated
  - For a given category of uncertainty:
    - take into account correlations between individual measurements

arXiv:1403.4427 [hep-ex]

Combination methodology

- The combination is performed using BLUE:
  - BLUE: Best Linear Unbiased Estimate
    - Obtain best unbiased estimate via linear combination of input measurements by minimising the total uncertainty on the combined result
  - Assume uncertainties are Gaussian
  - Use categories of uncertainties that are uncorrelated
  - For a given category of uncertainty:
    - take into account correlations between individual measurements

This is the tricky bit, discuss in the following + detailed cross-checks

arXiv:1403.4427 [hep-ex]

Categorisation of uncertainties

- **Jet energy scale (JES):**
- **Theory and signal modelling:**
  - Signal MC generator + associated PDF, hadronisation model, underlying event + colour reconnection
- **Detector modelling:**
  - Detector resolution effects, reconstruction efficiencies, b-quark jet identification (b-tagging), …
- **Background contamination**
- **Pile-up**

arXiv:1403.4427 [hep-ex]

Categorisation of uncertainties

- **Jet energy scale (JES):**
  - iJES → statistical component (cf. next page)
  - stdJES → response variations versus η and p_T
  - flavourJES → response variations versus jet flavour
  - bJES → response difference between b quark jets and light quark jets
- **Theory and signal modelling:**
  - Signal MC generator + associated PDF, hadronisation model, underlying event + colour reconnection
- **Detector modelling:**
  - Detector resolution effects, reconstruction efficiencies, b-quark jet identification (b-tagging), …
- **Background contamination**
- **Pile-up**

arXiv:1403.4427 [hep-ex]

Correlations between uncertainties

arXiv:1403.4427 [hep-ex]

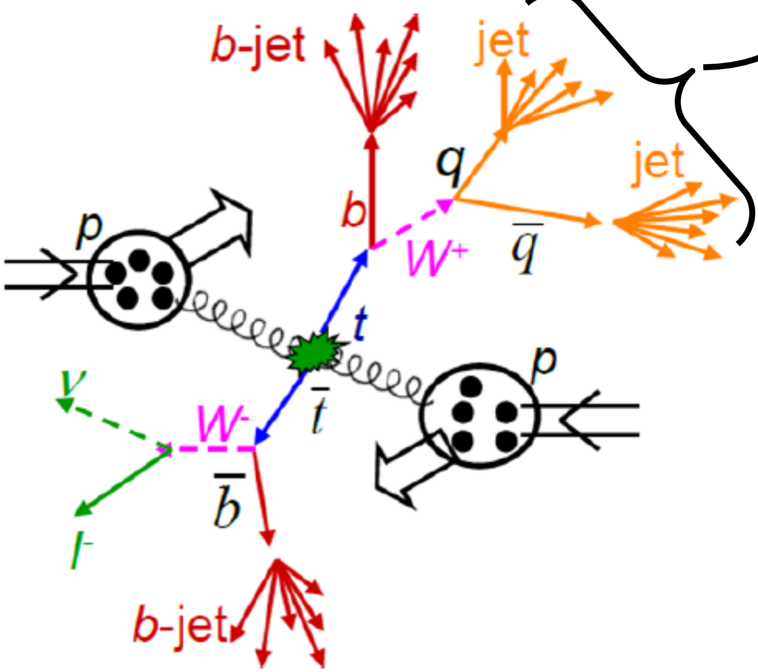
- **Input:** correlations between uncertainty categories:

	ρ_{EXP}				ρ_{LHC}	ρ_{TEV}	ρ_{COL}	
	ρ_{CDF}	ρ_{D0}	ρ_{ATL}	ρ_{CMS}			$\rho_{ATL-TEV}$	$\rho_{CMS-TEV}$
Stat	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
iJES	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
stdJES	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
flavourJES	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
bJES	1.0	1.0	1.0	1.0	0.5	1.0	1.0	0.5
MC	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Rad	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5
CR	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
PDF	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5
DetMod	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
b-tag	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
LepPt	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
BGMC†	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
BGData	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Meth	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MHI	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0

- ρ_{CDF}, ρ_{D0}, ρ_{ATL} ρ_{CMS} : correlations within an experiment
- ρ_{LHC}, ρ_{TEV} : correlations within the collider (LHC/Tevatron)
- $\rho_{ATL-TEV}$, $\rho_{CMS-TEV}$: correlations between ATLAS or CMS and Tevatron

Example: iJES category

- perform an in-situ calibration of the JSF:
  - Constrain energies of the two jets assumed to come from W to be consistent with M_W
  - This allows a simultaneous extraction of m_t and the overall JES factor JSF and constrains various physics effects, e.g. parton→hadron transition



M_W ~ JSF

Cartoon shown:
l+jets channel

arXiv:1403.4427 [hep-ex]

Correlations between uncertainties

- **Input: correlations between uncertainty categories:**

	ρ_{EXP}				ρ_{LHC}	ρ_{TEV}	ρ_{COL}	
	ρ_{CDF}	ρ_{D0}	ρ_{ATL}	ρ_{CMS}			$\rho_{\mathrm{ATL-TEV}}$	$\rho_{\mathrm{CMS-TEV}}$
Stat	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
iJES	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
stdJES	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
flavourJES	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
bJES	1.0	1.0	1.0	1.0	0.5	1.0	1.0	0.5
MC	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Rad	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5
CR	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
PDF	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5
DetMod	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
BGData	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Meth	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MHI	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0

Statistical iJES component fully uncorrelated
(exception: DØ transfers JSF constraint l+jets → dilepton)

- ρ_{CDF}, ρ_{D0}, ρ_{ATL} ρ_{CMS}: **correlations within an experiment**
- ρ_{LHC}, ρ_{TEV}: **correlations within the collider (LHC/Tevatron)**
- $\rho_{\mathrm{ATL-TEV}}$, $\rho_{\mathrm{CMS-TEV}}$: **correlations between ATLAS or CMS and Tevatron**

arXiv:1403.4427 [hep-ex]

Correlations between uncertainties

arXiv:1403.4427 [hep-ex]

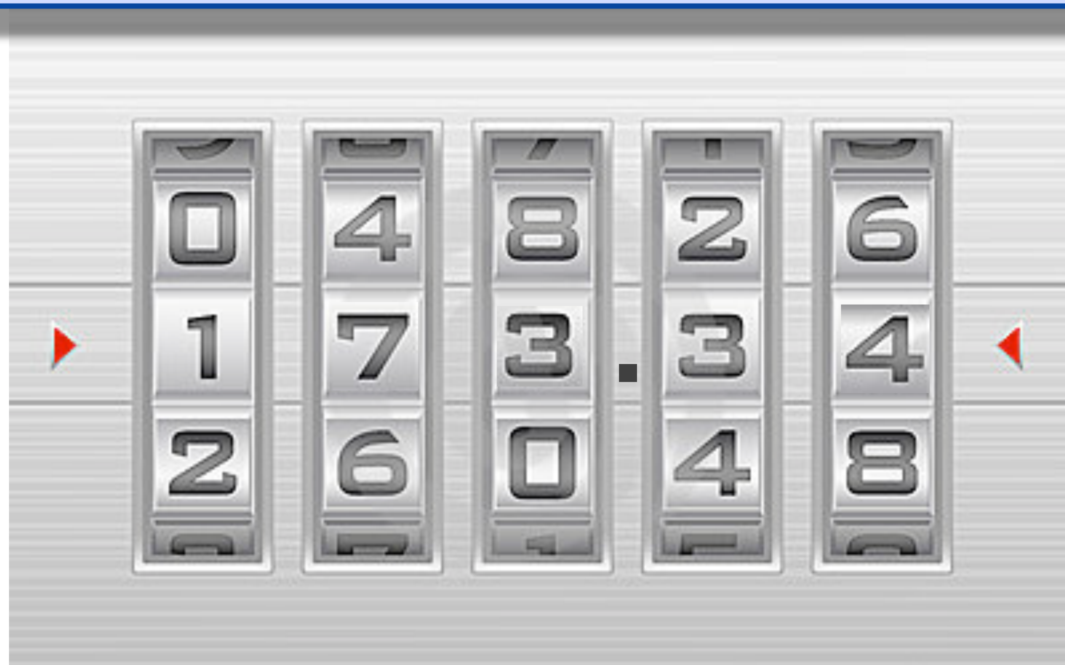
- **Input: correlations between uncertainty categories:**

	$\rho_{\rm EXP}$				$\rho_{\rm LHC}$	$\rho_{\rm TEV}$	$\rho_{\rm COL}$	
	$\rho_{\rm CDF}$	$\rho_{\rm D0}$	$\rho_{\rm ATL}$	$\rho_{\rm CMS}$			$\rho_{\rm ATL-TEV}$	$\rho_{\rm CMS-TEV}$
Stat	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
iJES	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
stdJES	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
flavourJES	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
bJES	1.0	1.0	1.0	1.0	0.5	1.0	1.0	0.5
MC	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Rad	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5
CR	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
PDF	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5
DetMod	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
MHI	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0

Even though different generators are used,
they use similar approaches → fully correlated
Exception: radiation category (qq vs gg initial state)

- $\rho_{\rm CDF}$, $\rho_{\rm D0}$, $\rho_{\rm ATL}$ $\rho_{\rm CMS}$: **correlations within an experiment**
- $\rho_{\rm LHC}$, $\rho_{\rm TEV}$: **correlations within the collider (LHC/Tevatron)**
- $\rho_{\rm ATL-TEV}$, $\rho_{\rm CMS-TEV}$: **correlations between ATLAS or CMS and Tevatron**

Combined result



Combined result

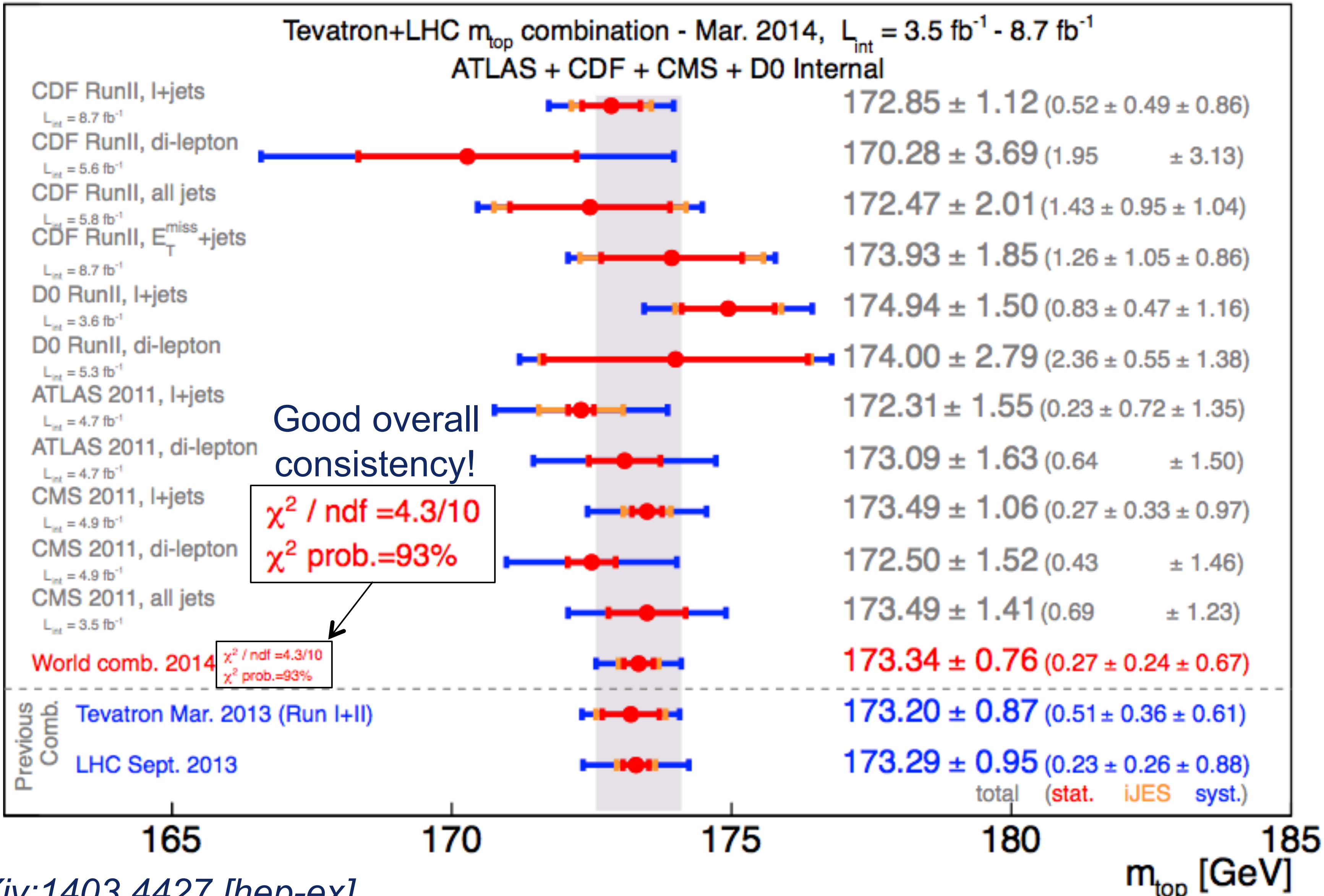
	Input measurements and uncertainties in GeV											
	CDF				D0		ATLAS		CMS			World
Uncertainty	l+jets	di-l	all jets	E_T^{miss}	l+jets	di-l	l+jets	di-l	l+jets	di-l	all jets	Combination
m_{top}	172.85	170.28	172.47	173.93	174.94	174.00	172.31	173.09	173.49	172.50	173.49	173.34
Stat	0.52	1.95	1.43	1.26	0.83	2.36	0.23	0.64	0.27	0.43	0.69	0.27
iJES	0.49	n.a.	0.95	1.05	0.47	0.55	0.72	n.a.	0.33	n.a.	n.a.	0.24
stdJES	0.53	2.99	0.45	0.44	0.63	0.56	0.70	0.89	0.24	0.78	0.78	0.20
flavourJES	0.09	0.14	0.03	0.10	0.26	0.40	0.36	0.02	0.11	0.58	0.58	0.12
bJES	0.16	0.33	0.15	0.17	0.07	0.20	0.08	0.71	0.61	0.76	0.49	0.25
MC	0.56	0.36	0.49	0.48	0.63	0.50	0.35	0.64	0.15	0.06	0.28	0.38
Rad	0.06	0.22	0.10	0.28	0.26	0.30	0.45	0.37	0.30	0.58	0.33	0.21
CR	0.21	0.51	0.32	0.28	0.28	0.55	0.32	0.29	0.54	0.13	0.15	0.31
PDF	0.08	0.31	0.19	0.16	0.21	0.30	0.17	0.12	0.07	0.09	0.06	0.09
DetMod	< 0.01	<0.01	<0.01	<0.01	0.36	0.50	0.23	0.22	0.24	0.18	0.28	0.10
b-tag	0.03	n.e.	0.10	n.e.	0.10	<0.01	0.81	0.46	0.12	0.09	0.06	0.11
LepPt	0.03	0.27	n.a.	n.a.	0.18	0.35	0.04	0.12	0.02	0.14	n.a.	0.02
BGMC	0.12	0.24	n.a.	n.a.	0.18	n.a.	n.a.	0.14	0.13	0.05	n.a.	0.10
BGData	0.16	0.14	0.56	0.15	0.21	0.20	0.10	n.a.	n.a.	n.a.	0.13	0.07
Meth	0.05	0.12	0.38	0.21	0.16	0.51	0.13	0.07	0.06	0.40	0.13	0.05
MHI	0.07	0.23	0.08	0.18	0.05	<0.01	0.03	0.01	0.07	0.11	0.06	0.04
Total Syst	0.99	3.13	1.41	1.36	1.25	1.49	1.53	1.50	1.03	1.46	1.23	0.71
Total	1.12	3.69	2.01	1.85	1.50	2.79	1.55	1.63	1.06	1.52	1.41	0.76

$$m_{top} = 173.34 \pm 0.27\ (\text{stat}) \pm 0.71\ (\text{syst})\ \ \text{GeV}.$$

0.44% relative precision achieved!

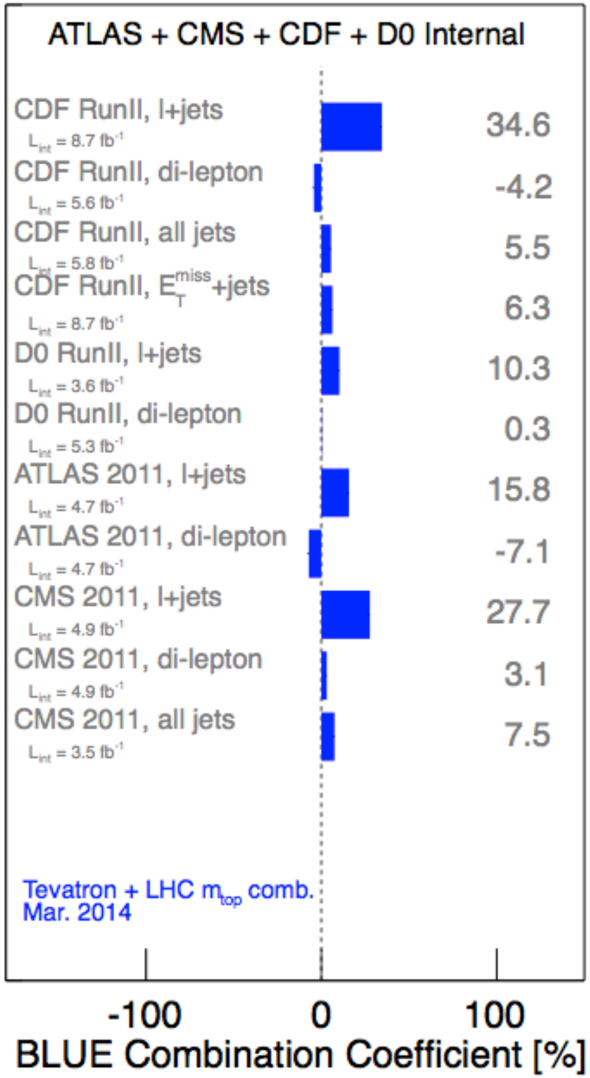
arXiv:1403.4427 [hep-ex]

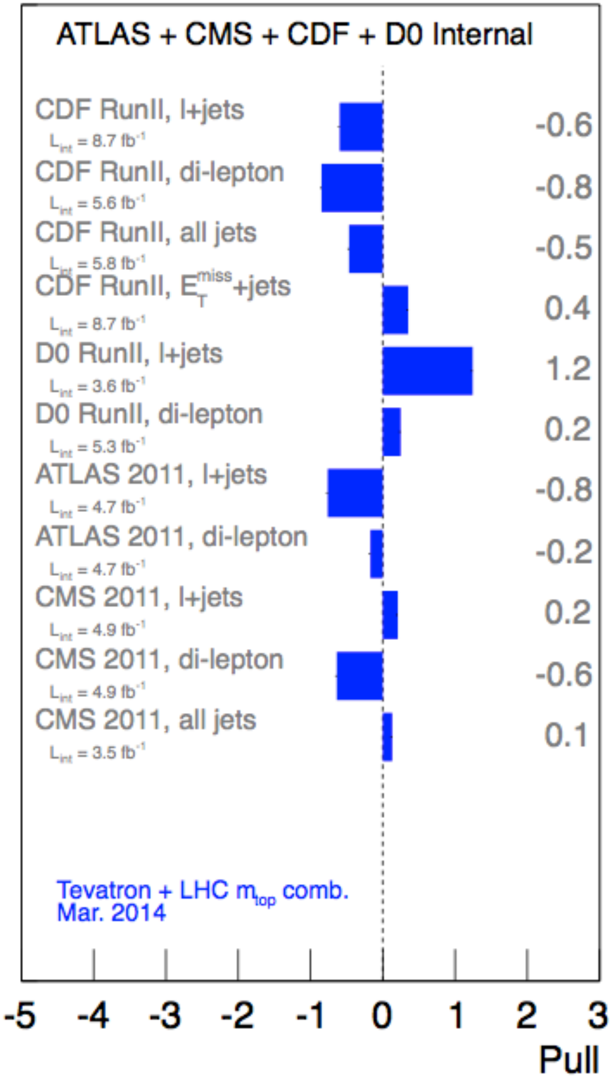
Combined result



arXiv:1403.4427 [hep-ex]

Combined result

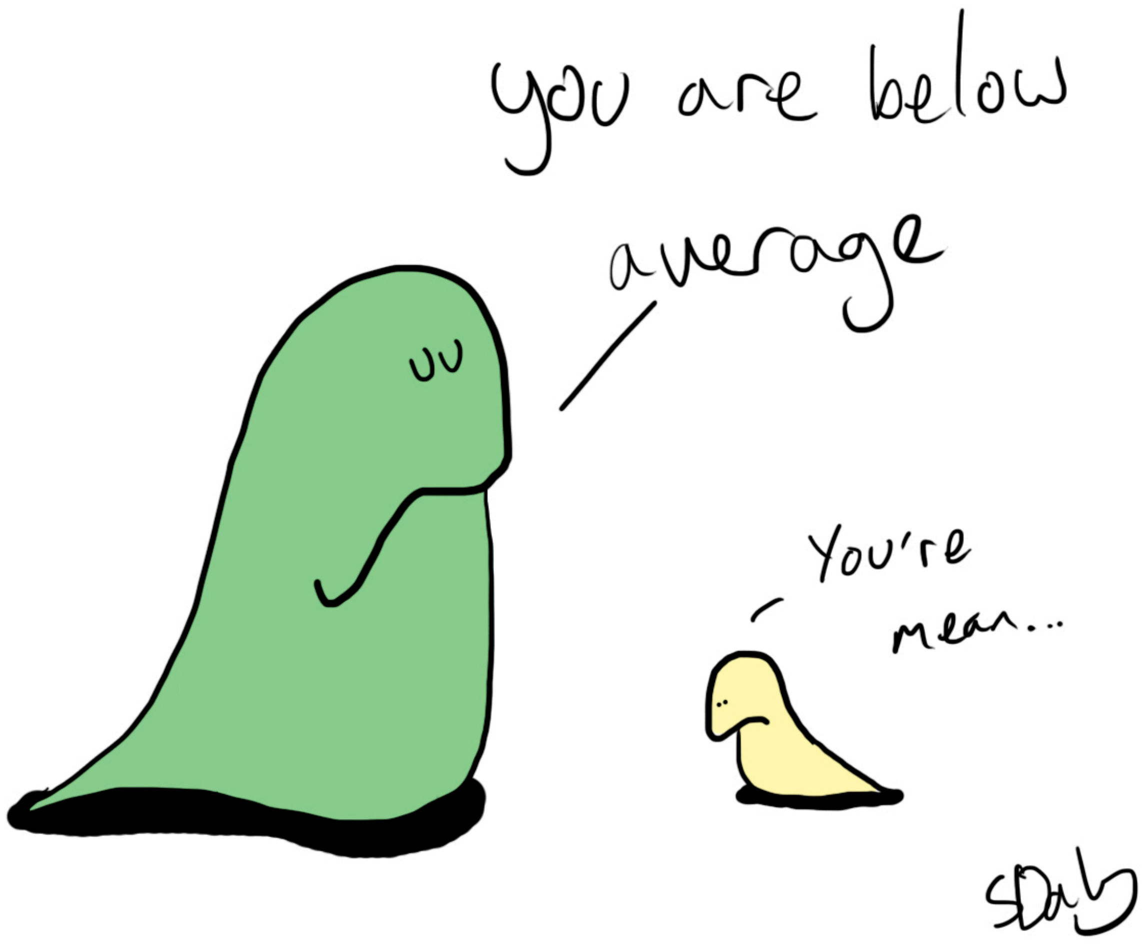




arXiv:1403.4427 [hep-ex]

