Experimental Top Quark Physics
Part II

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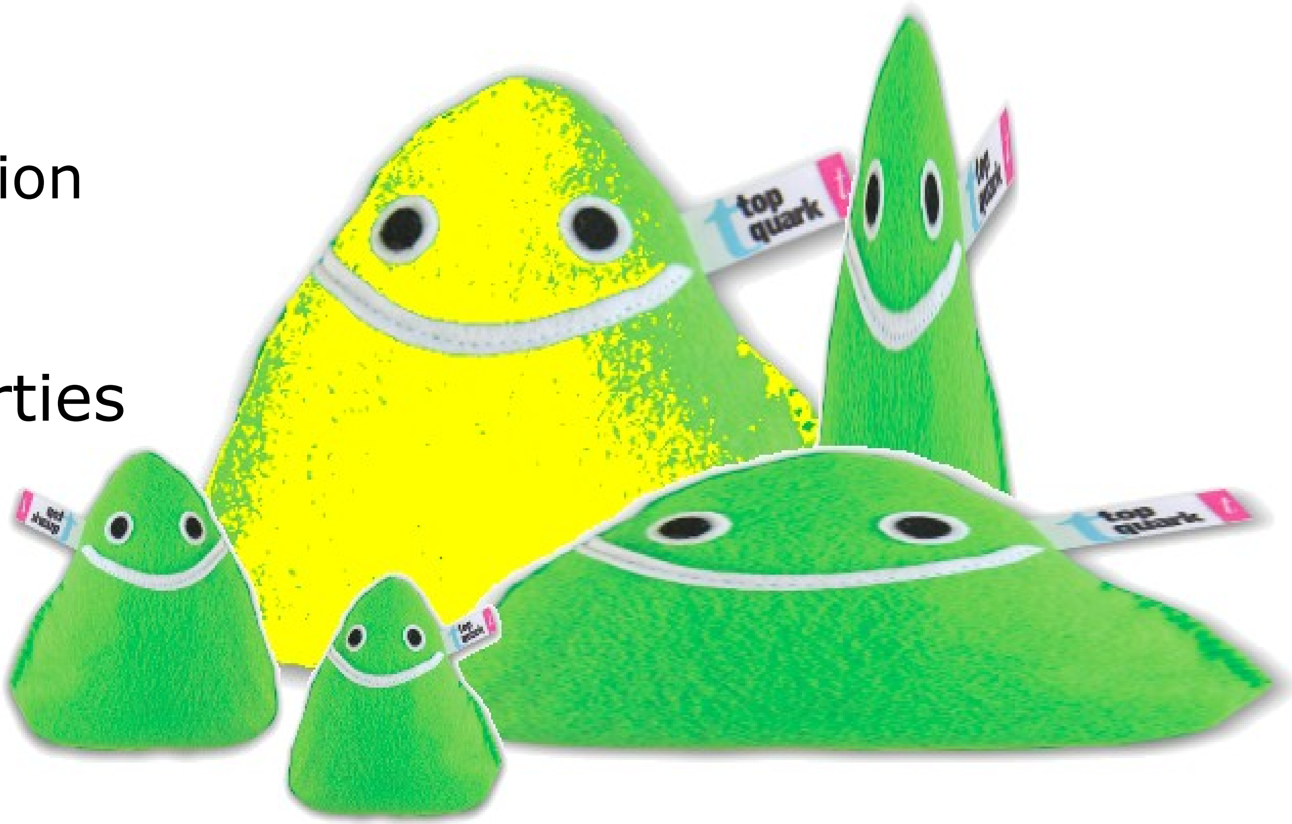
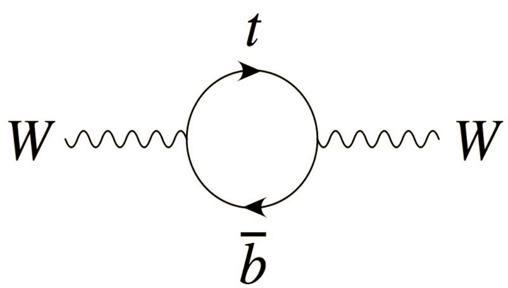
Part II: Properties

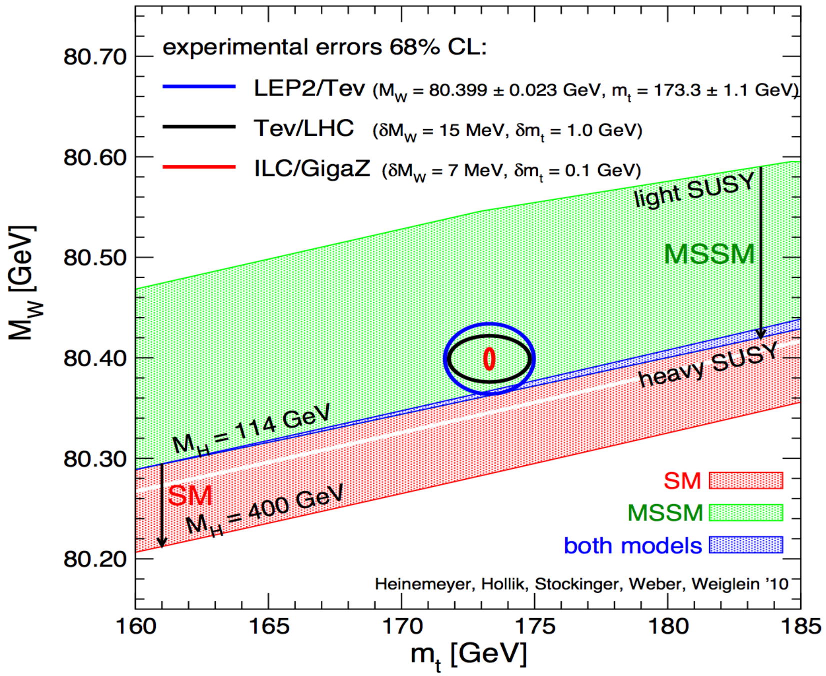
- Top Quark Mass:
  - Methods
  - Mass from cross section
- Spin Correlations
- Overview other properties

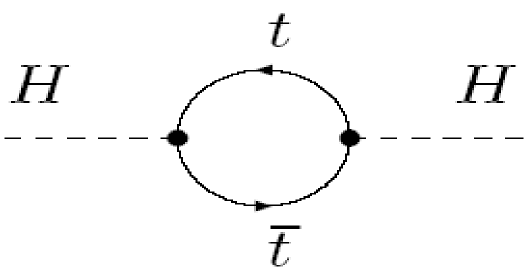


Top Quark Mass

- Free parameter of the SM
- Together with W mass: puts constraint on Higgs mass → self-consistency check



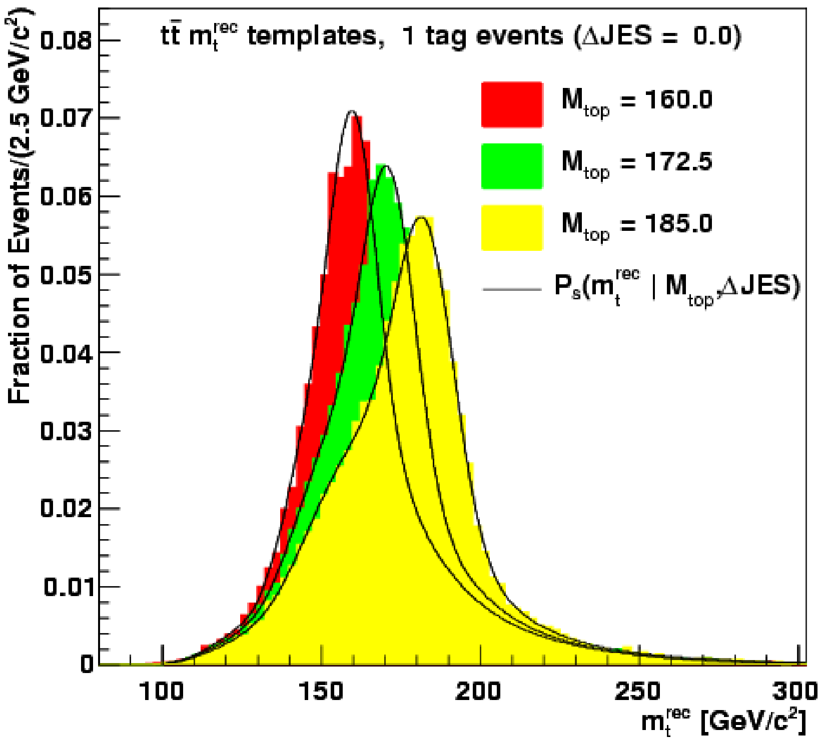




- Measurement done with several methods: Template method, ideogram, matrix element, etc.
  - Methods also used for other analyses, e. g. W helicity & spin correlations

Top Quark Mass: Template Method

- Construct mass dependent template
- Compare MC for different top masses to data → "done"



