Differential top quark cross sections at D0 and their implications

- Introduction
- Analysis Strategy
- Event Selection
- Results & Implications
- Conclusions & Outlook

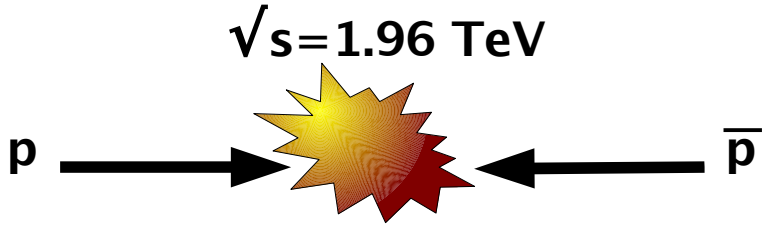
Fermilab

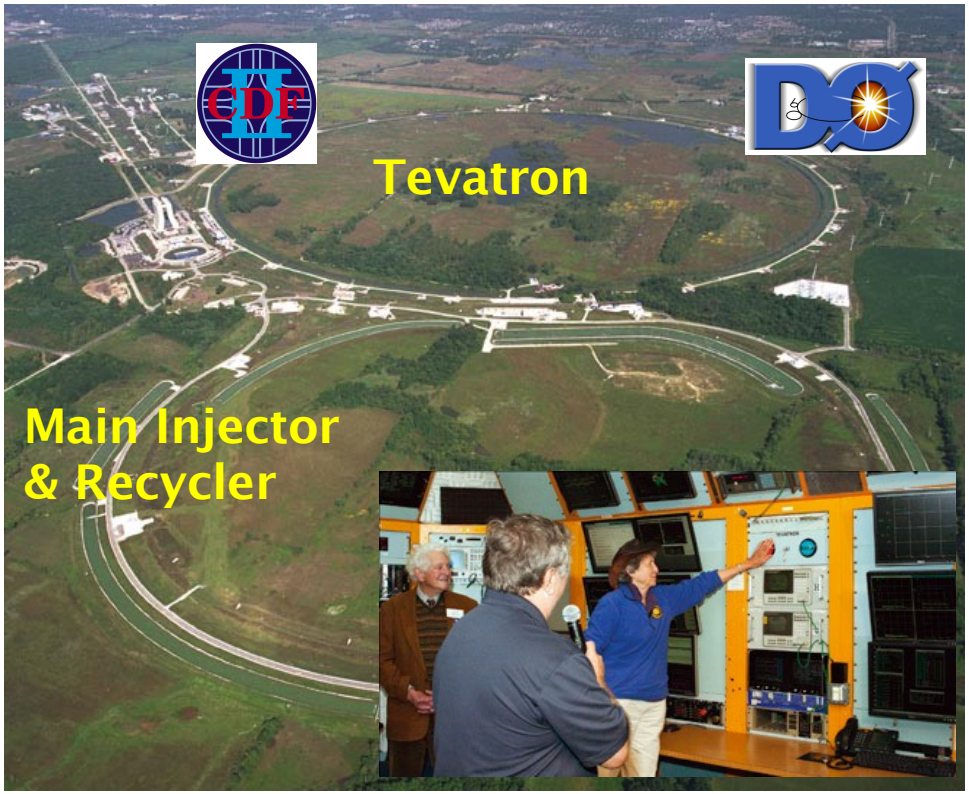
Andreas Jung

February 6th, 2014

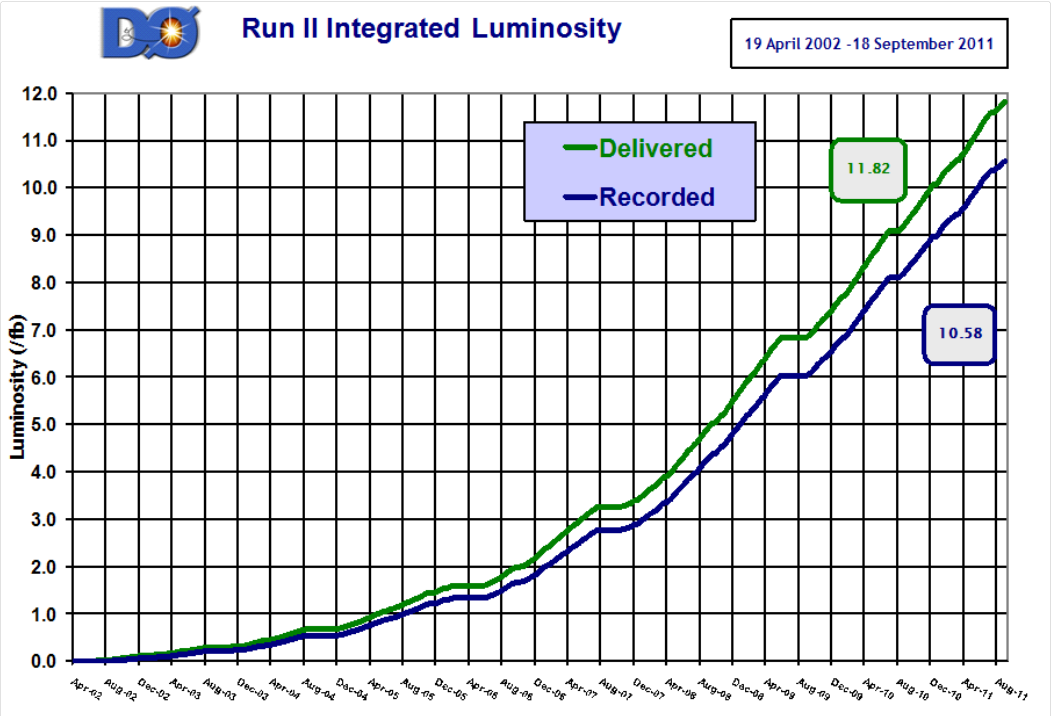
Joint Experimental & Theoretical Physics Seminar

Tevatron – Introduction





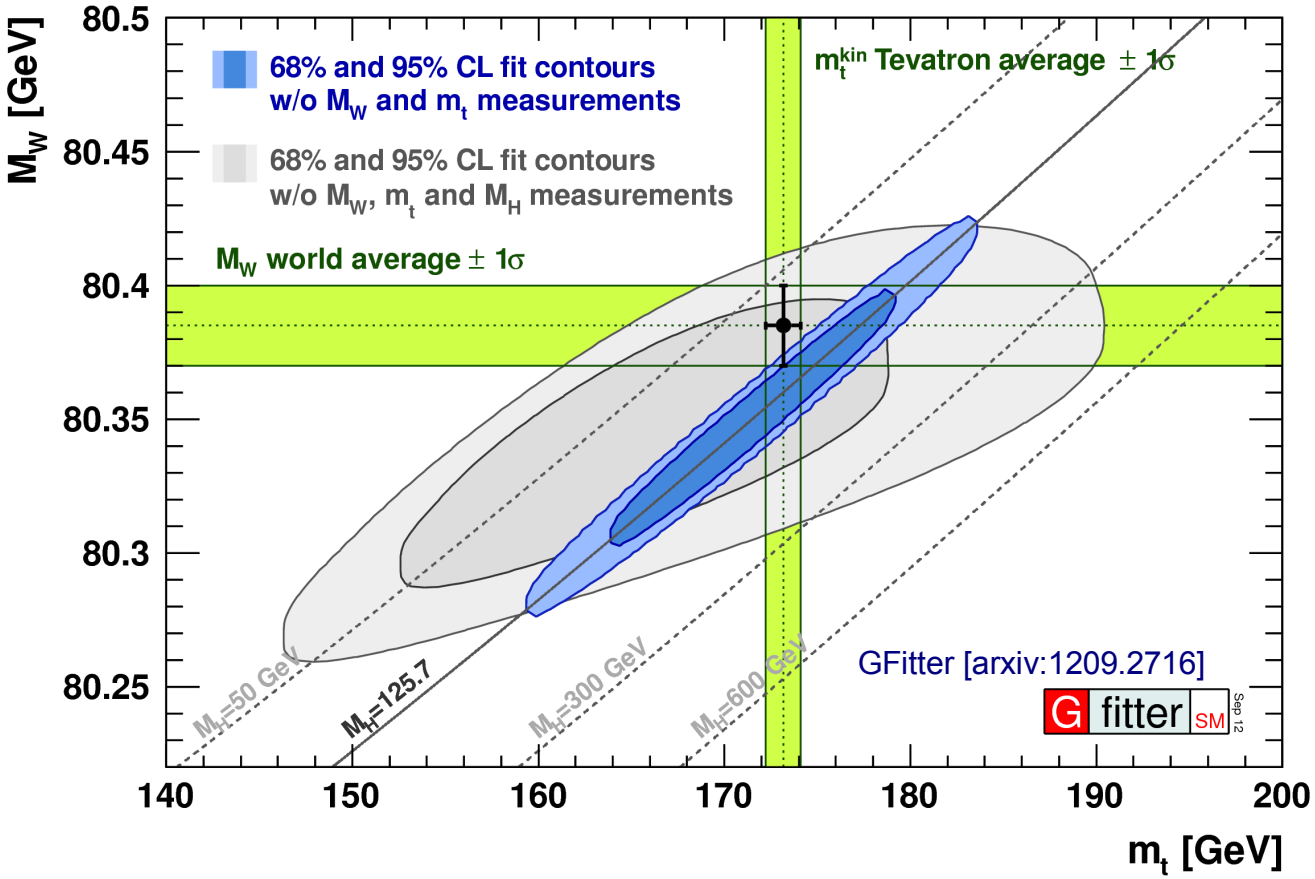
- Peak luminosities: 3 – 4 x 10^{32} $cm^{-2}s^{-1}$
- ~10 fb^{-1}/experiment recorded
- This measurement: 9.7 fb^{-1}



Big thanks to the Accelerator Division!

Tevatron – Strengths

- Worlds largest $p\bar{p}$ data set for a long time
- Well understood detectors
- Less pile-up effects than LHC
- Initial state allows for unique measurements



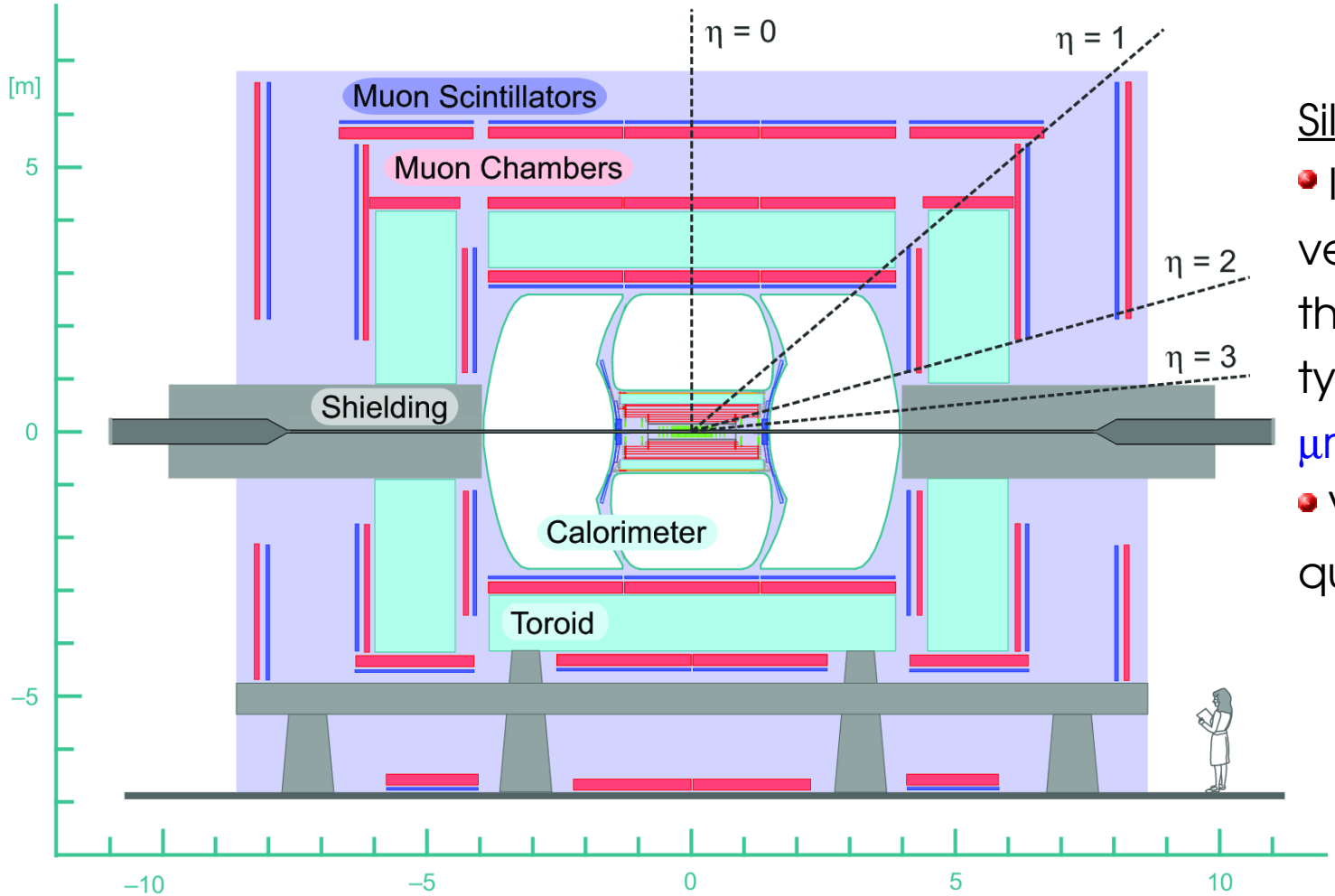
top mass measurements:

- Systematically limited
- Signal model uncertainties dominate:
  → differential top quark cross sections can help to understand these

The D0 Detector

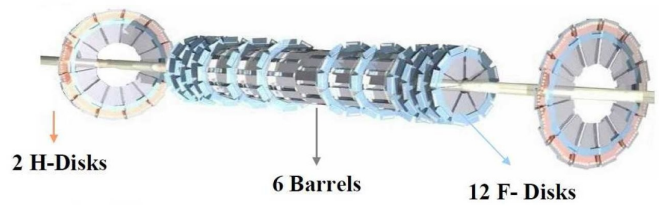
General purpose 4π detectors:

- **Tracker**: Detection and momentum measurement for charged particles
- **Calorimeter**: Identification and energy measurement of jets and electrons
- **Muon system**: Identification and momentum measurement of muons



Silicon Micro-strip Tracker:

- Identifies secondary vertices, typical resolutions for the impact parameter of typical tracks between 20-40 μm
- Vital for identification of *b* quarks

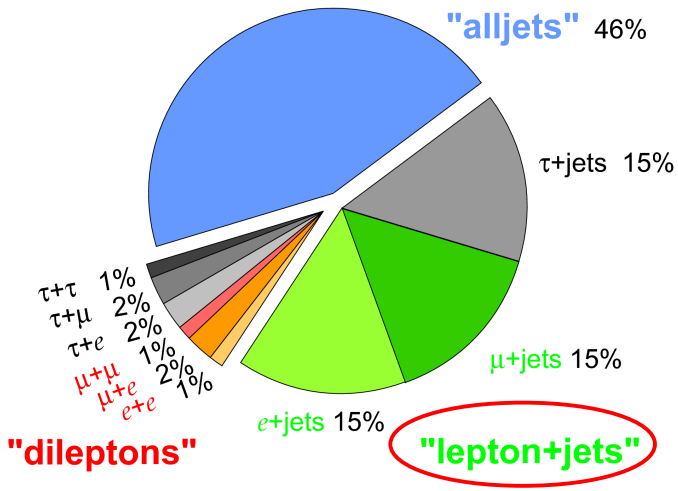


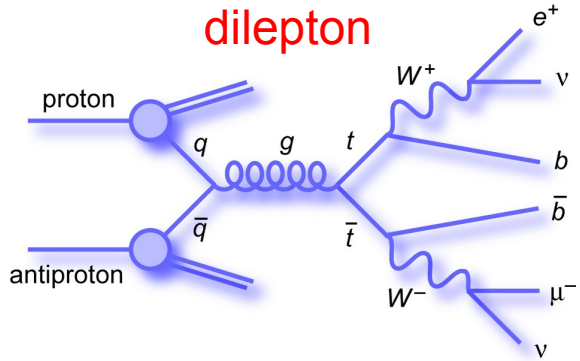
NIM A 634:8-46 (2011)

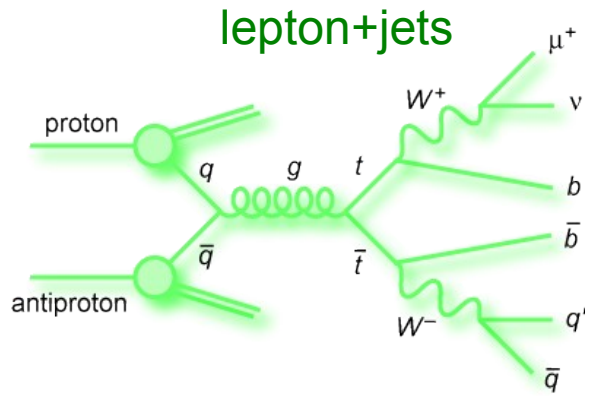
Top quark Introduction

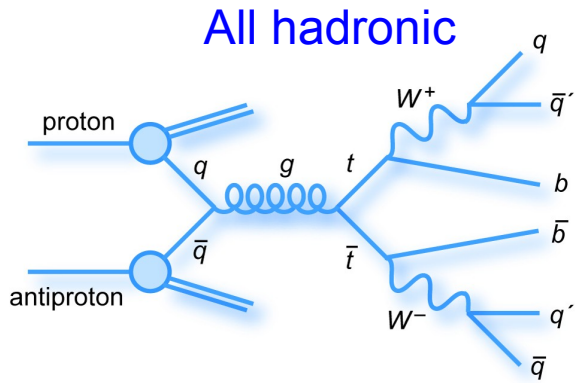
- Top is the heaviest fundamental particle discovered so far:
  → m_t = **173.2 ± 0.9 GeV** [arxiv:1305.3929]
- Top plays special role in EWSB ?
  → λ_t = **0.995 ± 0.005**
- Lifetime: $\tau \approx 5\times10^{-25}$ s << Γ_{QCD}
  → **Observe bare quark**
- Different decay channels:

Top Pair Branching Fractions









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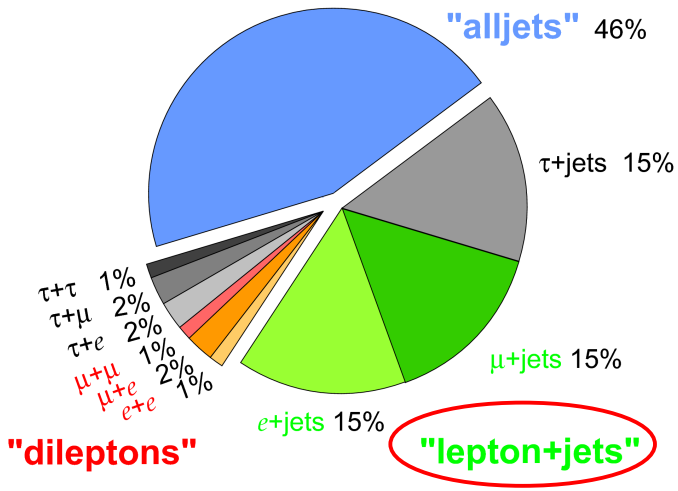
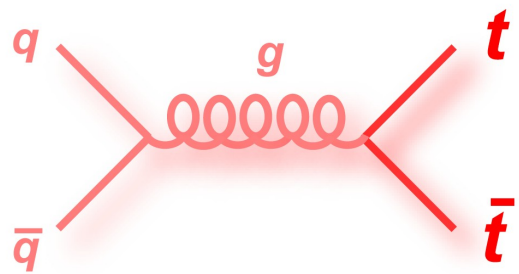
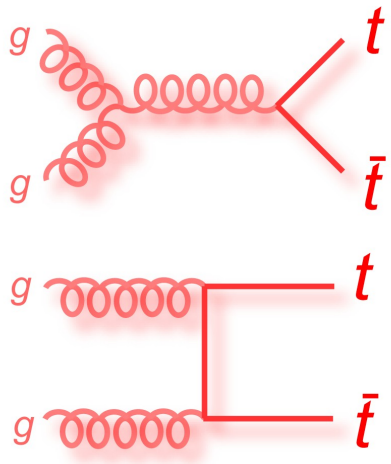


- <u>Strong interaction:</u> Top pairs



$q\bar{q}$ annihilation



gg fusion

<u>Tevatron vs. LHC:</u>

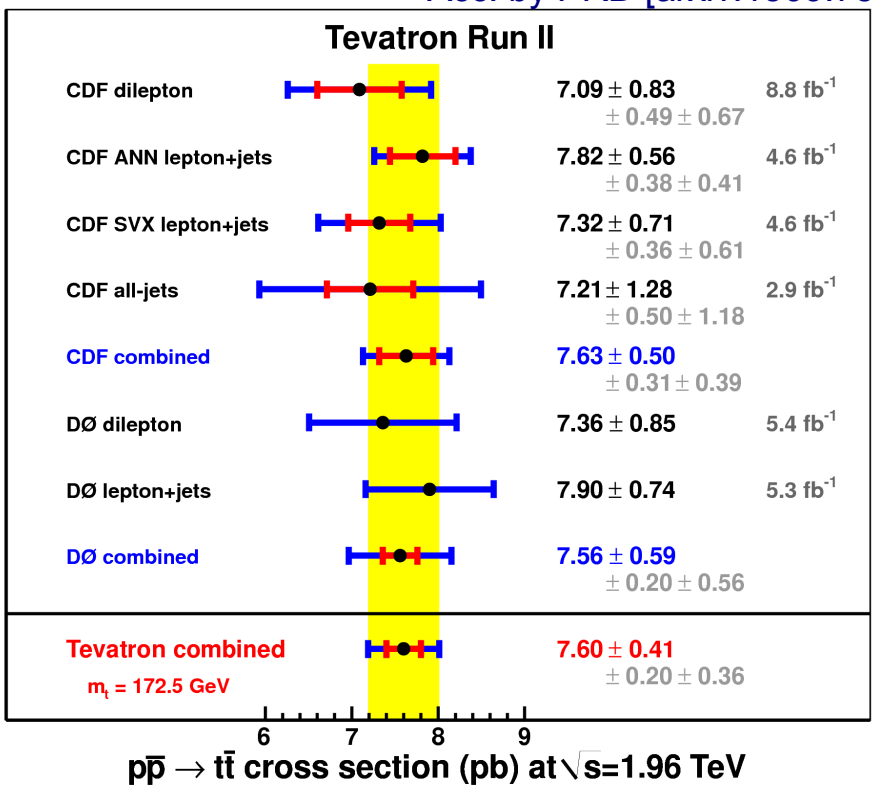
	(1.96 TeV	7/8 TeV)
$q\bar{q}$:	~85%	~15/13% (~10%, 14 TeV)
gg:	~15%	~85/87% (~90%, 14 TeV)

Top quark production

Tevatron production cross section:

- CDF inputs: 4 measurements, < 8.8 fb^{-1}
- D0 inputs: 2 measurements, < 5.4 fb^{-1}
- Correlations taken into account

Acc. by PRD [arxiv:1309.7570]



5.4% experimental precision !