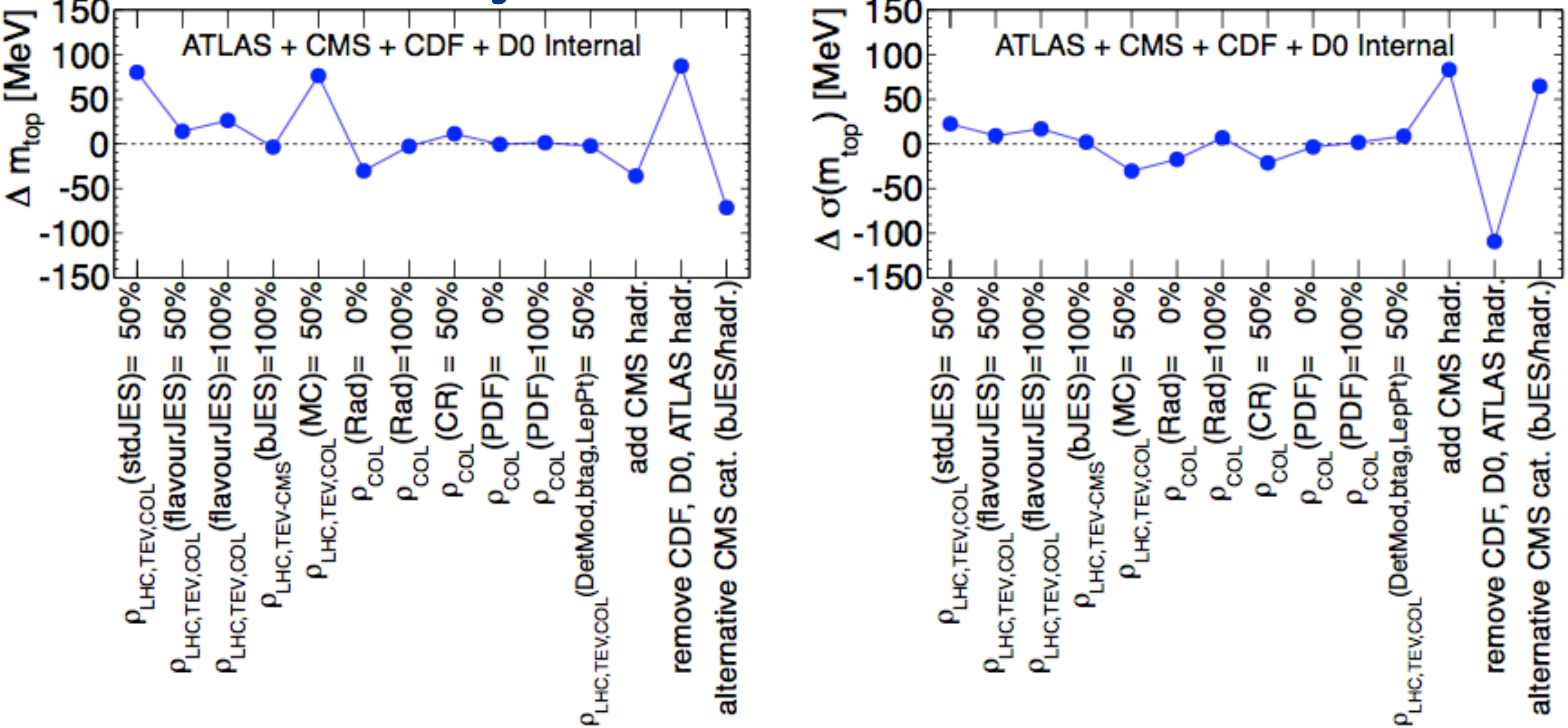
$$\text{pull}_i = (m_i - m_{\text{top}}) / \sqrt{\sigma_i^2 - \sigma_{m_{\text{top}}}^2}$$

Cross-checks



Cross-checks

- Can cover only **variation of assumed correlations** here:



- Result **stable** at the level of about **100 MeV**
- **Largest** effect from the **stdJES** uncertainty and the modelling of the **hadronisation** uncertainty

Differences between experiments

- We came a long way in the harmonisation of the treatment of systematic uncertainties
- However, we are not quite there yet
  - Typical example: uncertainty from hadronisation

	stdJES & bJES derivation	tt events
ATLAS	Herwig++ vs Pythia	Powheg+fHerwig vs Powheg+Pythia
CDF	fHerwig vs Pythia (stdJES only)	fHerwig vs Pythia
CMS	Herwig++ vs Pythia	evaluated but not included
DØ	All JES done consistently with one tune	Alpgen+fHerwig vs Alpgen+Pythia

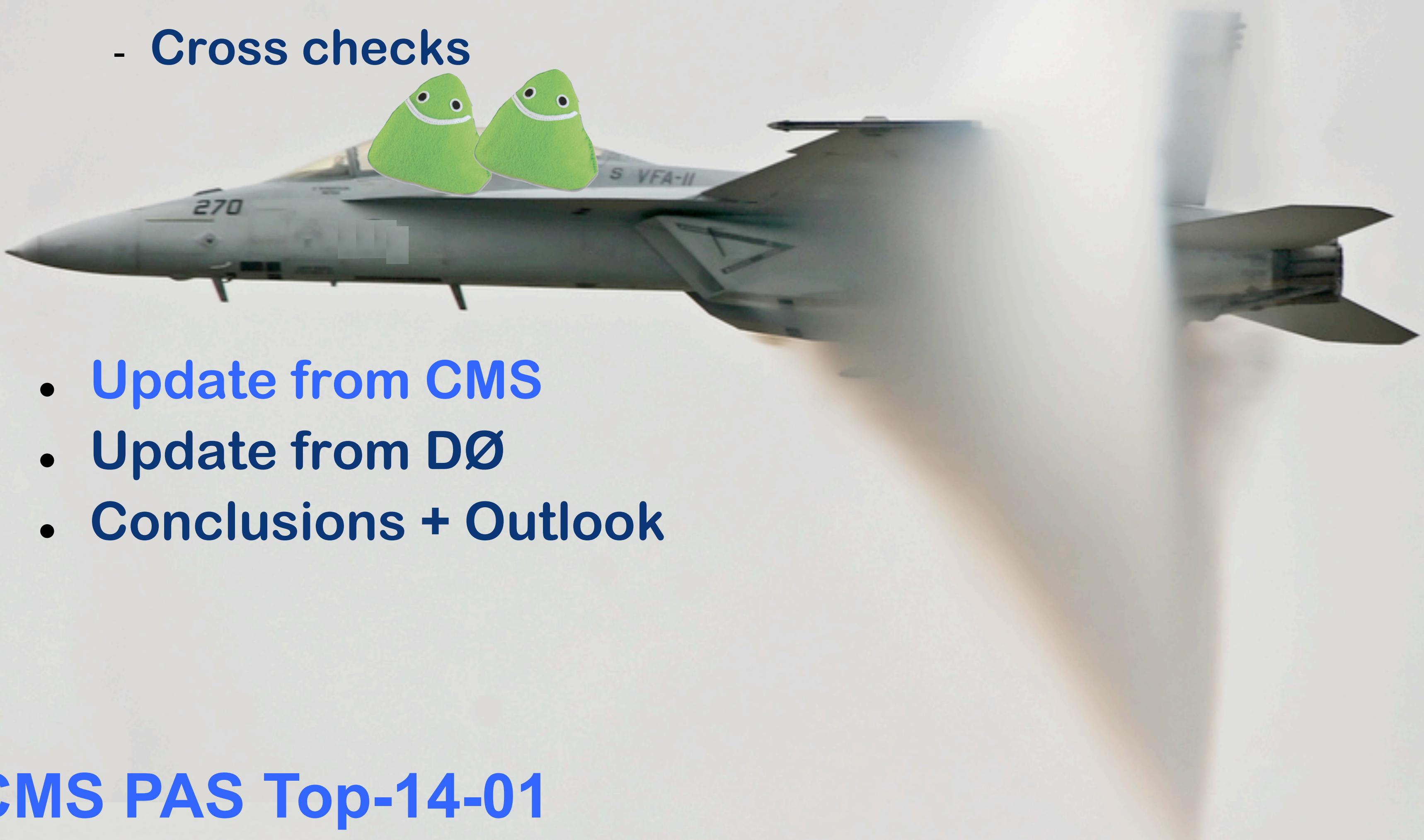
  - Similarly: JES uncertainty and its sub-categories
    - i.e. for stdJES, ATLAS considers 19 orthogonal sub-categories, CMS considers 4…

fHerwig: *Fortran Herwig*

Top quark mass:

breaking through the sound barrier of 0.5% relative precision

- (Motivation)
- First World Average
  - Inputs + procedure
  - Combined result
  - Cross checks



- Update from CMS
- Update from DØ
- Conclusions + Outlook

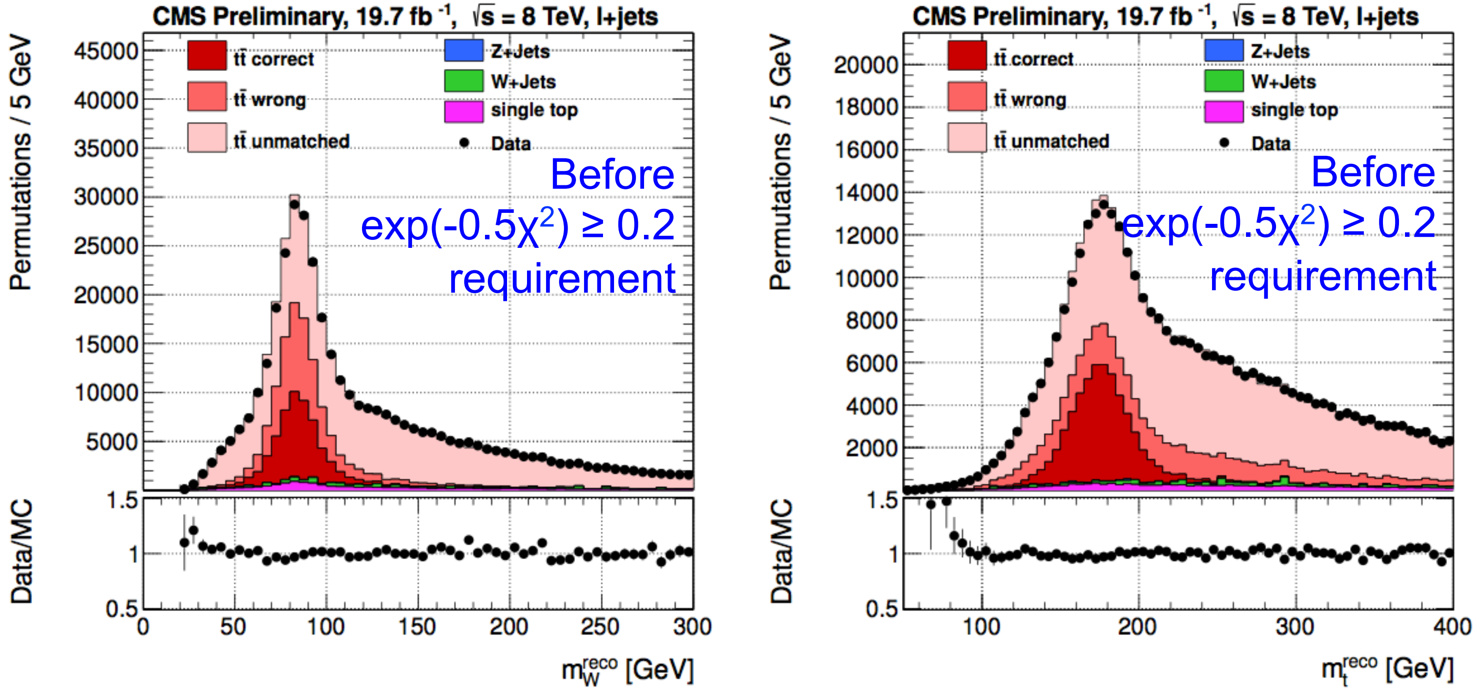
CMS PAS Top-14-01

Selection overview

- Use full 19.7 fb^{-1} of integrated luminosity & require
  - Exactly one isolated electron or muon
    - with p_T > 33 GeV, |η| < 2.1
  - ≥4 jets with cone parameter R=0.5 (particle flow)
    - With p_T > 30 GeV, |η| > 2.4
  - Exactly two b-tags
    - Reduce number of possible jet-to-parton assignments
  - tt signal purity: 95%

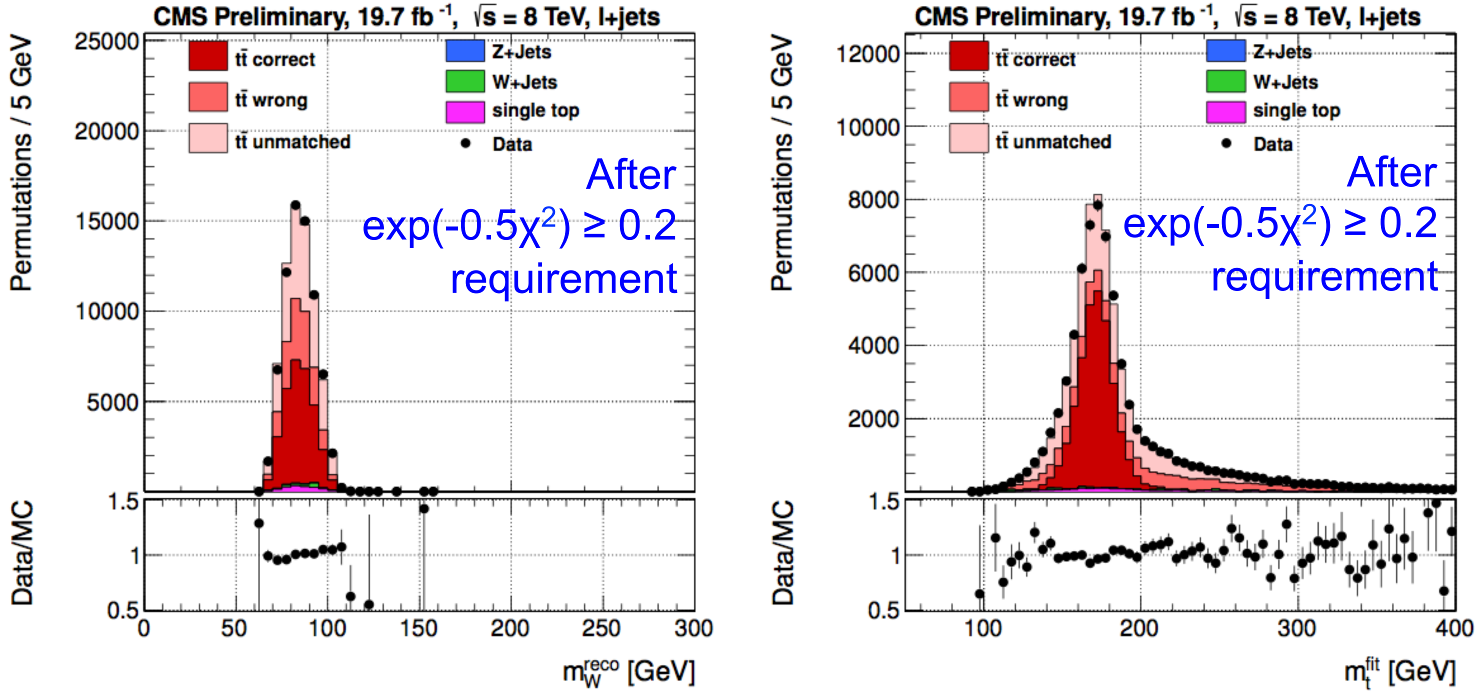
Kinematic reconstruction

- Kinematic reconstruction with a χ^2-based fitter
  - Consider only jet-parton assignments where two b-tagged jets are matched to b quarks (4)
  - Increase contribution of correct jet-parton assignments:
    - Require $\exp(-0.5\chi^2) \geq 0.2$
    - $\mathcal{L}\left(\text{sample}|m_t, \text{JSF}\right) = \prod_{\text{events}} \left(\sum_{i=1}^{n} P_{\text{gof}}(i) \left(\sum_j f_j P_j(m_{t,i}^{\text{fit}}|m_t, \text{JSF}) \times P_j(m_{W,i}^{\text{reco}}|m_t, \text{JSF}) \right) \right)^{w_{\text{event}}}$

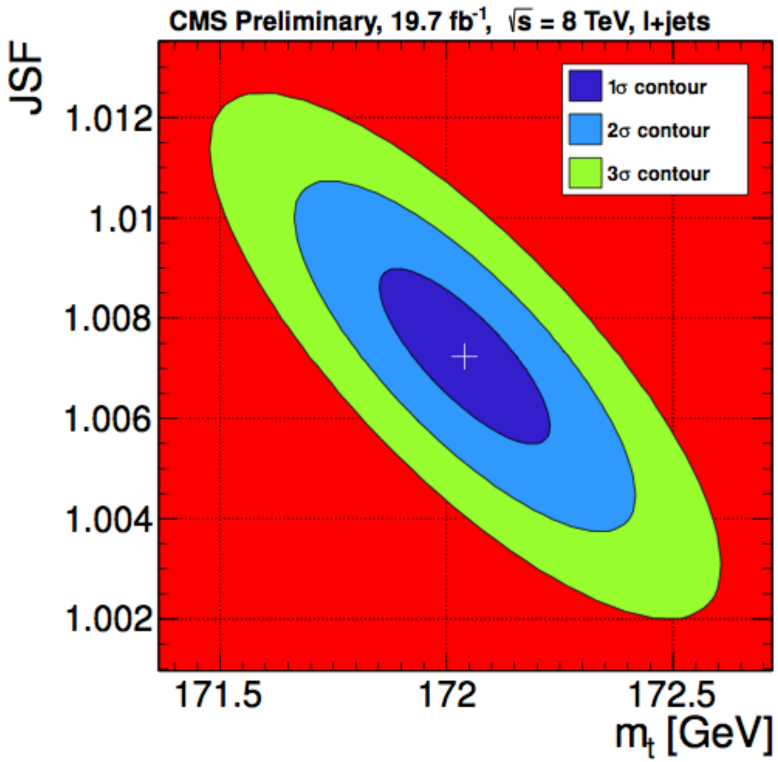


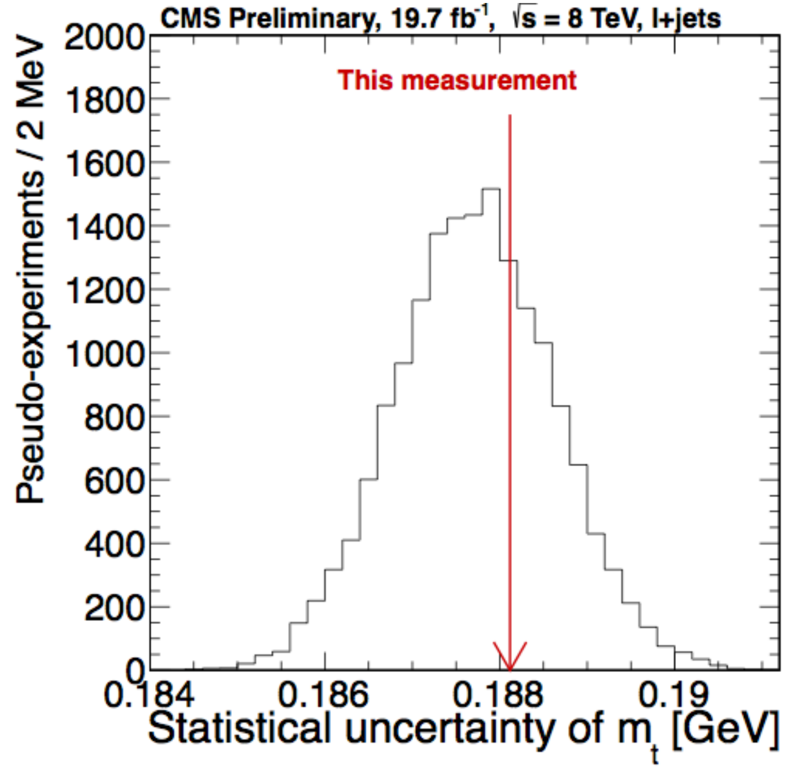
Kinematic reconstruction

- Kinematic reconstruction with a χ^2-based fitter
  - Consider only jet-parton assignments where two b-tagged jets are matched to b quarks (4)
  - Increase contribution of correct jet-parton assignments:
    - Require $\exp(-0.5\chi^2) \geq 0.2$
    - $\mathcal{L}(\text{sample}|m_t, \text{JSF}) = \prod_{\text{events}} \left(\sum_{i=1}^{n} P_{\text{gof}}(i) \left(\sum_j f_j P_j(m_{t,i}^{\text{fit}}|m_t, \text{JSF}) \times P_j(m_{W,i}^{\text{reco}}|m_t, \text{JSF}) \right) \right)^{w_{\text{event}}}$



- **New CMS result in l+jets final states using 19.7 fb^{-1} of data (statistical uncertainty only):**





$$m_t = 172.04 \pm 0.19\,(\text{stat.+JSF})\ \text{GeV}$$

CMS PAS TOP 14-1-001

Systematic uncertainties

	This measurement		7 TeV measurement [1]
	δm_t^{2D} (GeV)	δJSF	δm_t^{2D} (GeV)
Experimental uncertainties			
Fit calibration	0.10	0.001	0.06
p_T- and η-dependent JES	0.18	0.007	0.28
Lepton energy scale	0.03	<0.001	0.02
MET	0.09	0.001	0.06
Jet energy resolution	0.26	0.004	0.23
b tagging	0.02	<0.001	0.12
Pileup	0.27	0.005	0.07
Non-$t\bar{t}$ background	0.11	0.001	0.13
Modeling of hadronization			
Flavor-dependent JSF	0.41	0.004	0.61
b fragmentation	0.06	0.001	n/e
Semi-leptonic B hadron decays	0.16	<0.001	n/e
Modeling of the hard scattering process			
PDF	0.09	0.001	0.07
Renormalization and factorization scales	0.12±0.13	0.004±0.001	0.24
ME-PS matching threshold	0.15±0.13	0.003±0.001	0.18
ME generator	0.23±0.14	0.003±0.001	n/e
Modeling of non-perturbative QCD			
Underlying event	0.14±0.17	0.002±0.002	0.15
Color reconnection modeling	0.08±0.15	0.002±0.001	0.54
Total	0.75	0.012	0.98

n/e: not explicitly evaluated in paper, but evaluated later and included in World average