Top Quark Mass: Template Method

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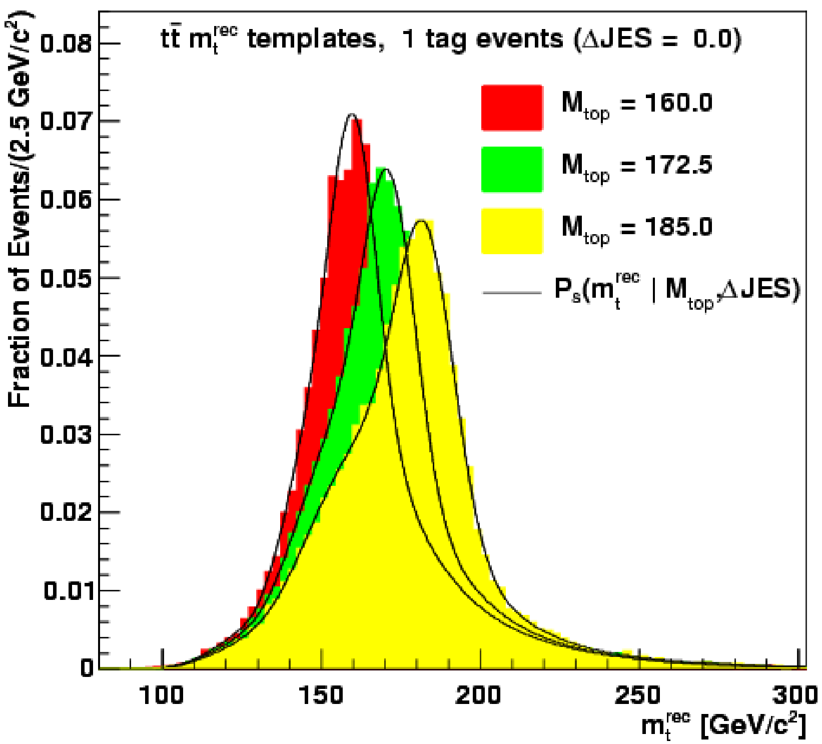
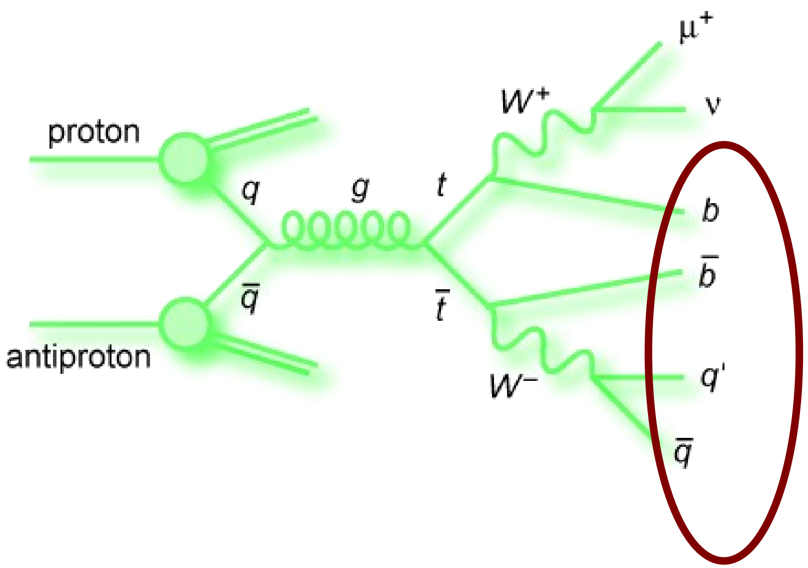
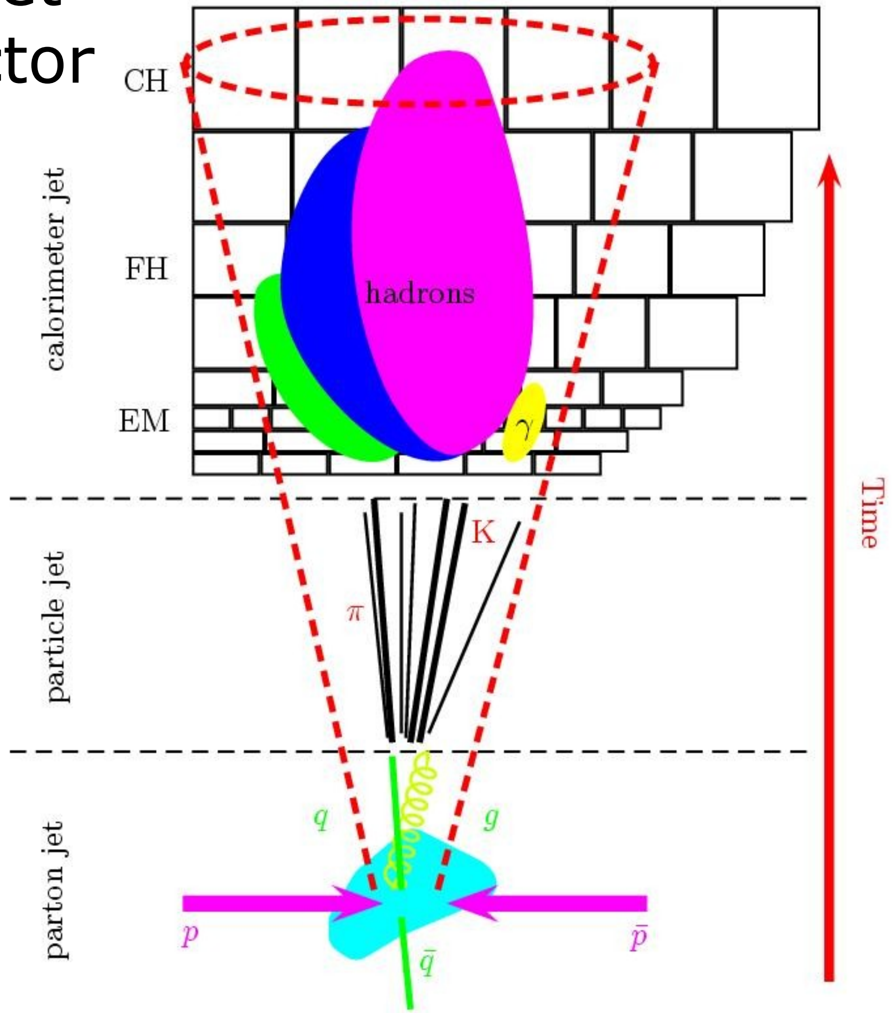
- Main systematic uncertainty: Jet Energy Scale





Intermezzo: Jet Energy Scale

- Goal of jet energy scale (JES) correction: correct the calorimeter jet energy back to the stable-particle jet level, before interaction with the detector



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E_{jet}^{ptcl}: corrected jet energy

E_{jet}^{raw}: uncorrected jet energy

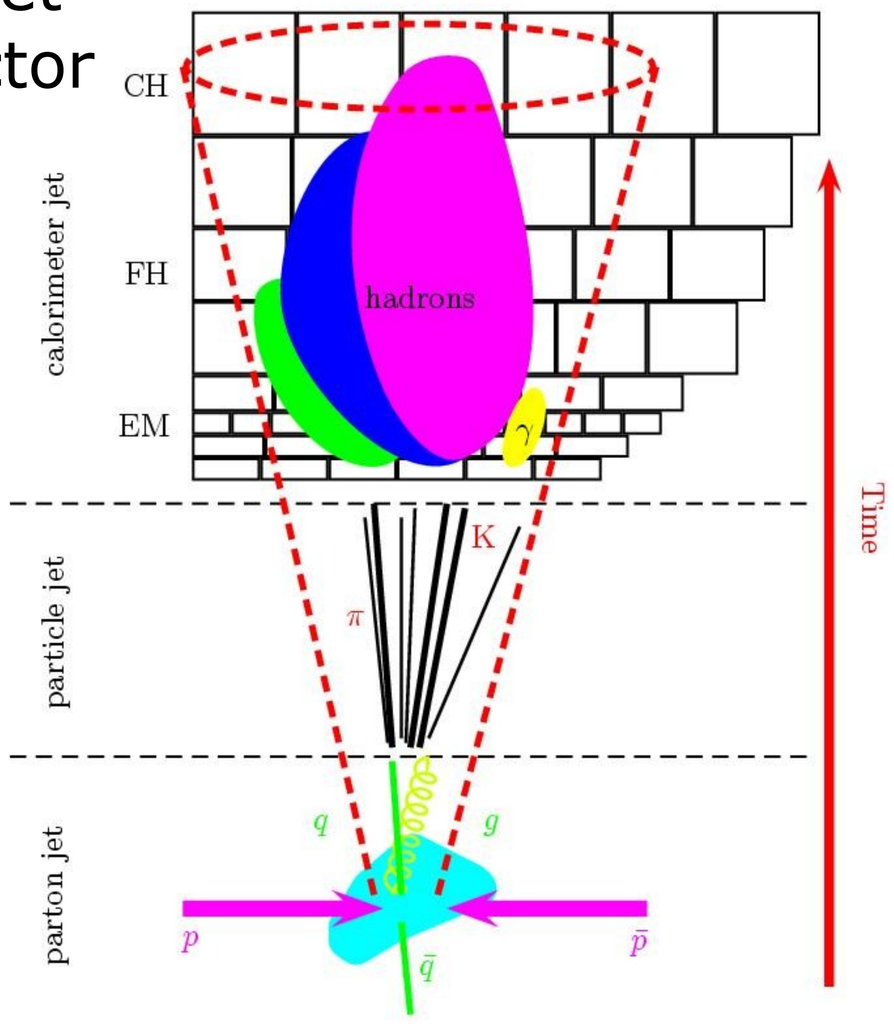
O: offset energy correction

F_η: relative response correction (η-intercalibration)