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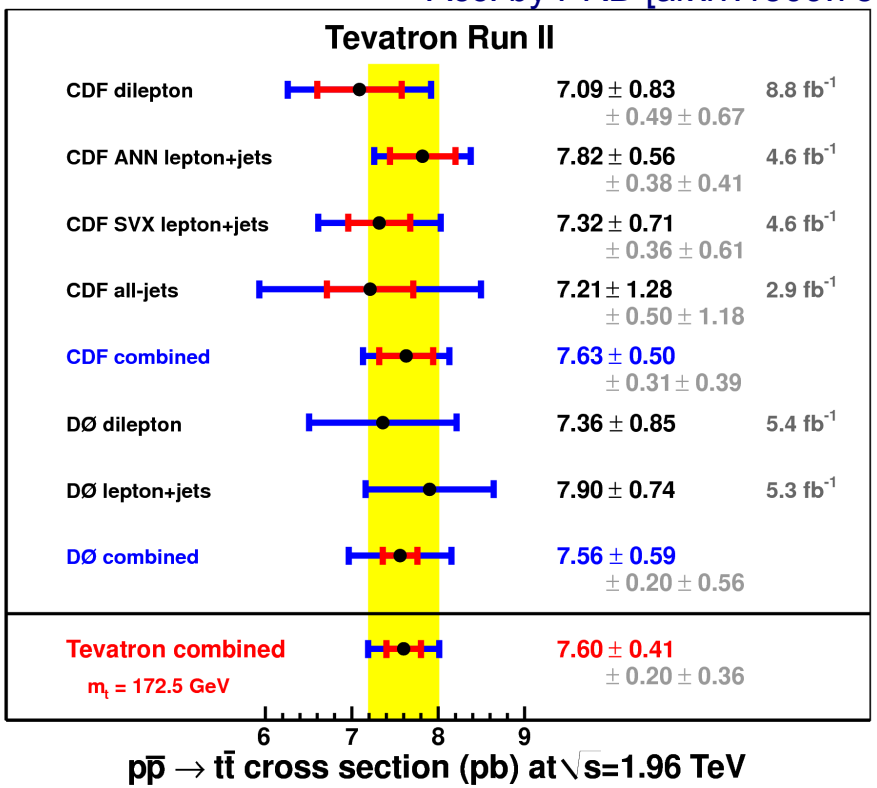

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Theory prediction of $\sigma(t\bar{t})$:

- Precision is a real challenge to experiments:
  - ~ 3.5 % for Tevatron
  - ~ 4.4 % (4.2%) for LHC 7 (8) TeV

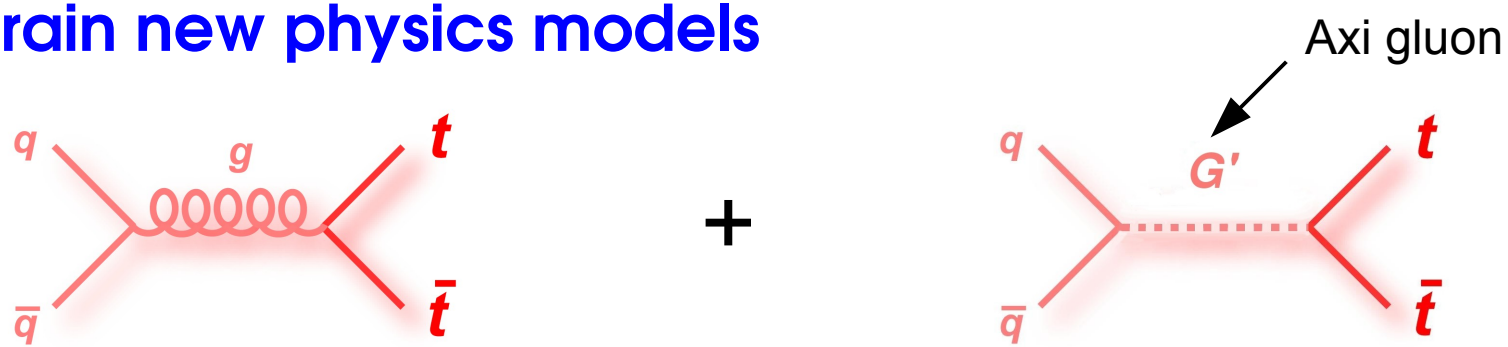
(Czakon, Fiedler, Mitov); [arxiv:1303.6254]
Phys. Rev. Lett. 110, 252004 (2013)

Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$^{+0.110(1.5\%)}_{-0.200(2.8\%)}$	$^{+0.169(2.4\%)}_{-0.122(1.7\%)}$
LHC 7 TeV	172.0	$^{+4.4(2.6\%)}_{-5.8(3.4\%)}$	$^{+4.7(2.7\%)}_{-4.8(2.8\%)}$
LHC 8 TeV	245.8	$^{+6.2(2.5\%)}_{-8.4(3.4\%)}$	$^{+6.2(2.5\%)}_{-6.4(2.6\%)}$

- Need high experimental precision to 'compete' with theory uncertainties
- Differential top quark cross sections are first step towards precision inclusive $\sigma(t\bar{t})$ measurement

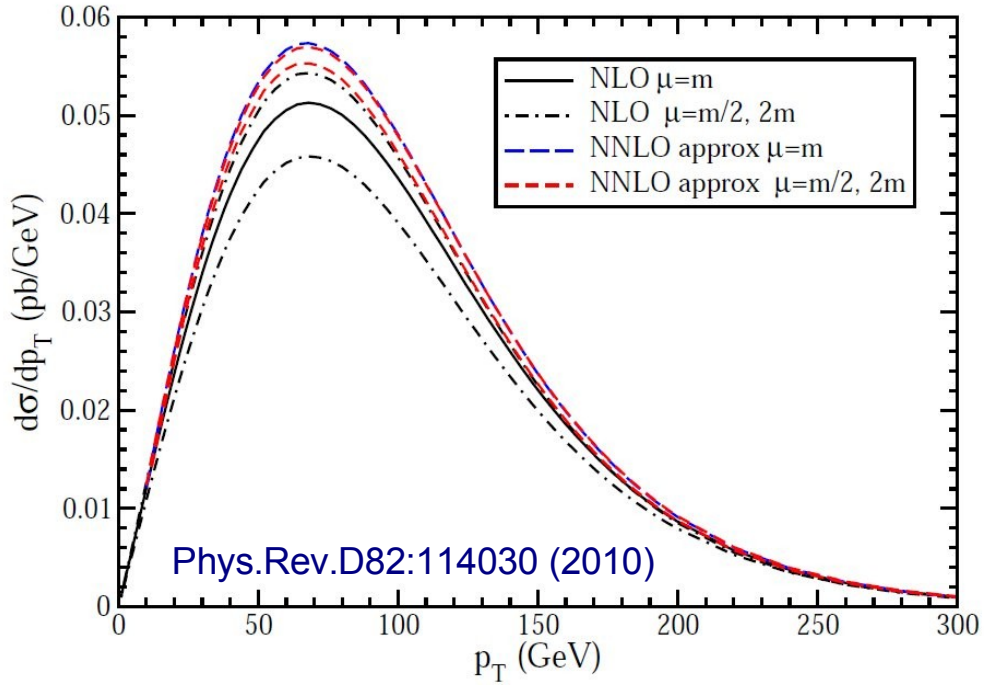
Theory

- Differential cross section distributions **test QCD calculations** and **enhance our understanding** of top quark production:
  - **Constrain new physics models**



SM $q\bar{q}$ annihilation

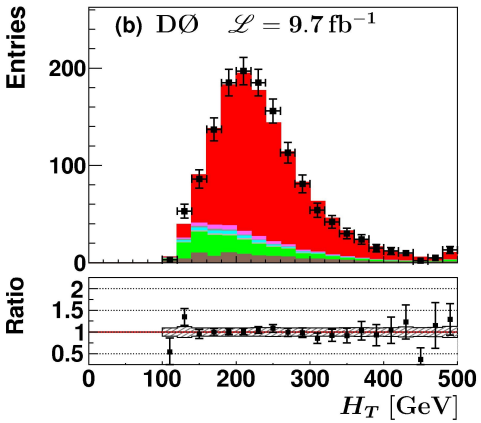
- Differential cross section predictions at approximate NNLO pQCD:
  - Smaller uncertainties
  - No calculations at full NNLO yet



<u>Remark:</u> Experimental determination of cross sections use theory predictions at tree or NLO for extrapolation

Measurement strategy

I. Event selection & Sample Composition



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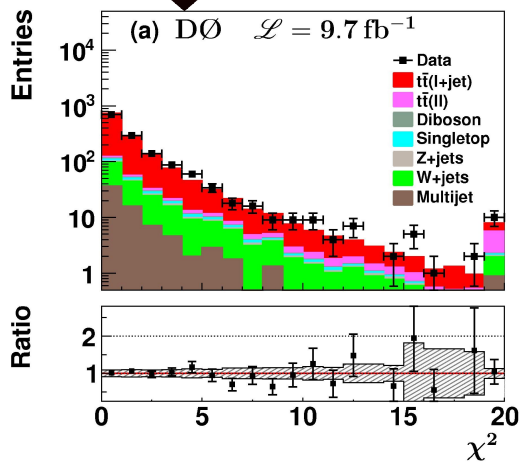

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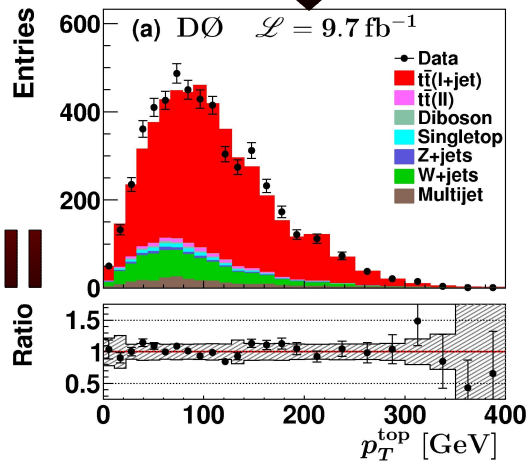

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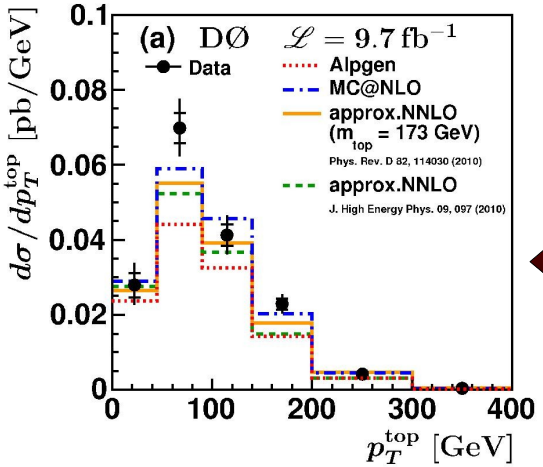
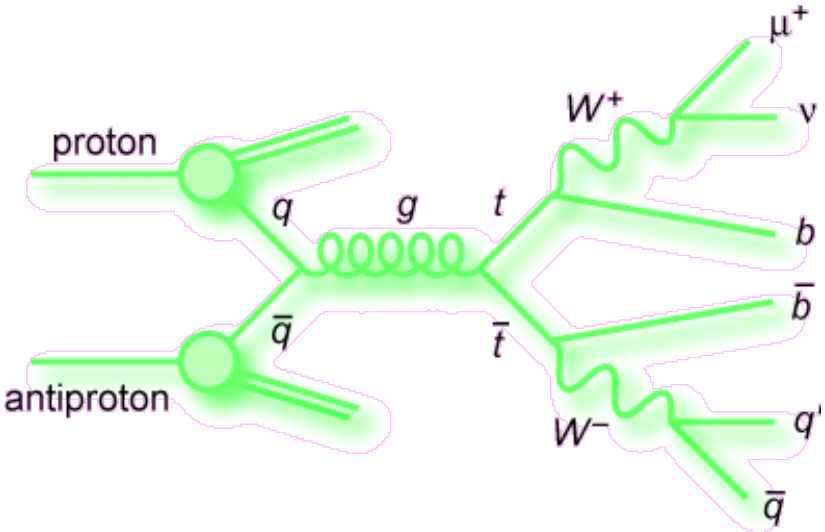


Event selection

- Lepton+jets decay channel: **Full Run II data recorded by D0, 9.7/fb**



variable	kinematic range
lepton $\eta(\ell)$	$\lvert\eta(e)\rvert < 1.1$ and $\lvert\eta(\mu)\rvert < 2.0$
lepton $p_T(\ell)$	$p_T(\ell) > 20$ GeV
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+ additional quality cuts

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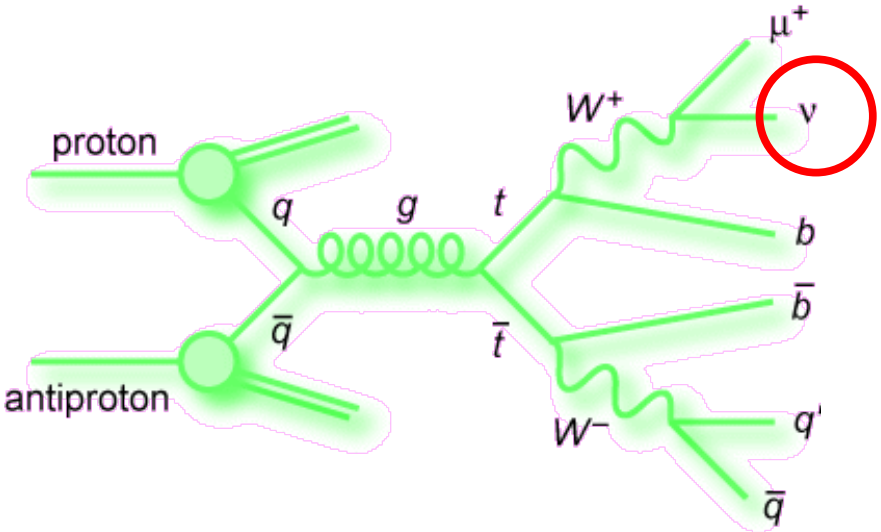

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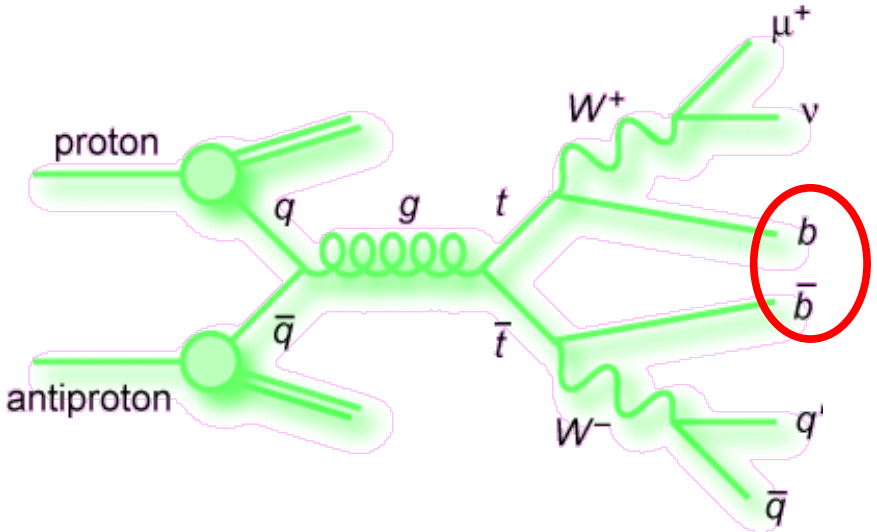

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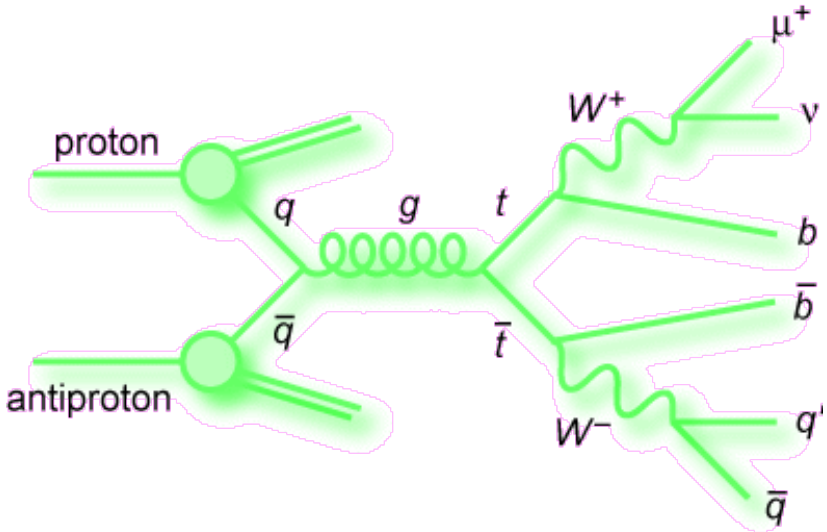

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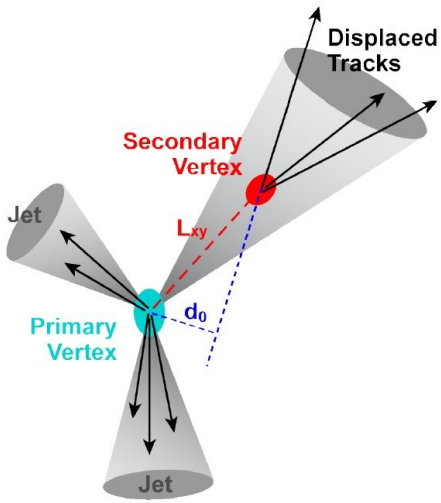
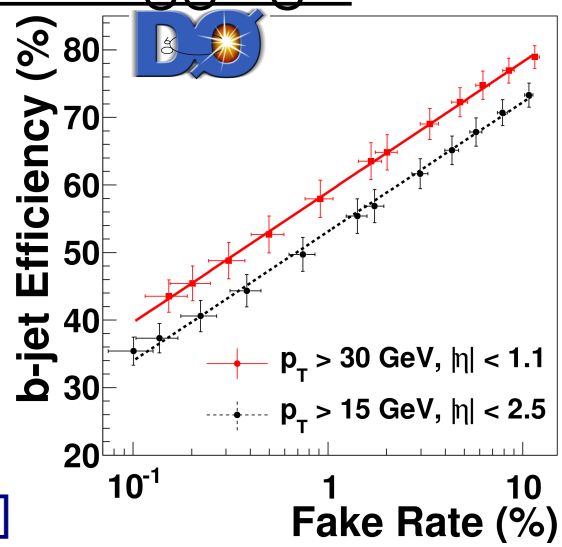
- One of the most important experimental techniques "b-tagging":



- *b* quarks hadronize before decaying into a *c* quark:
  - → Long-lived *b* hadrons decay some mm away
  - → Multivariate Analysis technique

Subm. to NIM [arxiv:1312.7623]



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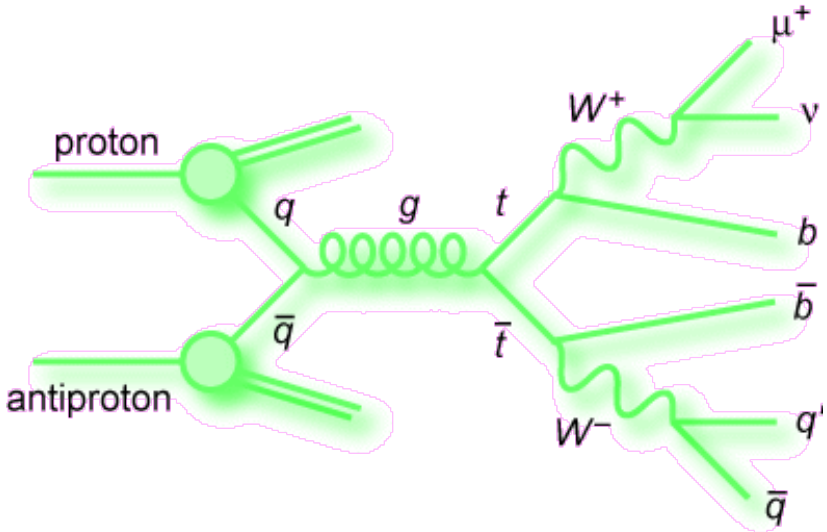

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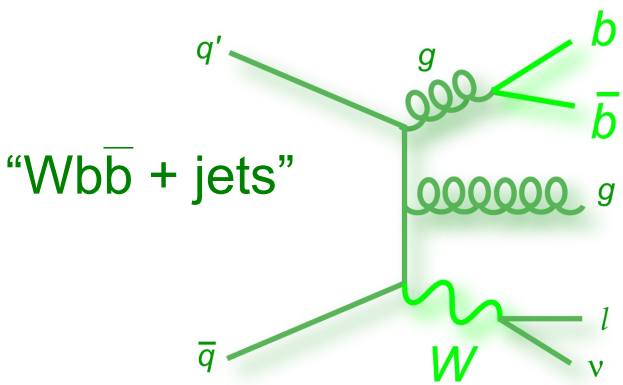
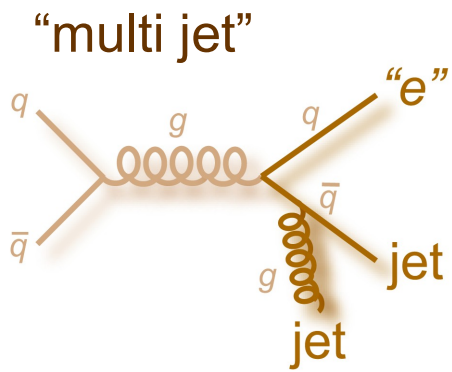
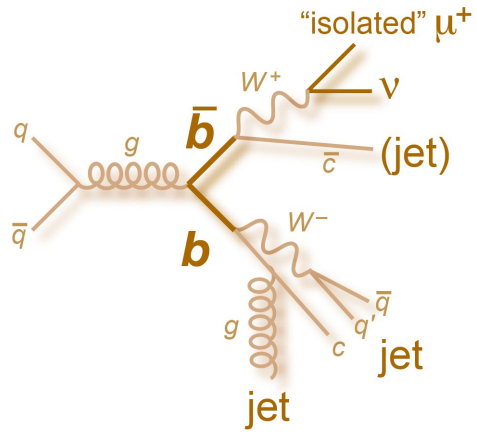
- Background from other physics processes and instrumental sources, e.g.