[1] JHEP 12 (2012) 105

Refinement: match categories of World combo

	This measurement		7 TeV measurement [1]
	δm_t^{2D} (GeV)	δJSF	δm_t^{2D} (GeV)
Experimental uncertainties			
Fit calibration	0.10	0.001	0.06
p_T- and η-dependent JES	0.18	0.007	0.28
Lepton energy scale	0.03	<0.001	0.02
MET	0.09	0.001	0.06
Jet energy resolution	0.26	0.004	0.23
b tagging	0.02	<0.001	0.12
Pileup	0.27	0.005	0.07
Non-$t\bar{t}$ background	0.11	0.001	0.13
Modeling of hadronization			
Flavor-dependent JSF	0.41	0.004	0.61
b fragmentation	0.06	0.001	n/e
Semi-leptonic B hadron decays	0.16	<0.001	n/e
Modeling of the hard scattering process			
PDF	0.09	0.001	0.07
Renormalization and factorization scales	0.12±0.13	0.004±0.001	0.24
ME-PS matching threshold	0.15±0.13	0.003±0.001	0.18
ME generator	0.23±0.14	0.003±0.001	n/e
Modeling of non-perturbative QCD			
Underlying event	0.14±0.17	0.002±0.002	0.15
Color reconnection modeling	0.08±0.15	0.002±0.001	0.54
Total	0.75	0.012	0.98

n/e: not explicitly evaluated in paper, but evaluated later and included in World average

[1] JHEP 12 (2012) 105

Refinement from increased MC samples

	This measurement δm_t^{2D} (GeV)	This measurement δJSF	7 TeV measurement [1] δm_t^{2D} (GeV)
Experimental uncertainties			
Fit calibration	0.10	0.001	0.06
p_T- and η-dependent JES	0.18	0.007	0.28
Lepton energy scale	0.03	<0.001	0.02
MET	0.09	0.001	0.06
Jet energy resolution	0.26	0.004	0.23
b tagging	0.02	<0.001	0.12
Pileup	0.27	0.005	0.07
Non-$t\bar{t}$ background	0.11	0.001	0.13
Modeling of hadronization			
Flavor-dependent JSF	0.41	0.004	0.61
b fragmentation	0.06	0.001	n/e
Semi-leptonic B hadron decays	0.16	<0.001	n/e
Modeling of the hard scattering process			
PDF	0.09	0.001	0.07
Renormalization and factorization scales	0.12±0.13	0.004±0.001	0.24
ME-PS matching threshold	0.15±0.13	0.003±0.001	0.18
ME generator	0.23±0.14	0.003±0.001	n/e
Modeling of non-perturbative QCD			
Underlying event	0.14±0.17	0.002±0.002	0.15
Color reconnection modeling	0.08±0.15	0.002±0.001	0.54
Total	0.75	0.012	0.98

n/e: not explicitly evaluated in paper, but evaluated later and included in World average

[1] JHEP 12 (2012) 105

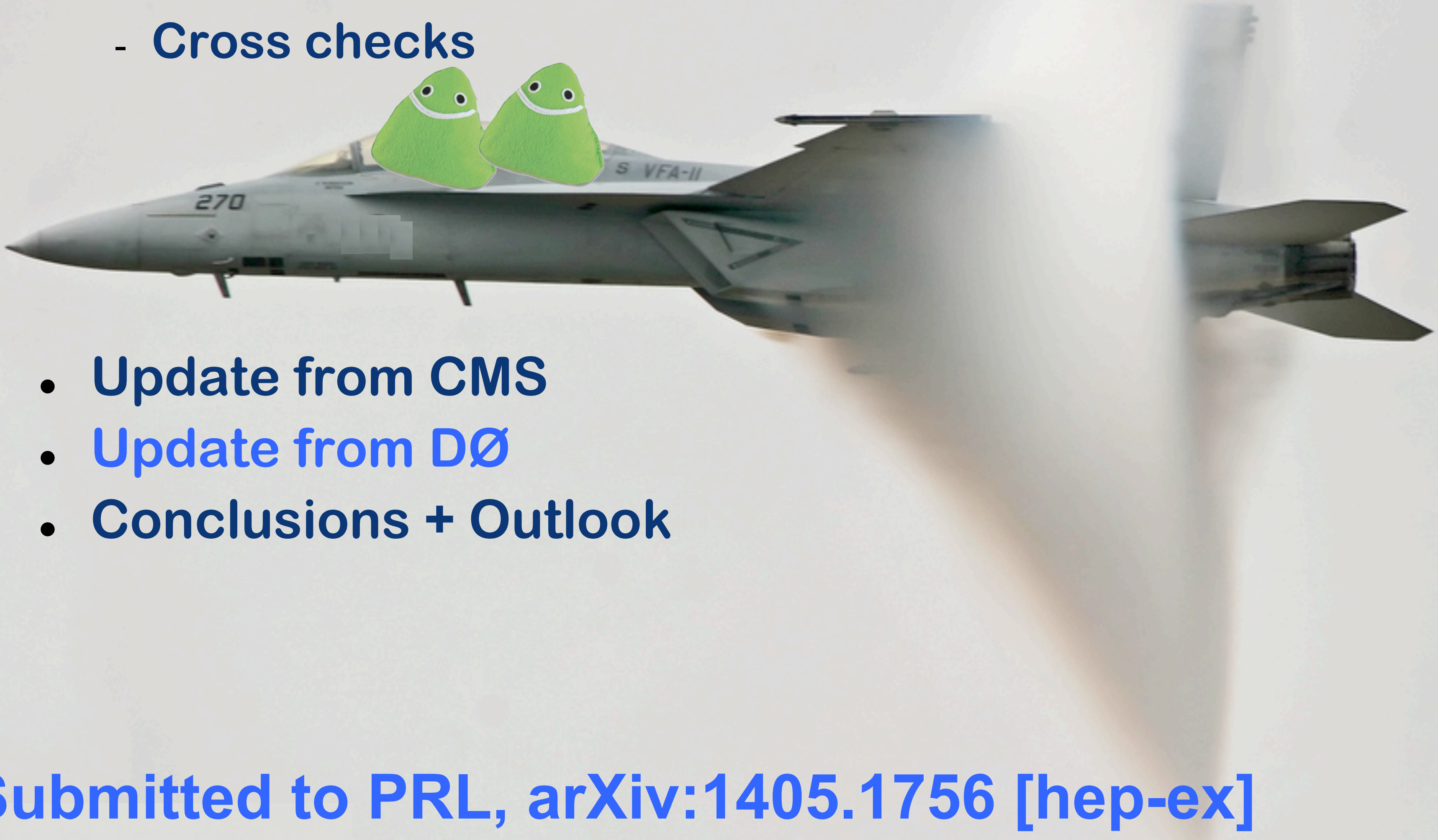
Refinement from more detailed evaluation

- Uncertainty from JES for b quark jets:
  - Now state response difference between pythia and herwig separately for each of the categories:
    - u,d,c,s quark jets
    - Gluon jets
    - b quark jets
    - Quadratically add effects propagated to mt
  - For 7 TeV measurement:
    - Consider inclusive response difference between pythia and herwig for Z+jets events
    - Apply above (same) response difference separately to
      - b quark jets and
      - all jets

Top quark mass:

breaking through the sound barrier of 0.5% relative precision

- (Motivation)
- First World Average
  - Inputs + procedure
  - Combined result
  - Cross checks



- Update from CMS
- Update from DØ
- Conclusions + Outlook

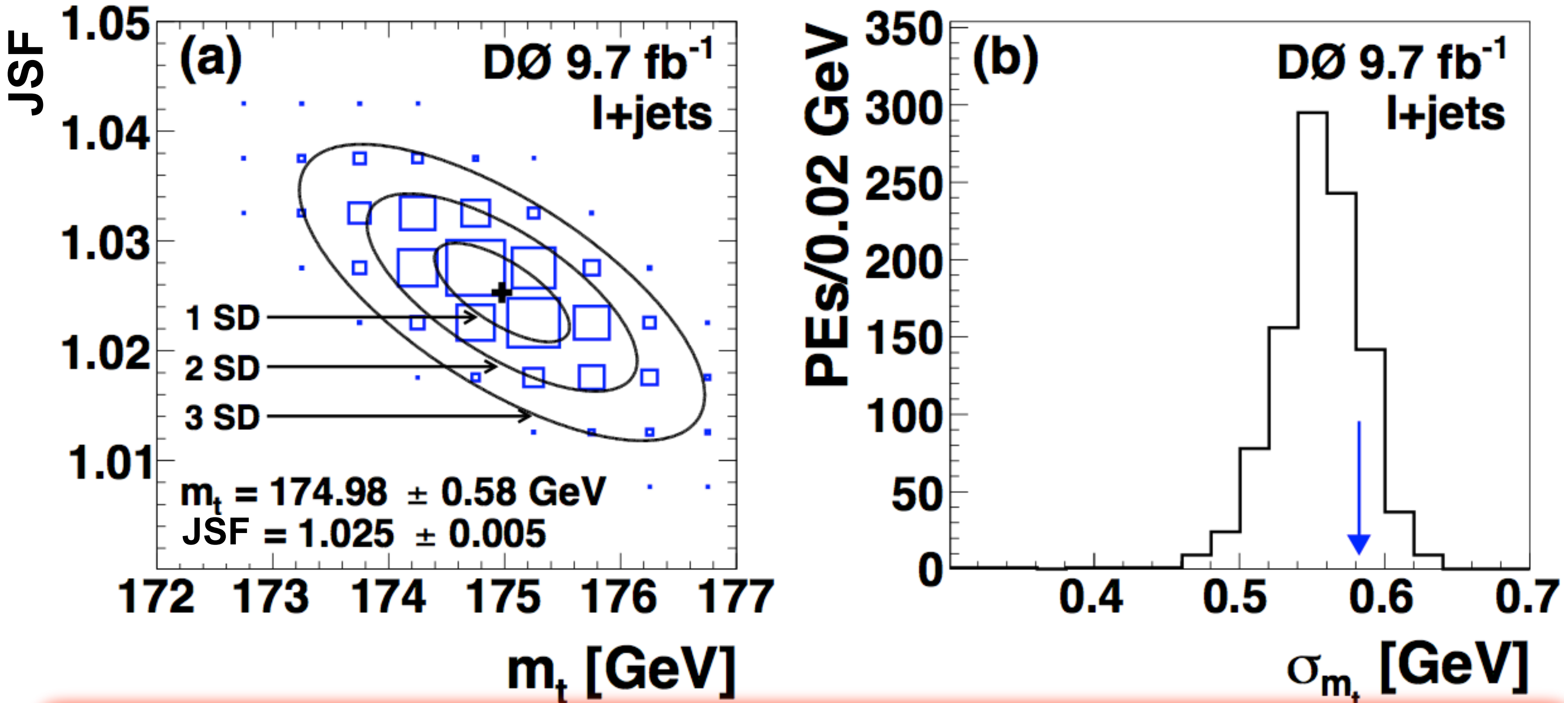
Submitted to PRL, arXiv:1405.1756 [hep-ex]

Selection overview + analysis technique

- Use **full 9.7 fb^{-1}** of integrated luminosity & require:
  - Exactly **one** tight isolated **electron or muon** with:
    - p_T > 20 GeV, $|\eta_{muon}| < 2$, $|\eta_{electron}| < 1.1$
  - **Exactly four jets** with cone parameter R=0.5 and:
    - p_T > 20 GeV, leading jet p_T > 40 GeV
  - **One or more b-tagged jet** ($\varepsilon_b \approx 65\%$, $\varepsilon_{light} \approx 5\%$) to further reject backgrounds
  - Resulting signal purity ≈ 65% assuming $\sigma_{t\bar{t}} = 7.24$ pb [1]
- Use the **matrix element technique**
  - Utilise LO matrix element [2]:
    - → match selection phase space requiring exactly 4 jets
    - Inclusion of beyond LO effects through **calibration with fully simulated alpgen+pythia events**

[1] Czakon et al, *PRL* ***109****, 132001 (2012).*
[2] *PRD 53, 4886 (1996), PLB 411, 173 (1997)*

- New DØ result in l+jets final states using 9.7 fb^{-1} of data (statistical uncertainty only):



$$m_t = 174.98 \pm 0.41(\text{stat}) \pm 0.41(\text{JES})\ \text{GeV}.$$

- Note: analysis was performed blinded in m_t
  - (all results shown are after unblinding)

Submitted to PRL, arXiv:1405.1756 [hep-ex]

Refinement from increased MC samples

- Keep in mind that, for a given uncertainty, we cite:
  - max{ statistical uncertainty, |face value of systematic| }

This measurement

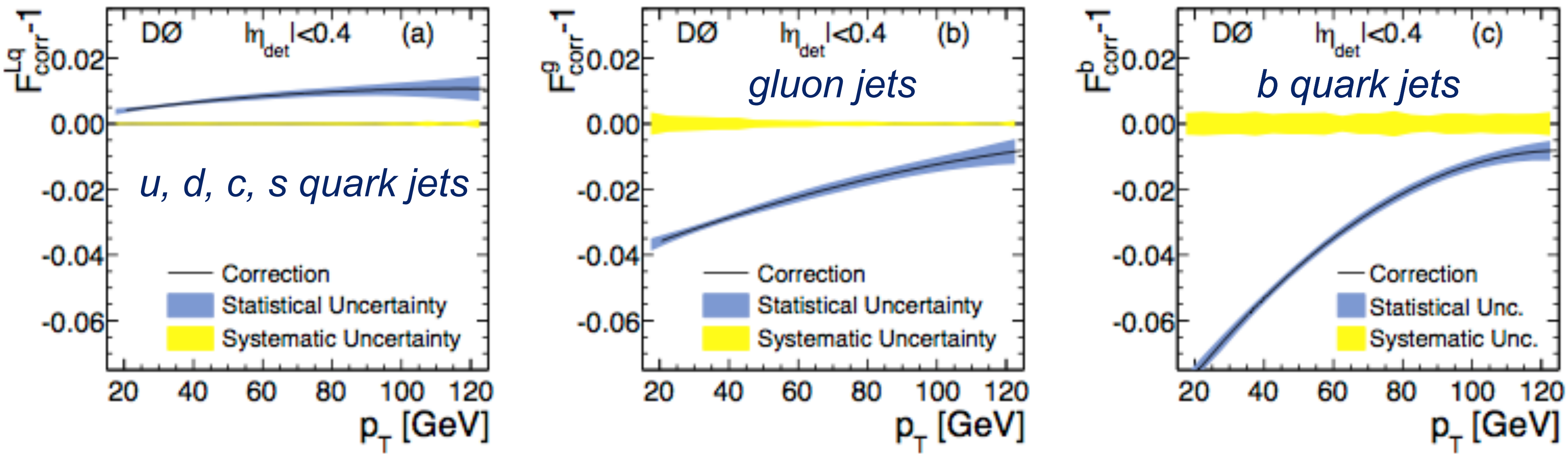
Source of uncertainty	Effect on m_t (GeV)
Signal and background modeling:	
Higher order corrections*	0.15
Initial/final state radiation*	0.09
Hadronization & UE*	0.26
Color reconnection*	0.10
Multiple $p\bar{p}$ interactions	0.06
Heavy flavor scale factor	0.06
b-jet modeling	0.09
PDF uncertainty	0.11
Detector modeling:	
Residual jet energy scale	0.21
Data-MC jet response difference	0.16
b-tagging	0.10
Trigger	0.01
Lepton momentum scale	0.01
Jet energy resolution	0.07
Jet ID efficiency	0.01
Method:	
Modeling of multijet events	0.04
Signal fraction	0.08
MC calibration	0.07
Total systematic uncertainty	0.49
Total statistical uncertainty	0.58
Total uncertainty	0.76

*Result using 3.6 fb⁻¹: DØ Coll., PRD **84**, 032004 (2011)*

Source	Uncertainty (GeV)
Modeling of production:	
Modeling of signal:	
Higher-order effects	±0.25
ISR/FSR	±0.26
Hadronization and UE	±0.58
Color reconnection	±0.28
Multiple $p\bar{p}$ interactions	±0.07
Modeling of background	±0.16
W+jets heavy-flavor scale factor	±0.07
Modeling of b jets	±0.09
Choice of PDF	±0.24
Modeling of detector:	
Residual jet energy scale	±0.21
Data-MC jet response difference	±0.28
b-tagging efficiency	±0.08
Trigger efficiency	±0.01
Lepton momentum scale	±0.17
Jet energy resolution	±0.32
Jet ID efficiency	±0.26
Method:	
Multijet contamination	±0.14
Signal fraction	±0.10
MC calibration	±0.20
Total	±1.02

Refinement from new calibrations

- **Use new JES calibration including flavour-dependent response correction:**

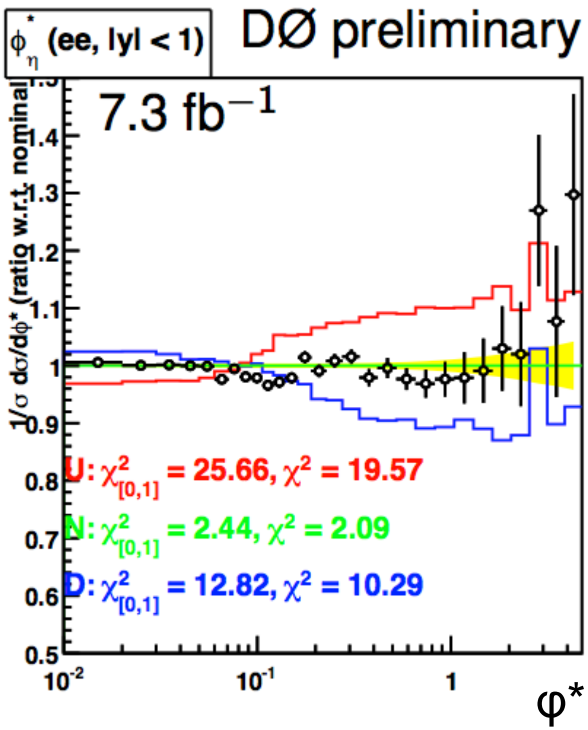


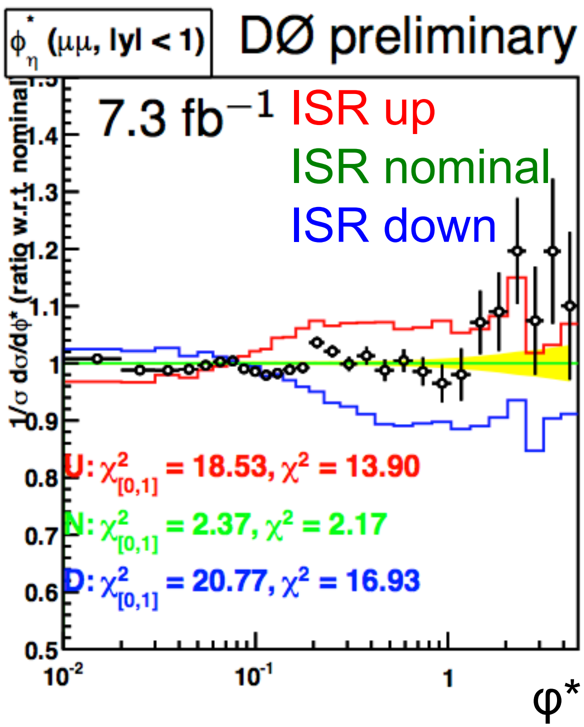
  - → **Uncertainty from flavor-dependent response:**
    - **0.16 GeV (was 0.28 GeV)**
  - **This uncertainty accounts for JES difference between light quark jets and b quark jets**

$$F_{\mathrm{corr}} = \frac{1}{\langle F \rangle_{\gamma+\mathrm{jet}}} \cdot \frac{\sum_i E_i \cdot R_i^{\mathrm{data}}}{\sum_i E_i \cdot R_i^{\mathrm{MC}}}$$

Refinement from $t\bar{t}$ modeling (ISR/FSR)

- Constrain **ISR/FSR by studying Drell-Yan events**
  - Measurement of $p_T(Z)$ using φ^* variable [1]
  - Vary ISR/FSR via **CKKW renormalization scale in alpgen** (`ktfac`), as suggested in [2]
    - `ktfac` variations by **±1.5** cover excursions of MC from data





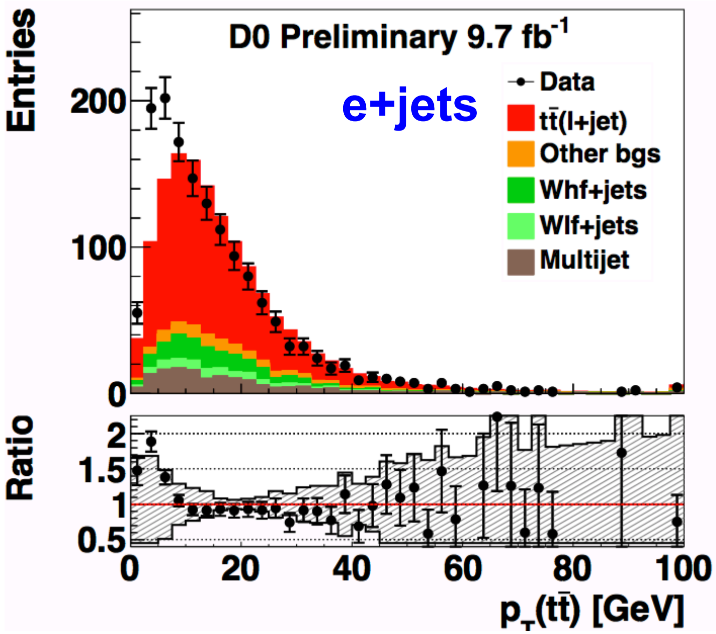
Also tune in other kinematic regions:
- 1<|y|<2
- |y|>2

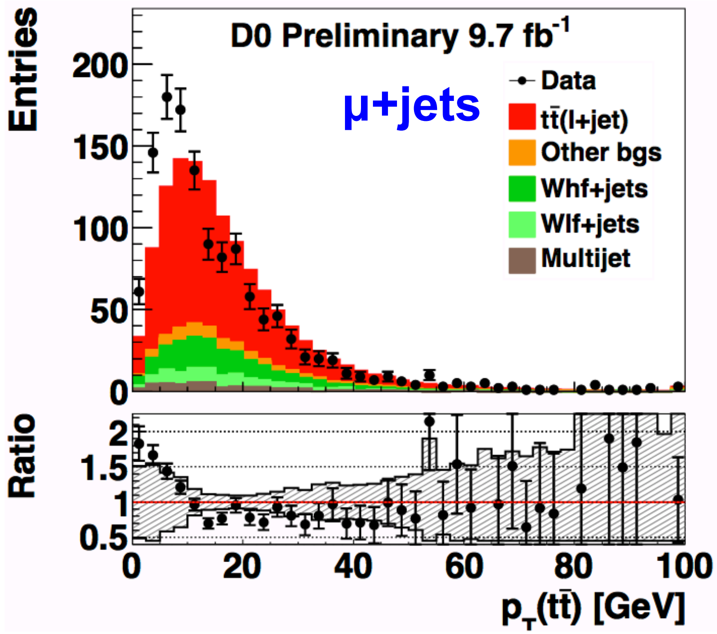
(cf. backup)