R: absolute response correction

S: showering correction

k_{bias}: correction for remaining biases



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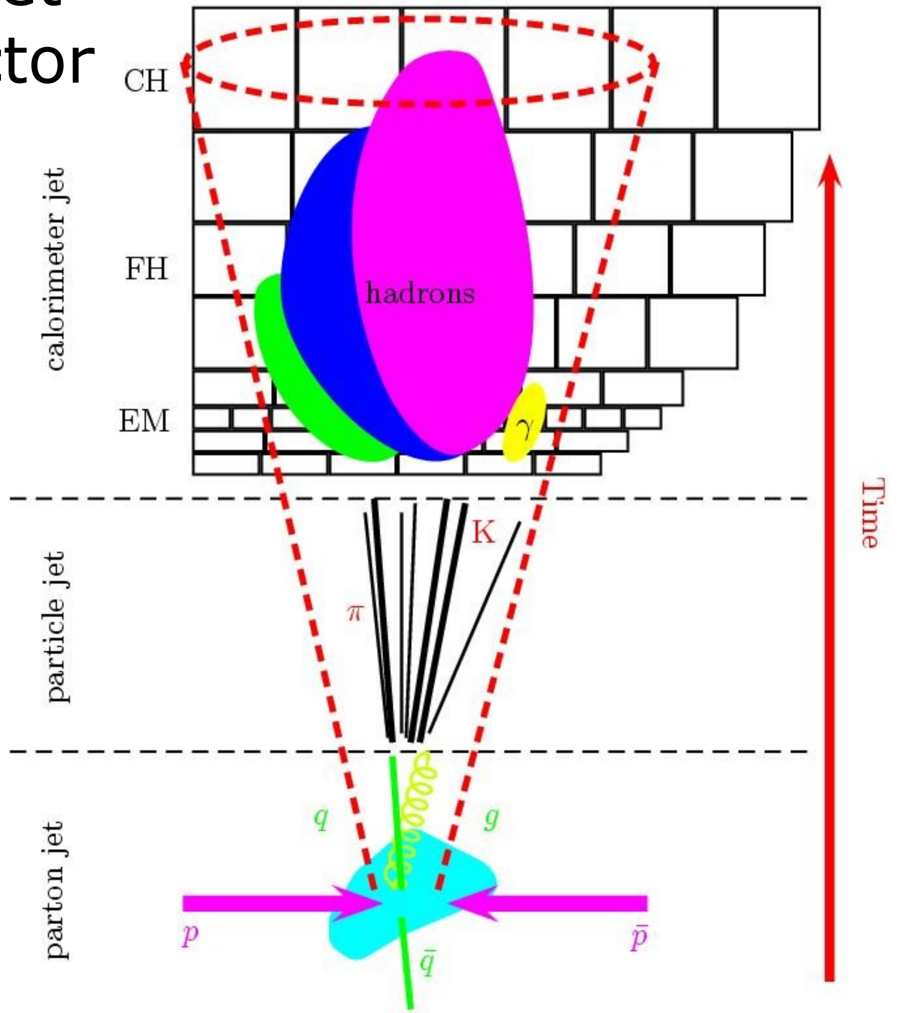
Offset: energy deposited within jet cone, not associated with primary interaction (e. g. noise)



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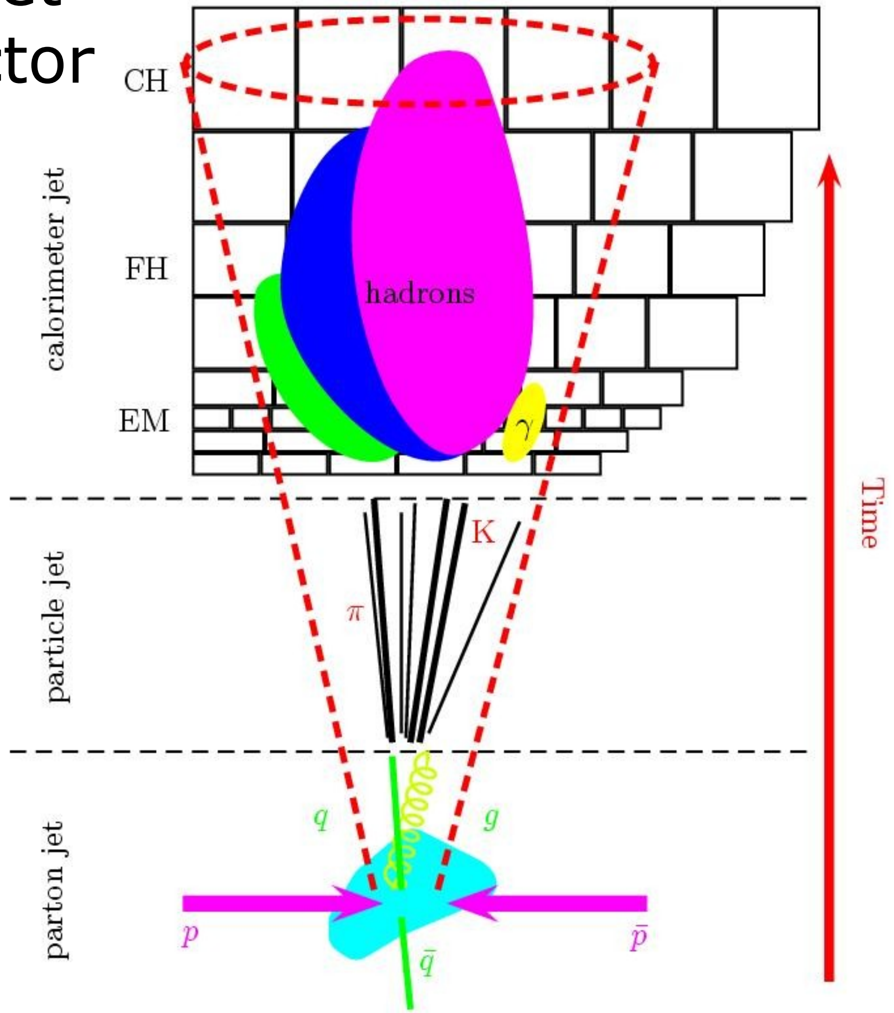
Correct for non-uniformity of calorimeter versus eta (e. g. region between cryostats)



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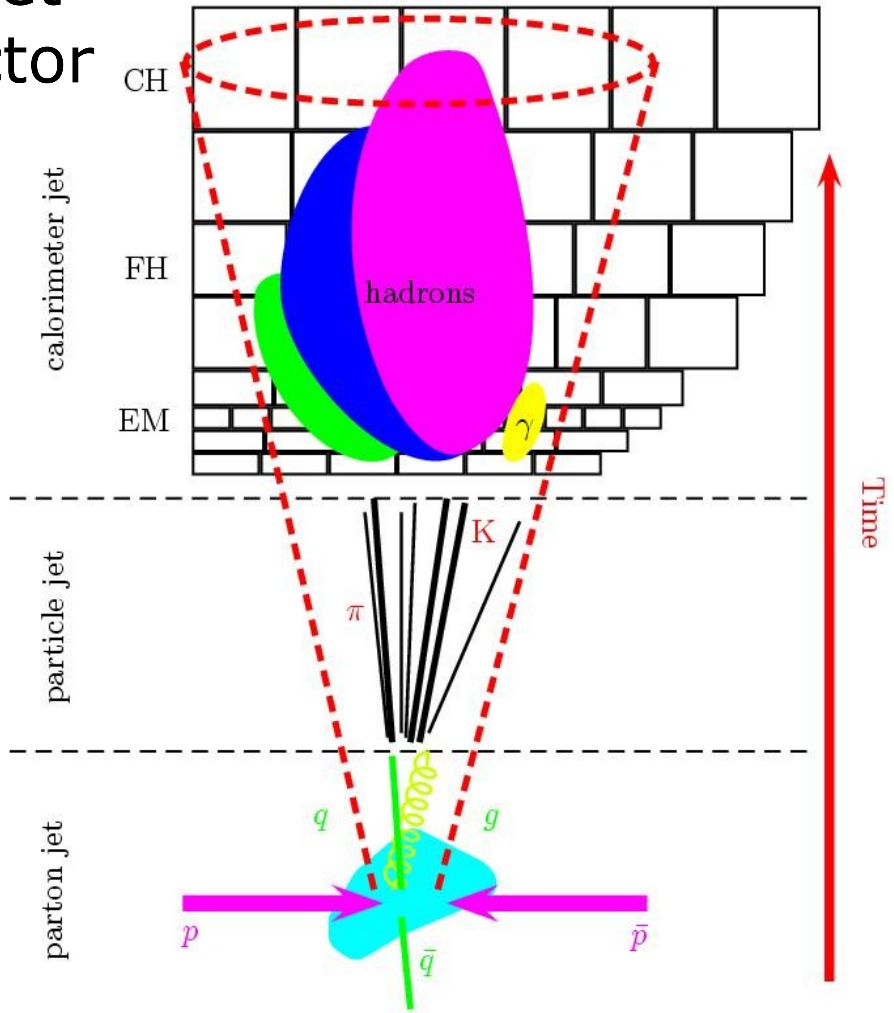
Absolute response accounts for effects like energy loss in uninstrumented detector regions, lower calorimeter response to hadrons as compared to electrons/photons, etc.



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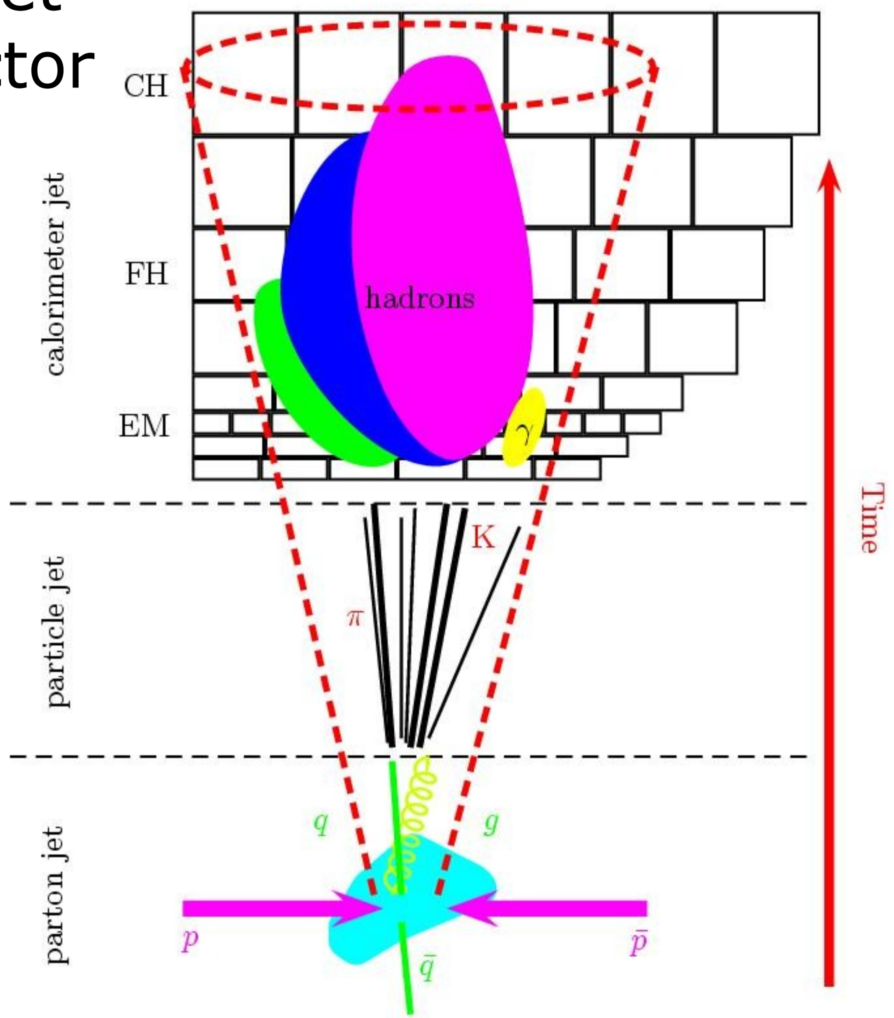
Showering correction: takes into account the energy deposited outside (inside) the calorimeter jet cone from particles inside (outside) the particle jet as a result of shower development in the calorimeter, magnetic field bending, etc