- Multi jet and W+heavy flavor (Whf) contribution derived from data

Sample composition

- W + heavy flavor + jets contributions constrained by using the 2, 3, and >= 4 jet-bin output distribution of the multi-variate *b*-ID technique
- Apply 0.15 ("medium") cut on output values

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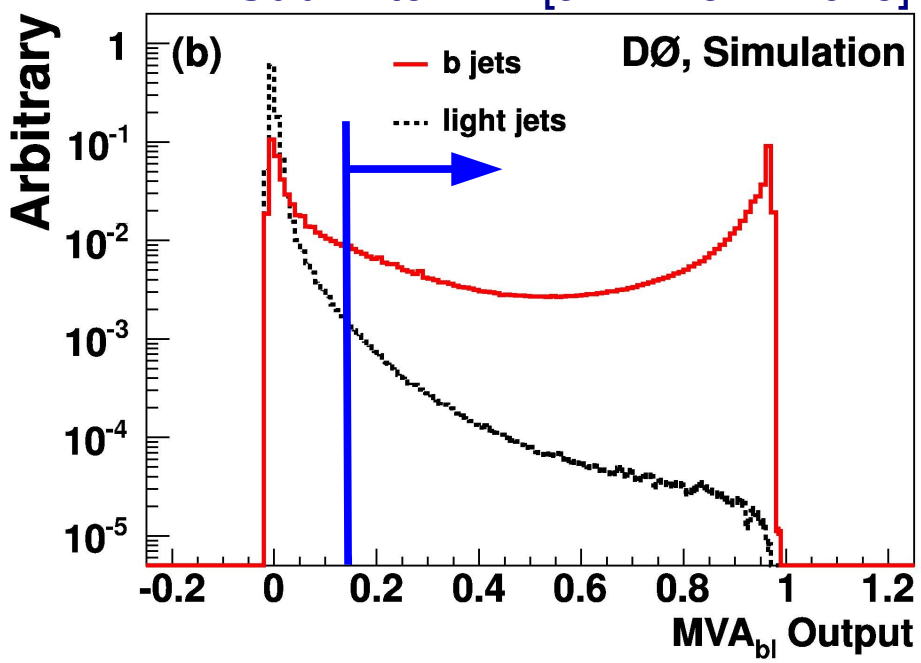

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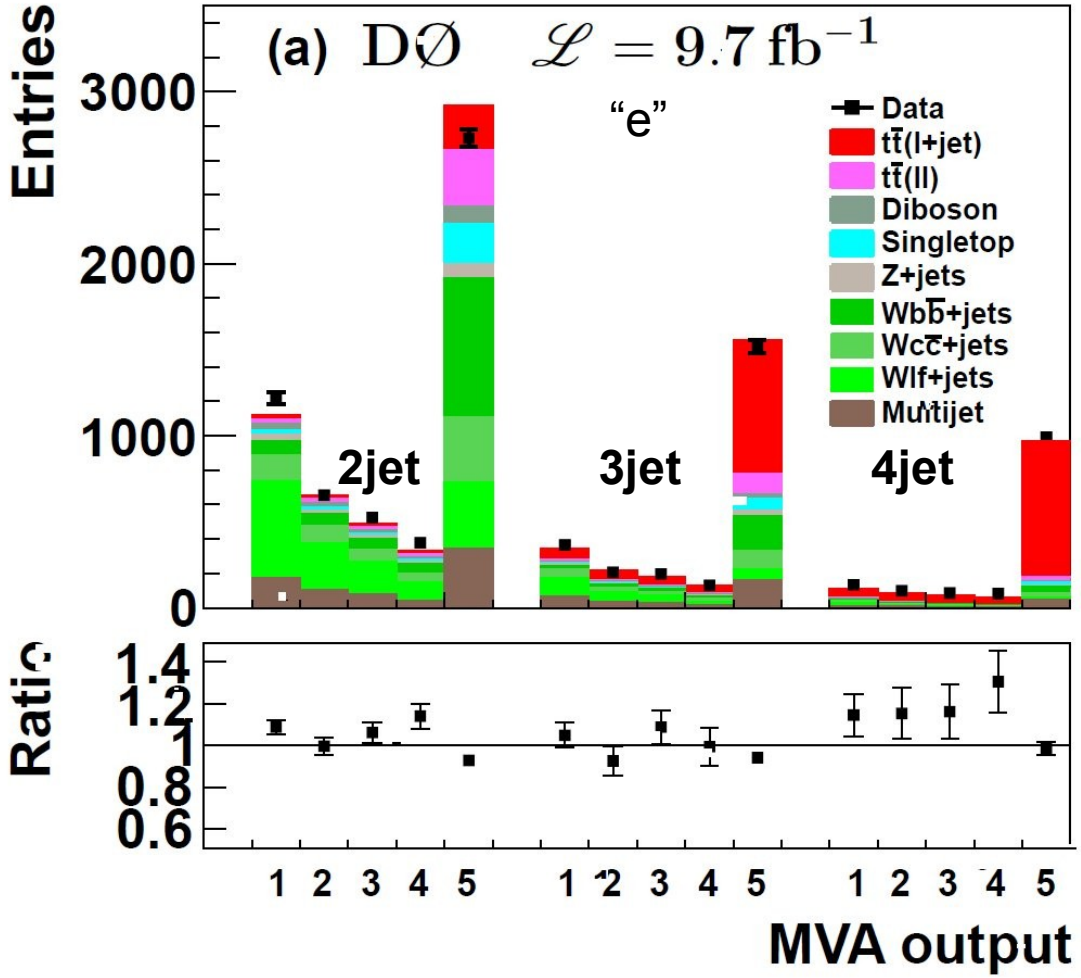
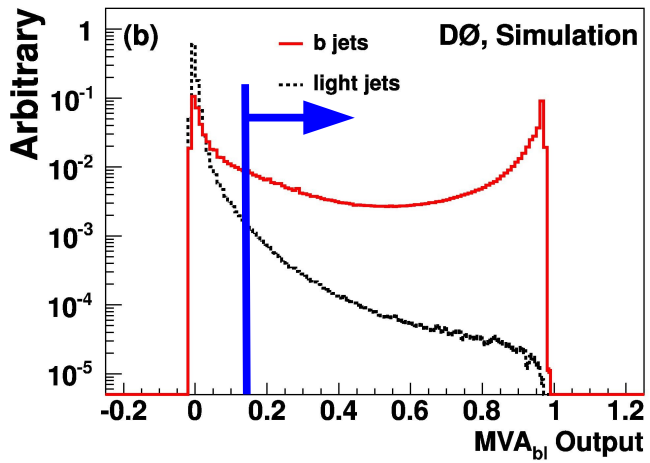
- Simultaneous fit of *Whf*+jets & $t\bar{t}$ contribution:





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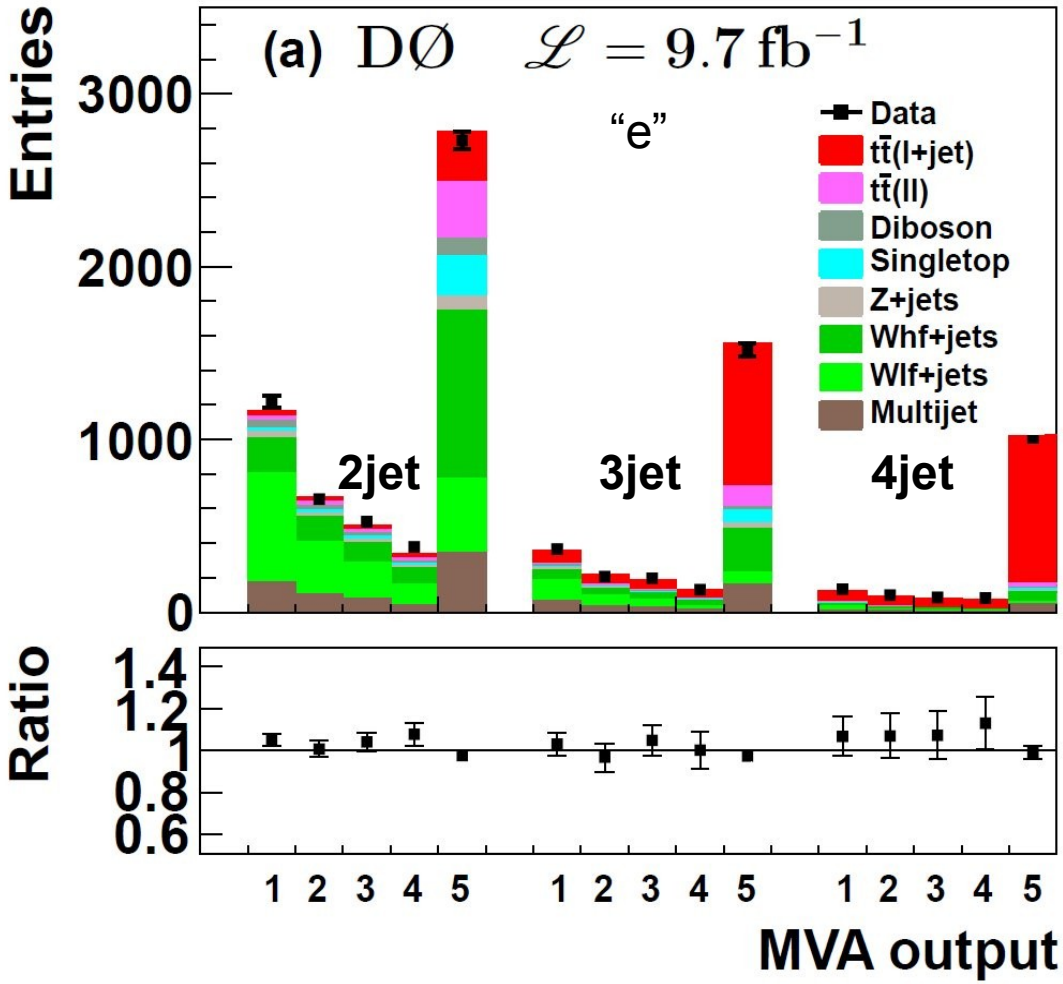


- Result: *k(Whf+jets) = 0.89 ± 0.08* applied in addition to NLO *k*-factor of 1.47 derived using MCFM

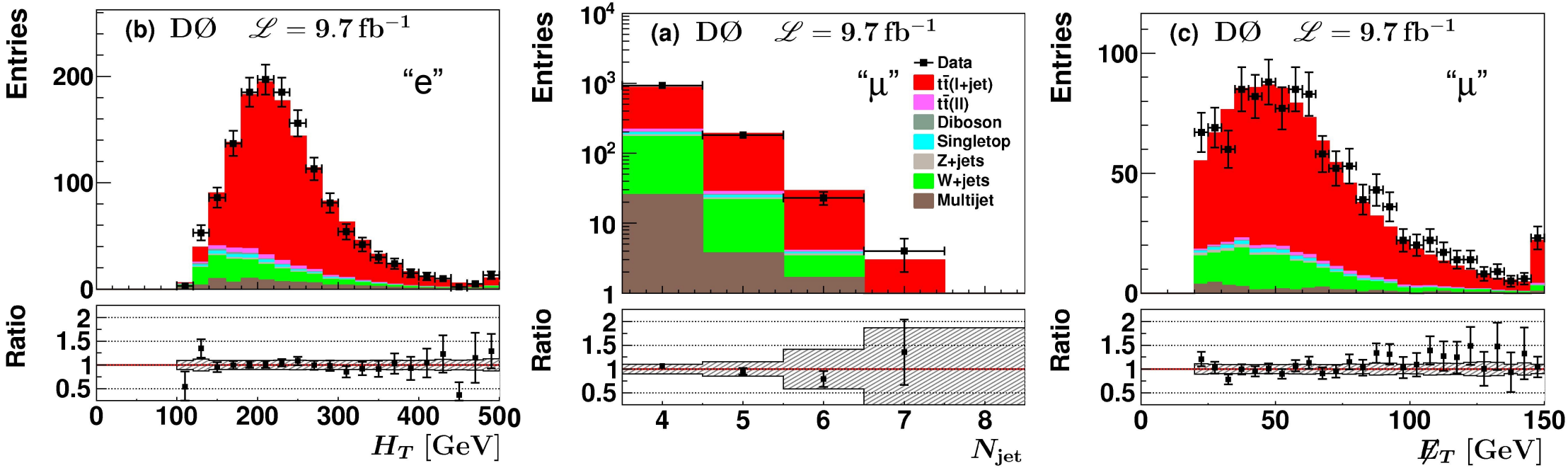
- Yields:

Process	μ+jets	e+jets
Multijet	31.1 ± 10.0	75.1 ± 13.0
W+jets	164.9 ± 3.1	148.8 ± 2.6
Diboson	9.1 ± 0.3	10.5 ± 0.3
Z/γ^*+jets	11.9 ± 0.4	12.4 ± 0.4
Single top	16.1 ± 0.2	21.8 ± 0.3
$t\bar{t}$, $\ell\ell$	22.6 ± 0.2	33.5 ± 0.3
$\sum$ bgs	254.4 ± 10.5	302.1 ± 13.3
$t\bar{t}$, ℓ+jets	838.7 ± 3.2	1088.7 ± 3.8
$\sum$ (sig + bgs)	1093.1 ± 11.0	1390.8 ± 13.8
Data	1137	1403

(assuming the measured $t\bar{t}$ cross section)

Control distributions

- Now check the signal region to measure differential cross sections: e or μ + ≥ 4 jets



- More control distributions in the backup
- Very good description/modeling of the data within systematic uncertainties
  (assuming the measured $t\bar{t}$ cross section)

Measurement strategy

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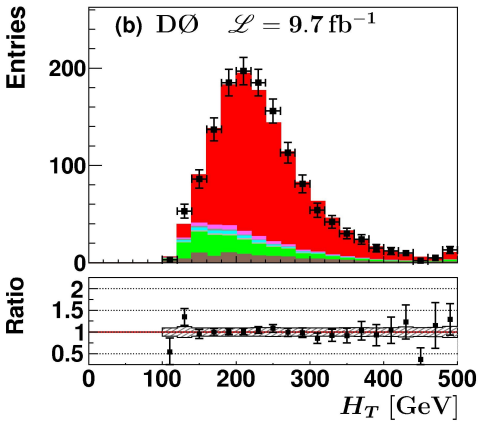

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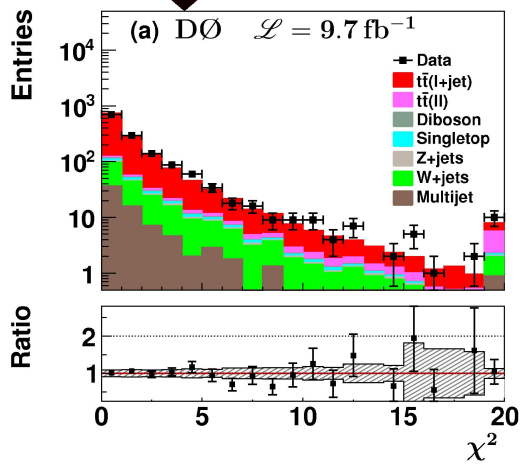

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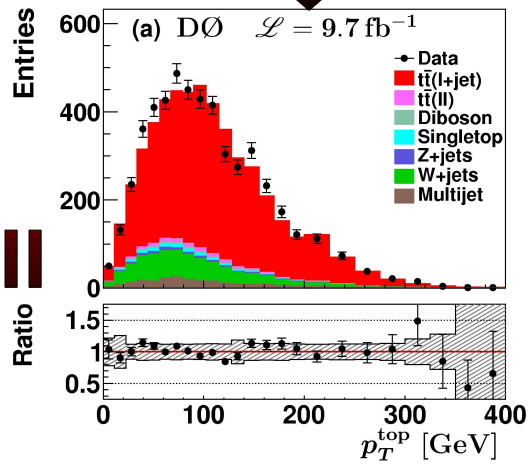
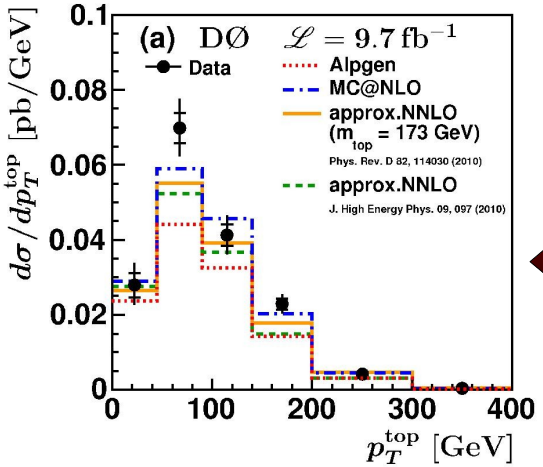
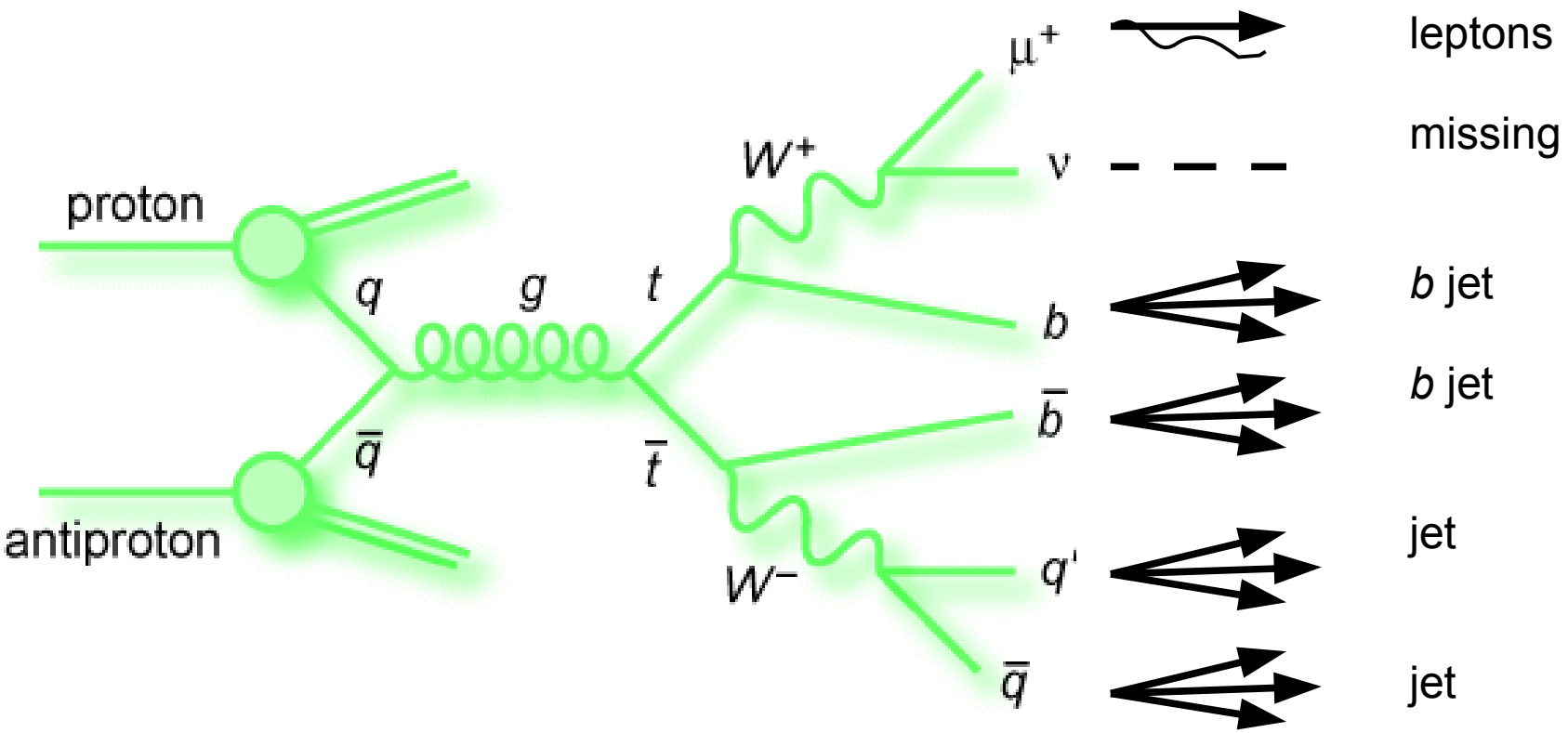


IV. Results and Implications



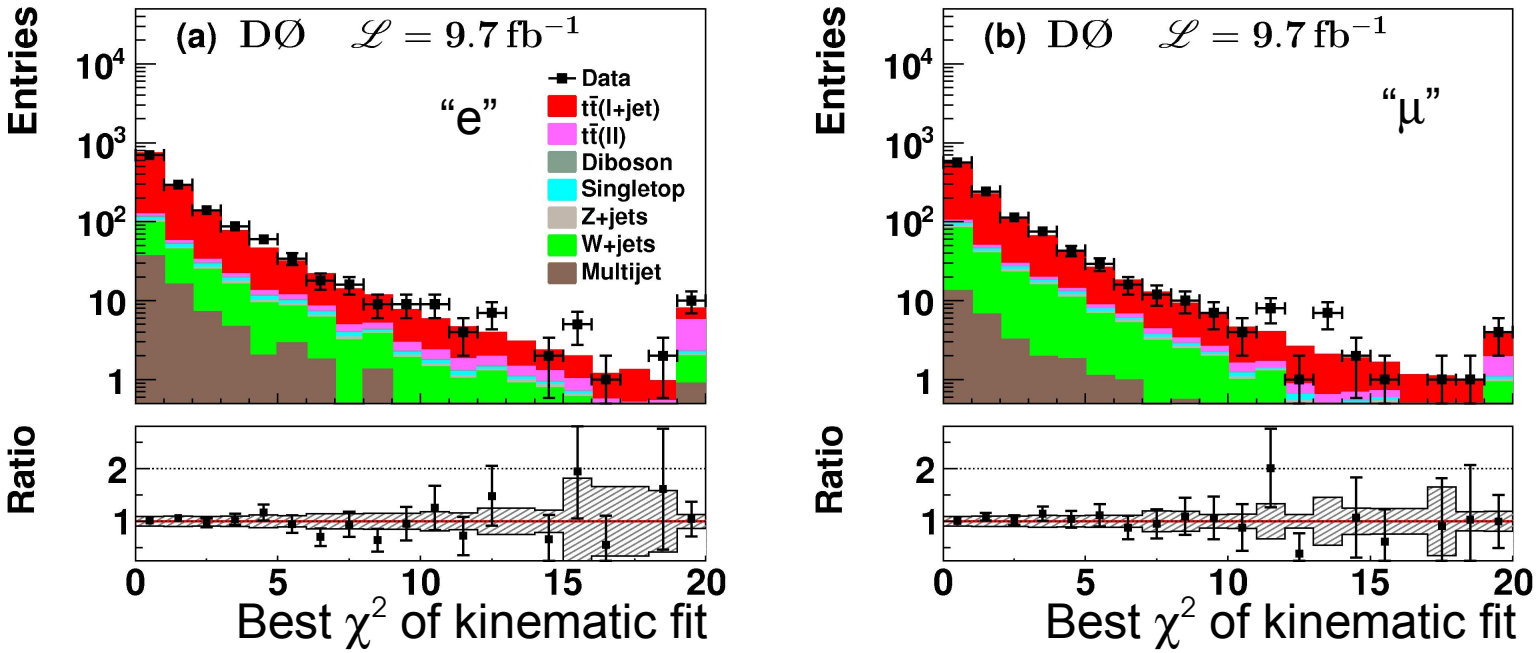
Top quark reconstruction

- Associate leptons and jets with individual top quark decay particles:
  - 12 possible jet to quark assignments, reduced with *b* tag information
  - Additional 2 solution for longitudinal momentum of neutrino