[1] DØ Coll., PRL **106**, 122001 (2011)
[2] M. Mangano, P. Skands et al, EPJ **C72** 2078 (2012)

Refinement from $t\bar{t}$ modeling (ISR/FSR)

- Constrain ISR/FSR by studying Drell-Yan events
  - Measurement of $p_T(Z)$ using φ^* variable [1]
  - Vary ISR/FSR via CKKW renormalization scale in alpgen (ktfac), as suggested in [2]
    - ktfac variations by ±1.5 cover excursions of MC
- In addition: reweight $t\bar{t}$ simulations in $p_T(t\bar{t})$ to data





  - Effect may be related to ISR/FSR mismodelling

0.06 GeV

Total: 0.09 GeV
(was: 0.26 GeV)

0.07 GeV

Refinement from $t\bar{t}$ modeling (hadronisation)

- Factor out the component from different JES
  - Evaluate using the momenta of particle level jets matched to detector level jets with $\Delta R=0.25$
  - Apply default selection at detector level
    - → minimize bias from acceptance etc.
- We also factor out the effect of different $p_T(t\bar{t})$ in:
    - Default (alpgen+pythia)
    - Alternative model (alpgen+herwig)
  - Achieved by reweighting default simulation in $p_T(t\bar{t})$ to match the alternative model
  - This effect is already taken into account in ISR/FSR uncertainty
- → Hadronization and underlying event uncertainty:
  - 0.26 GeV (was: 0.58 GeV)

Conclusions / Outlook

- Sound barrier of 0.5% of relative precision is broken:
  - World average:

$$173.34 \pm 0.27\ (\text{stat}) \pm 0.71\ (\text{syst})\ \text{GeV}$$

0.43%

    - Solid average with detailed cross-checks
    - Further harmonisation of the treatment of systematic uncertainties needed

  - New CMS result using 19.7 fb^{-1} of data @ 8 TeV:

$$172.04 \pm 0.19\ (\text{stat.+JSF}) \pm 0.75\ (\text{syst.})\ \text{GeV}$$

0.44%

  - New DØ result using 9.7 fb^{-1} of data @ 1.96 TeV

$$174.98 \pm 0.58\ (\text{stat} + \text{JES}) \pm 0.49\ (\text{syst})\ \text{GeV}$$

0.43%

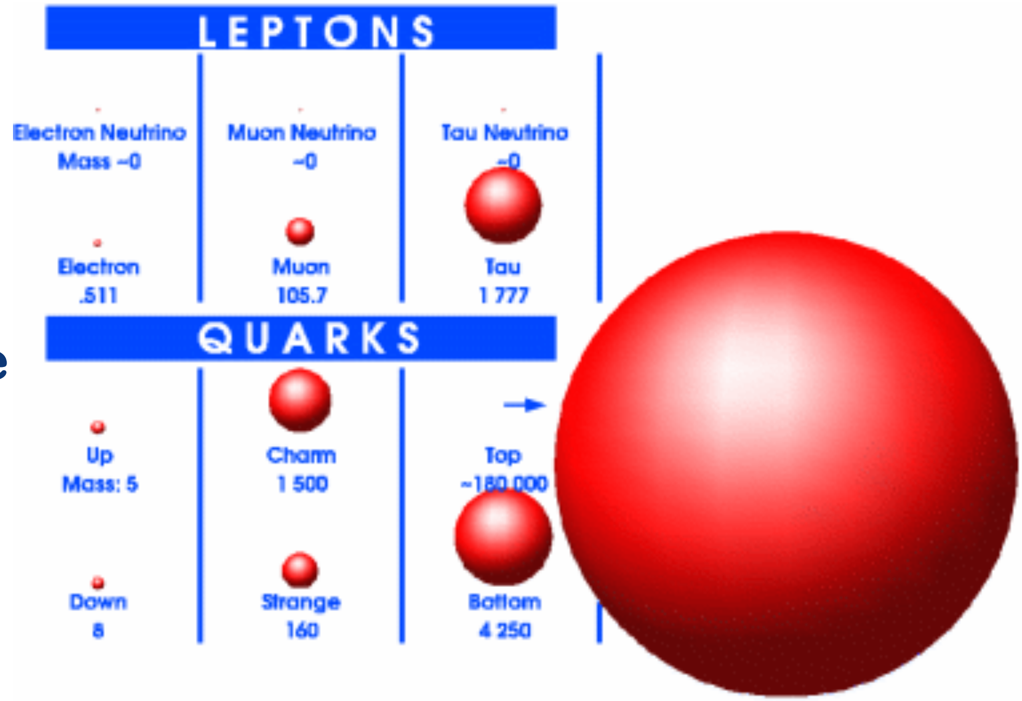
- We are looking forward to more exciting and even more precise results from hadron colliders!


GAME OVER
BONUS MATERIAL

2/24/1995

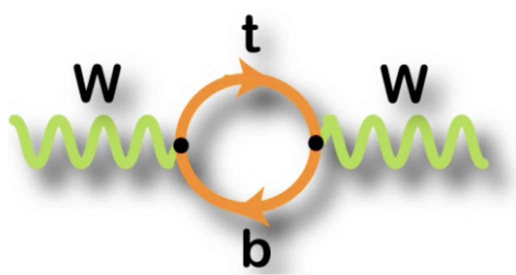
Motivation

- The **top quark is special**:
  - It is the heaviest quark of the SM!
    - Why is it so heavy?
    - Does it play a special role in EWSB?

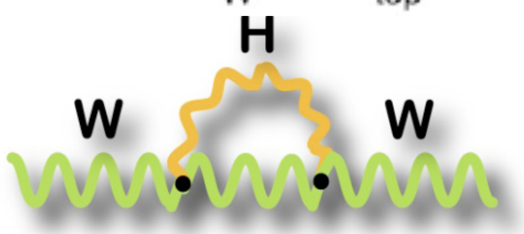


Motivation

- The **top quark is special:**
  - It is the heaviest quark of the SM!
    - Why is it so heavy?
    - Does it play a special role in EWSB?
  - M_W related to m_t & M_{Higgs}:



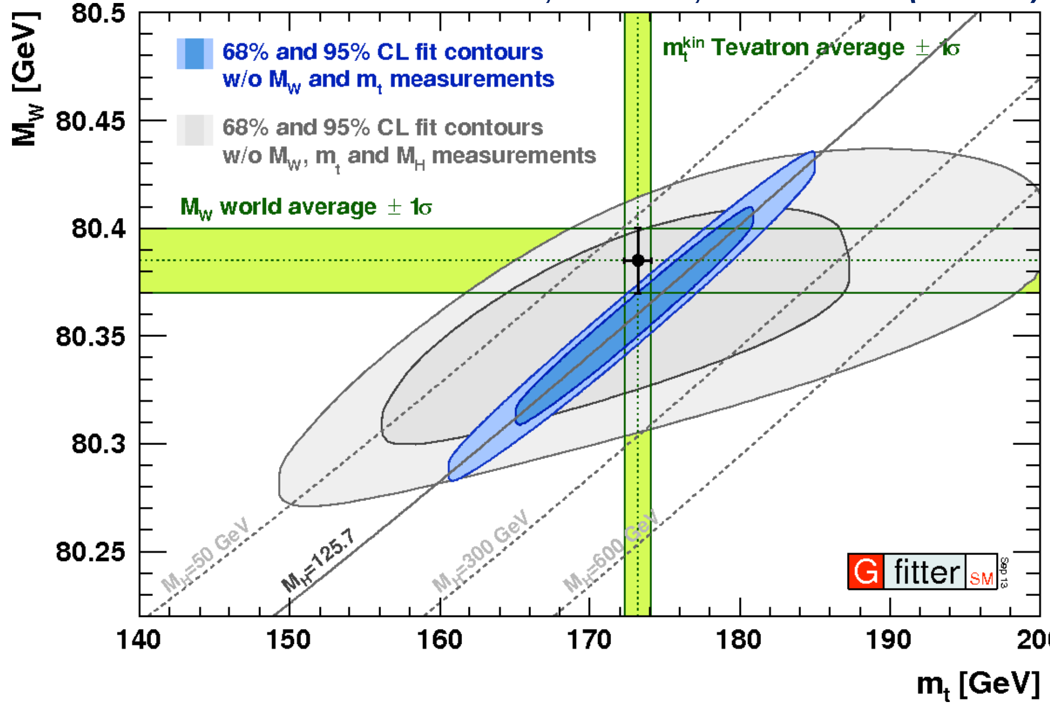
$$\Delta M_W \propto M_{top}^2$$



$$\Delta M_W \propto \ln M_H$$

Overconstrain M_W, m_t, and M_{Higgs}
→ Consistency check of the SM!

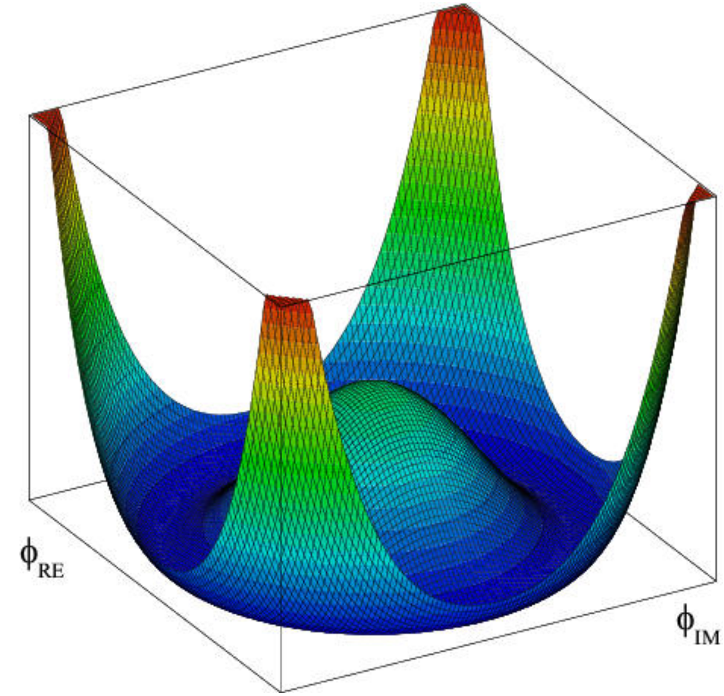
*GFitter Coll., EPJC, **72** 2005 (2012)*



- If this is not enough, the **top quark mass** is a **fundamental parameter of the SM**
- The **fate of our Universe depends on m_t**!
  - Consider the Higgs Lagrangian:

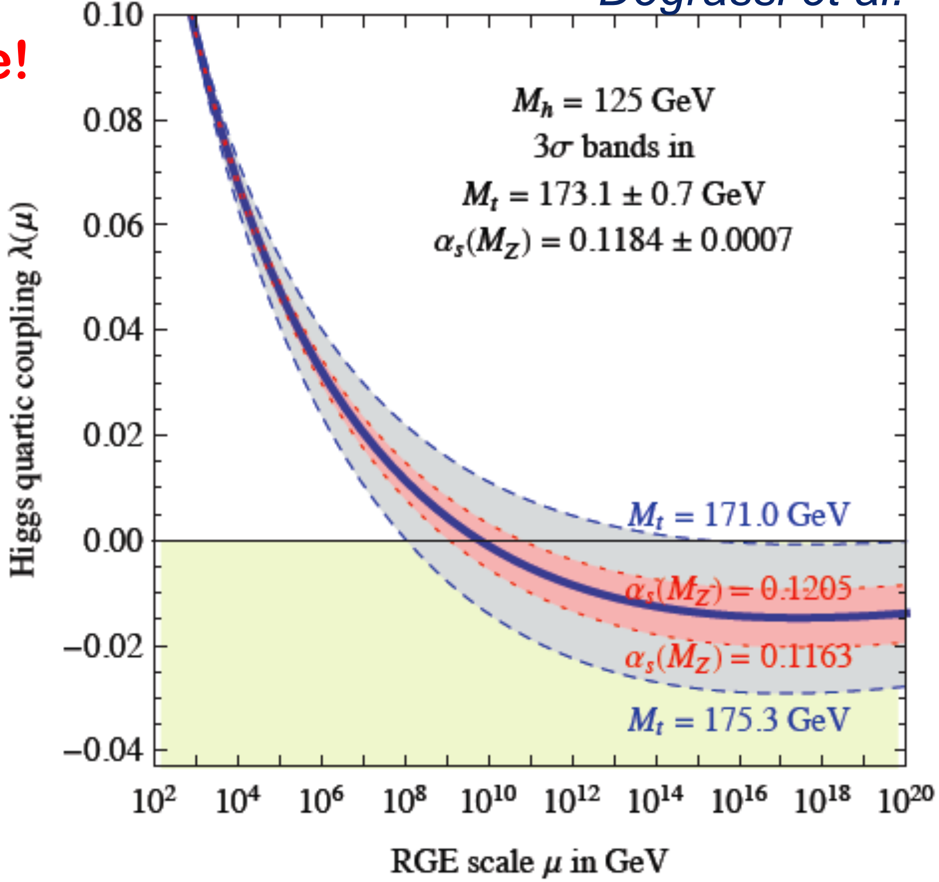
$$\mathcal{L}_H = \left| \left(\partial_\mu - igW_\mu^a \tau^a - i\frac{g'}{2} B_\mu \right) \phi \right|^2 + \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2,$$

  - The quartic Higgs self-coupling term $\lambda(\phi^\dagger\phi)^2$ is responsible for the mexican-hat shape of the potential
  - This works only if λ is positive…



- λ receives **radiative corrections** from all particles of the SM, **mostly from the top quark!**
  - We can evolve these corrections using running group equation to Planck scale:
    - **λ should remain positive!**

Degrassi et al.



With the current world's best values for m_t and m_{Higgs}:
→ **Our Universe is only metastable!**

The calculation includes NNLO effects, RG equation at NNNLO

Combined result

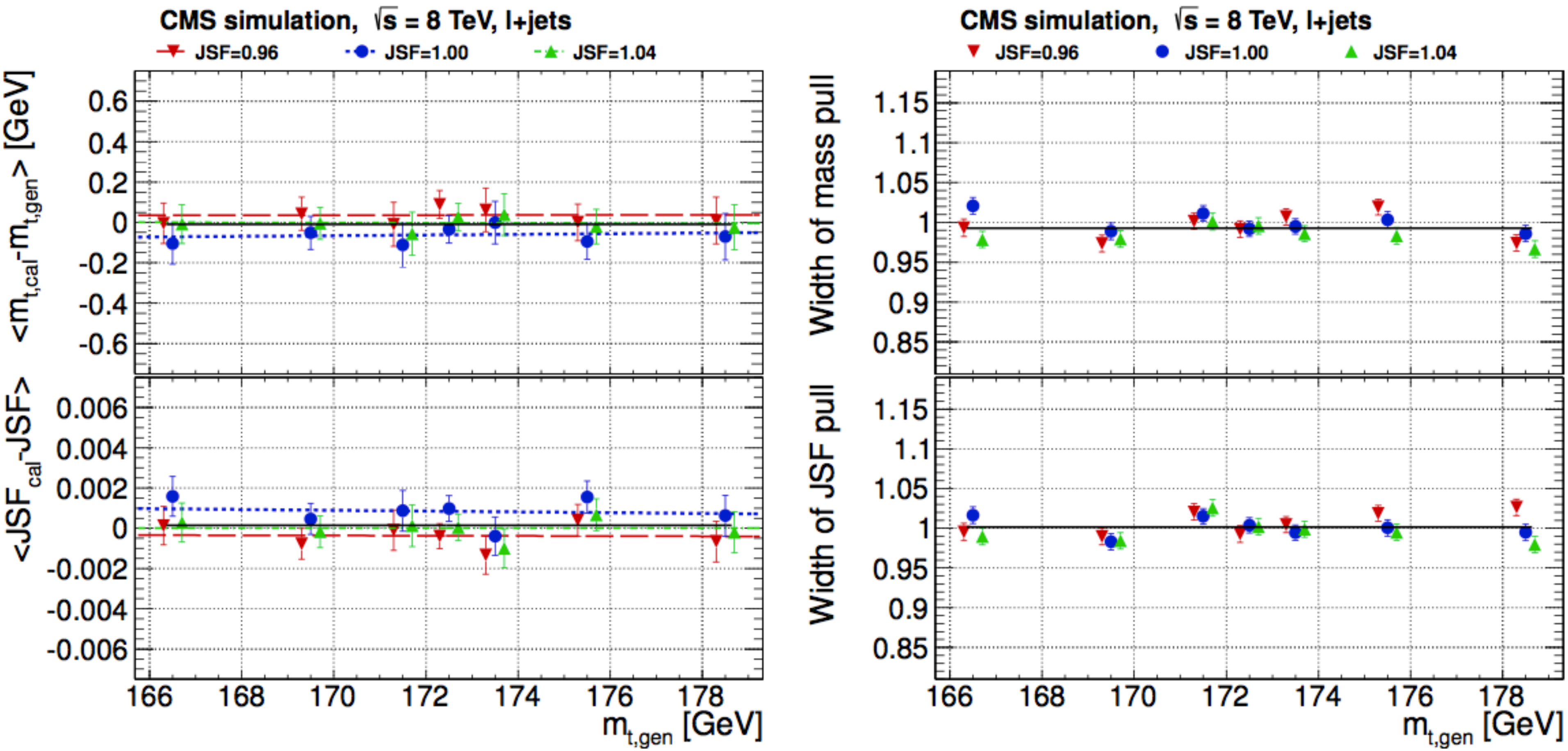
		CDF l+jets	CDF di-l	CDF all jets	CDF E_T^{miss}	D0 l+jets	D0 di-l	ATLAS l+jets	ATLAS di-l	CMS l+jets	CMS di-l	CMS all jets
CDF	l+jets	1.00										
	di-l	0.49	1.00									
	all jets	0.28	0.25	1.00								
	E_T^{miss}	0.31	0.27	0.17	1.00							
D0	l+jets	0.29	0.09	0.16	0.18	1.00						
	di-l	0.15	0.07	0.10	0.11	0.38	1.00					
ATLAS	l+jets	0.17	0.07	0.10	0.12	0.17	0.11	1.00				
	di-l	0.30	0.12	0.17	0.19	0.24	0.15	0.64	1.00			
CMS	l+jets	0.23	0.12	0.15	0.16	0.21	0.16	0.24	0.34	1.00		
	di-l	0.09	0.05	0.05	0.08	0.08	0.07	0.16	0.24	0.64	1.00	
	all jets	0.15	0.06	0.09	0.10	0.13	0.08	0.15	0.23	0.57	0.75	1.00

	Individual comb. [GeV]	Parameter value [GeV]	Correlations m^{CDF}	m^{D0}	m^{ATL}	m^{CMS}	χ^2/ndf (χ^2 probability) m^{CDF}	m^{D0}	m^{ATL}	m^{CMS}
m^{CDF}	173.19 ± 1.00	172.96 ± 0.98	1.00				–			
m^{D0}	174.85 ± 1.48	174.62 ± 1.46	0.31	1.00			1.25/1 (0.27)	–		
m^{ATL}	172.65 ± 1.44	172.70 ± 1.43	0.29	0.23	1.00		0.03/1 (0.86)	1.14/1 (0.29)	–	
m^{CMS}	173.58 ± 1.03	173.54 ± 1.02	0.25	0.22	0.32	1.00	0.23/1 (0.64)	0.46/1 (0.50)	0.32/1 (0.57)	–

arXiv:1403.4427 [hep-ex]

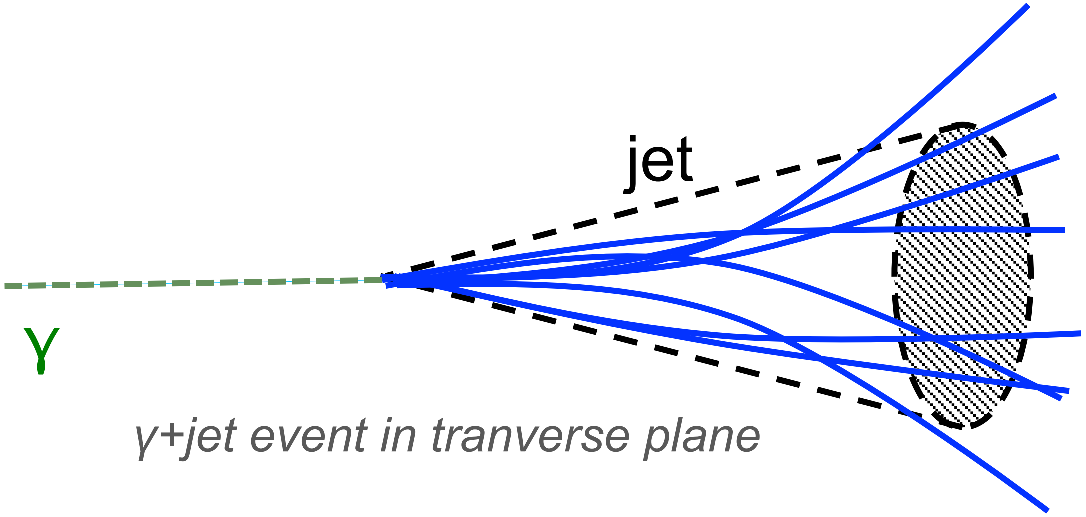
CMS method response validation

- **Validation:**



Jet energy scale (JES) calibration

- We **calibrate jet energies** at detector level to **particle level** (in data and MC)
- Calibration procedure in a nutshell:
  - Calibrate EM energy scale with $Z \rightarrow e^+e^-$
  - Correct energy scale for electrons to that of photons
  - Use **γ+jet events to calibrate major components of JES**
    - Expect momentum balance in transverse plane