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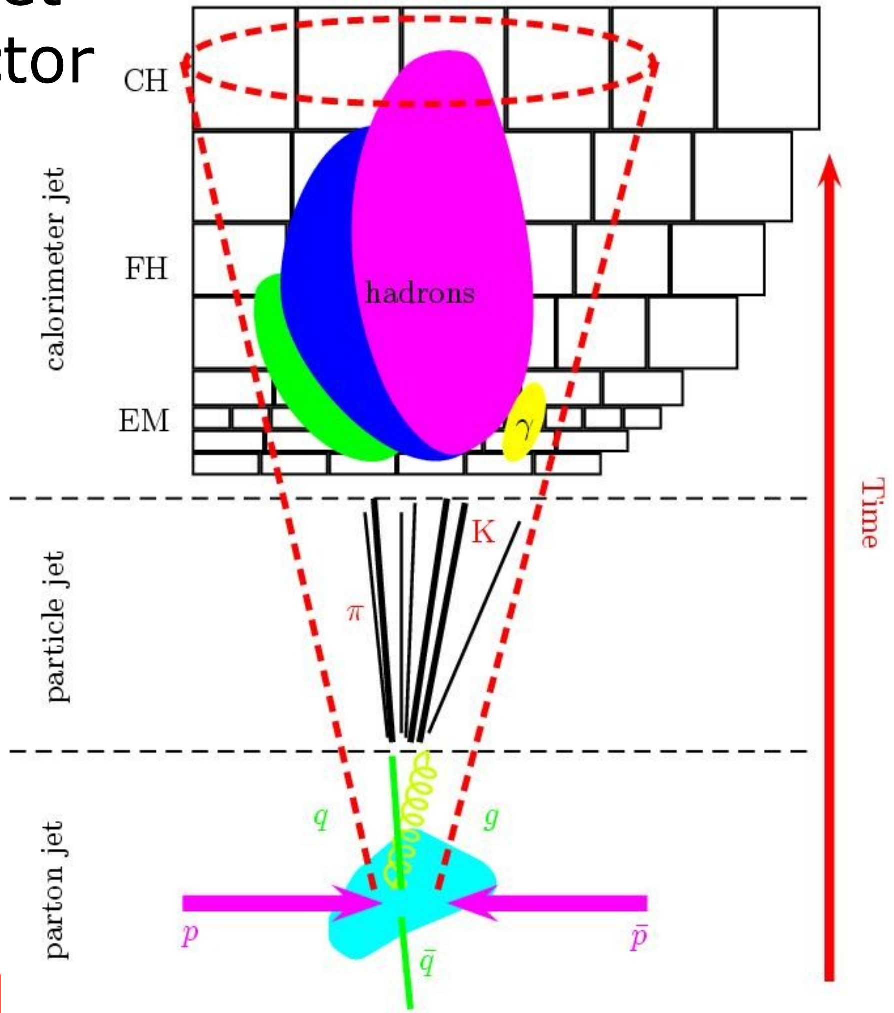
Remaining biases: correct for kinematic effects, etc.



Top Quark Mass: Template Method

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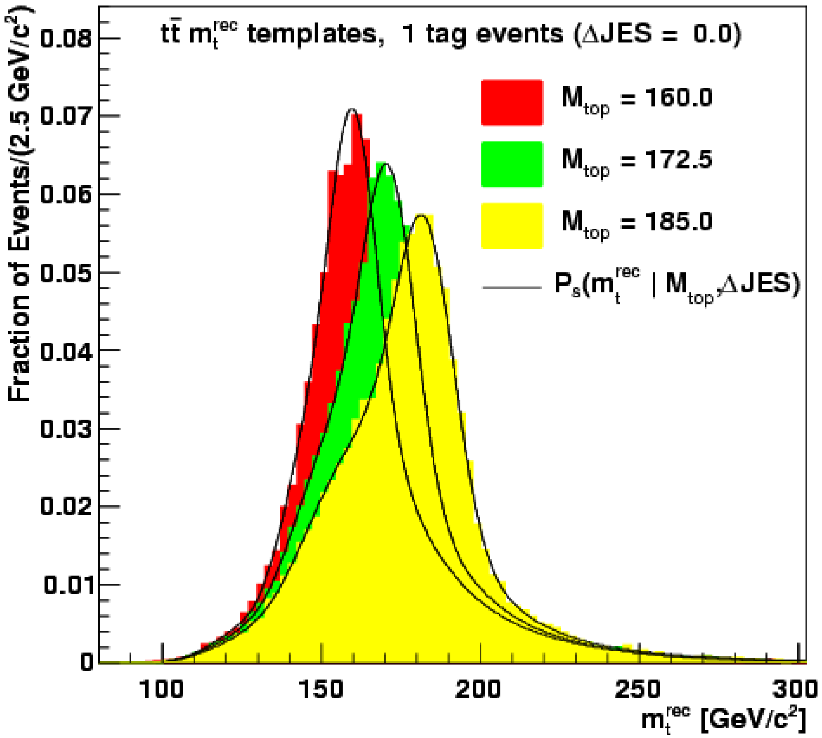
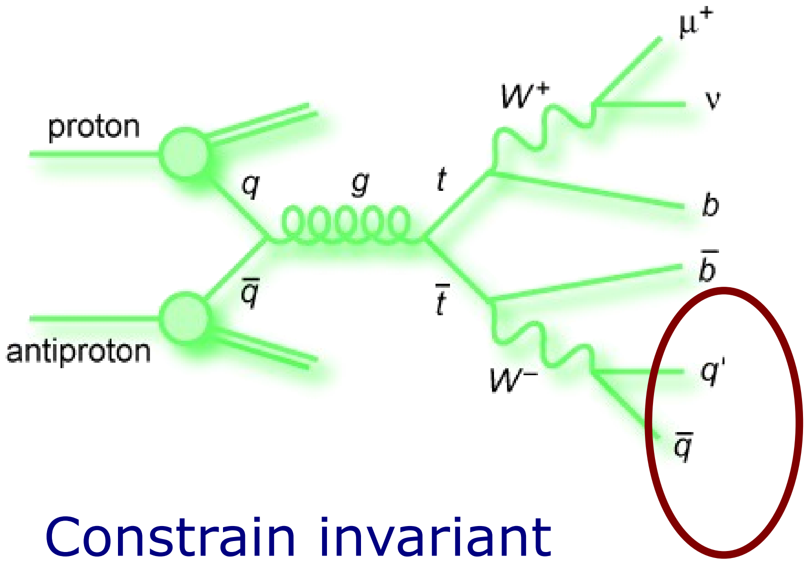
- Compare MC for different top masses to data → "done"
- Main systematic uncertainty: Jet Energy Scale
  - In-situ calibration





Constrain invariant mass of jets from W to known W mass

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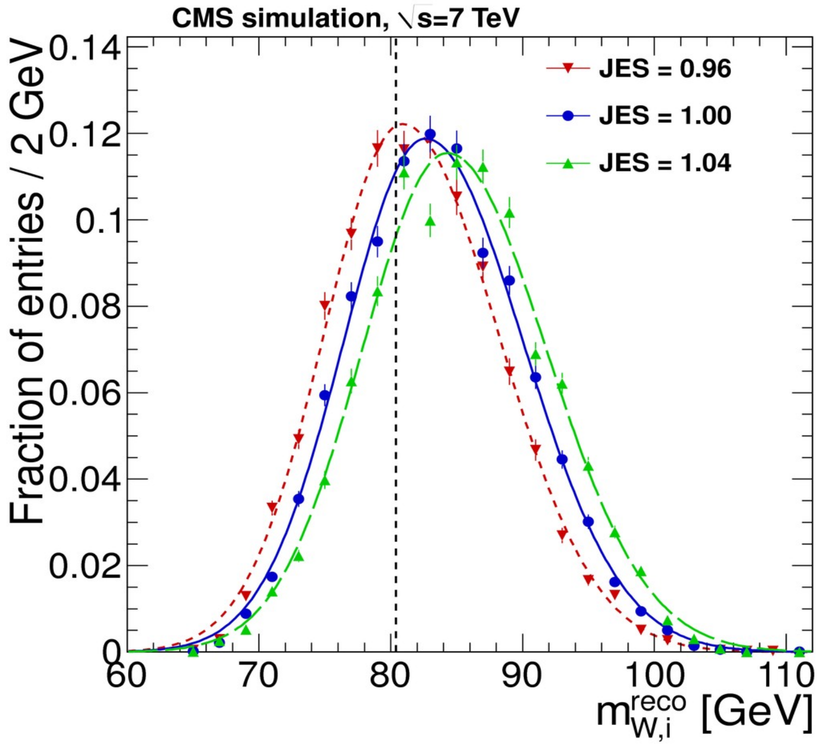
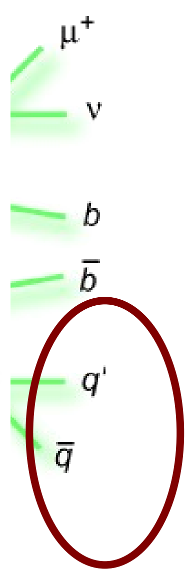
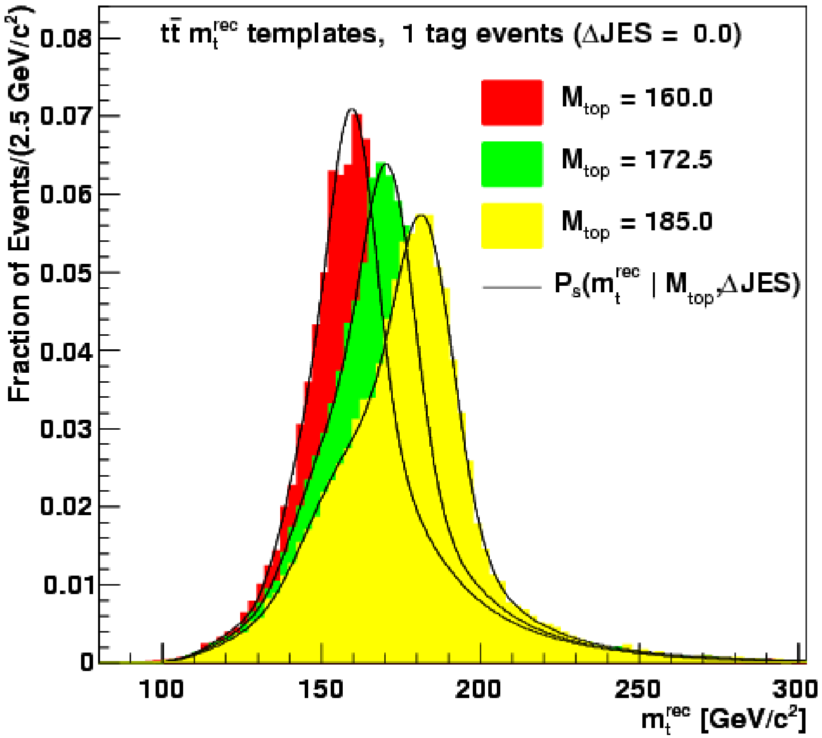