Top quark reconstruction

- Associate leptons and jets with individual top quarks by a constrained kinematic fit:
  - Top mass m_t=172.5 GeV/c^2 & m_W = 80.4 GeV/c^2
  - Experimental resolutions taken into account & assign *b*-tagged jets to b-quarks

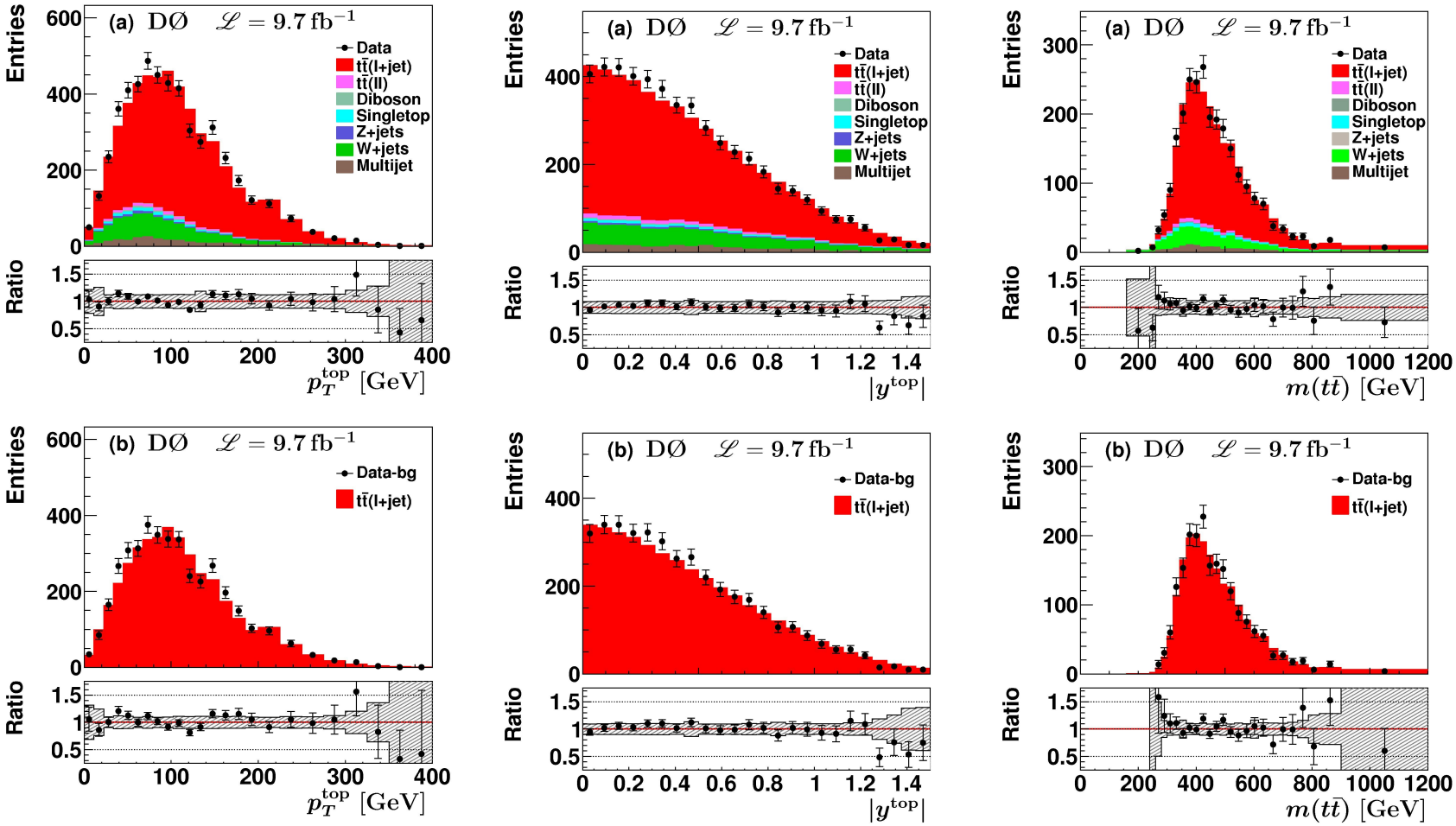


- Choose best solution, distribution of resulting χ^2 well modeled

Top quark reconstruction

- Control plots of the kinematic top quark reconstruction
- Sum of t and $\bar{t}$ for p_T(top) and $|y(\text{top})|$

e or μ + ≥ 4 jets

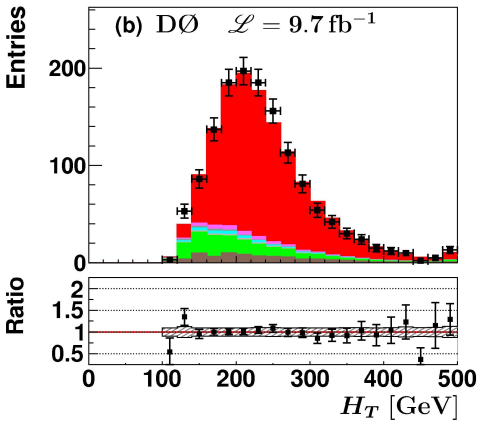


Background subtraction

- Reconstructed top quark distributions well modeled by MC
  (assuming the measured $t\bar{t}$ cross section)

Measurement strategy

I. Event selection & Sample Composition



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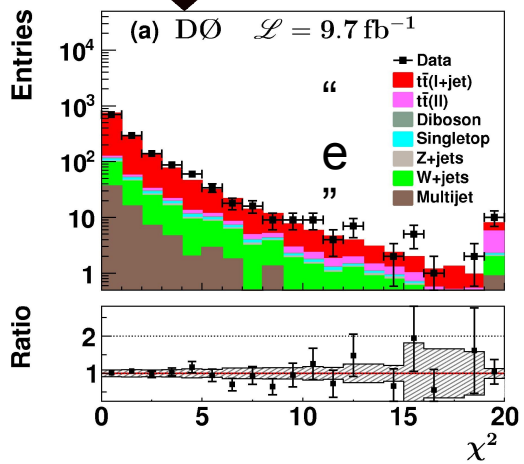
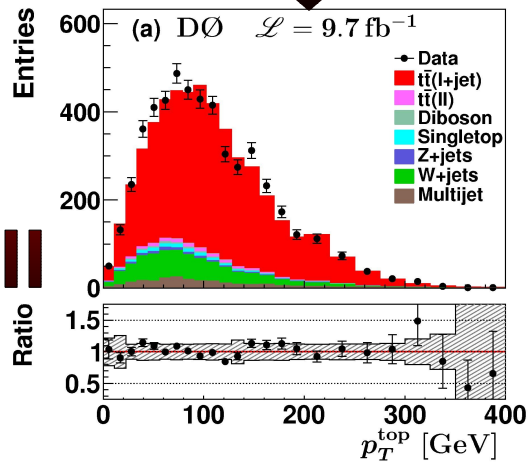


III. Correct data for detector effects & study systematic uncertainties

$$\frac{d\sigma}{dX_i} = \frac{N_i^{\mathrm{signal}}}{\epsilon \cdot \mathcal{L} \cdot \mathcal{BR} \cdot \Delta X_i}$$



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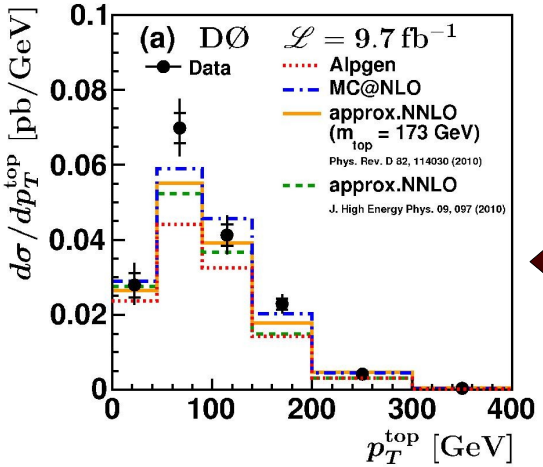
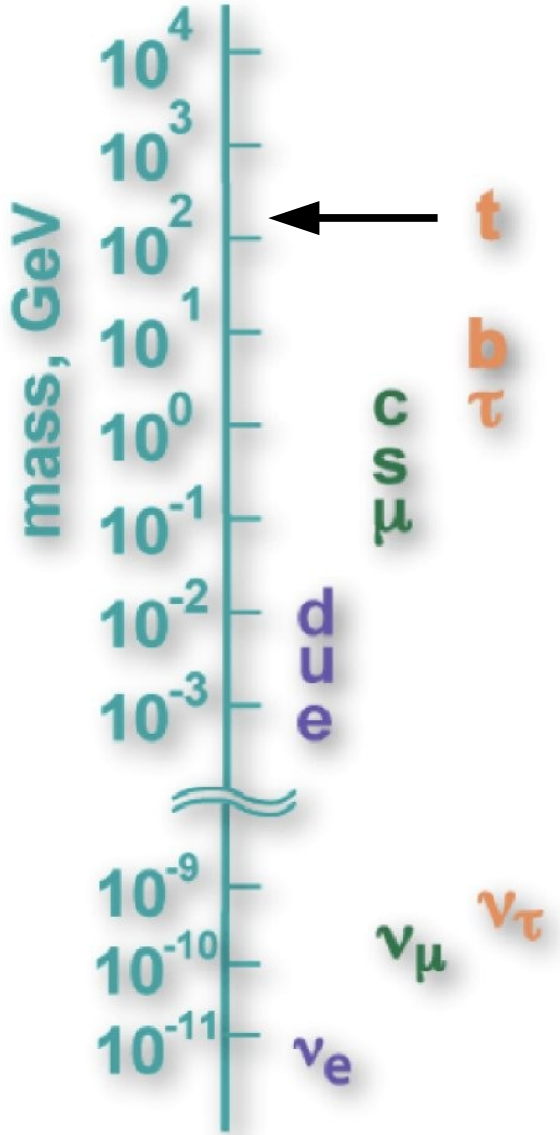


Correct data to what ?

- Most precise predictions at approx. NNLO:
  → Require to correct to parton level
- Heaviest elementary particle, decays before it can hadronize:
  - No fragmentation, like for *b* or *c* quarks
    → Effects from QCD and hadronization are reduced
- In addition $t\bar{t}$ pair produced almost at rest:
  → top quark decays almost always in detector acceptance



- In other words: **Nature helps a lot...**

Regularized Unfolding

- Bin-by-bin correction method (common) in HEP:
  - Possibly strong model dependencies
  - Errors in general too optimistic

$$\frac{d\sigma}{dX_i} = \frac{N_i^{\text{signal}}}{\epsilon \cdot \mathcal{L} \cdot \mathcal{BR} \cdot \Delta X_i}$$

- Matrix Unfolding introduces (ideal case):
  - No bias with respect to a particular model of the physical process and MC
  - No (small) bias, with respect to general requirements of solution (smoothness)

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  In Reality: → Migrations are treated more properly compared to Bin-by-bin, but:

  → Result tends to depend on the MC used, model uncertainty is reduced compared to Bin-by-bin but not zero

  → Regularized unfolding needs to be checked very carefully

$$\boldsymbol{Ax = y \;\rightarrow\; x = A^{-1}y} \qquad \boldsymbol{V_x = A^{-1}V_y(A^{-1})^T}$$

- For a discrete measurement with *n* bins:

  $\boldsymbol{x}$ = *n*-histogram of true variable *x*
  $\boldsymbol{y}$ = *m*-histogram of measured variable *y*
  $\boldsymbol{A}$ = $m \times n$ response matrix

  $\boldsymbol{V_x}$ = error propagation for true variable *x*
  $\boldsymbol{V_y}$ = error of measured variable *y*

Regularized Unfolding

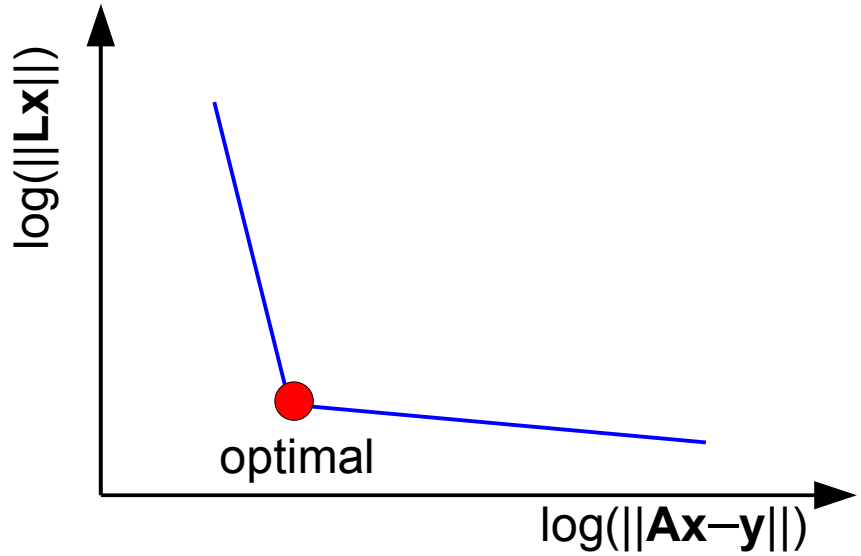
- Bin size ≈ resolution → large fluctuations from contributions of non-significant bins
- Use regularization (or if possible: larger bins):

  $$F(x) = ||\boldsymbol{Ax} - \boldsymbol{y}||^2 + \tau\,||\boldsymbol{Lx}||^2 = min \qquad \tau > 0$$

  - '*L*' Condition based on: size, curvature, etc.

    they act on (y-x_0) where x_0 is taken from the migration matrix
- <u>Optimal value of τ:</u>

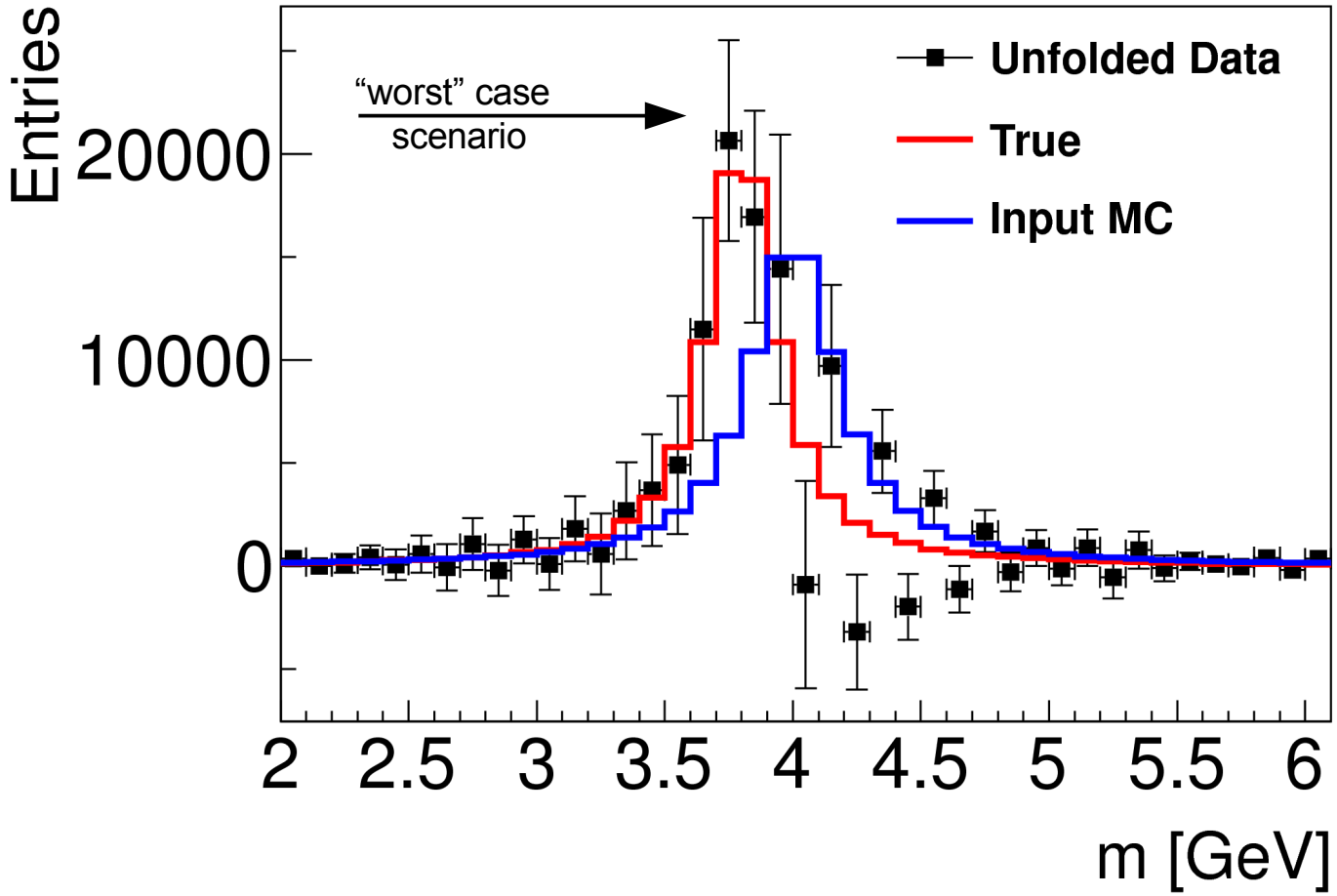
  L–curve method



→ Several conditions for the regularization possible – choice is non-trivial & depends on the problem/analysis

Regularized Unfolding

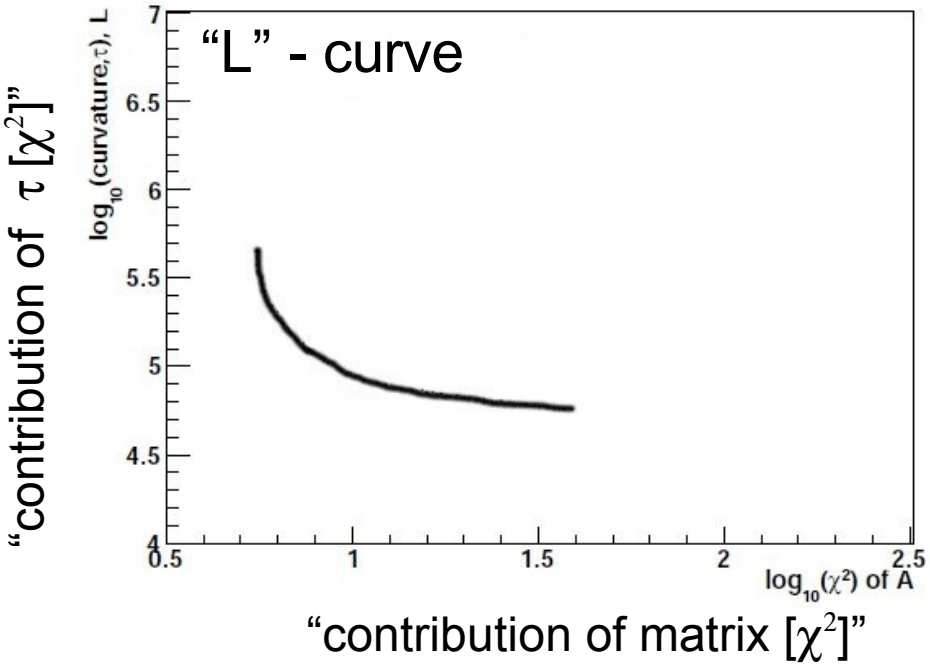
- Bin size ≈ resolution → large fluctuations from contributions of non-significant bins
- "worst" case scenario: plain matrix inversion or non-regularized unfolding

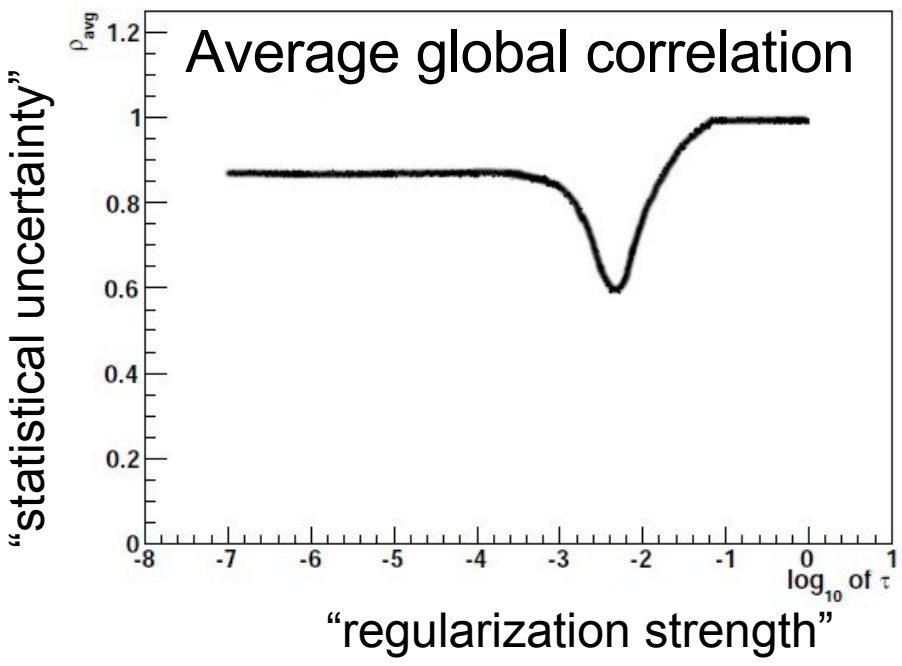


Regularized Unfolding

- What does the regularized unfolding 'do' by looking at L-curve ?
- A χ^2 statistics measures tension between *x* and data and the scatter of *x*

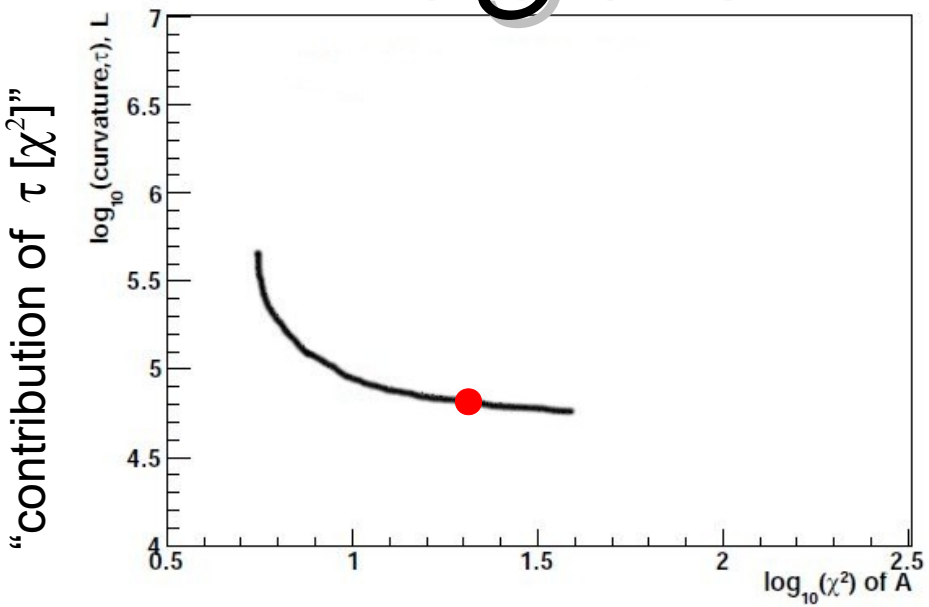
  → Regularized matrix unfolding 'balances' these two