γ+jet event in tranverse plane

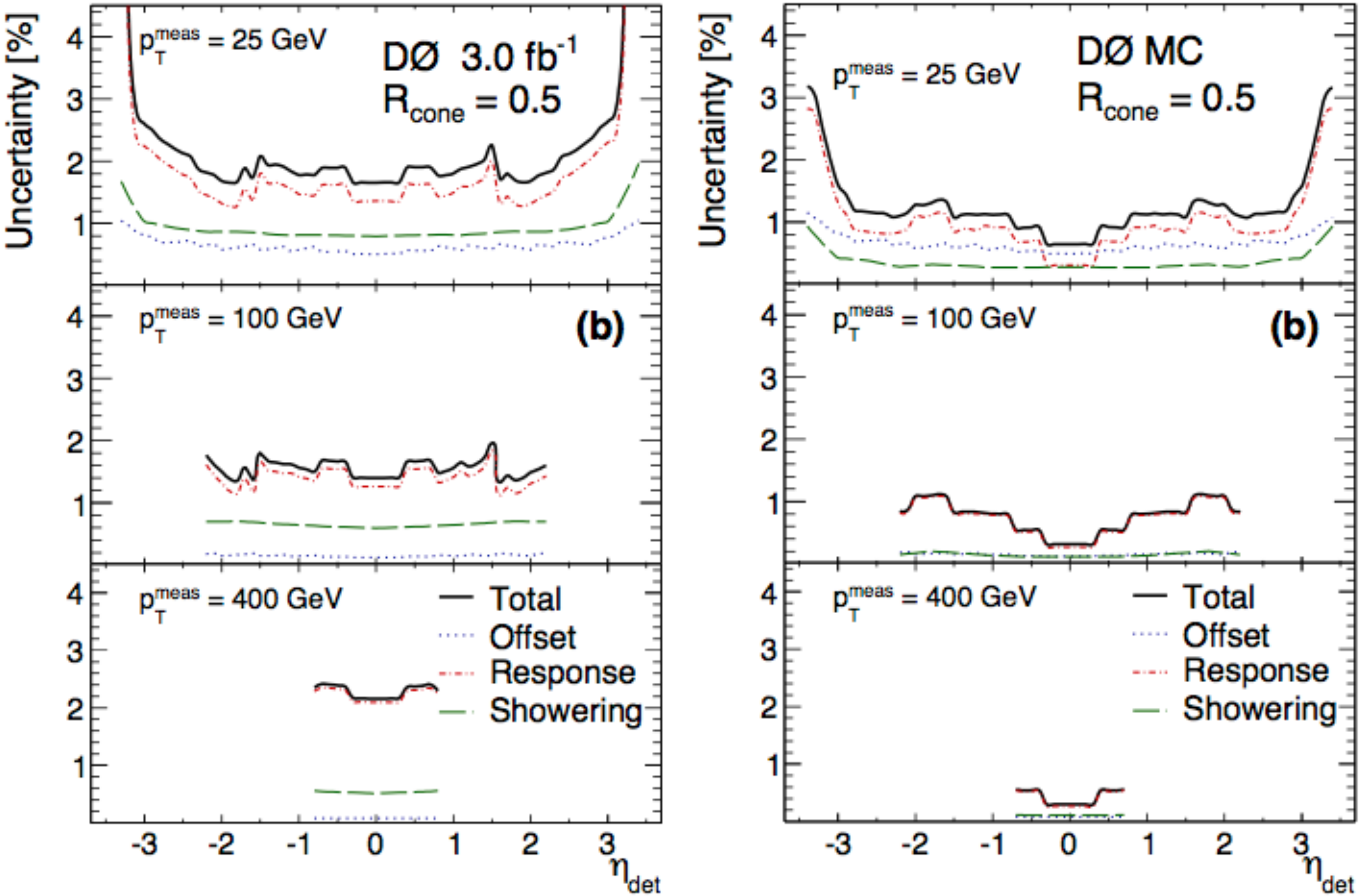
$$E^{\text{ptcl}} = \frac{E^{\text{meas}} - E_{\text{O}}}{R \cdot S}$$

  - Use γ+jet and dijet events to extend calibration in pT,η

Refined jet energy scale calibration

- We use the **new jet energy scale** (JES) calibration:

DØ Coll, arXiv:1312.6873 [hep-ex], submitted to NIM



Figures are representative of all Run II

Refined jet energy scale calibration

- Apply dedicated corrections for:
  - u, d, c, s quark jets
  - b quark jets
  - gluon jets
- The correction is given by:

$$F_{\text{corr}} = \frac{1}{\langle F \rangle_{\gamma+\text{jet}}} \cdot \frac{\sum_i E_i \cdot R_i^{\text{data}}}{\sum_i E_i \cdot R_i^{\text{MC}}}$$

  - F_{corr} preserves default JES by construction
- Derive single particle responses R_i in data/MC for:
  - γ, $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, K_0^S, K_0^L, $p^{\pm}$, n and Λ
  - (Keep in mind that DØ corrects jet energies to particle level in data and in MC)

DØ Coll, arXiv:1312.6873 [hep-ex], submitted to NIM

The matrix element technique

- **Matrix Element (ME) technique:**
  - Calculate the event probability on an event-by-event basis:

$$P_{\mathrm{evt}}(m_{\mathrm{top}}) \propto f P_{\mathrm{sig}}(m_{\mathrm{top}}) + (1-f) P_{\mathrm{bgr}}$$

$$P_{\mathrm{sig}}(m_{\mathrm{top}}) \propto \int \ldots \underline{\mathrm{d}\sigma_{t\bar{t}}(m_{\mathrm{top}})}$$

$$\mathrm{d}\sigma_{t\bar{t}} \propto |\mathcal{M}_{t\bar{t}}|^2 (m_{\mathrm{top}})$$

  - **Advantages:**
    - Use 4-vectors with maximal kinematic and topological information → maximal statistical power
  - **Disadvantages:**
    - High computational demand + theory assumptions

The ME technique in our measurement

DØ matrix element technique in l+jets final states

b tagging-based weight to identify relevant jet-parton assignments

Integration over phase space (10 dim)

$$P_{\mathrm{sig}} = \frac{1}{\sigma_{\mathrm{obs}}^{t\bar{t}}} \sum_{i=1}^{24} w_i \int d\rho\, dm_1^2\, dM_1^2\, dm_2^2\, dM_2^2\, d\rho_\ell\, dq_1^x\, dq_1^y\, dq_2^x\, dq_2^y$$

$$\sum_{\mathrm{flavors},\nu} |\mathcal{M}_{t\bar{t}}|^2 \frac{f'(q_1) f'(q_2)}{\sqrt{(\eta_{\alpha\beta} q_1^\alpha q_2^\beta)^2 - m_{q_1}^2 m_{q_2}^2}} \Phi_6 W(x, y; k_{\mathrm{JES}})$$

LO matrix element
PRD 53, 4886 (1996)
PLB 411, 173 (1997)

Phase space factor

Transfer functions (TFs) to map
parton level quantities y to reco level quantities x

*PRD **84**, 032004 (2011)*

The ME technique in our measurement

DØ matrix element technique in l+jets final states

Normalisation by observed cross section using the same LO ME

Sum over all 24 possible jet-parton assignments

$$P_{\rm sig} = \frac{1}{\sigma_{\rm obs}^{t\bar{t}}} \sum_{i=1}^{24} w_i \int d\rho\, dm_1^2\, dM_1^2\, dm_2^2\, dM_2^2\, d\rho_\ell\, dq_1^{\rm x}\, dq_1^{\rm y}\, dq_2^{\rm x}\, dq_2^{\rm y}$$

$$\sum_{\rm flavors,\nu} |\mathcal{M}_{t\bar{t}}|^2 \frac{f'(q_1) f'(q_2)}{\sqrt{(\eta_{\alpha\beta} q_1^\alpha q_2^\beta)^2 - m_{q_1}^2 m_{q_2}^2}} \Phi_6 W(x, y; k_{\rm JES})$$

Sum over incoming parton flavours and all neutrino p_z solutions

PDFs for Björken-x and transverse momenta of incoming partons

*PRD **84**, 032004 (2011)*

The ME techique: improvements

- We **numerically calculate a 10 dimensional integral** using MC integration techniques
  - Identical to the 3.6 fb^{-1} result except:
    - Use **low-discrepancy sequences for the MC integration**
      - Deterministic sequence of points in our 10-dim parameter space providing optimal convergence
    - **Factorise the JES factor k_{JES} from the ME calculation**
      - Include it via the transfer function
  - **Reduction of calculation time by o(100)!**

The ME techique: improvements

- We **numerically calculate a 10 dimensional integral** using MC integration techniques
  - Identical to the 3.6 fb^{-1} result except:
    - Use **low-discrepancy sequences for the MC integration**
      - Deterministic sequence of points in our 10-dim parameter space providing optimal convergence
    - **Factorise the JES factor k_{JES} from the ME calculation**
      - Include it via the transfer function
  - **Reduction of calculation time by o(100)**
- Increase the size of calibration samples!
  - Typical **statistical uncertainty** from size of MC samples:
    - **≈ 0.25 GeV → 0.01–0.05 GeV**

Uncertainty (GeV)
±0.25
±0.26
±0.58
±0.28
±0.07
±0.16
±0.07
±0.09
±0.24
±0.21
±0.28

Excerpt from the table of systematic uncertainties of the 3.6 fb^{-1} analysis [1]

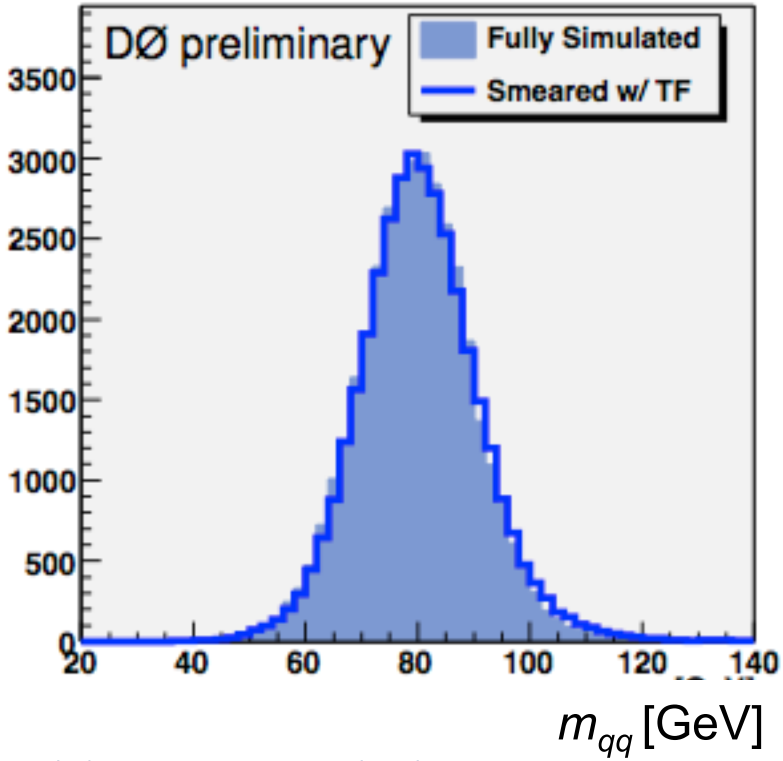
[1] *DØ Coll. PRD 85 032004 (2011)*

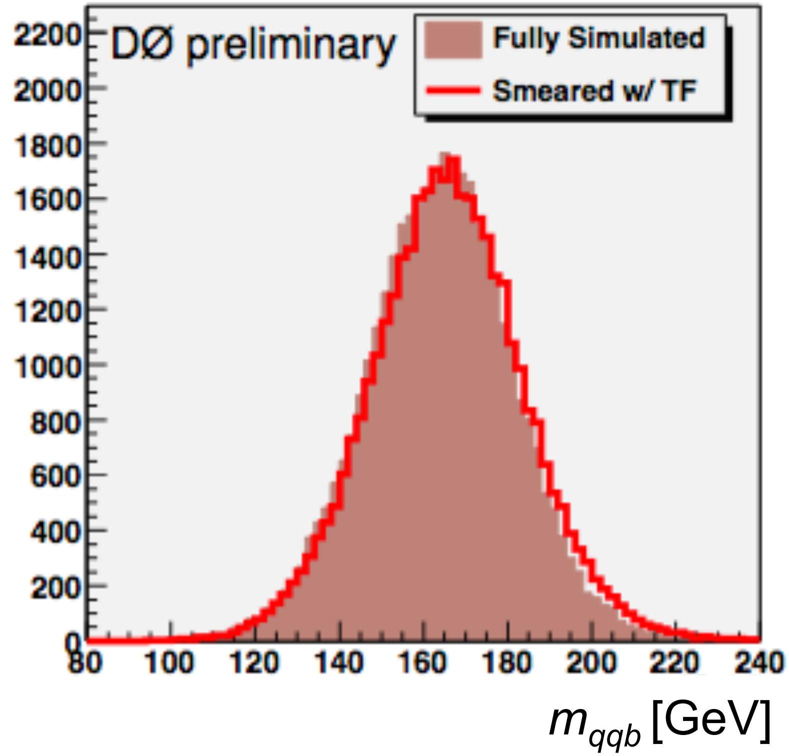
Transfer functions

- The Transfer Functions $W(x, y; k_{JES})$ relate parton-level quantities to reconstruction-level ones
- Parametrise the detector response:
  - For jets, we use the sum of two Gaussians:
- Parametrise jet energies:
  - treat separately: light quark jets, b-tagged jets with soft muon tag, all other b-jets
  - x 4 | η | regions for each
- Direction of jets and leptons in η x ϕ well-measured:
  - → use δ-function as transfer function!

Transfer function validation

- Compare parton momenta smeared with transfer functions to jet momenta in full simulation in:
  - Invariant mass of dijet system matched to W boson
  - Invariant mass of trijet system matched to top quark





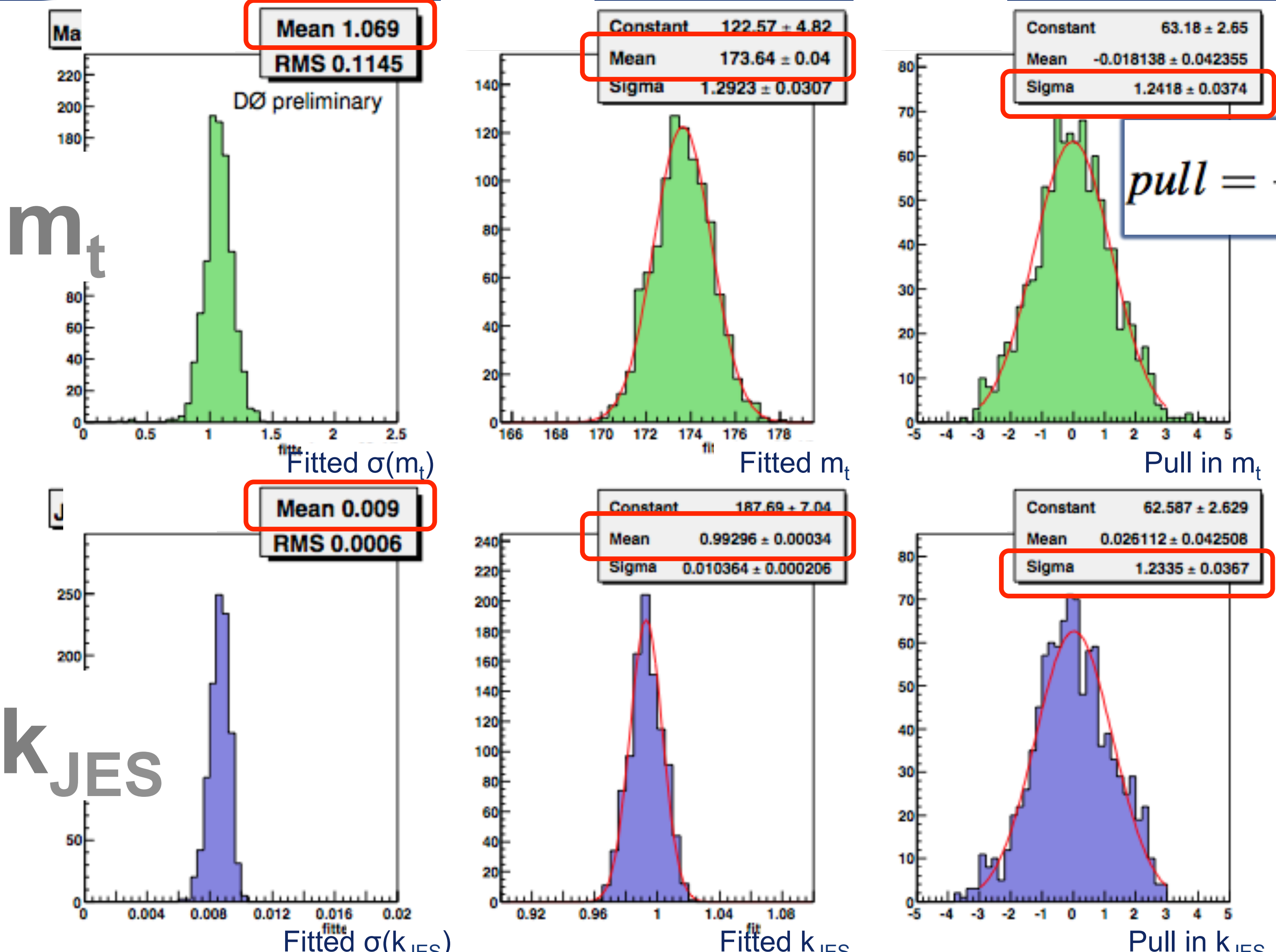
- Very good description of detector response!

Representative MC simulations → cf. backup for all

Calibration of method response in m_t, k_{JES}

- For calibration of **method response in m_t and k_{JES}**:
  - Construct PEs according to the signal fractions measured for given epoch+channel
    - **W+jets background** (dominant, adjusted according to f)
    - **MJ background** (11% and 4% for e and mu+jets)
    - (Other backgrounds contribute few % in each channel)
  - Vary N_{sig} in PEs according to binomial statistics
  - 1000 PEs performed at each calibration point
- Calibrate m_t with samples at
    - m_t = 165,170,172.5,175,180 GeV
    - k_{JES} = 1
- Calibrate k_{JES} with samples at
    - k_{JES} = 0.95, 1, 1.05
    - m_t = 172.5 GeV
    - k_{JES} variation is done for background as well

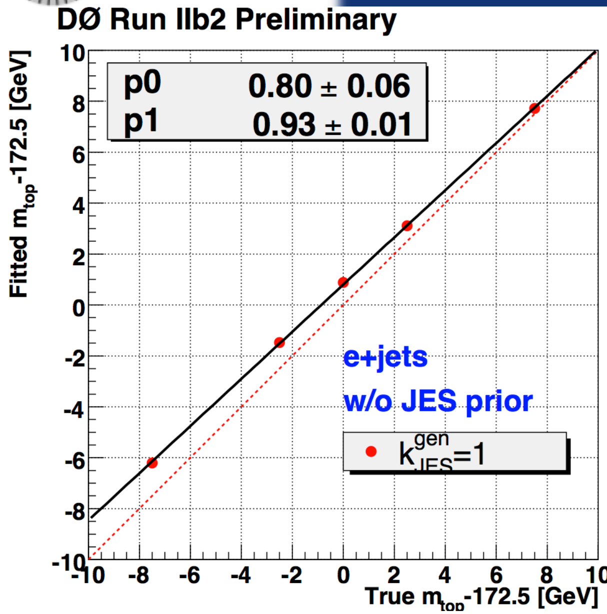
Calibration of method response in m_t, k_{JES}

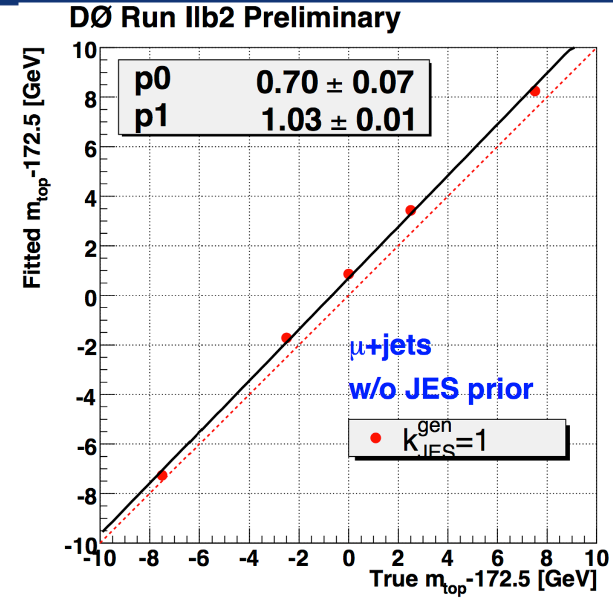


$$pull = \frac{\langle x \rangle - \bar{x}}{\sigma}$$

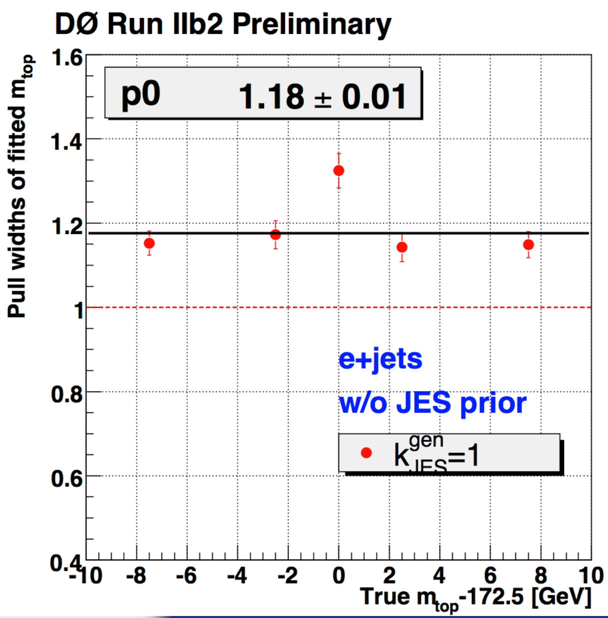
e+jets
Run IIb2, $m_t^{gen} = 172.5$ GeV, $k_{JES} = 1$