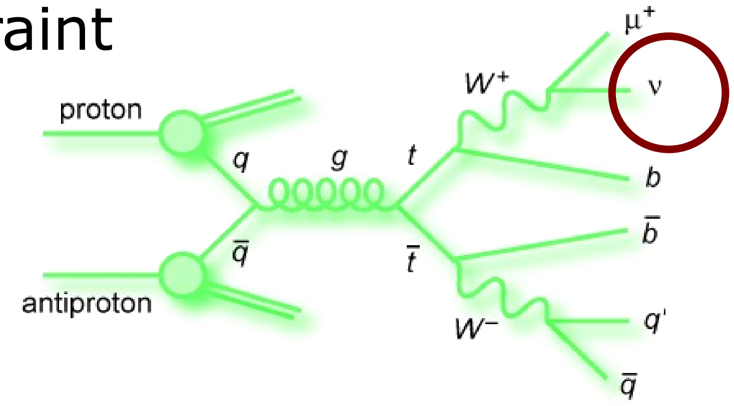


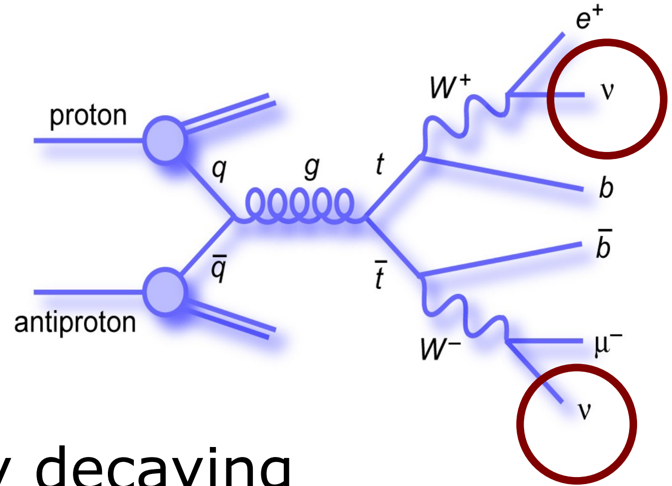


Constrain invariant mass of jets from W to known W mass

Template Methods Dilepton

- Dilepton: Construction of templates more complicated due to presence of two neutrinos
  - l+jets: missing neutrino info can be extracted from W mass constraint

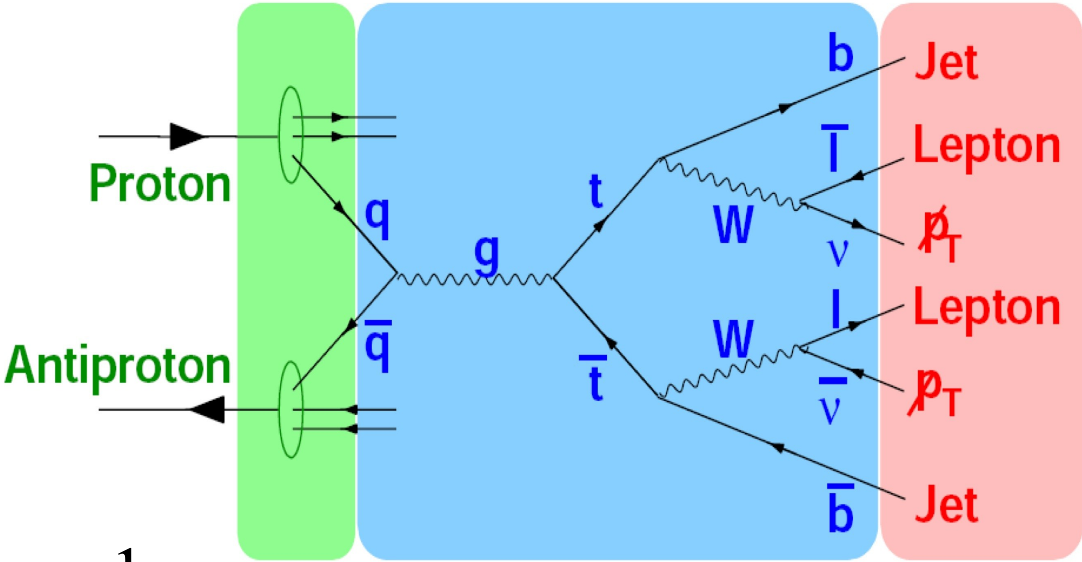




  - Additional complication: No hadonically decaying W for in-situ JES calibration → larger uncertainties
- Neutrino weighting, Matrix Weighting,..

Top Quark Mass: Matrix Element Method

- Use full event kinematics → most precise method
- For each event calculate probability to belong to certain top mass



$$P_{sig}(x;m_{top}) = \frac{1}{\sigma_{obs}} \int \sum_{flavors} dq_1 dq_2 dy\, f(q_1)\, f(q_2)\, \sigma(y;m_{top})\, W(x,y)$$

PDFs

Matrix element & phase space

Transfer function: mapping of true momenta y to measured momenta x

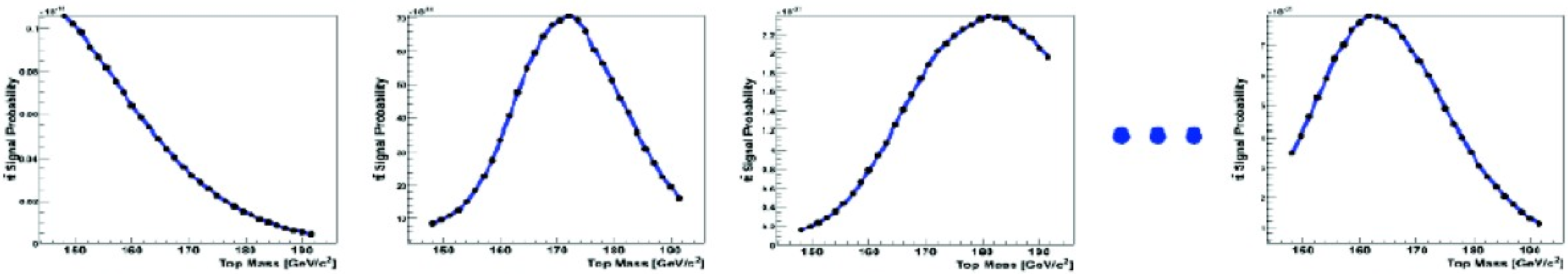
Matrix Element Method: Extraction

- In the same way as signal probabilities, calculate background probabilities $P_{bkg}(x)$
- Per-event probability:

$$P_{evt}(x, m_{top}) = f_{sig} P_{sig}(x, m_{top}) + (1 - f_{sig}) P_{bkg}(x)$$

  - f_{sig}: fraction of signal events in data sample
- Perform event-by-event likelihood:

$$-\ln L(m_{top}) = -\ln \prod_i^n P_{evt}(x, m_{top})$$



Event 1 Event 2 Event 3 Event n

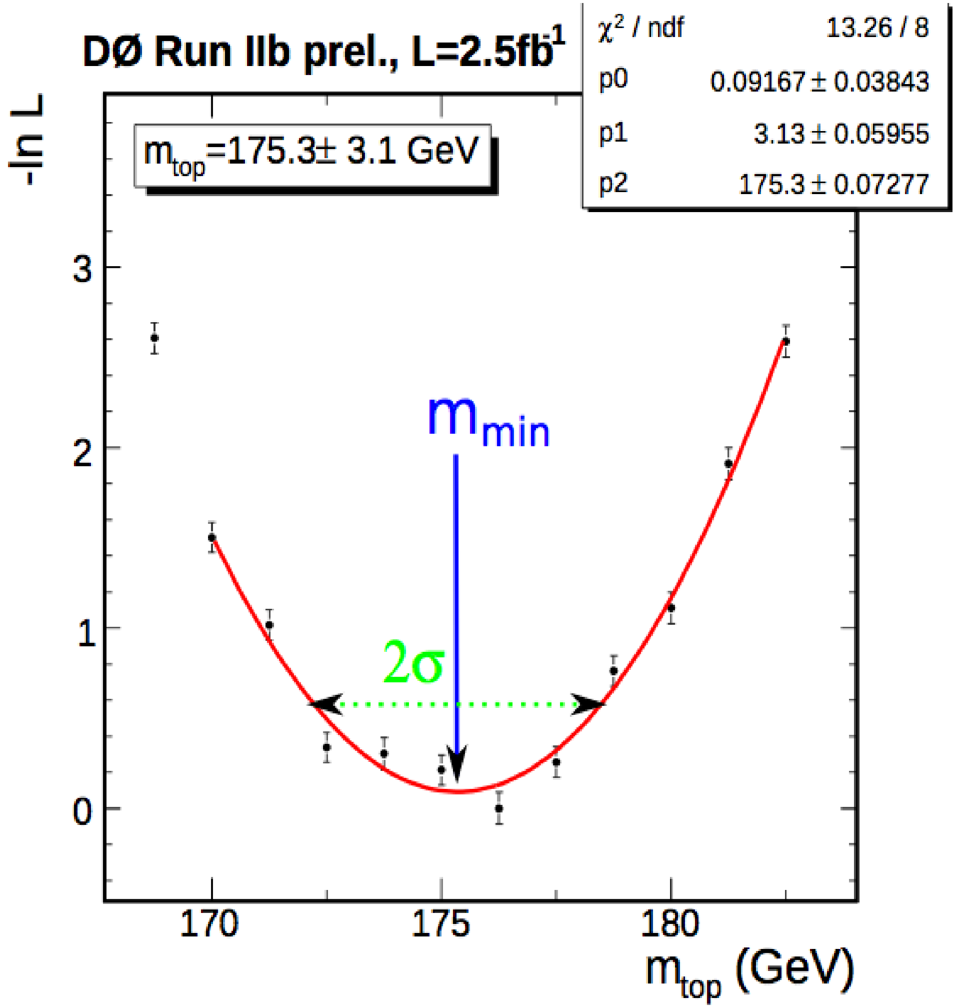
Matrix Element Method: Extraction

- Likelihood of the mulitplied event probabilities:

- Problem: several assumptions are included in the method
  - LO ME
  - Background probabilities might be simplified
  - Assumptions of the generator...

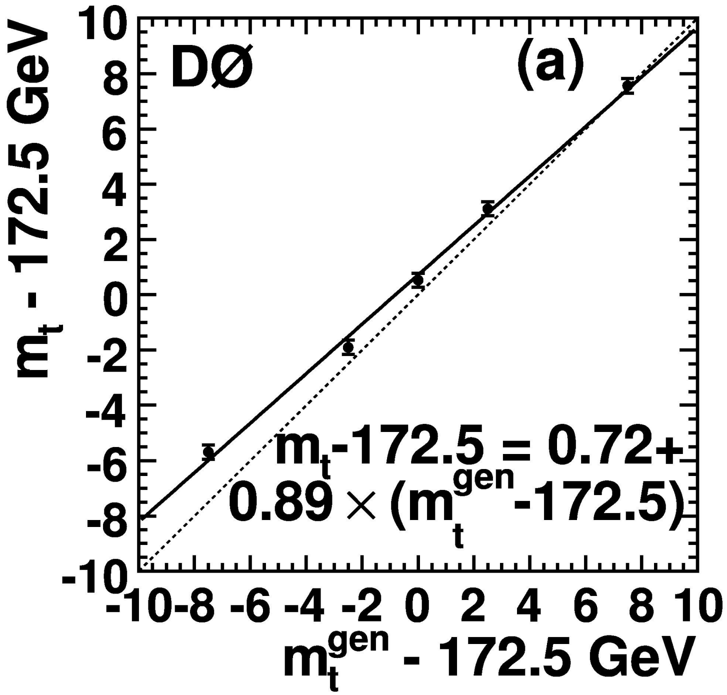
→ extracted top mass not directly the measured mass

- Calibration needed!



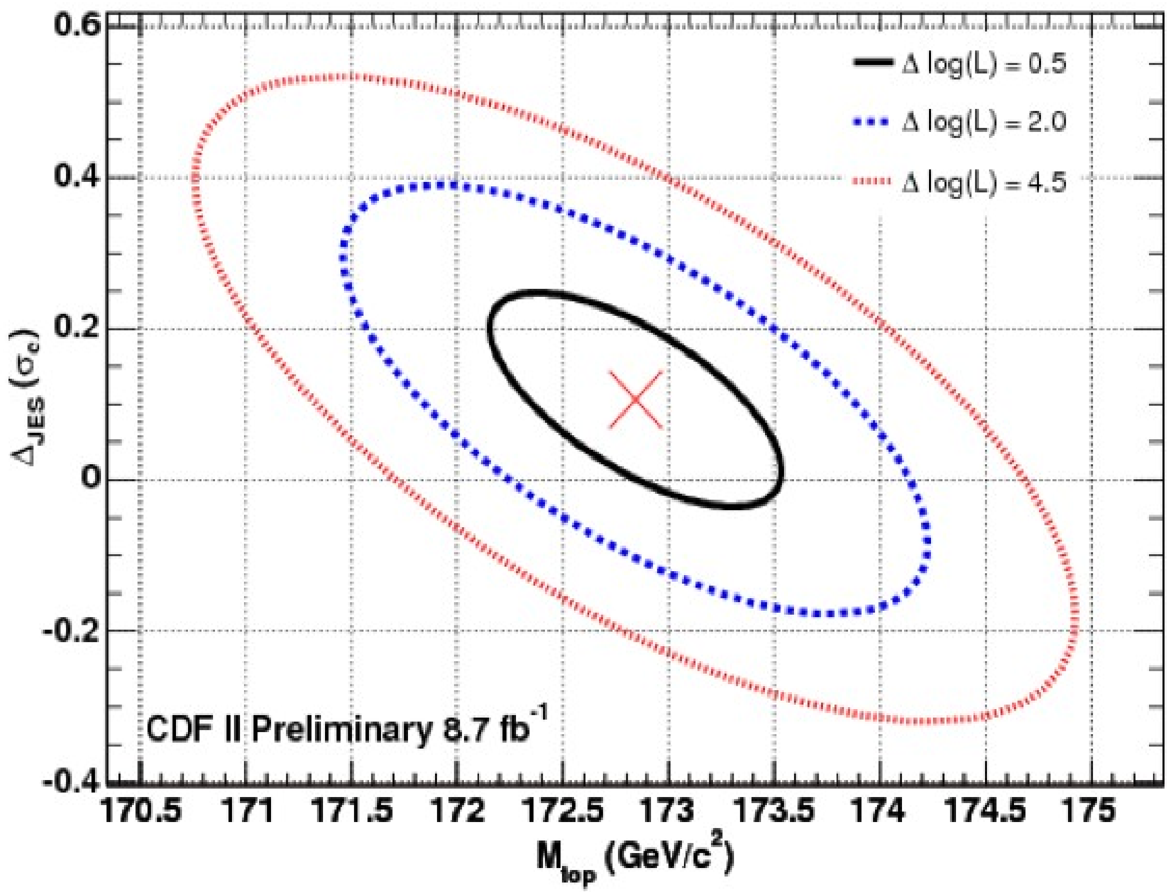
Matrix Element Method: Calibration

- 1) Use fully simulated MC samples of different top quark masses
- 2) Measure the mass for each sample
  - Using an ensemble of pseudo-data from this sample; for each pseudo-dataset the randomly chosen events follow the number of expected signal and background events in data
  - Extract top mass for each pseudo-dataset
- 3) Extract calibration curve
  - For central value and uncertainty