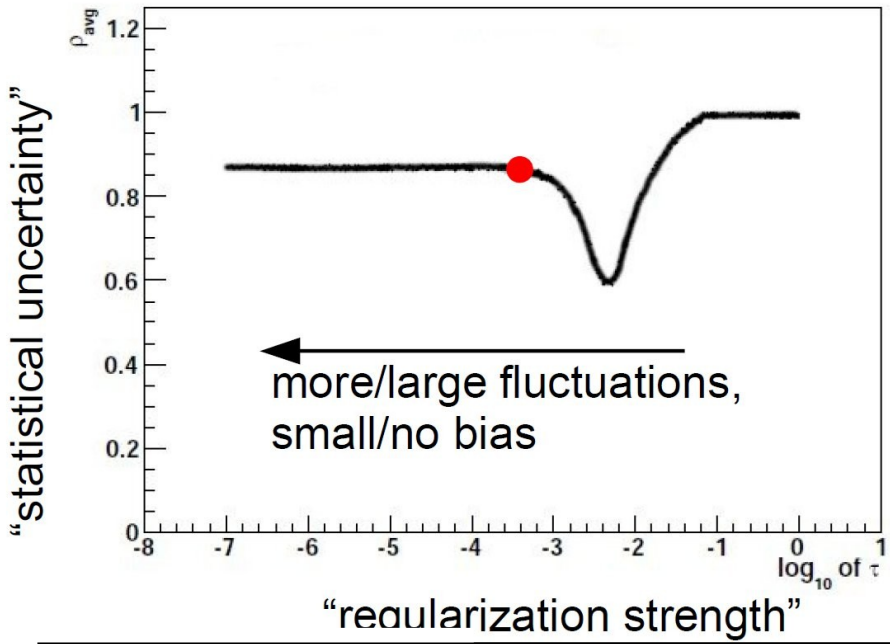




- Toy model example: → Unfold smeared detector distribution to "true"

Regularized Unfolding





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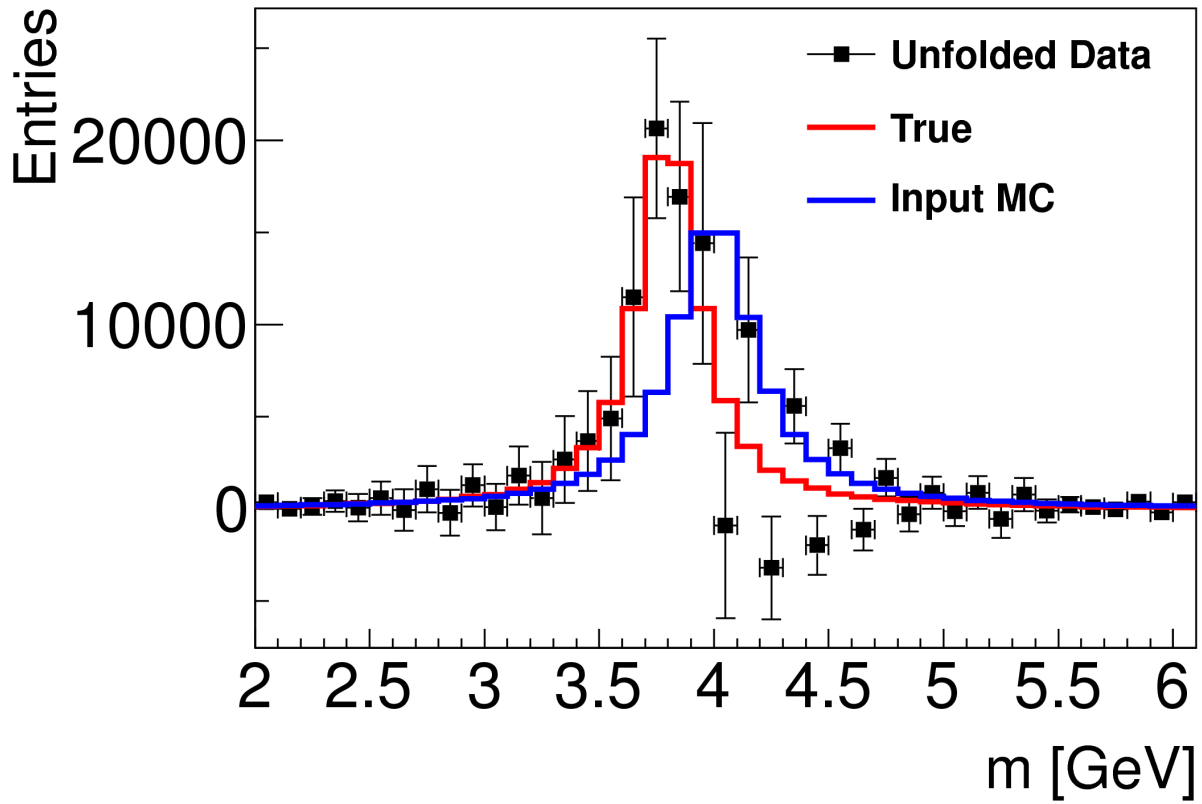

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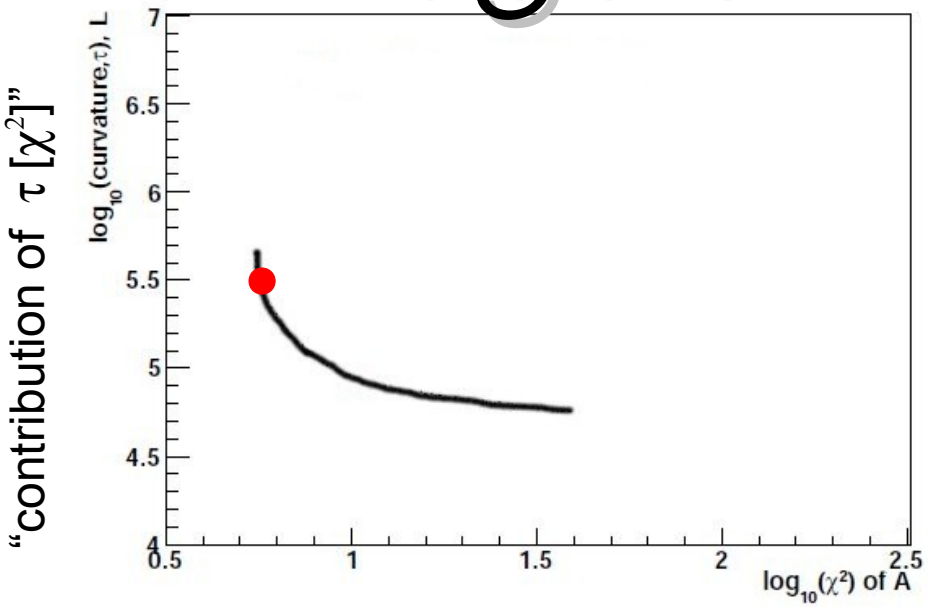

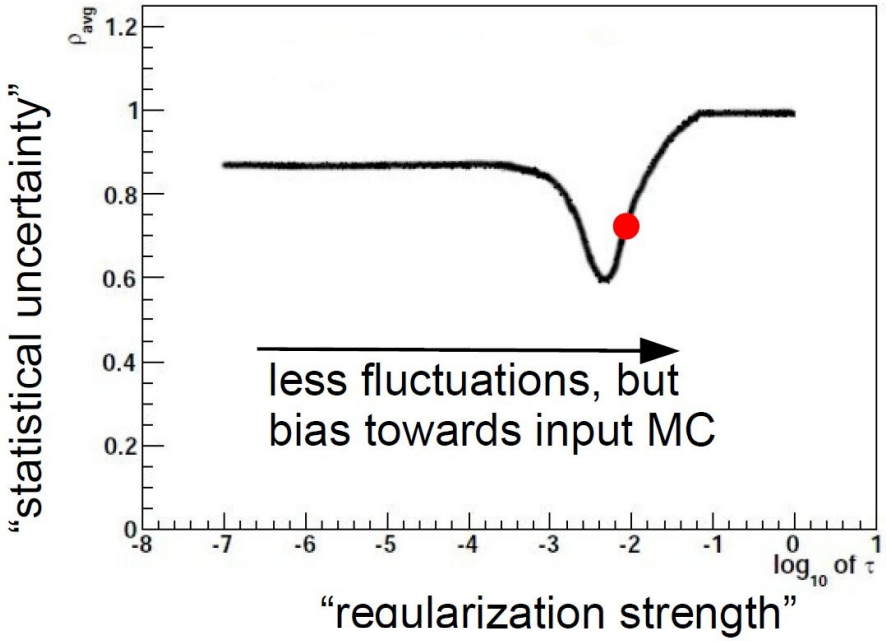

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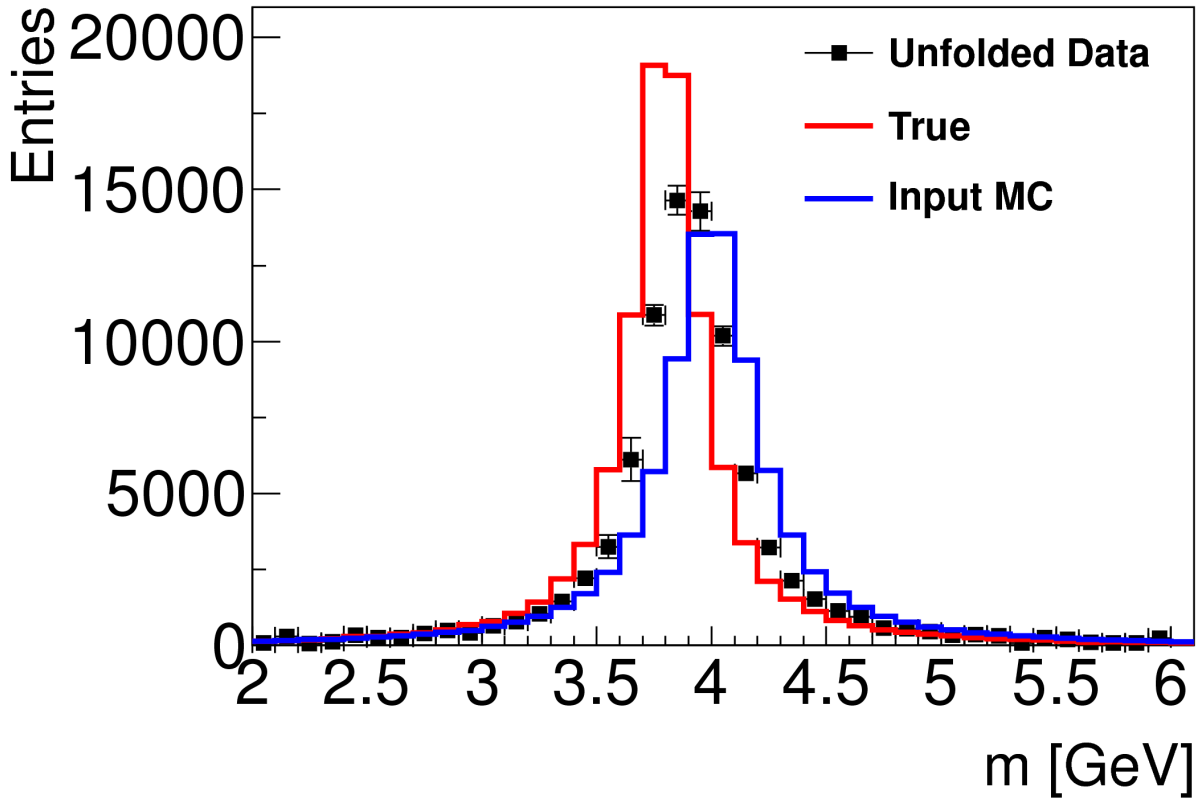
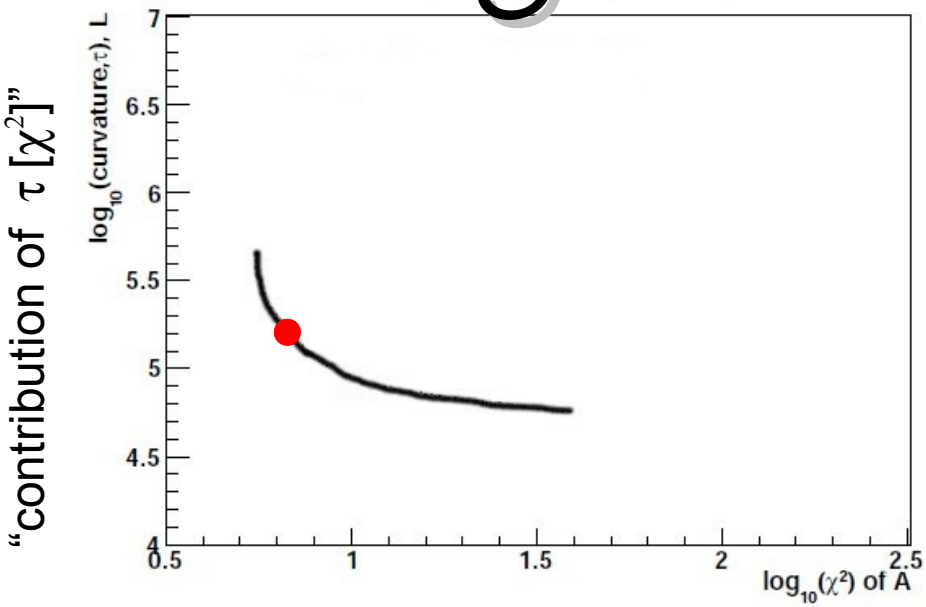
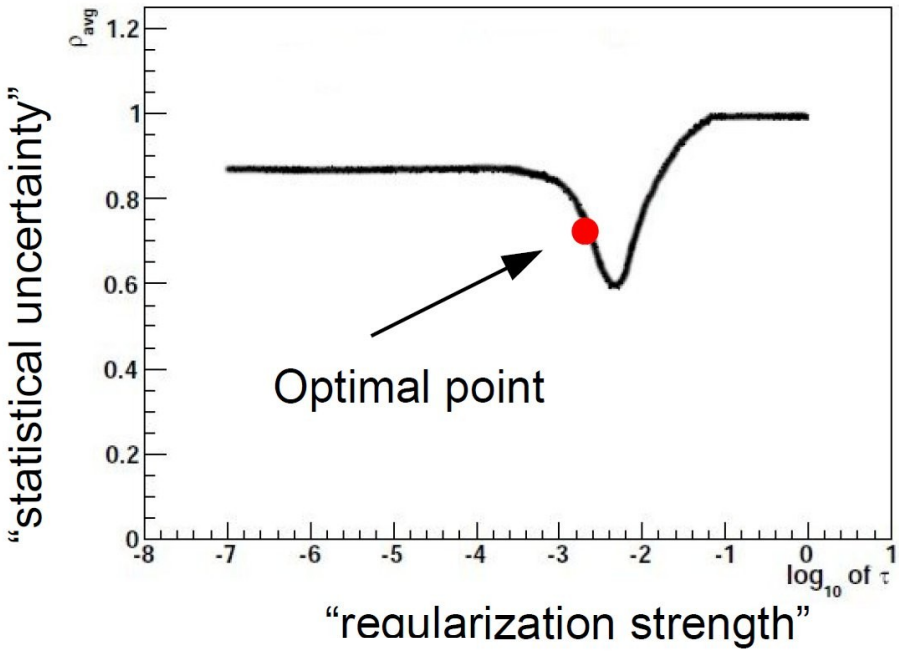


Regularized Unfolding





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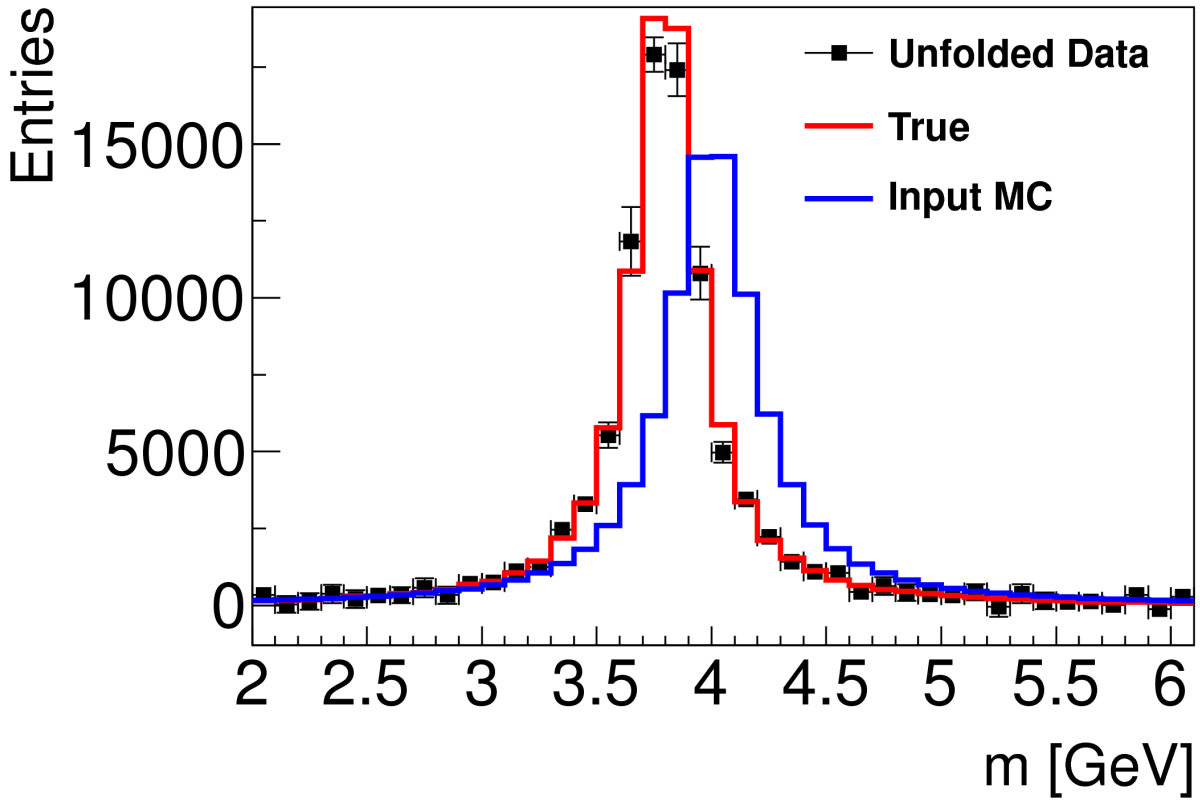
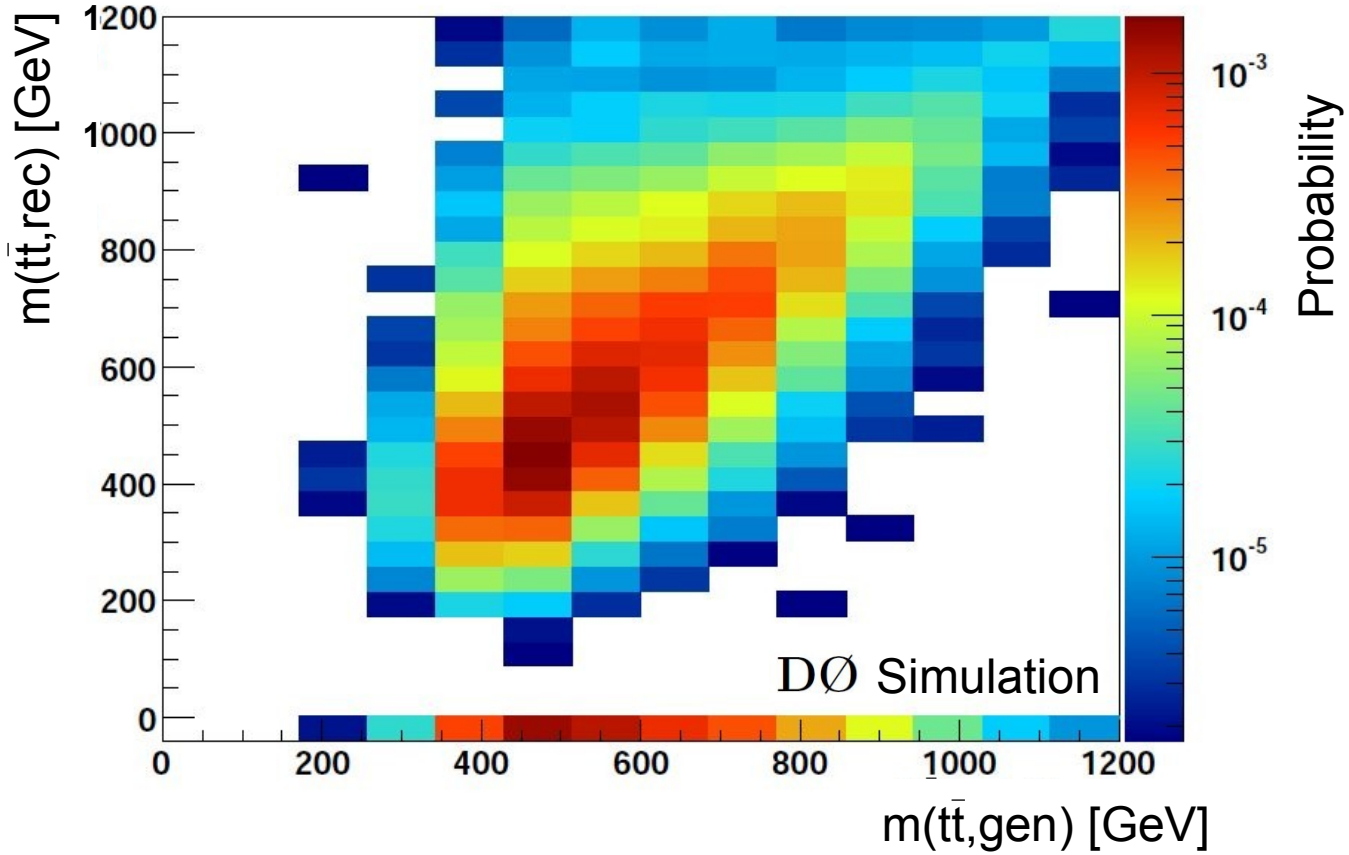


Correcting the data...