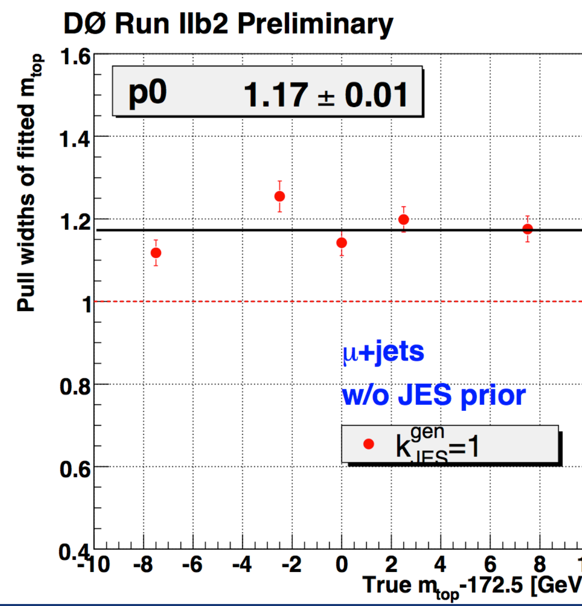
Calibration of method response in m_t





Calibrate m_t & $\sigma(m_t)$

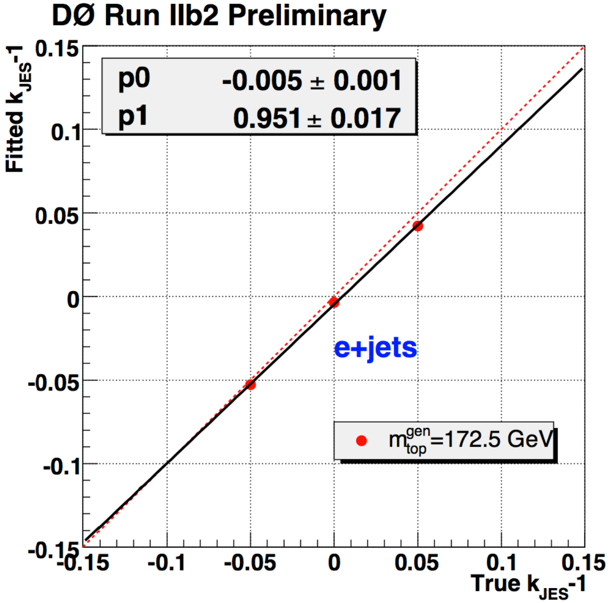


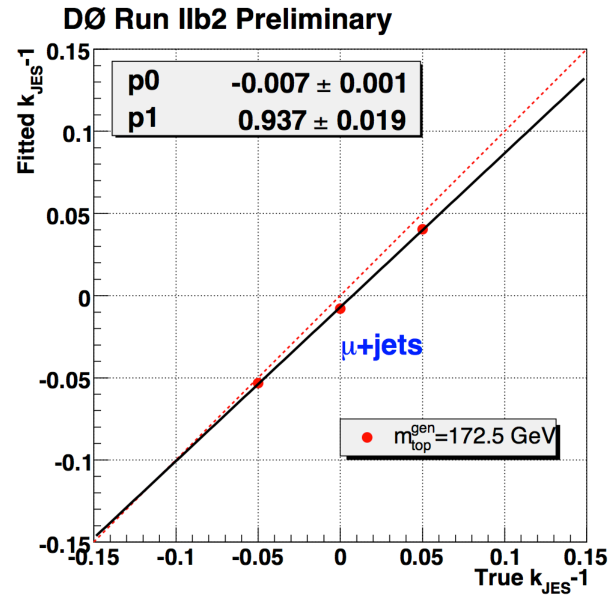


Calibrate $\sigma(m_t)$

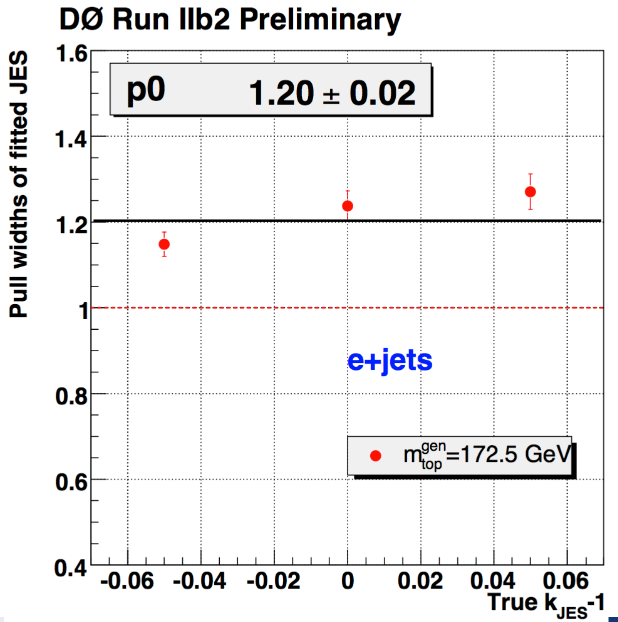
Representative MC simulations for Run IIb2 data
→ cf. backup for others

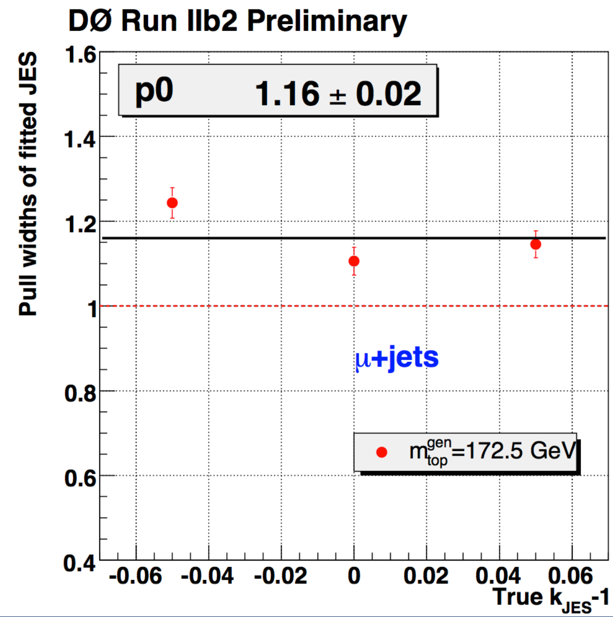
Calibration of method response in k_{JES}





Calibrate k_{JES} & $\sigma(k_{JES})$





Calibrate $\sigma(k_{JES})$

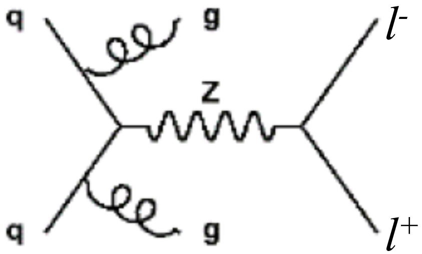
Representative MC simulations for Run IIb2 data
→ cf. backup for others

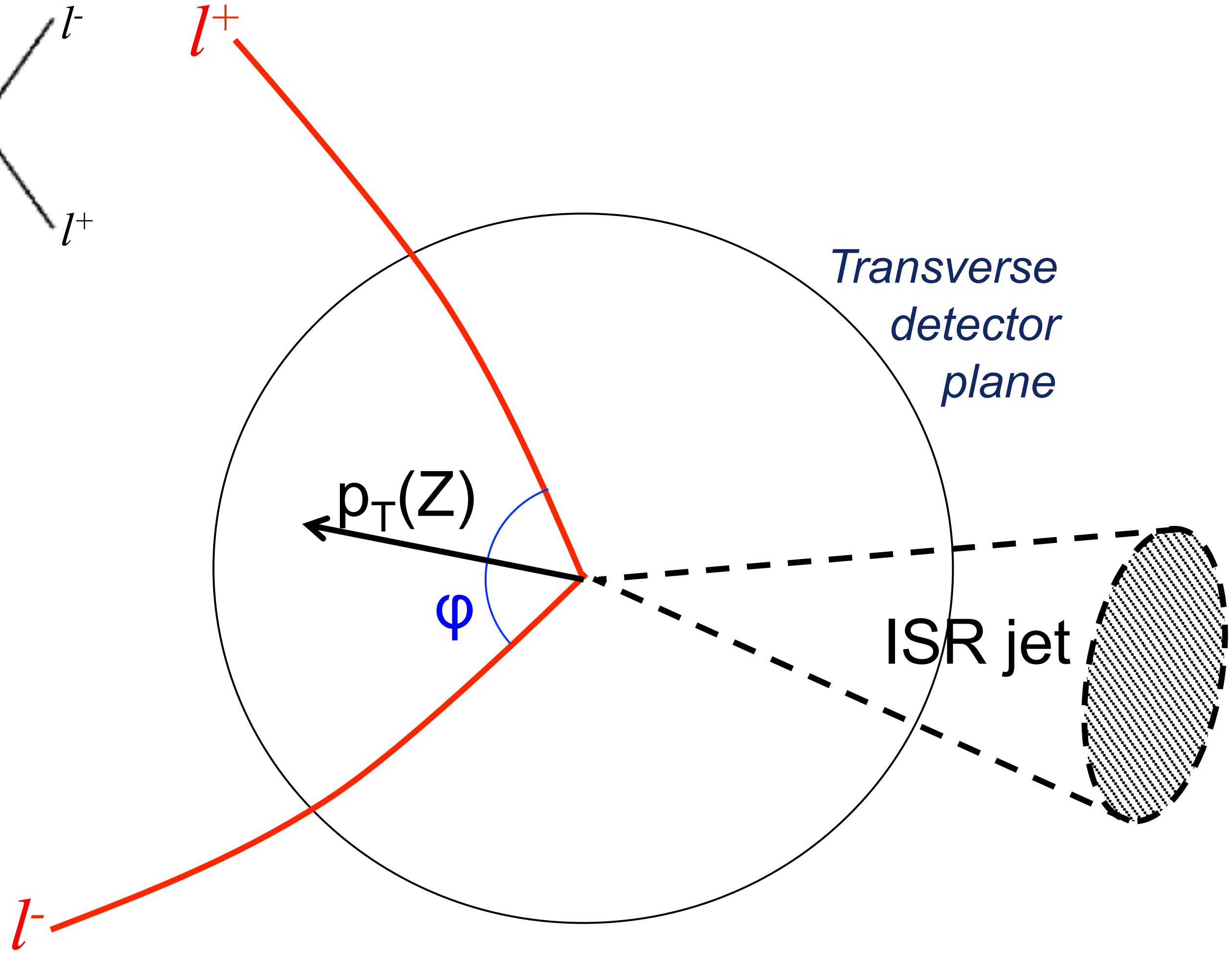
Systematic uncertainties

- **Procedures:**
  - Construct pseudo-experiments identically to the default calibration:
    - including W+jets background
    - Method-related uncertainties also include MJ background
  - For four signal modeling uncertainties:
    - Compare different models for m_t=172.5 GeV, k_{JES}=1
    - Stat. uncert. *O*(0.05 GeV)
  - For all other uncertainties, re-derive calibration
    - Stat. uncert. *O*(0.01 GeV)
- Discuss **refinements** in the following:
  1. Uncertainty due to limited size of MC samples
  2. New calibration of the detector
  3. Refined treatment of signal modeling uncertainties

Initial/final state radiation

- Constrain ISR/FSR by studying Drell-Yan events
  - Measurement of $p_T(Z)$ using φ* variable [1]



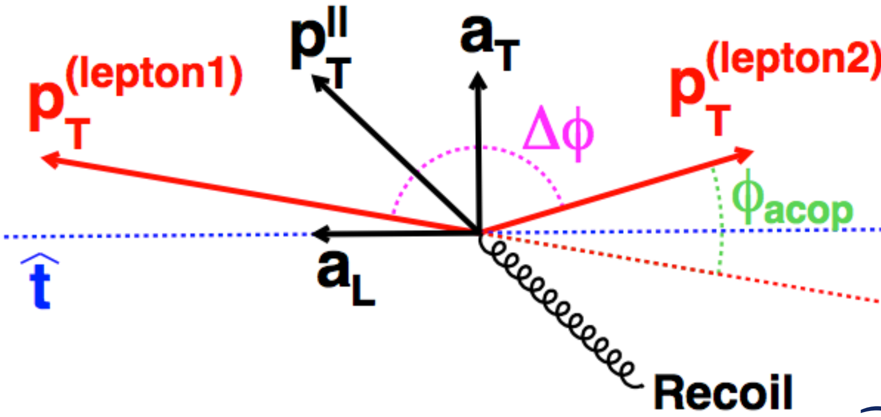


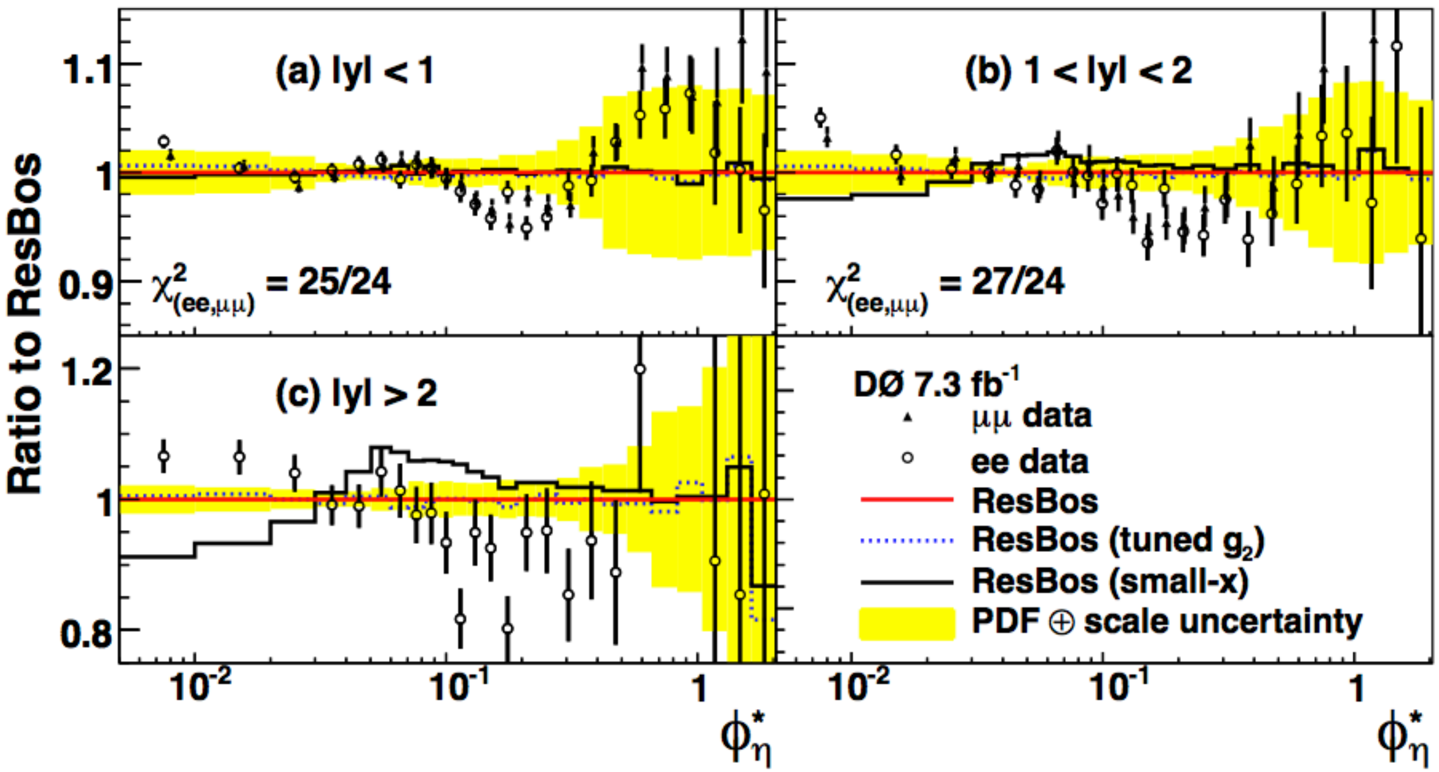
[1] DØ Coll., PRL **106**, 122001 (2011)

φ* measurement

- Based on 7.3 fb^{-1} of data
- Observable:

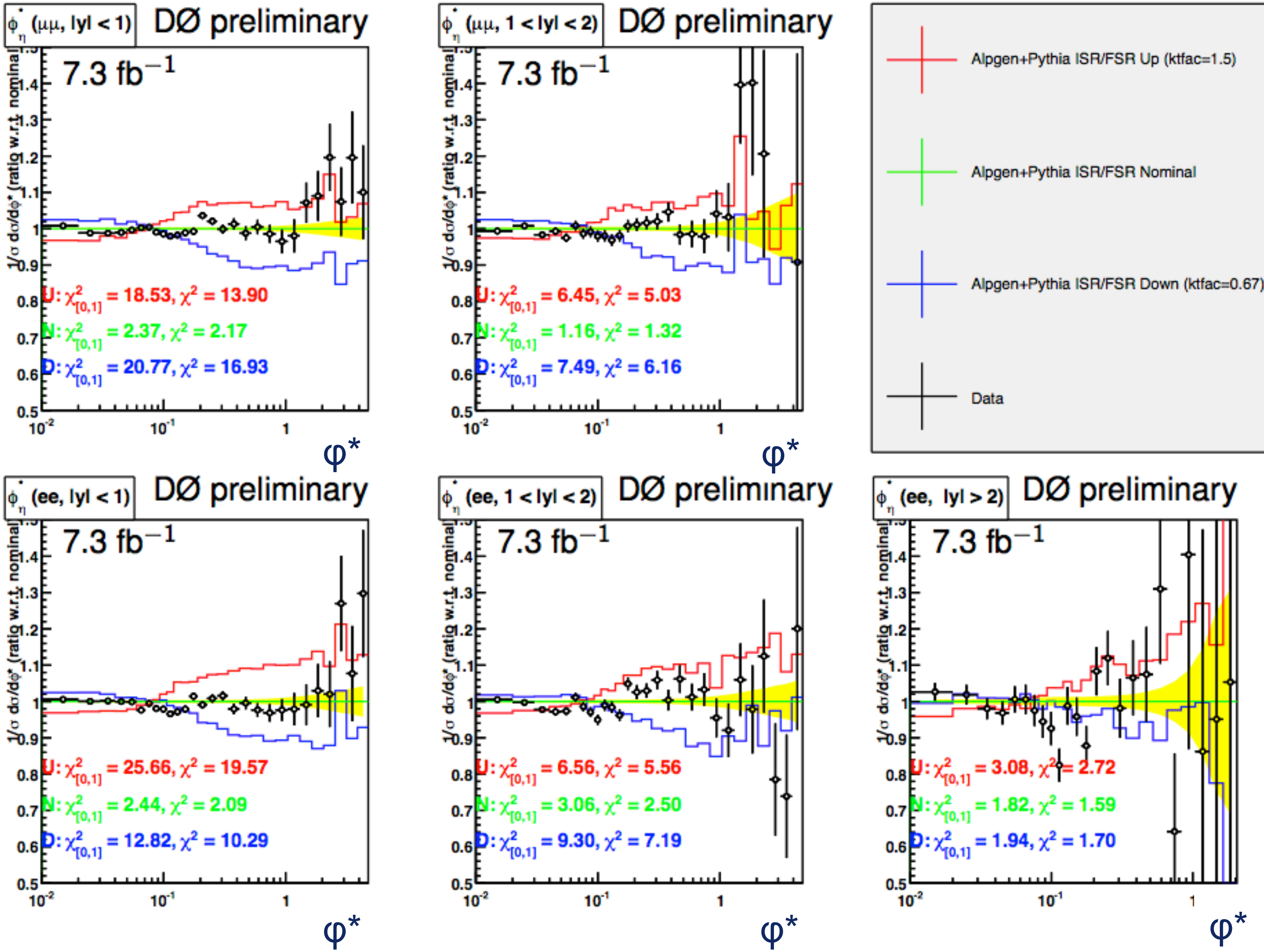
$$\phi^*_\eta = \tan(\phi_{acop}/2)\sin(\theta^*_\eta)$$





[1] DØ Coll., PRL **106**, 122001 (2011)

ISR/FSR

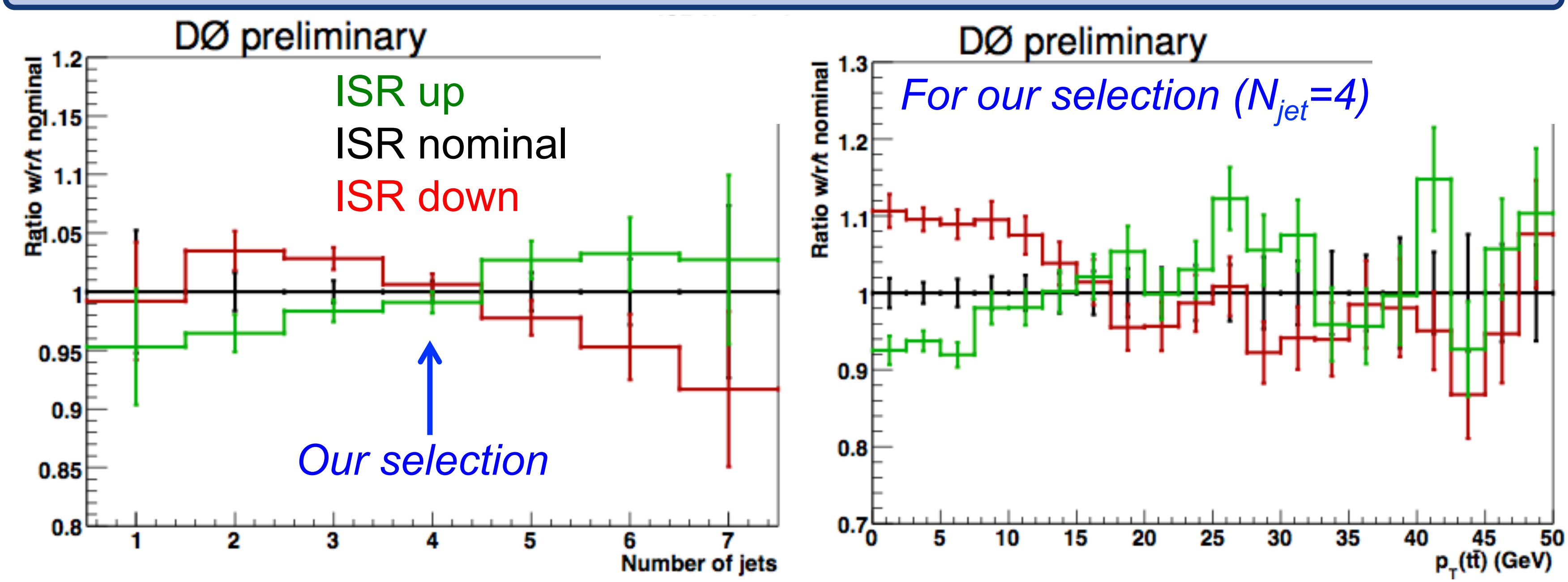


Unfolded spectra from: *DØ Coll., PRL* ***106***, *122001 (2011)*

Initial/final state radiation

- **Constrain ISR/FSR by studying Drell-Yan events**
  - **Measurement of $p_T(Z)$ using φ^* variable [1]**
- **Vary ISR/FSR via CKKW renormalization scale in alpgen (ktfac), as suggested in [2]**
  - **ktfac variations by ±1.5 cover excursions of MC from data**