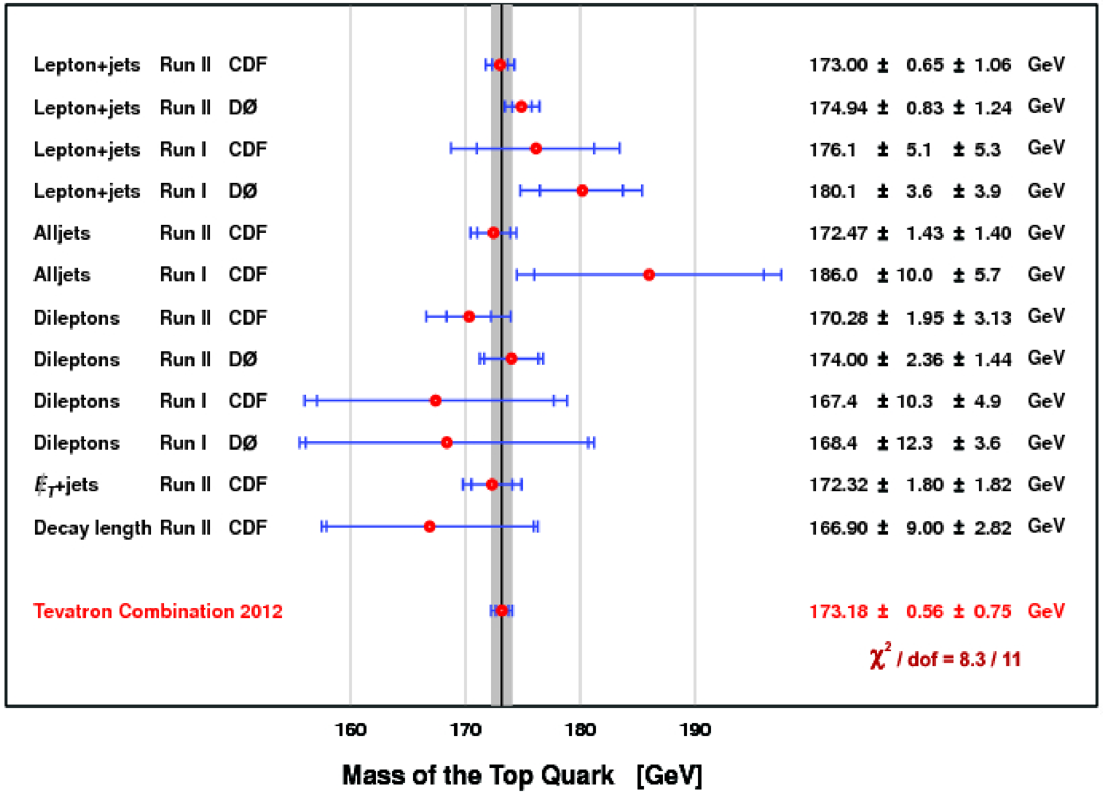
Fitted Results

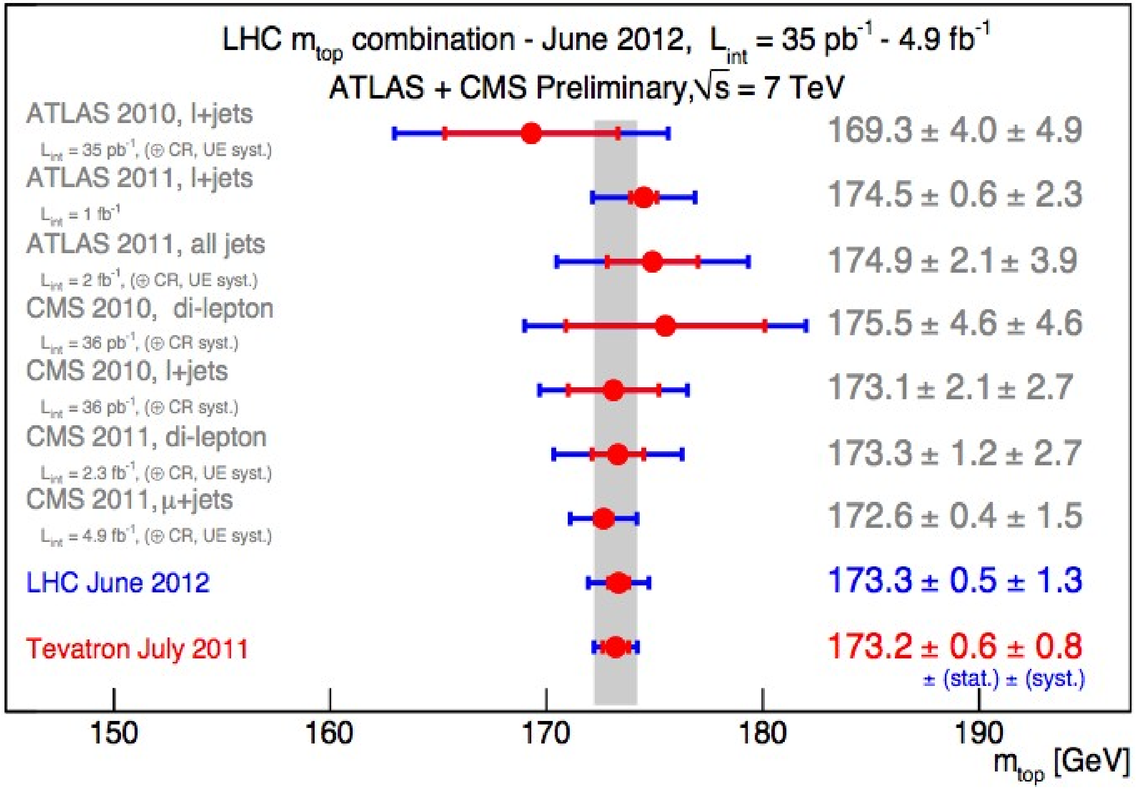
- Extraction of top mass and in-situ JES factor simultaneously



Mass Overview

- Several top mass measurements in several channels with several techniques performed at Tevatron and LHC





- Total uncertainty <1%!

Systematics

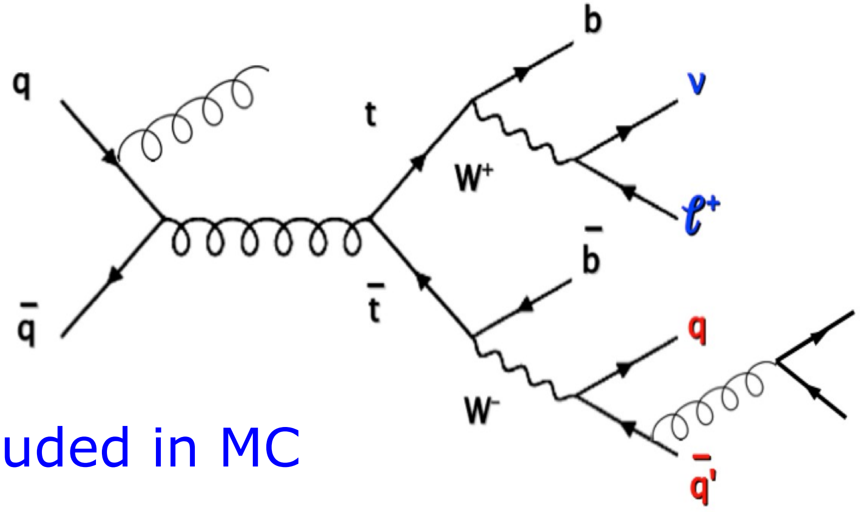
- Mass measurements: dominated by systematic uncertainties
- Several categories are related to MC modeling
  - Initial state radiation (ISR)
  - Color reconnection
  - …
- Main focus at experiments: understand and reduce these systematic contributions
  - Preferentially using measurements on data; not only simulation
  - Example: jet veto analysis used to reduce ISR

Top Quark Mass: Be aware

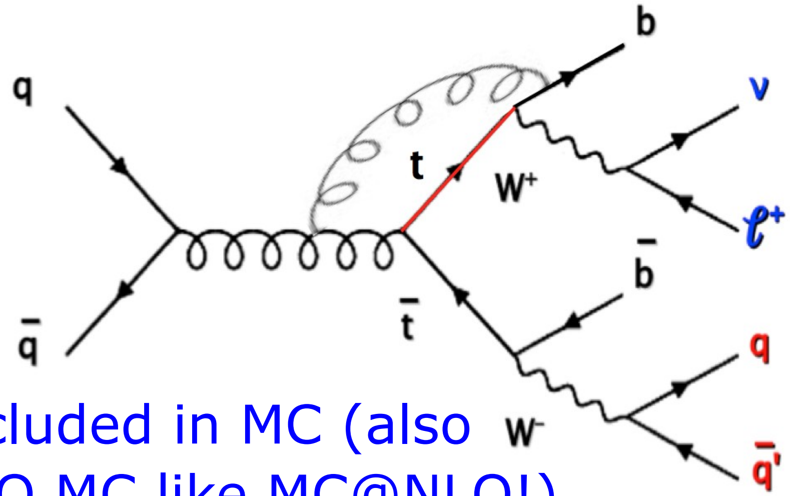
- Ongoing discussion: What is theoretical interpretation of the measured parameter?
  - We measure the Monte Carlo top mass parameter
  - Is it the pole mass?

$$\frac{1}{p^2 - M_t^2 - i\Gamma_t M_t}$$

    - Parton showers simulate higher orders
    - But not all components included

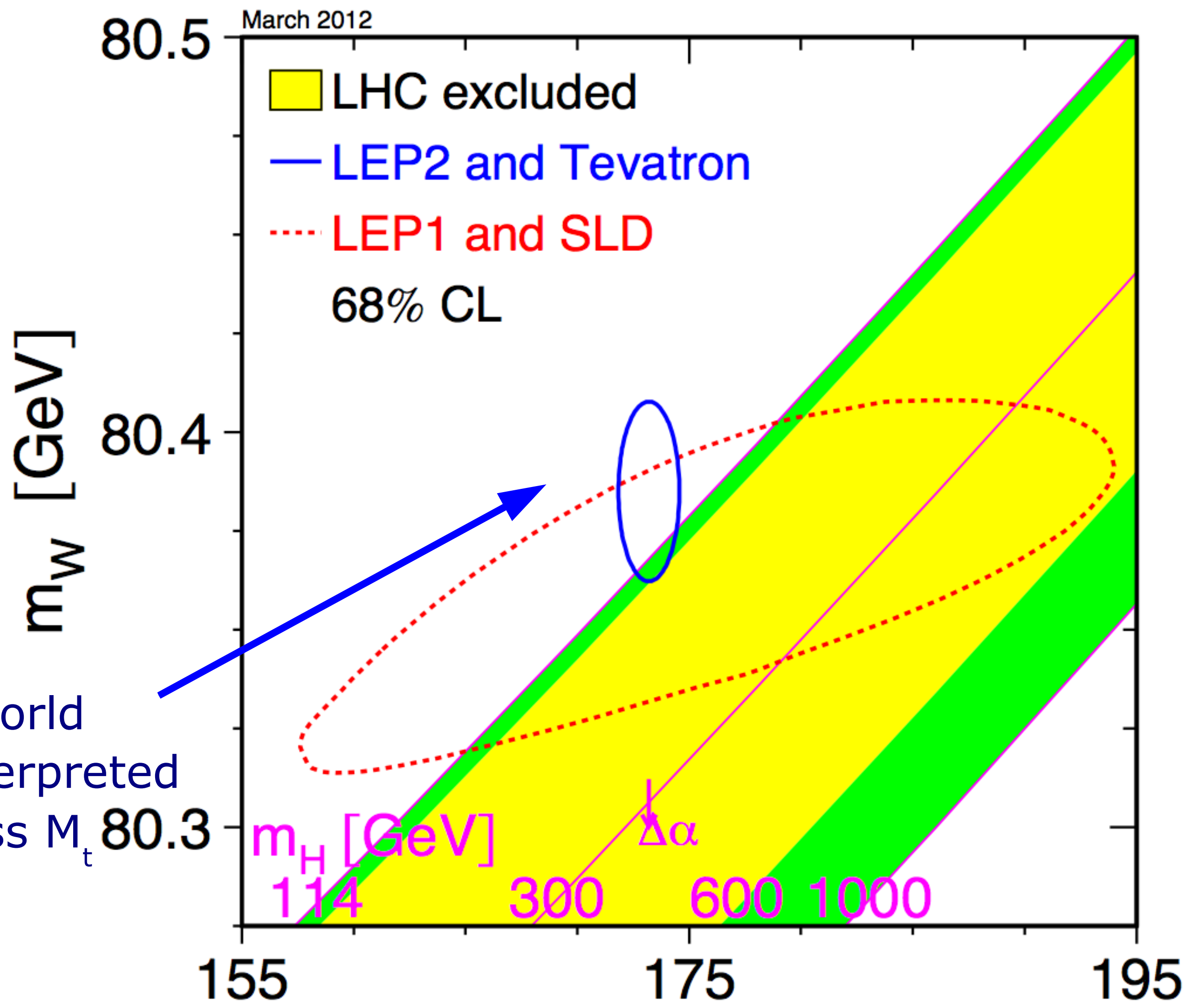


Included in MC



Not included in MC (also not NLO MC like MC@NLO!)