- The migration matrix is <u>the</u> crucial ingredient for unfolding:



$$\frac{d\sigma_i}{dX} = \frac{N_i^{\text{unfold}}}{\mathscr{L} \cdot B \cdot \Delta X_i}$$

- Use twice as many bins on 'reconstructed' level as on 'generated' level
  → provides more information to the unfolding process
- Use a so-called 'gen-row' to correct for detector efficiency

Systematic uncertainties

- Study systematic uncertainties and their effect on differential cross sections by:
  - Migration matrix derived from simulation with variation of parameters or modified background subtracted data
  - Systematic uncertainty is difference in unfolded results to nominal

Source of uncertainty	Uncertainties, %	
	δ_{incl}	$\lvert\delta_{\mathrm{diff}}\rvert$
Signal modeling	$^{+5.2}_{-4.4}$	4.0 – 14.2
PDF	$^{+3.0}_{-3.4}$	0.9 – 4.4
Detector Modeling	$^{+4.0}_{-4.1}$	3.1 – 13.7
Sample composition	± 1.8	2.8 – 9.2
Regularization strength	± 0.2	0.8 – 2.1
Integrated luminosity	± 6.1	6.1 – 6.1
Total systematic uncertainty	$^{+9.6}_{-9.3}$	8.5 – 23.1

(for covariance matrix: systematic uncertainties assumed 100% correlated between bins)

- Total systematic uncertainty (includes 6.1% luminosity): 9.4 % inclusive

Systematic uncertainties

- Study systematic uncertainties and their effect on differential cross sections by:
  - Migration matrix derived from simulation with variation of parameters or modified background subtracted data
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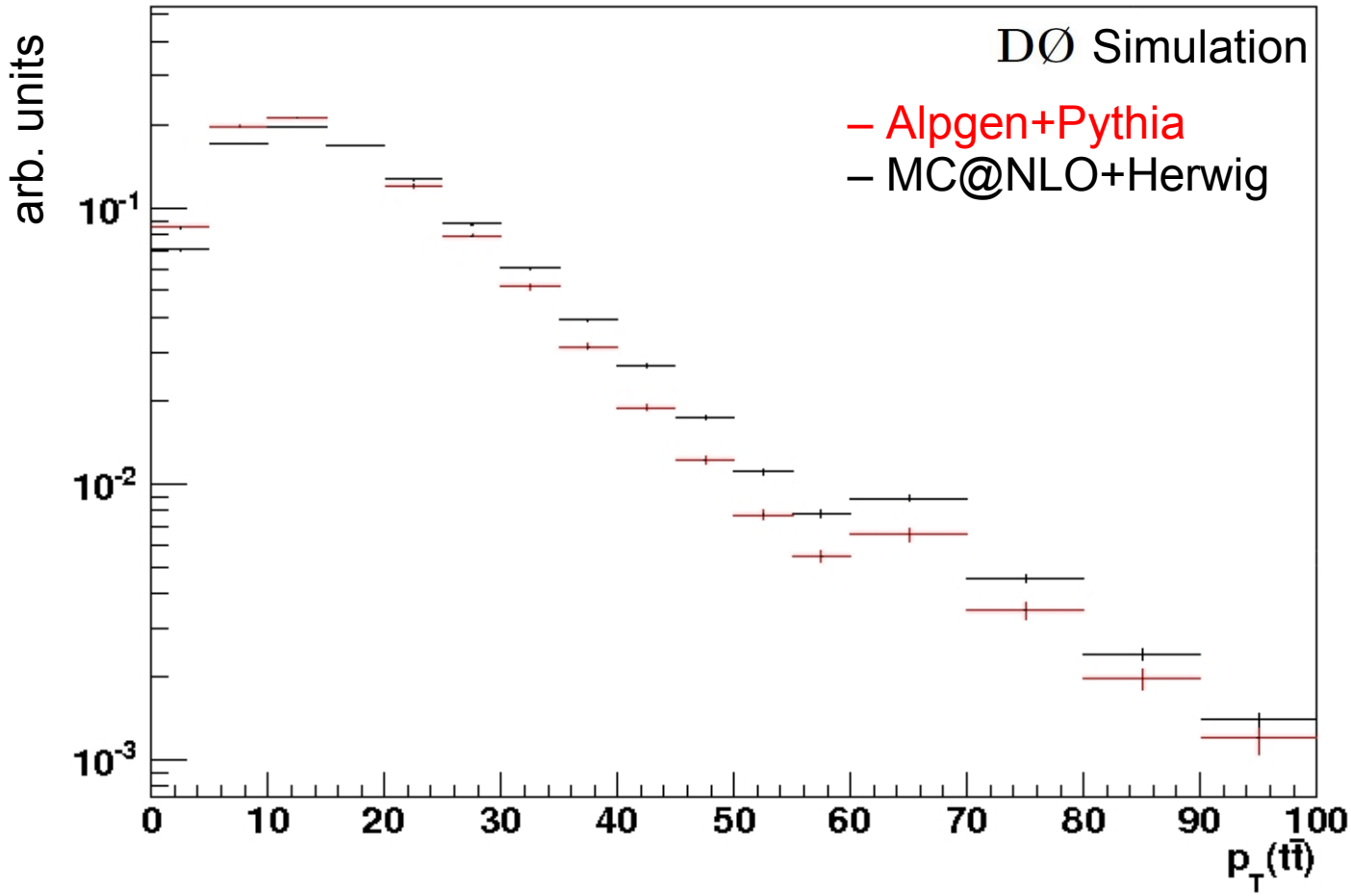

Measurement strategy

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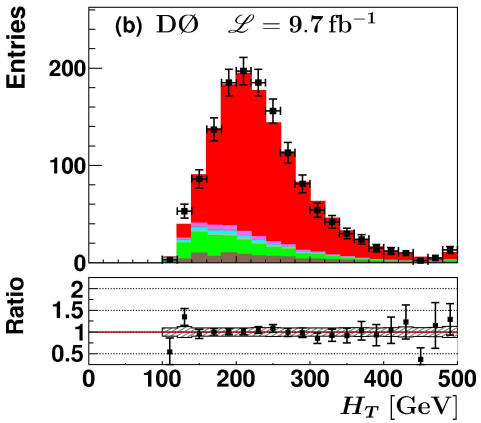
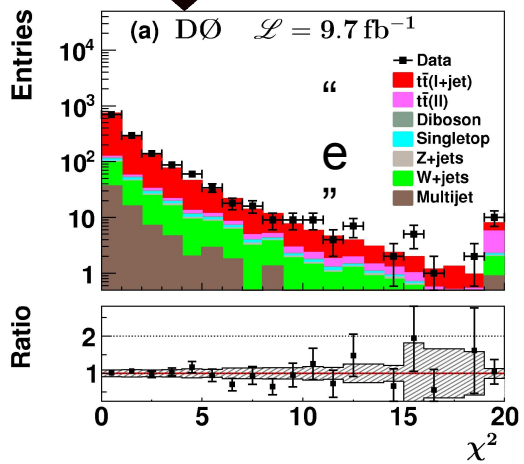


II. Kinematic reconstruction of top quarks



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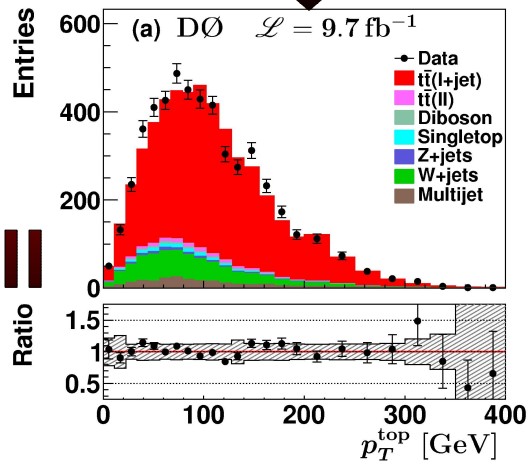

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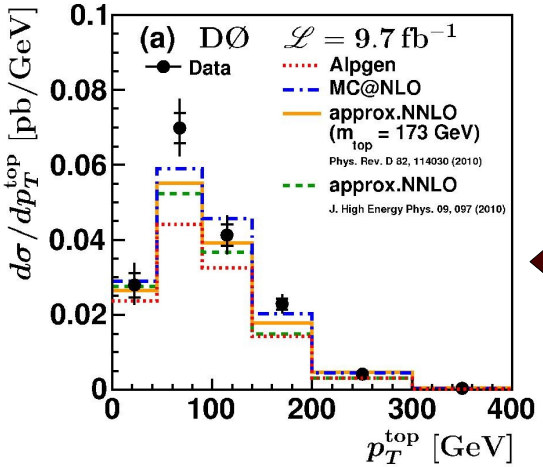
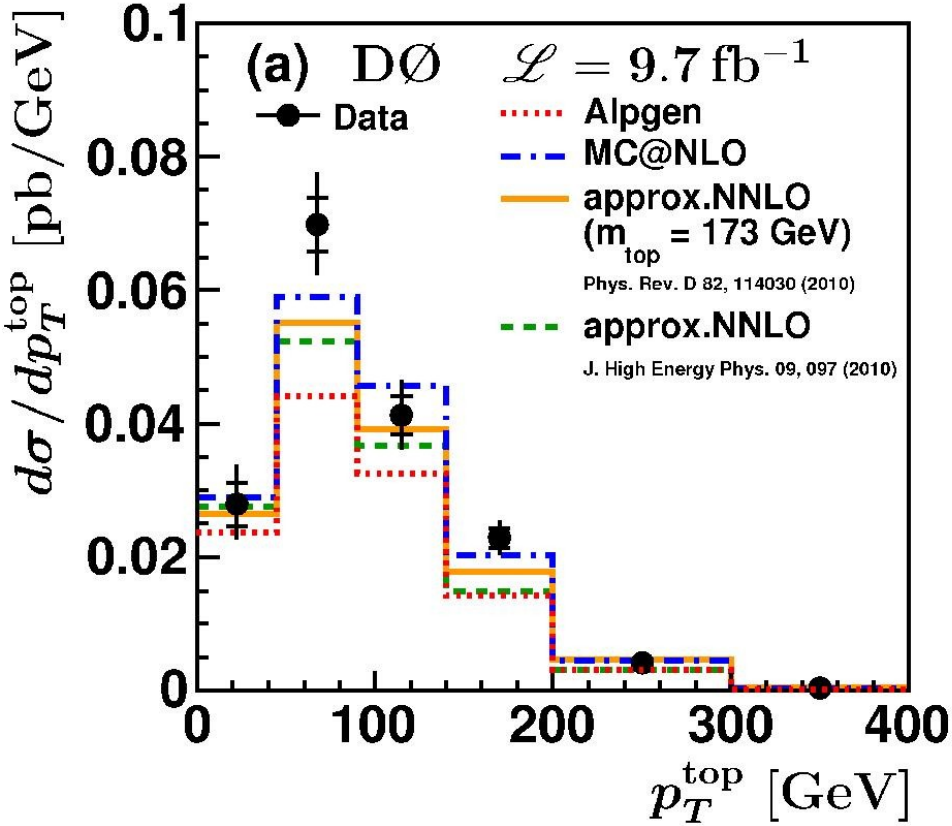
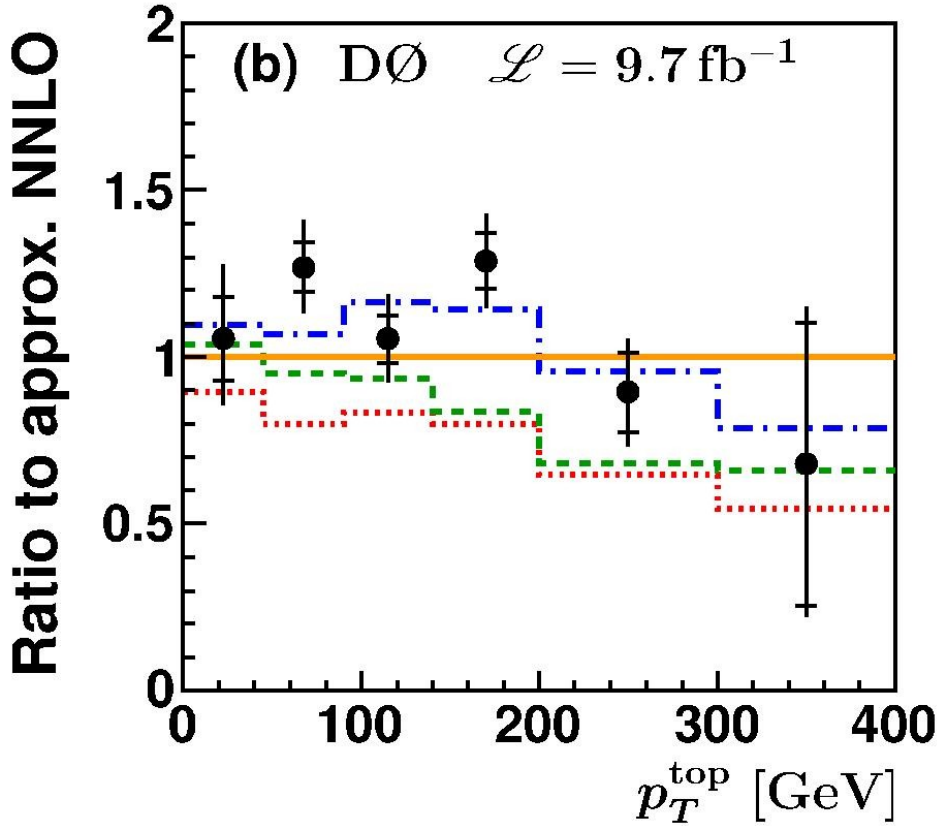


Differential cross sections

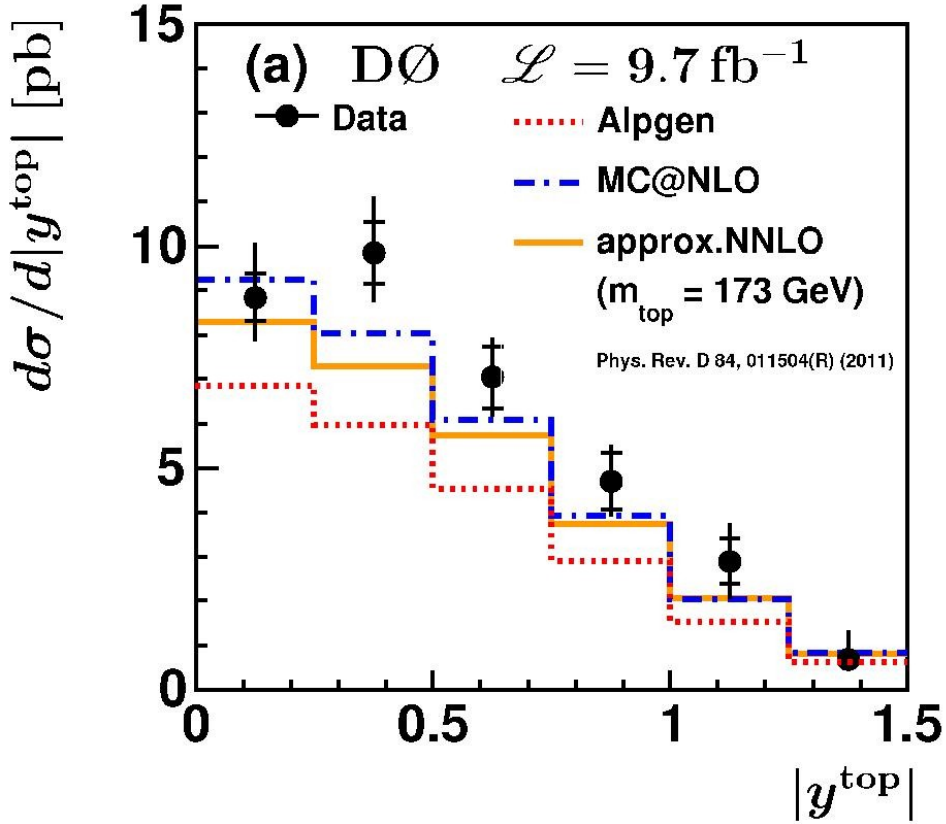


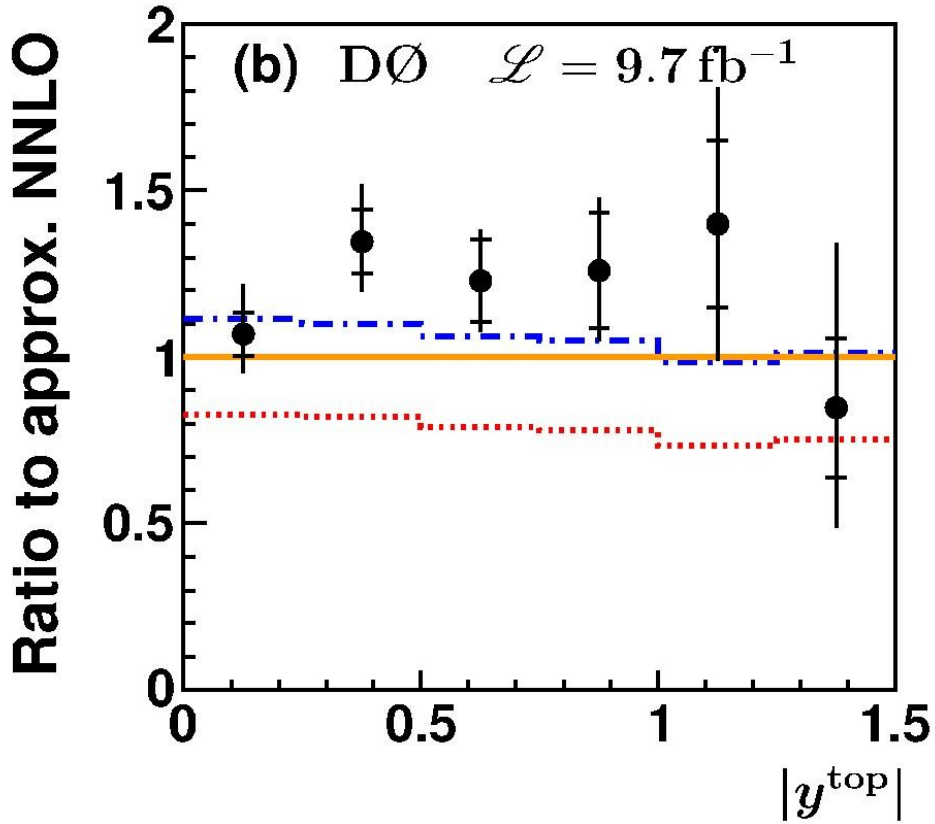


- Average t and $\bar{t}$ cross section
- Differential shape of data modeled by MC@NLO & approx. NNLO
- Not the full information: Correlations, all provided in the paper

- Alpgen: σ_{tot}= 5.61 pb
- MC@NLO: σ_{tot}= 7.56 pb
- app. NNLO by N.Kidonakis: p_T , arXiv:1009.4935
  σ_{tot}= 7.05 + 0.10 – 0.17 pb
- app. NNLO by L.Yang et al.: JHEP 09 (2010) 097
  σ_{tot} (NNLO + NNLL):σ_{tot}= $7.24^{+0.24}_{-0.26}$ pb
  [arXiv:hep-ph/1204.5201]

Differential cross sections





- Average t and $\bar{t}$ cross section
- Differential shape of data not so well modeled by MC@NLO & approx. NNLO
- Mid-|y| region: data above predictions
- Not the full information: Correlations, all provided in the paper

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- app. NNLO by N.Kidonakis: p_T , arXiv:1009.4935
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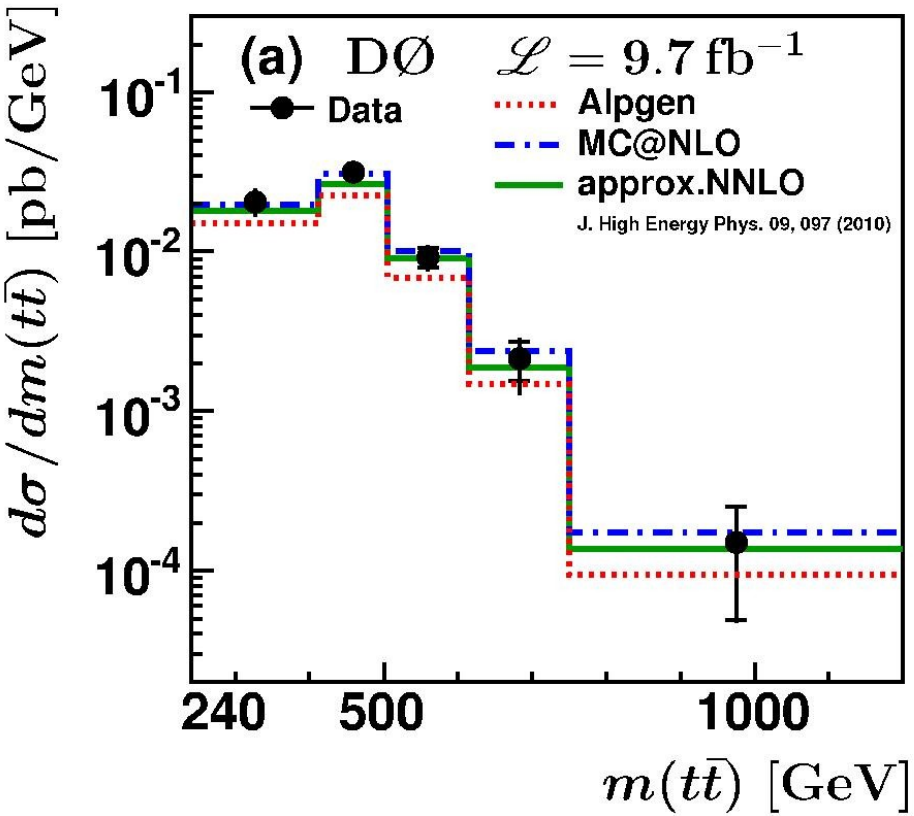
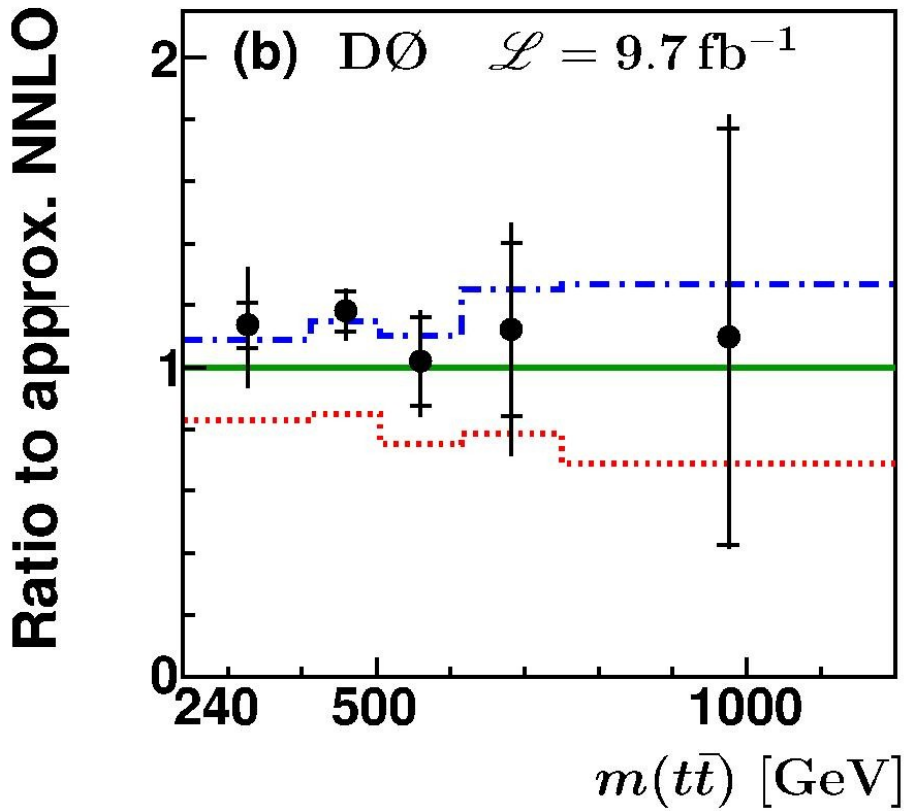
Differential cross sections