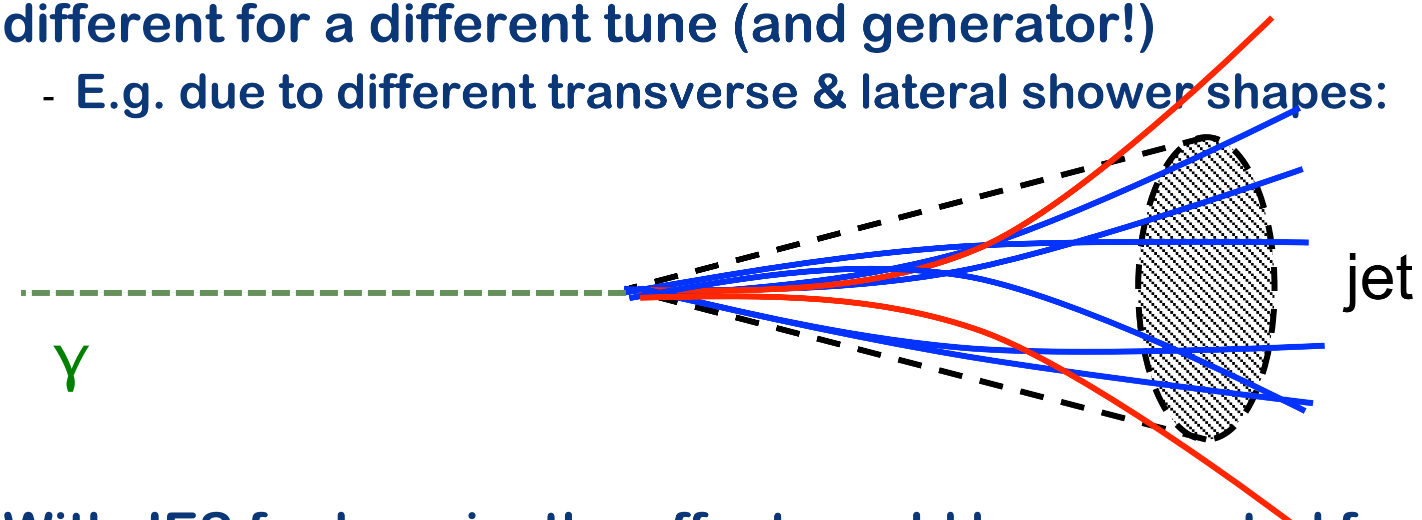
The effect of ISR/FSR variations in top-antitop events



[1] DØ Coll., PRL **106**, 122001 (2011)
[2] M. Mangano, P. Skands et al, EPJ **C72** 2078 (2012)

Hadronization and underlying event

- Compare alpgen+herwig vs alpgen+pythia (default)
- Combination of two effects:
  1. The actual effect we are interested in
  2. Component from different JES (differential in p_T,η)
     - Strictly, our JES is valid only for pythia with D0 Tune A
     - One can argue from first principles that JES will be different for a different tune (and generator!)
       - E.g. due to different transverse & lateral shower shapes:



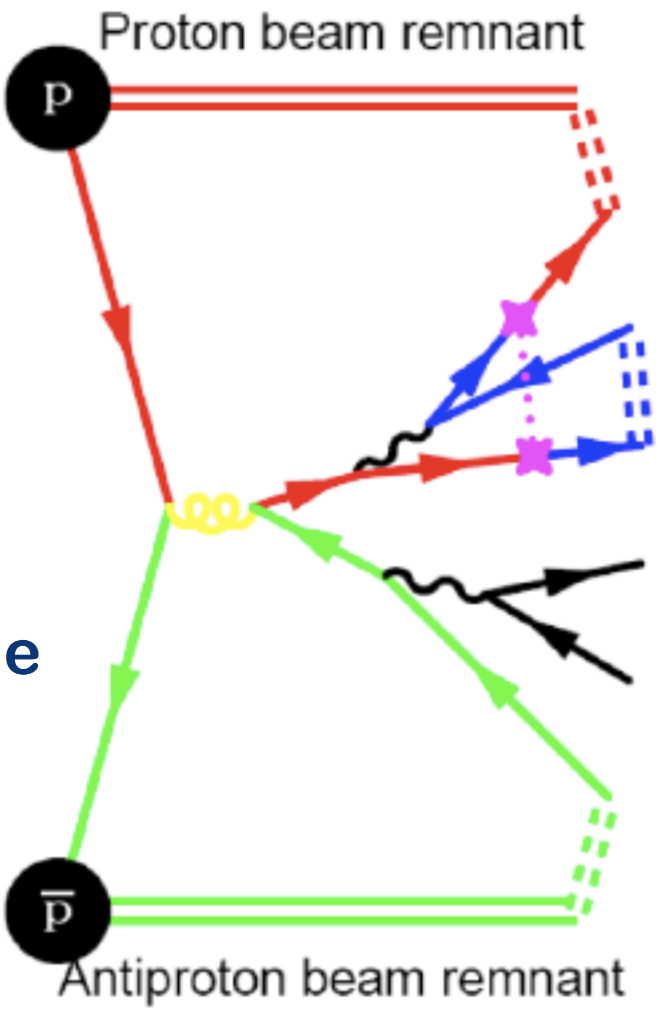
     - With JES for herwig, the effect would be accounted for
       - Factorize uncertainties to avoid double-counting:
         - We have an uncertainty for dependence of JES on p_T,η…

Hadronization and underlying event

- Factor out the component from different JES
  - Evaluate using the momenta of particle level jets matched to detector level jets with $\Delta R=0.25$
  - Apply default selection at detector level
    - → minimize bias from acceptance etc.
- We also factor out the effect of different $p_T(t\bar{t})$ in:
    - Default (alpgen+pythia)
    - Alternative model (alpgen+herwig)
  - Achieved by reweighting default simulation in $p_T(t\bar{t})$ to match the alternative model
  - This effect is already taken into account in ISR/FSR uncertainty
- → Hadronization and underlying event uncertainty:
  - 0.26 GeV (was: 0.58 GeV)

Color reconnection

- Use new color reconnection model:
  - Parametrises colour string survival probability in terms of the rapidity difference of beginning and end of color string
  - Old crude model:
    - ad-hoc breaking up of color connections with some probability
- Compare pythia with Perugia 2011 vs Perugia 2011NOCR tunes
- Use identical hard ME events for the comparison
- → Uncertainty from color reconnection:
  - 0.10 GeV (was: 0.28 GeV)



Comparison with previous measurements

- Current World average:

$$m_t = 173.34 \pm 0.76\,\text{GeV}$$

arXiv:1403.4427 [hep-ex]

- Assuming no statistical correlation between this result and the combination
  - Taking full uncertainty for the Tevatron average
  - Taking statistical uncertainty only for this measurement
  - Consistency at 1.71 SD level (p-value of 3.1%)

- Current Tevatron average:

$$m_t = 173.2 \pm 0.87\,\text{GeV}$$

arXiv:1305.3929 [hep-ex]

- Making the same assumptions:
  - Consistency at 1.70 SD level (p-value of 3.3%)

- **Correlations between input measurements**

		CDF				D0		ATLAS		CMS		
		l+jets	di-l	all jets	E_T^{miss}	l+jets	di-l	l+jets	di-l	l+jets	di-l	all jets
CDF	l+jets	1.00										
	di-l	0.49	1.00									
	all jets	0.28	0.25	1.00								
	E_T^{miss}	0.31	0.27	0.17	1.00							
D0	l+jets	0.29	0.09	0.16	0.18	1.00						
	di-l	0.15	0.07	0.10	0.11	0.38	1.00					
ATLAS	l+jets	0.17	0.07	0.10	0.12	0.17	0.11	1.00				
	di-l	0.30	0.12	0.17	0.19	0.24	0.15	0.64	1.00			
CMS	l+jets	0.23	0.12	0.15	0.16	0.21	0.16	0.24	0.34	1.00		
	di-l	0.09	0.05	0.05	0.08	0.08	0.07	0.16	0.24	0.64	1.00	
	all jets	0.15	0.06	0.09	0.10	0.13	0.08	0.15	0.23	0.57	0.75	1.00

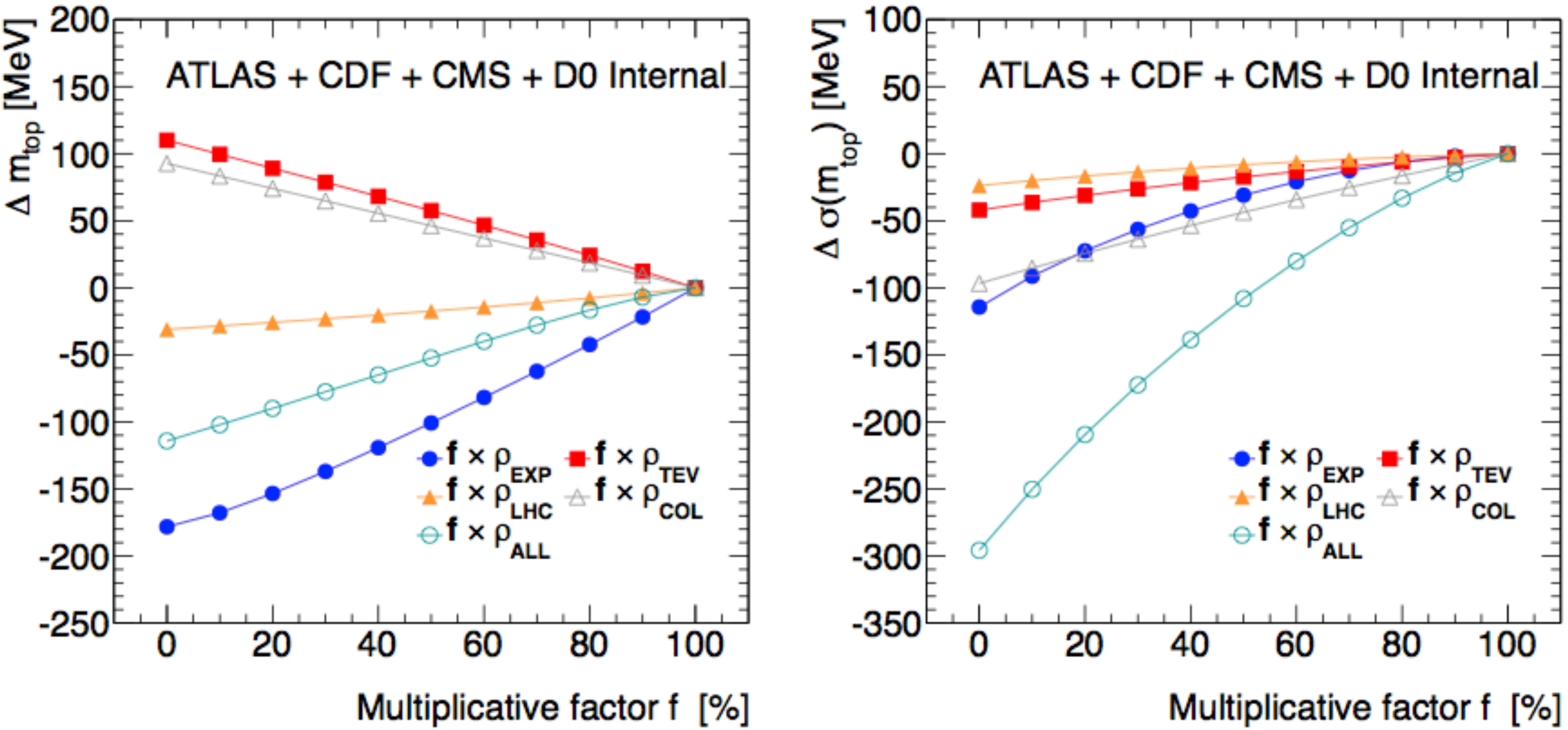
- **Correlation between final states:**

	Individual comb. [GeV]	Parameter value [GeV]	Correlations $m^{l\text{+jets}}$	$m^{\text{di-}l}$	$m^{\text{all jets}}$	$m^{E_T^{\text{miss}}}$	χ^2/ndf (χ^2 probability) $m^{l\text{+jets}}$	$m^{\text{di-}l}$	$m^{\text{all jets}}$	$m^{E_T^{\text{miss}}}$
$m^{l\text{+jets}}$	173.29 ± 0.80	173.23 ± 0.78	1.00				–			
$m^{\text{di-}l}$	172.74 ± 1.15	172.73 ± 1.09	0.71	1.00			0.43/1 (0.51)	–		
$m^{\text{all jets}}$	173.17 ± 1.20	173.35 ± 1.13	0.58	0.66	1.00		0.02/1 (0.90)	0.46/1 (0.50)	–	
$m^{E_T^{\text{miss}}}$	173.93 ± 1.85	174.03 ± 1.80	0.29	0.26	0.22	1.00	0.21/1 (0.65)	0.49/1 (0.48)	0.13/1 (0.72)	–

- **Correlation between experiments:**

	Individual comb. [GeV]	Parameter value [GeV]	Correlations m^{CDF}	m^{D0}	m^{ATL}	m^{CMS}	χ^2/ndf (χ^2 probability) m^{CDF}	m^{D0}	m^{ATL}	m^{CMS}
m^{CDF}	173.19 ± 1.00	172.96 ± 0.98	1.00				–			
m^{D0}	174.85 ± 1.48	174.62 ± 1.46	0.31	1.00			1.25/1 (0.27)	–		
m^{ATL}	172.65 ± 1.44	172.70 ± 1.43	0.29	0.23	1.00		0.03/1 (0.86)	1.14/1 (0.29)	–	
m^{CMS}	173.58 ± 1.03	173.54 ± 1.02	0.25	0.22	0.32	1.00	0.23/1 (0.64)	0.46/1 (0.50)	0.32/1 (0.57)	–

- **Stability under correlation assumptions**



Flavor-dependent correction

- Apply dedicated corrections for:
  - u, d, c, s quark jets
  - b quark jets
  - gluon jets
- The correction is given by:

$$F_{\rm corr} = \frac{1}{\langle F \rangle_{\gamma+\rm jet}} \cdot \frac{\sum_i E_i \cdot R_i^{\rm data}}{\sum_i E_i \cdot R_i^{\rm MC}}$$

  - $F_{\rm corr}$ preserves default JES by construction
- Derive single particle responses R_i in data/MC for:
  - γ, $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, K_0^S, K_0^L, $p^{\pm}$, n and Λ
  - (Keep in mind that DØ corrects jet energies to particle level in data and in MC)

DØ Coll, Section 14 in arXiv:1312.6873 [hep-ex], submitted to NIM

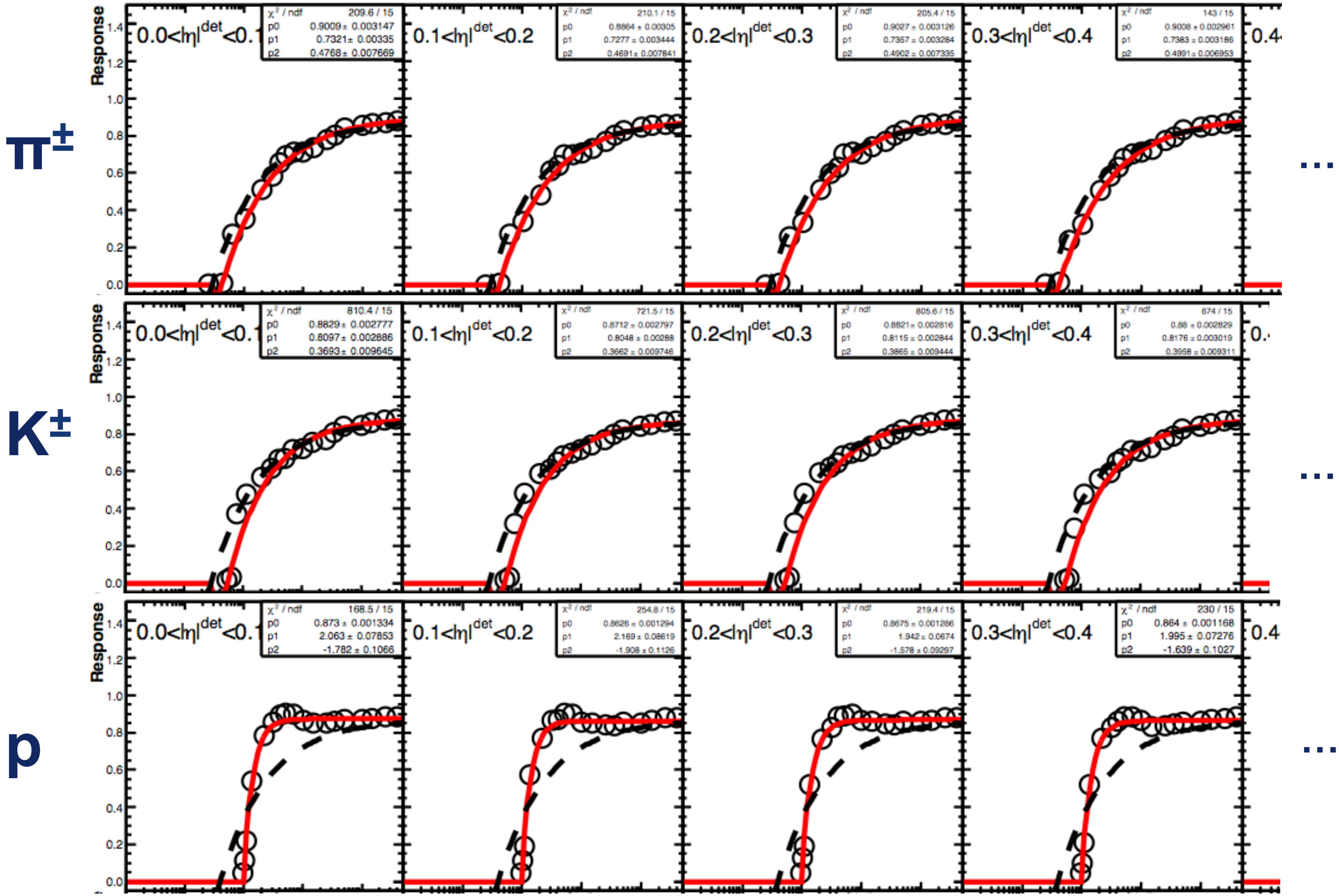
Flavor-dependent correction

- Derive single particle responses R_i in MC:
  - Use single particle MC samples for each of
    - γ, $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, K_0^S, K_0^L, $p^{\pm}$, n and Λ
  - Using:
    - Zero energy noise suppression off for default
    - (Noise suppression on → systematic uncertainty)
  - Fit with appropriate function:
    - e, μ, γ (not shown):
      - Calibrated separately and have one function each
    - For all hadrons:
      - Response function is (but different fit parameters!):
      - $R_h^{MC} \;=\; p_h^0 \cdot \left[1 - p_h^1 \cdot (E/0.75)^{p_h^2 - 1}\right]$ if $p_T > m_h$; 0 if $p_T < m_h$

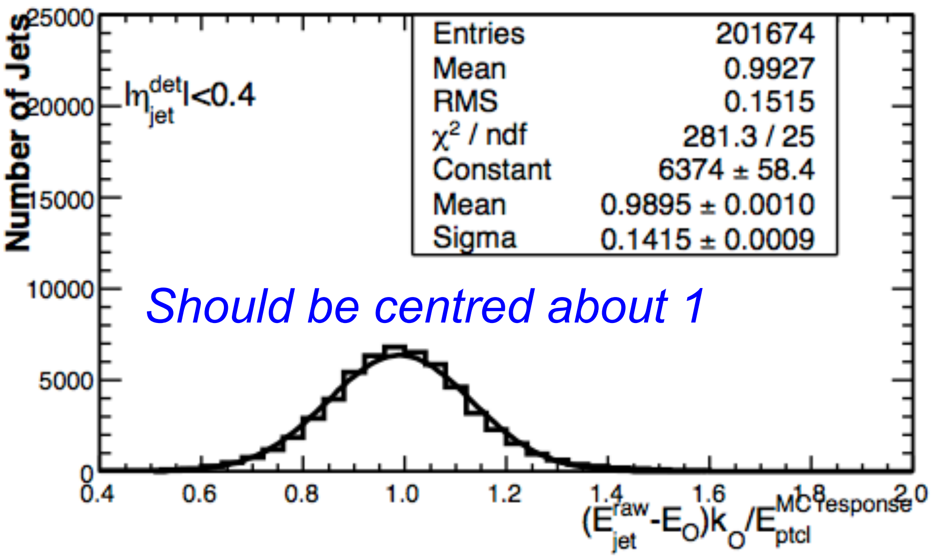
DØ Coll, Section 14 in arXiv:1312.6873 [hep-ex], submitted to NIM

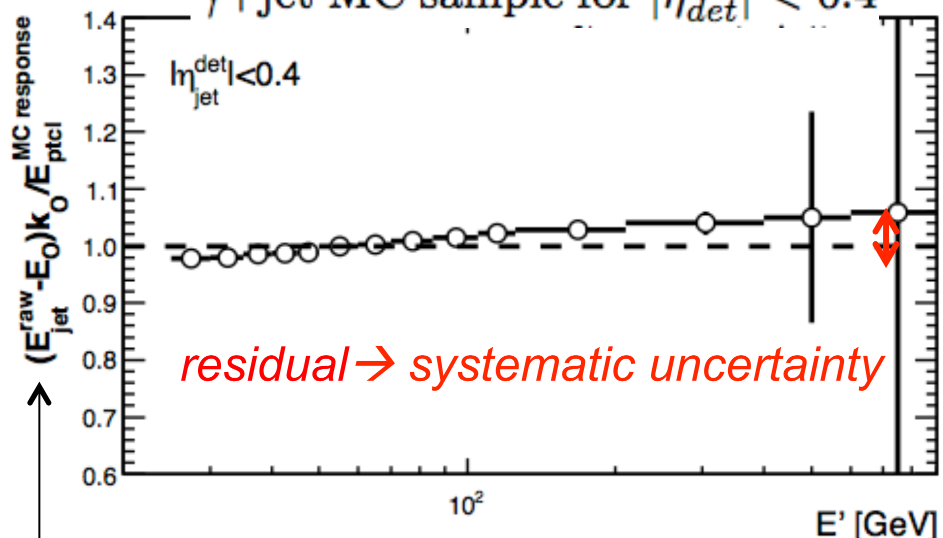
Flavor-dependent correction

- Few example fits of MC response for three particles:



- **Closure test: check that $\sum_i E_i \cdot R_i^{MC}$ describes the raw offset-corrected energy $(E_{jet}^{raw} - E_O) \cdot k_O$ correctly**
  - **Example:**





E' is given by $p_T^{\gamma} \cdot cosh(\eta^{jet})$

$$y = (E_{jet}^{raw} - E_O) \cdot k_O / \sum_i E_i \cdot R_i^{MC}$$

E_{jet}^{raw} is the raw jet energy

E_O is the offset correction for noise and pile-up (in- and out-of-time)

k_O is the correction for noise suppression bias & only needed to perform closure test