- Differential shape of data modeled by MC@NLO & approx. NNLO
- High tail sensitive to new physics
- Not the full information: Correlations, all provided in the paper

- Alpgen: σ_{tot}= 5.61 pb
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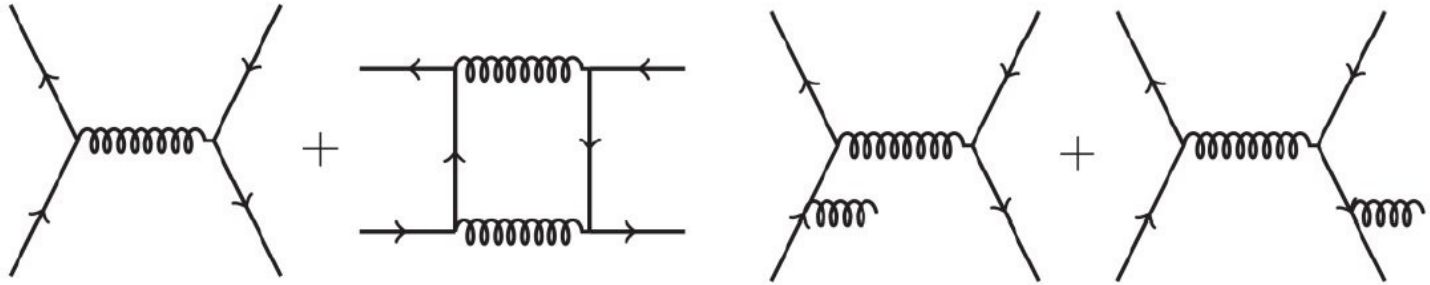
  [arXiv:hep-ph/1204.5201]

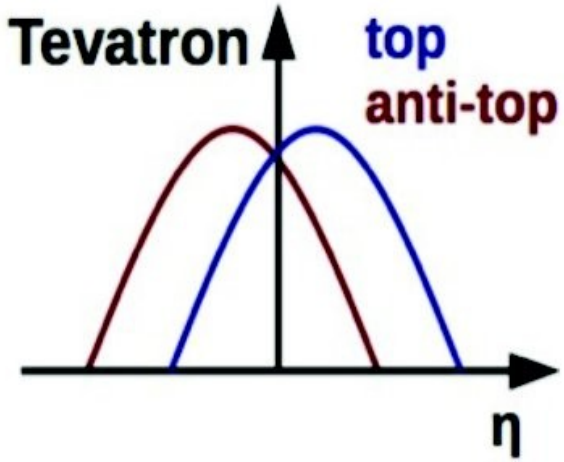
Top quark asymmetries

Interference appears at NLO QCD:



Positive asymmetry

Negative asymmetry



- This is a forward-backward asymmetry at Tevatron
  → initial state: $q\bar{q}$ vs. gg (fwd-bwd symmetric)
- SM prediction at NLO (QCD+EWK):
  - **A_{FB} ~ 8 %** (waiting for full NNLO pQCD predictions)

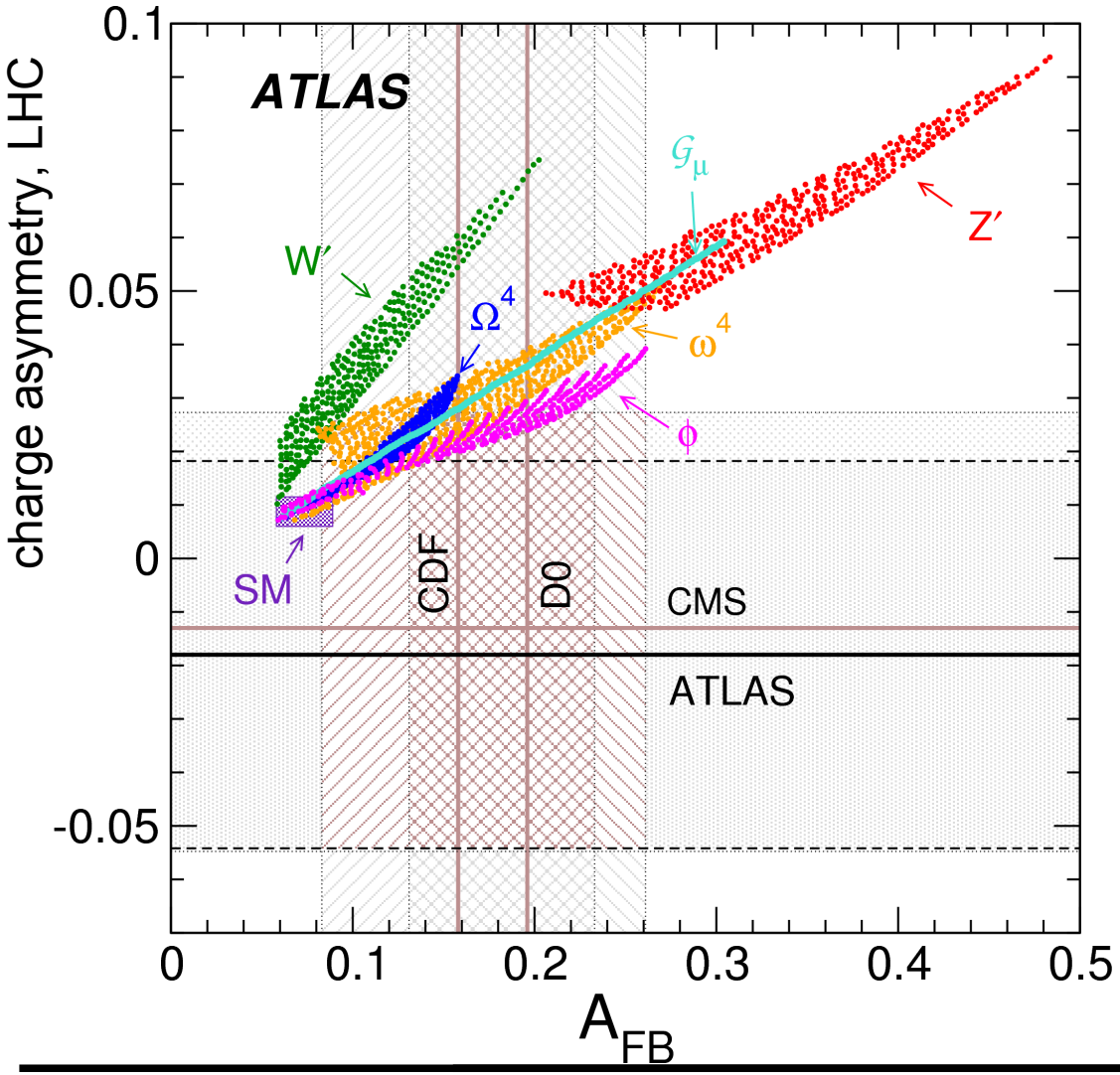
$$\Delta y = y_t - y_{\bar{t}} = q_l(y_{leptonic} - y_{hadronic})$$

$$A = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

- Current CDF & D0 measurements show ~2 s.d. deviation

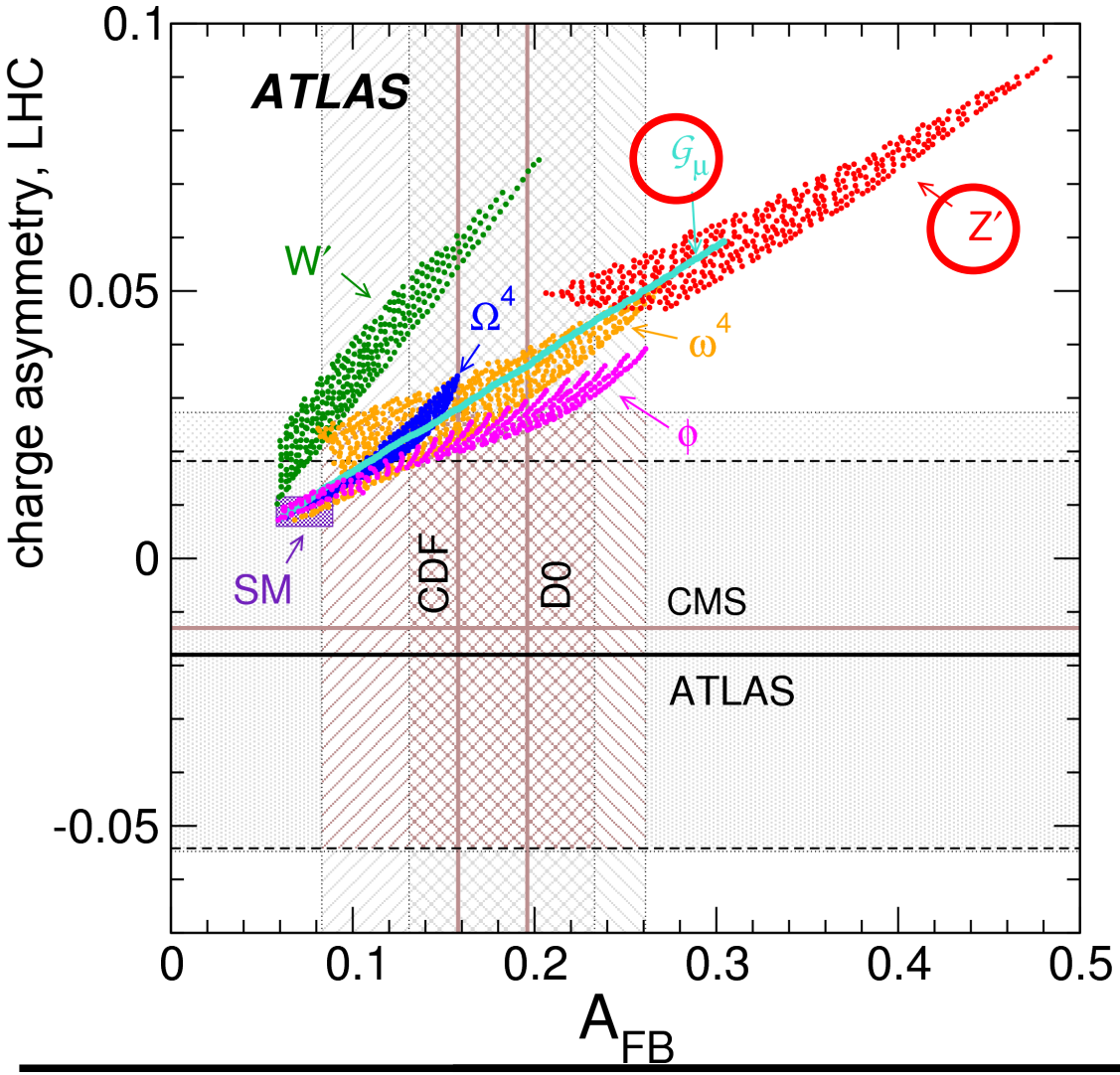
Top quark asymmetries

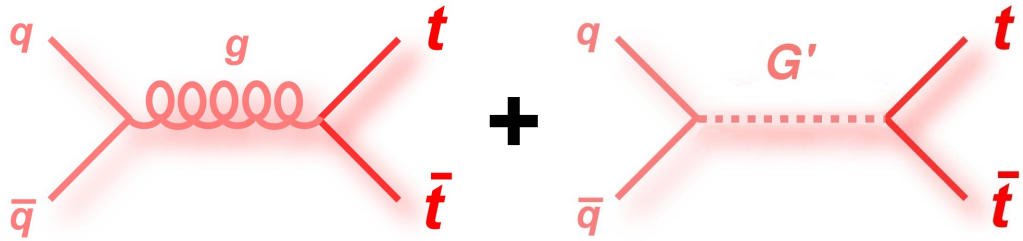
- **Large positive or negative asymmetry could indicate physics beyond SM:** → Axi gluons (s-channel), Z' (t-channel)



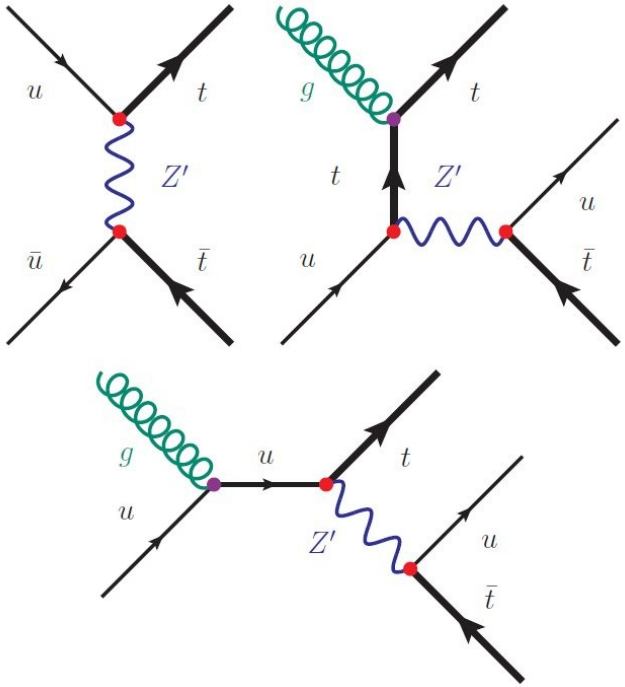
New physics

- **Large positive or negative asymmetry could indicate physics beyond SM:** → Axi gluons (s-channel), Z' (t-channel)





SM: $q\bar{q}$ annihilation



Axi gluon & Z' models

- Various axi gluon models with different couplings, differential cross section predictions provided by A. Falkowicz [arxiv:1401.2443]
- Models add ~5-10% to Forward-Backward Asymmetry, but also alter the differential cross section distributions
- Models are built by adding these new physics contributions to differential distributions as predicted at approx. NNLO pQCD

The following data have been used to build these models:

- $A_{FB}(t\bar{t})$ & A_{FB}(lep) by CDF and D0
  Phys. Rev. D. 88, 112002 (2013)
  Phys. Rev. D 84, 112005 (2011)
  CDF Conf. 11035
- Tevatron combined inclusive $\sigma(t\bar{t})$
  Acc. by PRD [arxiv:1309.7570]
- High tail of $m(t\bar{t})$ by CDF, D0, CMS
  CMS [arxiv:1309.2030]
  → D0 [arxiv:1401.5785]
  CDF PRL 102 222003

Axi gluon & Z' models

- Various axi gluon models with different couplings, differential cross section predictions provided by A. Falkowicz [arxiv:1401.2443]

Remarks:

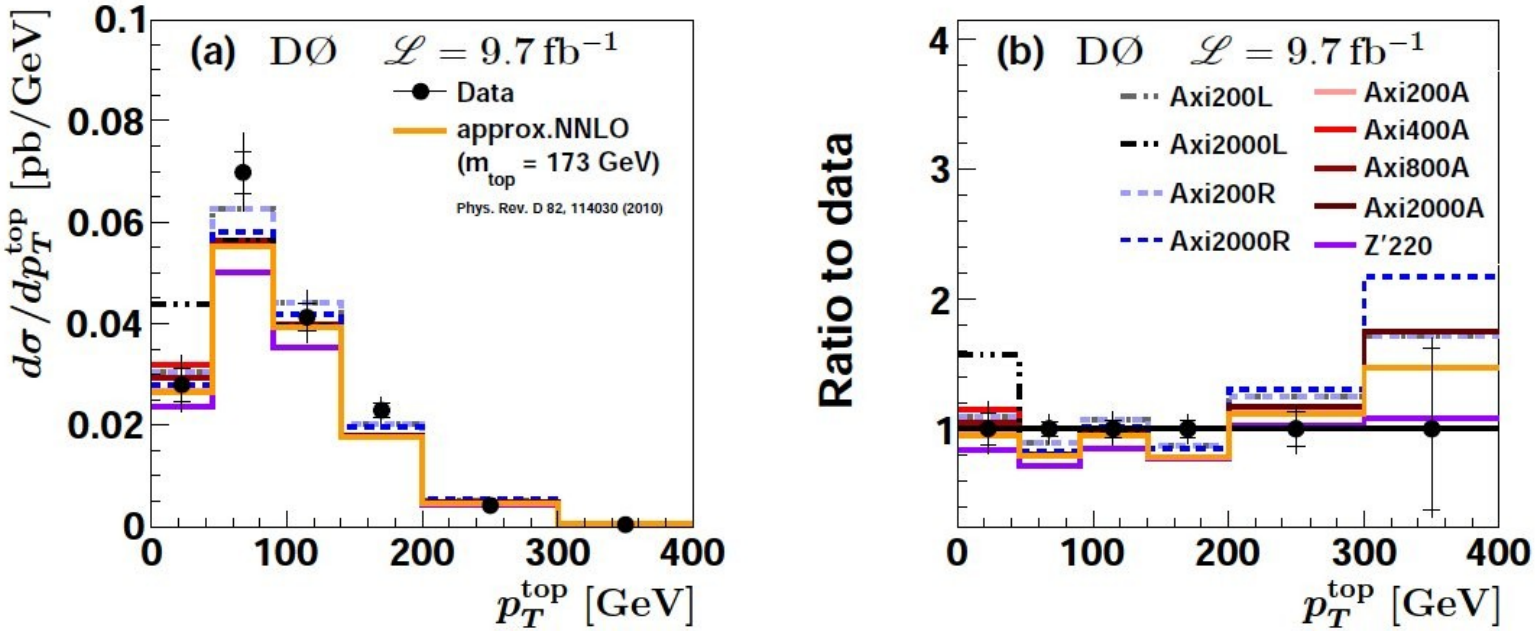
- Models with masses of 0.2 to 2 TeV and L (left), R (right), A (axial)
- Large masses highly constrained by LHC measurement
- Low masses not so much, but tough as effects are small

	$\sigma_{\text{tot}}(p\bar{p} \to t\bar{t})$ [pb]
Data	$8.27^{+0.92}_{-0.91}$ (stat. + syst.)
NNLO pQCD (SM)	$7.24^{+0.23}_{-0.27}$ (scales + pdf)

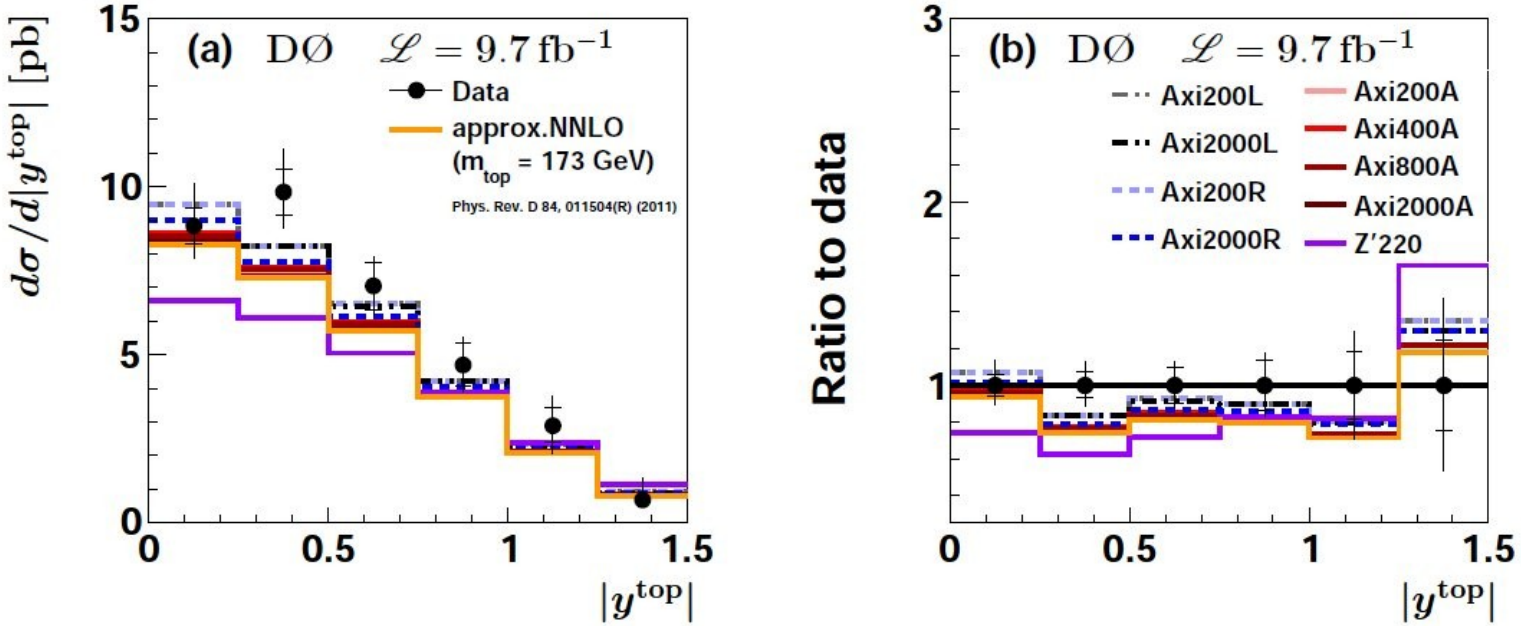
	$\Delta\sigma_{\text{tot}}(p\bar{p} \to t\bar{t})$ [pb]
axi200L	0.97 ± 0.06 (scale)
axi200R	0.97 ± 0.06 (scale)
axi200A	0.06 ± 0.04 (scale)
axi400A	0.26 ± 0.04 (scale)
axi800A	0.22 ± 0.04 (scale)
axi2000L	0.87 ± 0.15 (scale)
axi2000R	0.55 ± 0.06 (scale)
axi2000A	0.05 ± 0.06 (scale)
Z'220	-1.00 ± 0.06 (scale)

Axi gluon & Z' models

- Compare various models to unfolded cross section data
- Reminder: Bins are correlated, needs to be taken into account: χ^2 based on full covariance matrix

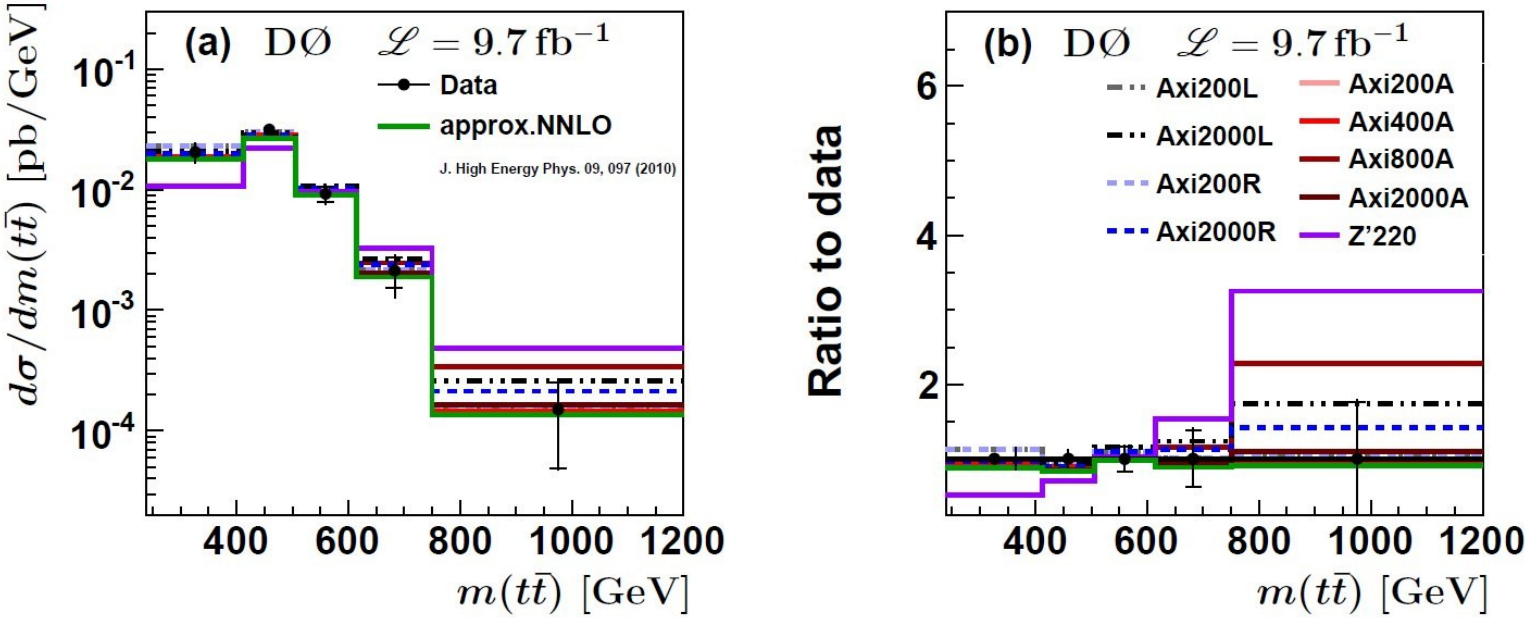


- Clearly some models are in tension with the presented data !
  - Z'
  - Various axi gluons



Axi gluon & Z' models

- Compare various models to unfolded cross section data
- Reminder: High tail is used to constrain models



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Axi gluon & Z' models

- Compare various models to unfolded cross section data
- Bins are correlated, needs to be taken into account
- χ^2 based on full covariance matrix:

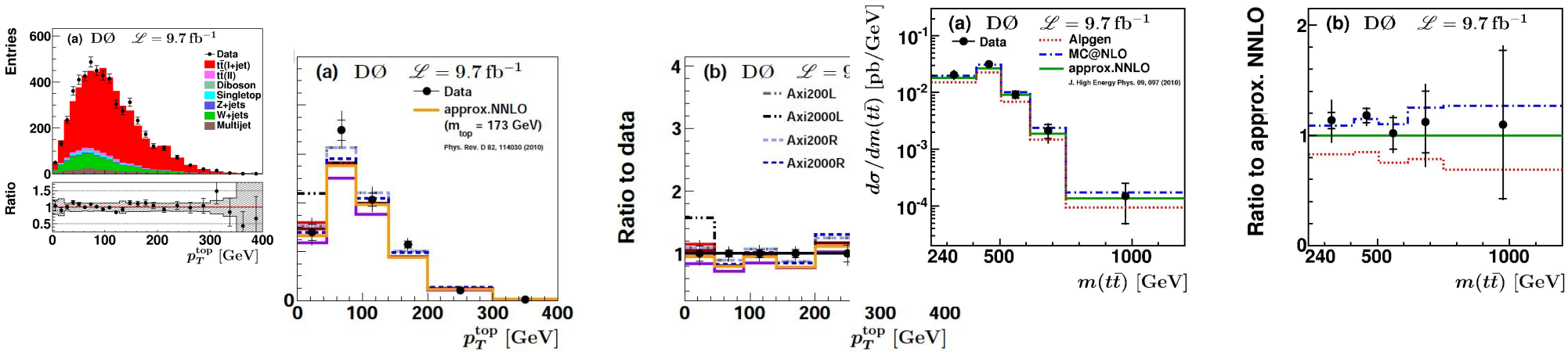
$$\chi^2 = \sum_{i,j} (y-\mu)_i \cdot \mathrm{cov}^{-1}_{i,j} \cdot (y-\mu)_j$$

	$M(t\bar{t})$ $[\chi^2/ndf]$	p_T^{top} $[\chi^2/ndf]$	$\lvert y^{\mathrm{top}}\rvert$ $[\chi^2/ndf]$
axi200L	0.96	1.07	1.20
axi200R	0.96	1.07	1.20
axi200A	0.85	3.55	3.88
axi400A	0.44	2.65	3.26
axi800A	0.97	2.86	3.23
axi2000L	0.58	1.27	3.78
axi2000R	0.43	1.94	2.75
axi2000A	0.88	3.56	4.11
Z'220	4.95	8.27	7.48

- Models depend on assumed couplings and included measurements

Summary & Conclusions

- Presented differential top quark distributions, using full D0 Run II data
  - Distributions described by approx. NNLO pQCD
  - Full covariance matrix and additional information provided for model building & testing
  - Measurement constrains contributions of new physics, like axi gluon models and Z'
  - Legacy measurement of the Tevatron



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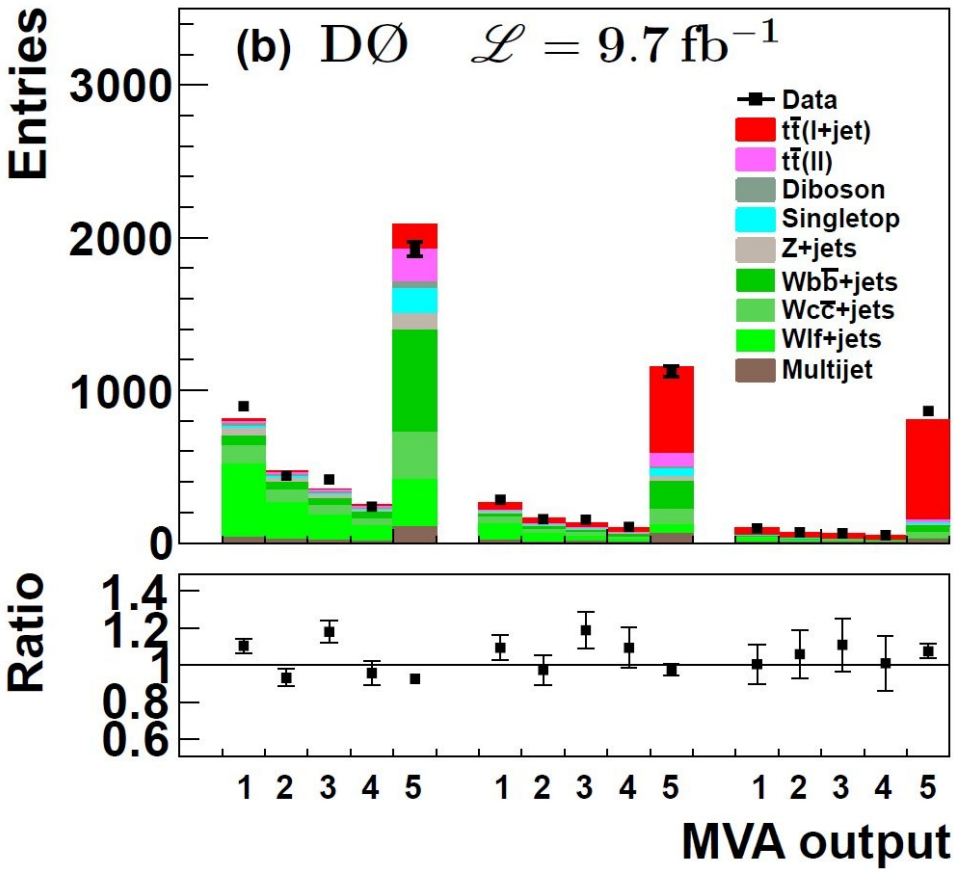
Submitted to PRD: [arxiv:1401.5785]

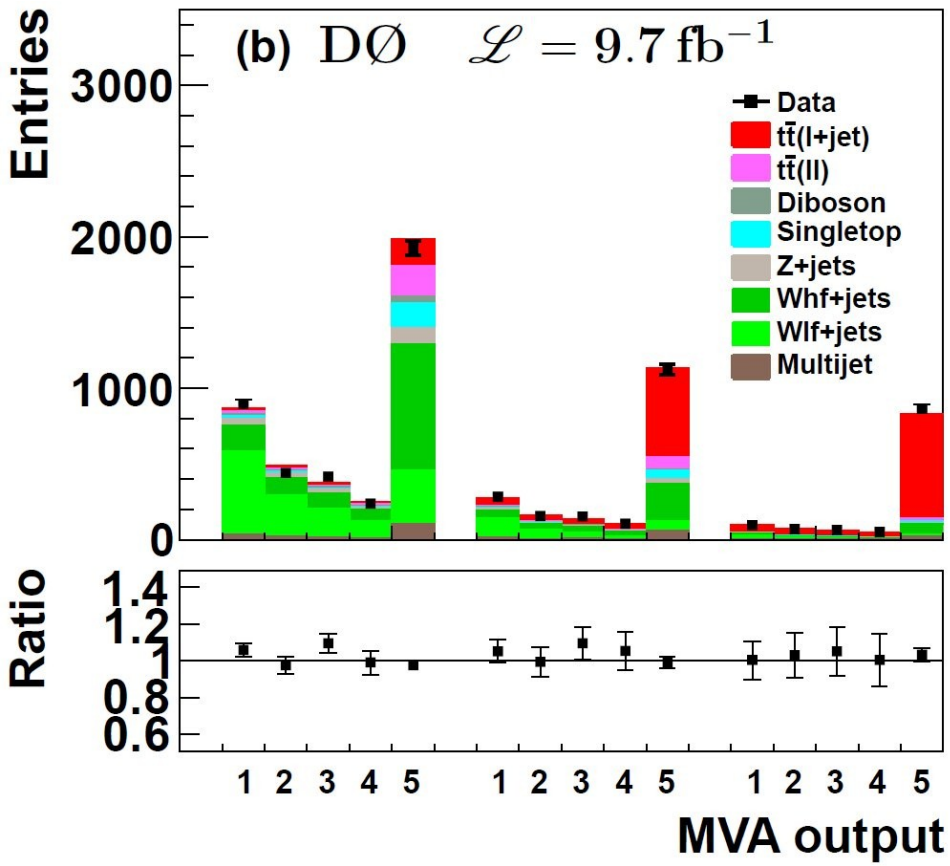
Thanks for your attention

Backup

Sample composition

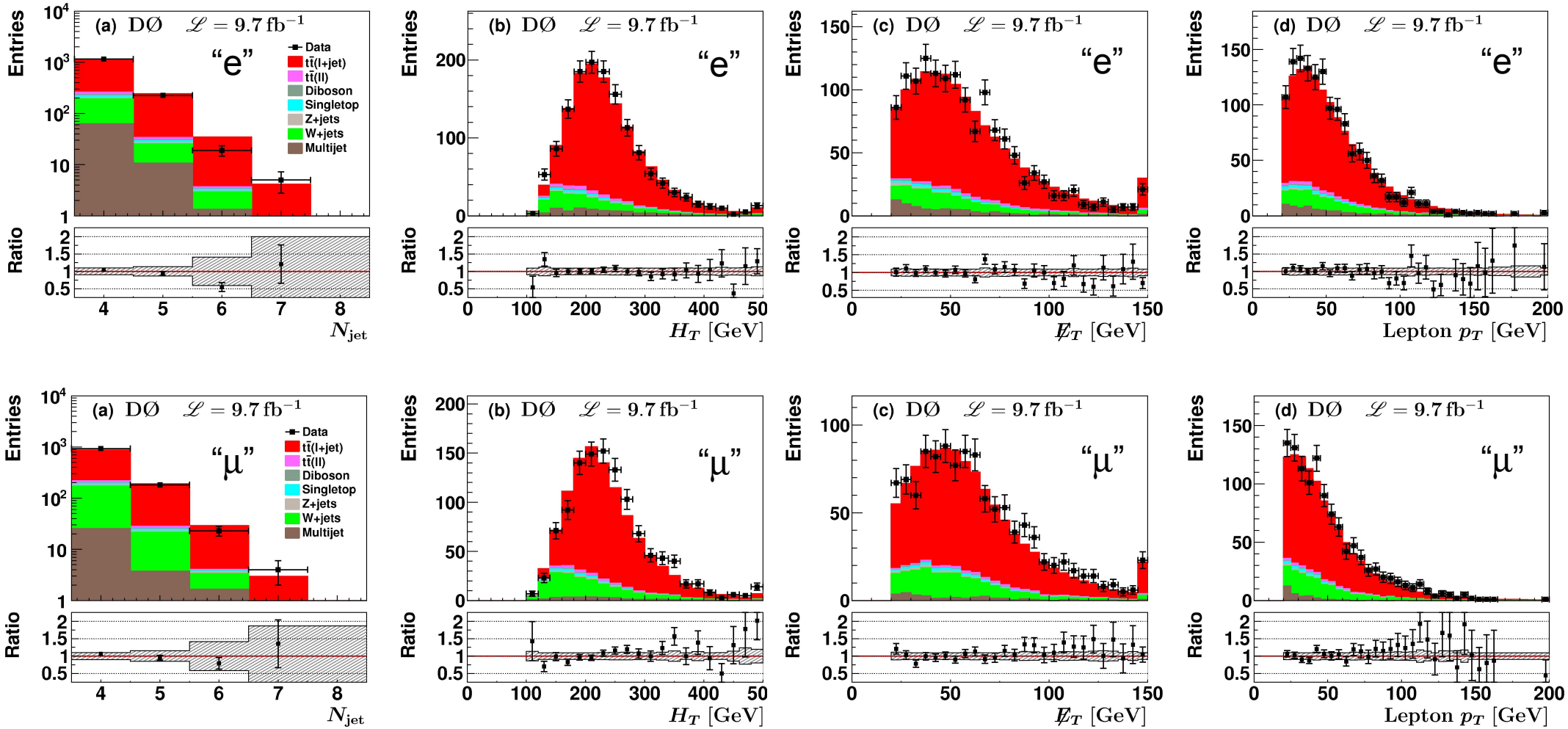
- W + heavy flavor + jets contributions constrained by using the 2, 3, and >= 4 jet-bin output distributions of the multi-variate *b*-ID technique
- Apply "medium" cut on output values
- Simultaneous fit of *Whf*+jets & $t\bar{t}$ contribution for muon+jets decay channel:





Control distributions

- Now check the signal region to measure differential cross sections: *e* or μ + ≥ 4 jets



- Very good description/modeling of the data within systematic uncertainties
  (assuming the measured $t\bar{t}$ cross section)

Differential cross sections

- Plots not the full information: Only full covariance matrices contain all information
- Diagonalized matrices as well, needed for model building / testing

$m(t\bar{t})$ [TeV]	0.2400 – 0.4125	0.4125 – 0.5050	0.5050 – 0.6150	0.6150 – 0.7500	0.7500 – 1.200
0.2400 – 0.4125	+16.832	−1.430	+0.364	−0.051	−0.001
0.4125 – 0.5050	−1.430	+6.436	−1.820	+0.321	+0.021
0.5050 – 0.6150	+0.364	−1.820	+2.570	−0.635	+0.020
0.6150 – 0.7500	−0.051	+0.321	−0.635	+0.633	−0.141
0.7500 – 1.2000	−0.001	+0.021	+0.020	−0.141	+0.129

Contribution [TeV]	λ	$m(t\bar{t})$ range [TeV]				
		0.2400 – 0.4125	0.4125 – 0.5050	0.5050 – 0.6150	0.6150 – 0.7500	0.7500 – 1.2000
1.655 ± 0.284	0.081	−0.000	+0.003	+0.079	+0.330	+0.941
6.361 ± 0.691	0.478	+0.000	+0.050	+0.316	+0.886	−0.337
19.747 ± 1.416	2.004	+0.015	+0.383	+0.867	−0.316	+0.037
28.166 ± 2.643	6.985	+0.147	+0.911	−0.375	+0.082	+0.000
16.360 ± 4.129	17.052	+0.989	−0.141	+0.043	−0.007	−0.000

Differential cross sections

- Detailed list of systematic uncertainties

Systematic error source	$\delta^{\mathrm{up}}_{\mathrm{incl,rel}}$ [%]	$\delta^{\mathrm{down}}_{\mathrm{incl,rel}}$ [%]
Procedural (Unfolding)	+0.18	−0.18
Alternative signal model	+5.17	−4.28
PDF (CTEQ6M 40 error sets)	−2.96	+3.38
Lepton ID	+0.51	−0.53
Jet energy scale	+2.41	−2.50
Jet energy resolution	+0.37	−0.38
Jet Identification	+0.31	−0.31
Jet response correction	−0.91	+0.76
b-tagging Uncertainty	+1.57	−1.58
b-fragmentation	+0.09	−0.09
Vertex confirmation	−0.82	+0.84
t-quark mass dependence	+0.32	−0.35
$p_T^{t\bar{t}}$ missmodeling	+0.79	−0.67
Trigger efficiency	+2.50	−2.50
Luminosity	+6.10	−6.10
W+jets heavy flavor scale factor	+0.75	−0.78
True and Fake lepton efficiencies	+0.55	−0.57
Theoretical cross section prediction	+1.58	−1.47
Total systematic uncertainty	+9.67	−9.34

Model parameters

Axi200A : $m_G = 200\text{GeV}$ $\Gamma_G = 50\text{GeV}$ $g_{R,i} = 0.4g_s$ $g_{L,i} = -0.4g_s$

Axi200R : $m_G = 200\text{GeV}$ $\Gamma_G = 50\text{GeV}$ $g_{R,i} = 0.5g_s$ $g_{L,i} = 0$

Axi200L : $m_G = 200\text{GeV}$ $\Gamma_G = 50\text{GeV}$ $g_{R,i} = 0$ $g_{L,i} = 0.5g_s$

Axi2000A : $m_G = 2\ \text{TeV}$ $\Gamma_G = 0.96\ \text{TeV}$

$g_{R,u} = -g_{L,q_1} = -0.6g_s$ $g_{R,t} = -g_{L,t} = 4g_s$

Axi2000R : $m_G = 2\ \text{TeV}$ $\Gamma_G = 1.0\ \text{TeV}$

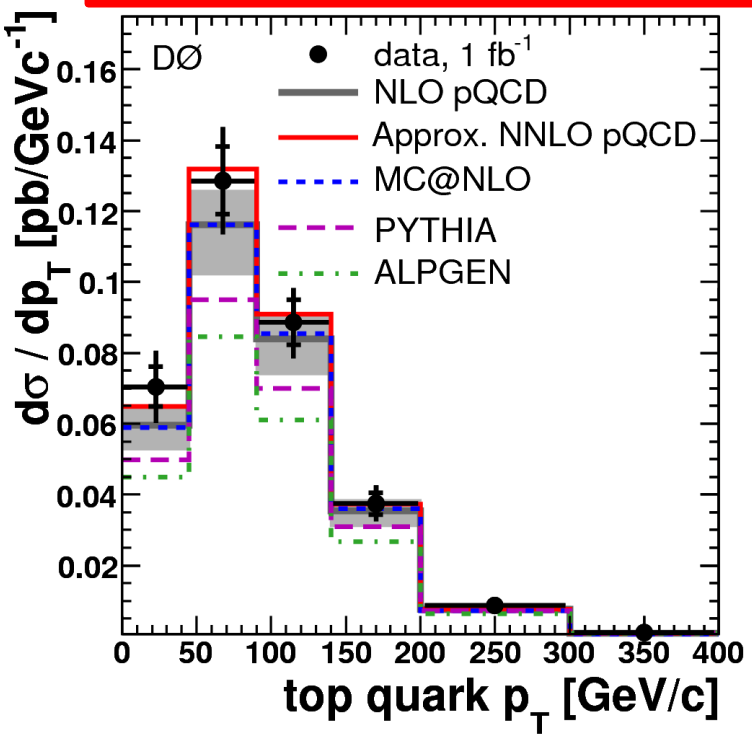
$g_{R,u} = -0.8g_s$ $g_{R,t} = 6g_s$

Zp220 : $m_{Z'} = 220\ \text{GeV}$ $g_{Z'} = 0.7$ $\Gamma_G = 2.9\ \text{GeV}$

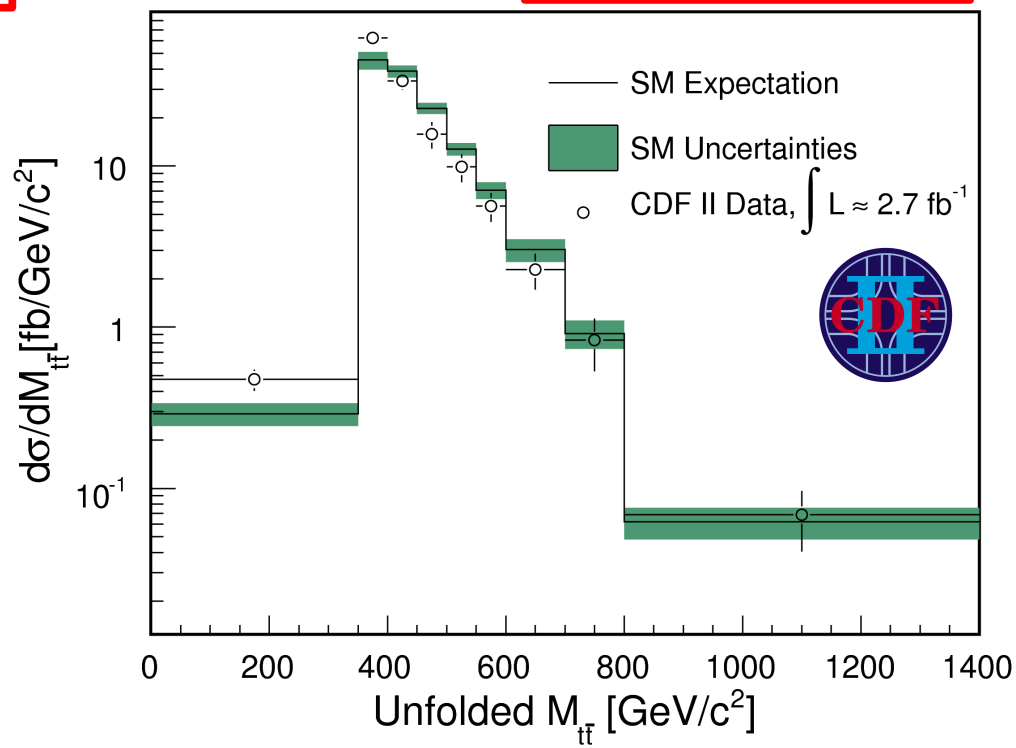
Previous measurements

- Corrected for detector effects by regularized unfolding (to full phase space)

Phys. Lett. B 693, 515 (2010), arXiv.org:1001.1900



PRL 102 222003 (2009)



- Dominant systematics: JES 2-8% and at high M(tt) PDF up to 18%
- Just a fraction of full data set used !
- Provides more insights to differential ttbar production and tests QCD calculations