Flavor-dependent correction

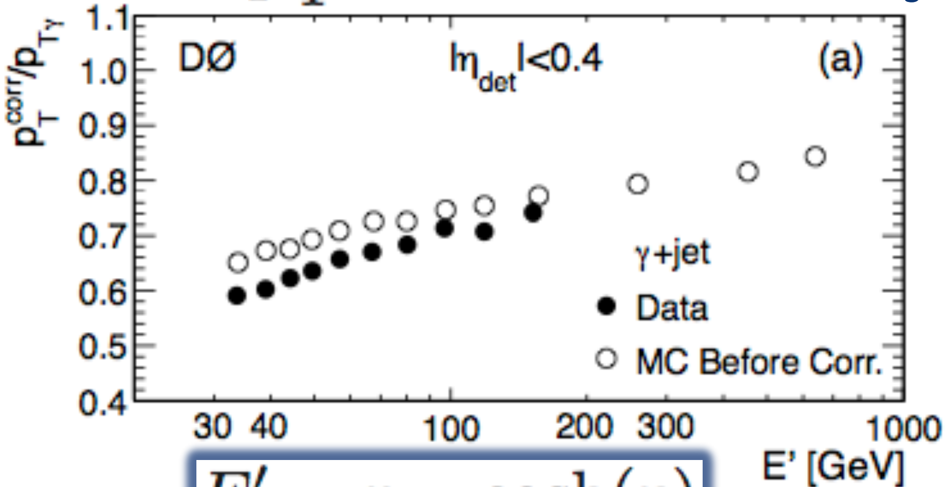
- Deriving single particle responses in data:
  - For e, μ, γ:
    - Assume perfect modelling of detector response by MC
      - Systematic uncertainty estimated on this assumption
  - For hadrons $\pi^{\pm}$, $K^{\pm}$, K_0^S, K_0^L, $p^{\pm}$, n and Λ:
    - Basic shapes in *E*,*η* (i.e. per-hadron fit parameters) from MC
    - Fit unique (not per-bin or hadron) parameters *A, B, C*:

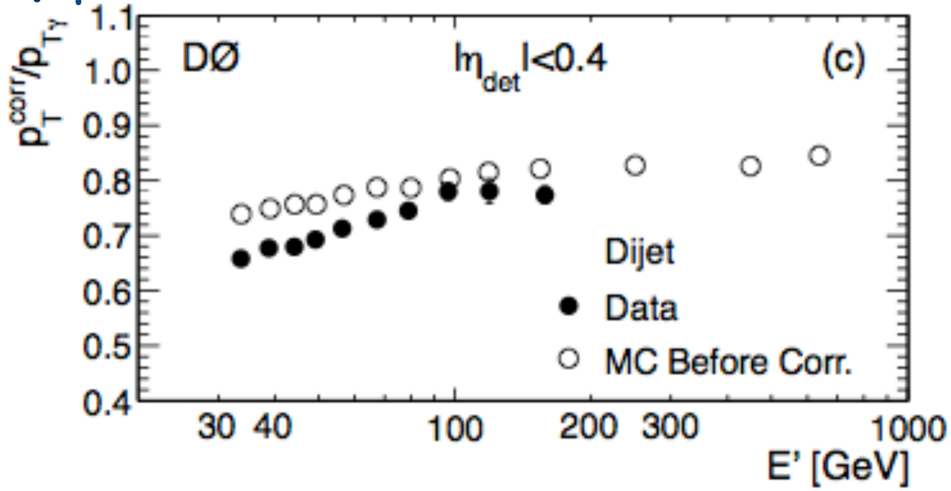
$$R_h^{data} = C \cdot p_h^0 \cdot \left[1 - A \cdot p_h^1 \cdot (E/0.75)^{p_h^2+B-1}\right] \text{ if } p_T > m_h;\ 0 \text{ if } p_T < m_h$$

      - Identical to R_h^{MC} for $A = C = 1$ and $B = 0$
    - Find an optimal set of *A, B, C* to tune MC jet responses such that the ratios $p_{T,\ corr}^{jet}/p_T^{\gamma}$ are consistent in data and MC
      - Use the particle composition of the jet from MC as a function of the jet energy and η
      - Measure $p_{T,\ corr}^{jet}/p_T^{\gamma}$ in data and MC samples enriched with isolated photons ("γ+jet") and inverted photon isolation ("dijet")
      - Here, $p_{T,\ corr}^{jet}$ is reconstructed jet p_T with offset correction

Flavor-dependent correction

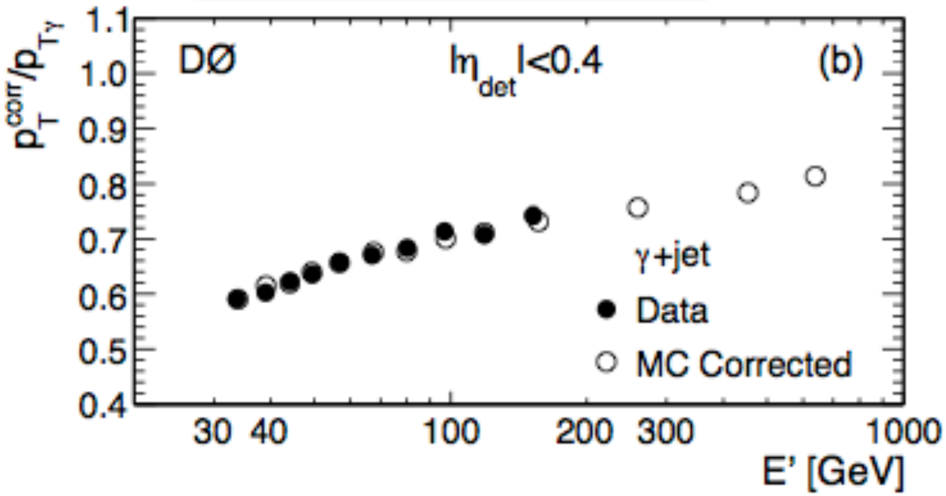
- **Closure test of the flavour-dependent response:**
  - p_T^{corr} is reconstructed jet p_T with offset correction

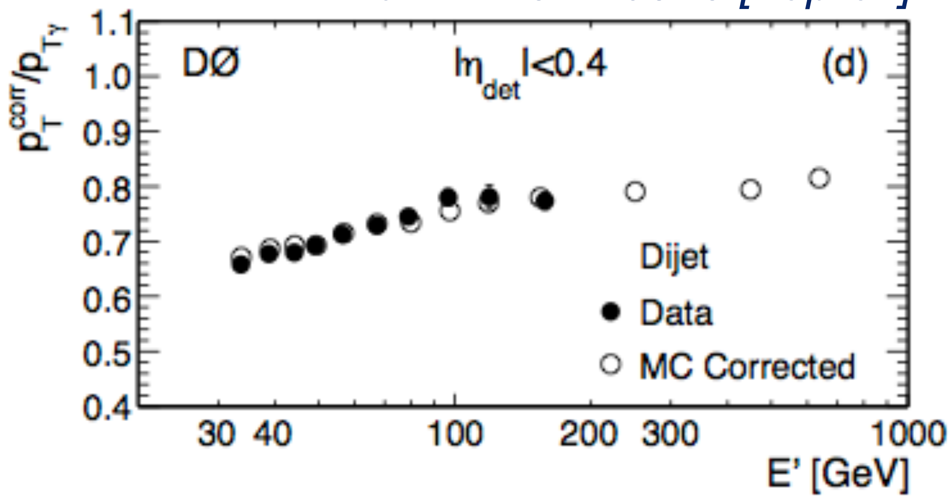




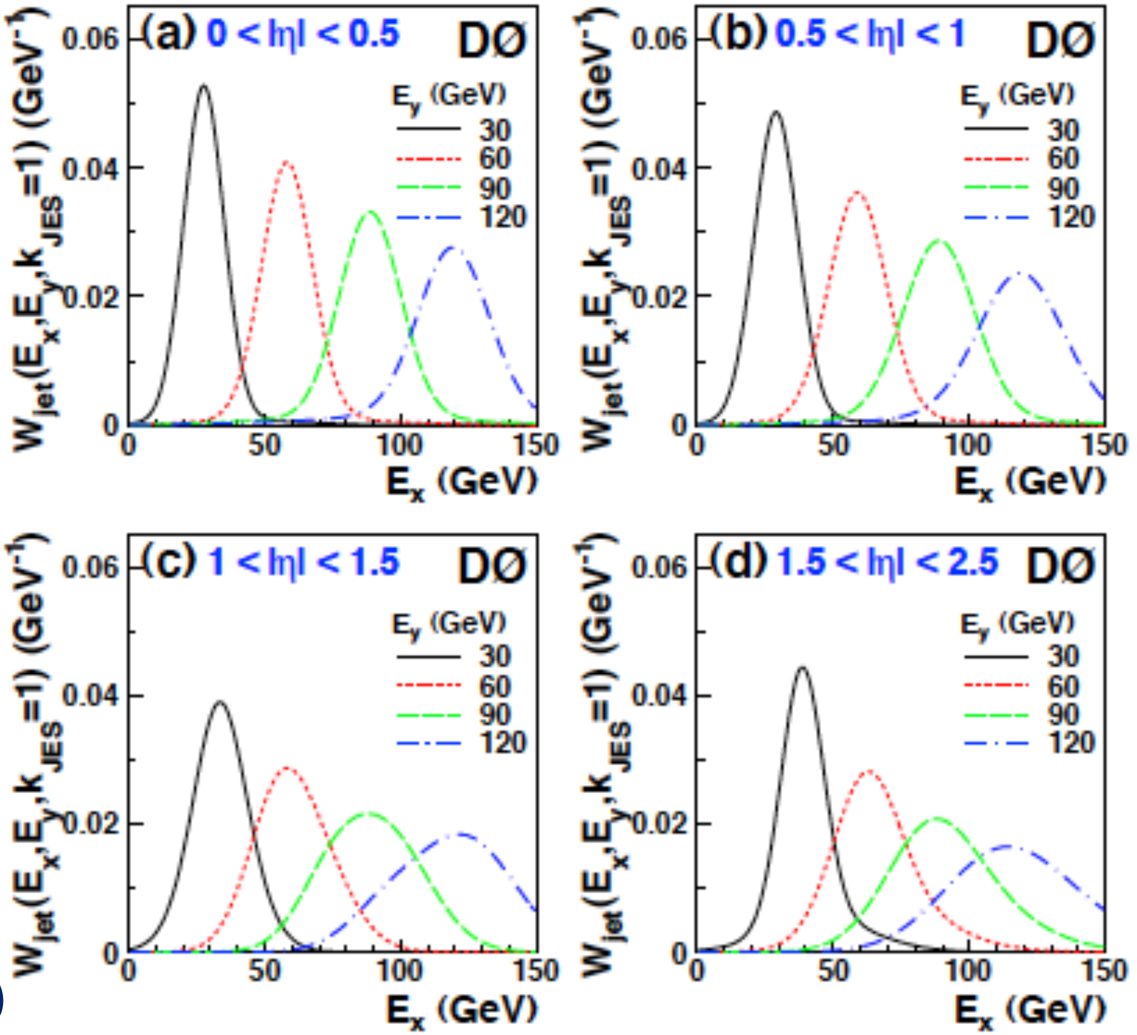
$$E' = p_{T\gamma}\cosh(\eta)$$

arXiv:1312.6873 [hep-ex]



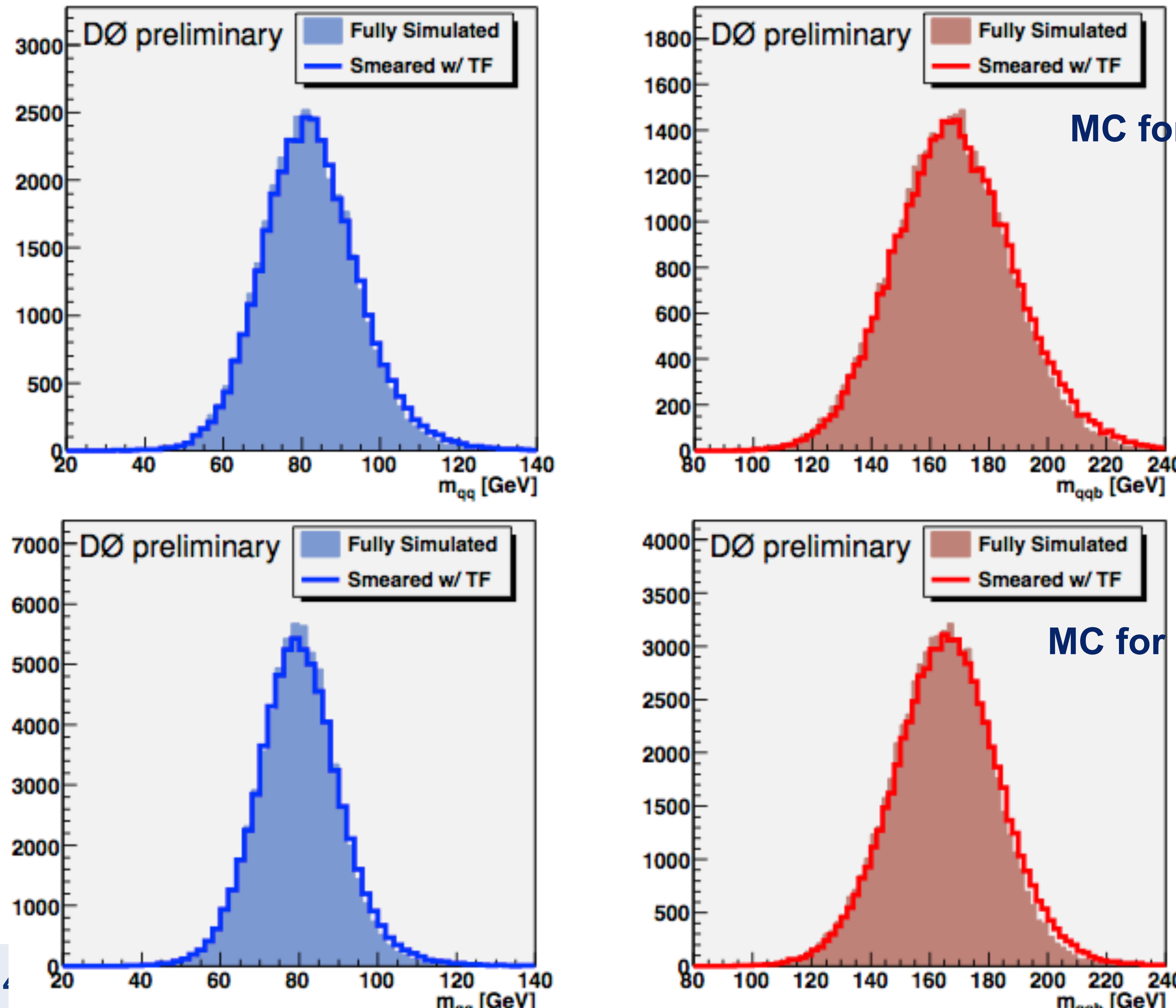


- The **Transfer Functions** $W(x, y; JES)$ relate parton-level quantities to reconstruction-level ones
- Some typical examples for light quark jets from [1]



[1] *DØ Coll, PRD **84**, 032004 (2011)*

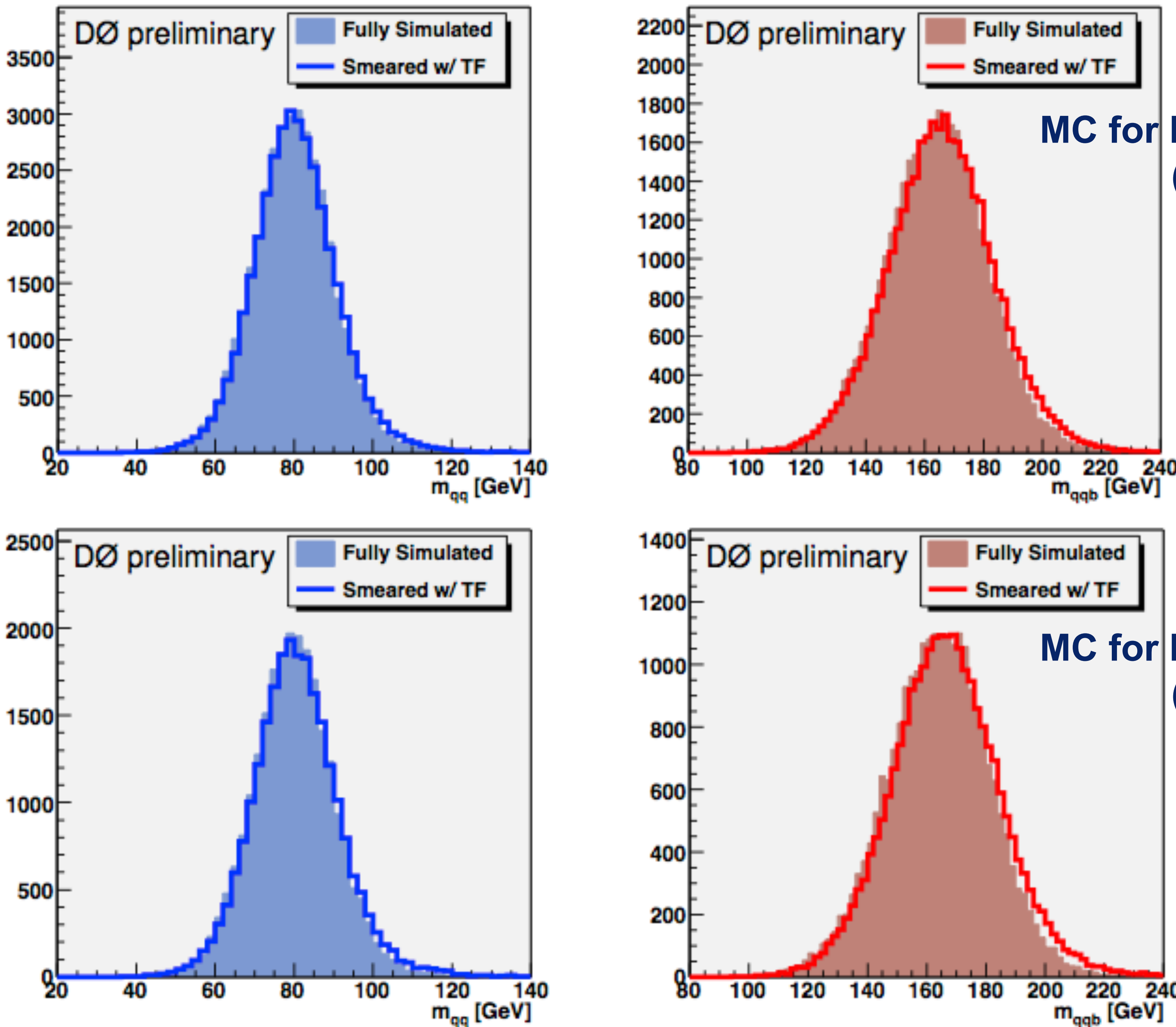
Transfer function validation



MC for Run IIa
(1.1 fb^{-1})

MC for Run IIb1
(1.3 fb^{-1})

Transfer function validation



MC for Run IIb2 ($3.0\ fb^{-1}$)

MC for Run IIb3 ($4.4\ fb^{-1}$)

Calibration of method response

- Calibrate the method with pseudo-experiments (PE)
  - Keep in mind we use P_{sig} and P_{bkg} obtained from first principles and parametrised detector response
    - → calibration imperative
    - (in template methods this is merely a consistency check)
  - Each PE consists of N_{data}
  - PEs include:
    - W+jets background (dominant, adjusted according to f)
    - MJ background (11% and 4% for e and mu+jets)
    - (Other backgrounds contribute few % in each channel)
  - Construct PEs according to signal fraction (f) measured from data
  - 1000 PEs performed at each calibration point

Extracting signal fraction from data

- We measure (after calibration):

Epoch	Channel	Signal fraction	$\sigma_{t\bar{t}}$ (pb)
Run IIa	e+jets	0.72	8.9
	μ+jets	0.65	7.8
Run IIb1	e+jets	0.77	7.6
	μ+jets	0.66	6.8
Run IIb2	e+jets	0.68	7.8
	μ+jets	0.66	7.5
Run II3+4	e+jets	0.56	7.6
	μ+jets	0.75	8.0
Run II	e+jets	0.63	7.8
	μ+jets	0.70	7.6

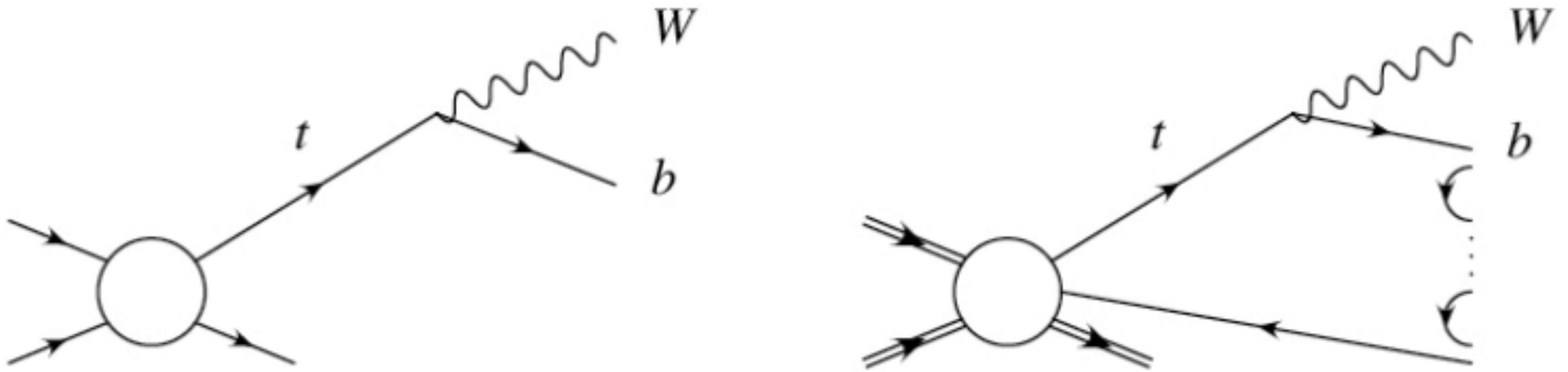
- Values in good agreement with $\sigma_{t\bar{t}} = 7.78^{+0.77}_{-0.64}$ pb [1]

Typical statistical+calibration uncertainty on signal fraction: 1%, on σ_{tt}: about 0.1 pb

*[1] DØ Collaboration, Phys. Rev. D **84**, 012008 (2011).*

Which m_{top} do we measure?

- *(I only want to refresh our memory here)*
- The top **mass** is **not an observable** per se and has to be inferred from its effect on kinematic observables
- The mass **cannot be well-defined at LO**
- The **pole mass** corresponds to our physical intuition of a stable particle
  - m_{top} is the "pole" in the top quark propagator
    - Although this is not fully correct (hadronisation effects)
  - The pole mass can never be determined with **precision** better than Λ_{QCD}:



Which m_{top} do we measure?

- Other popular mass definition schemes:
  - e.g. modified minimal subtraction scheme ($\overline{MS}$), also referred to as running mass $m_{top}(\mu_r)$
    - The μ_r dependence can be used to absorb logarithmic corrections through resummation (in specific cases)
      - better behaviour of perturbative predictions
  - The $\overline{MS}$ mass can be translated into the pole mass at any fixed order of perturbation theory
- What we typically measure at hadron colliders, is:
  - Neither the $\overline{MS}$ mass, nor the pole mass → m^{MC}
  - "Close" to the pole mass
    - "Close" not quantified yet
- True also for NLO generators like e.g. powheg
  - finite width effects of top propagator are not simulated, but generated via reweighting