Top Quark Mass: Impact of Mass Definition



Top mass world average interpreted as pole mass M_t

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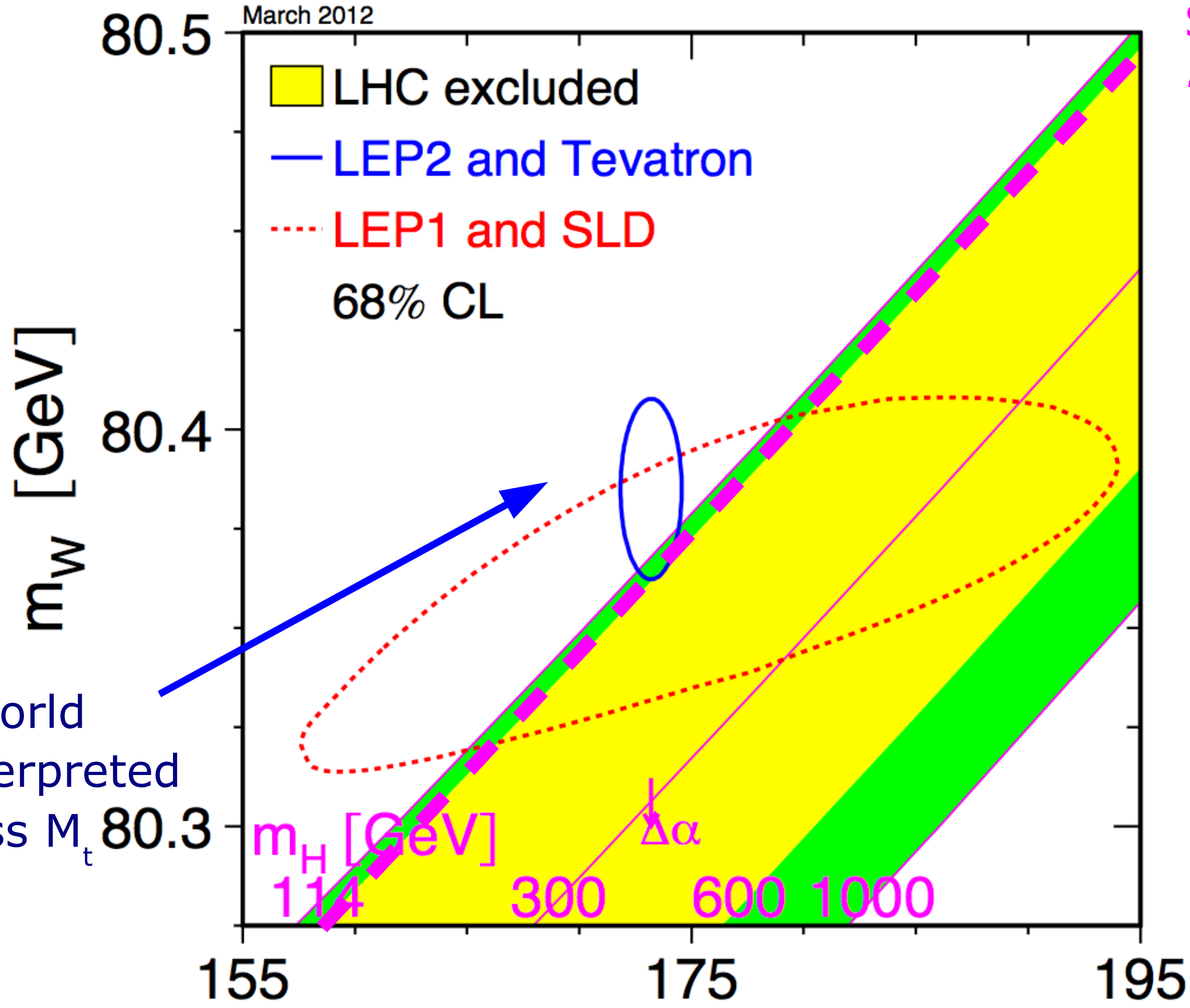

SM Higgs of mass ~125GeV

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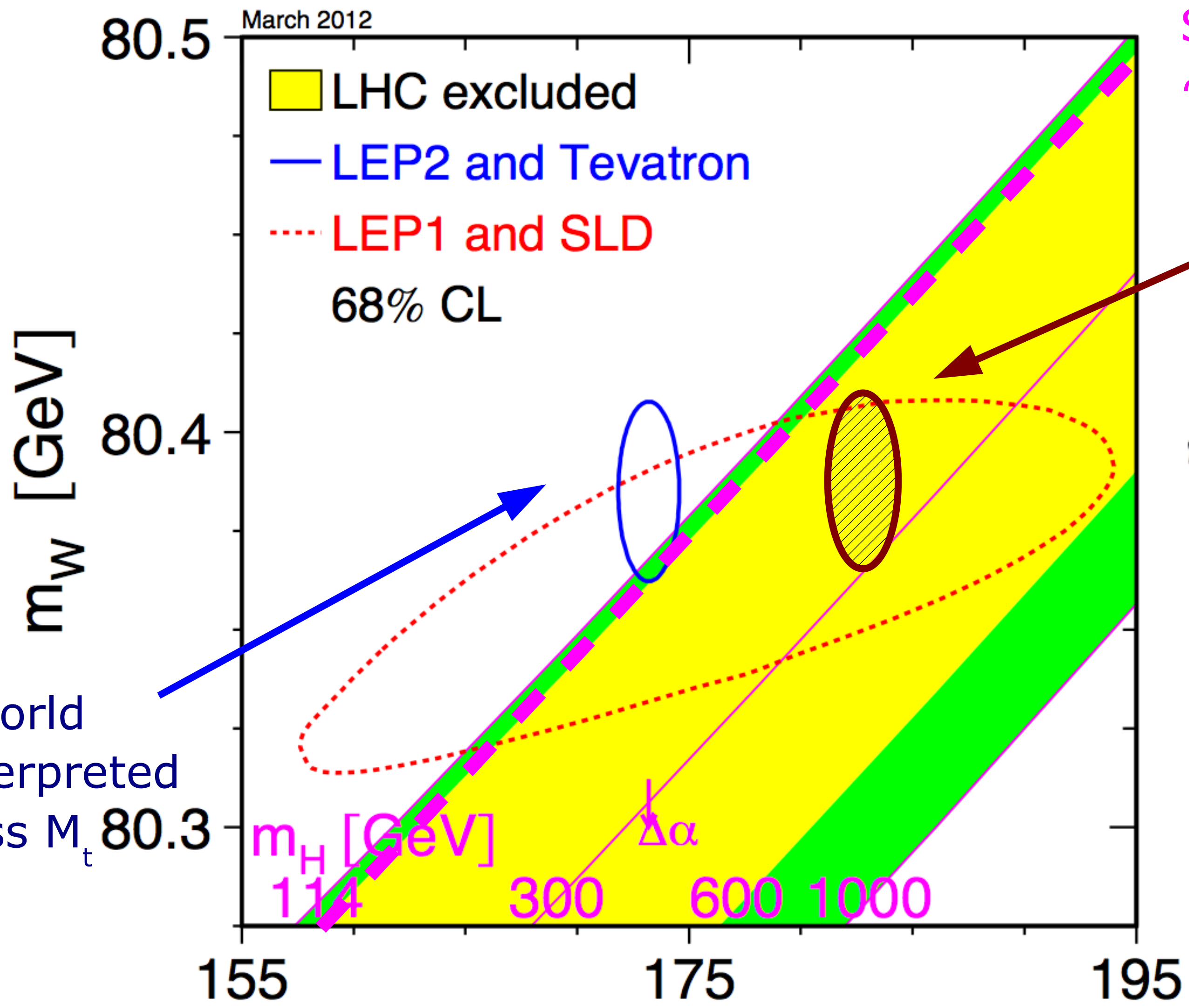


SM Higgs of mass ~125GeV

Top mass world average interpreted as $\overline{MS}$ mass

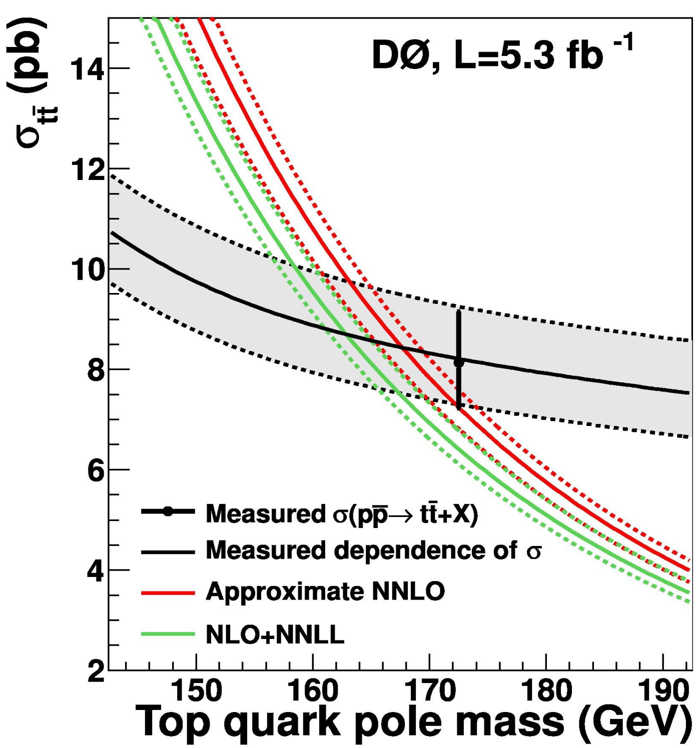
$$m_t^{\overline{MS}}(m_t) = \frac{M_t}{1 + \frac{4}{3\pi}\alpha_s(M_t)}$$

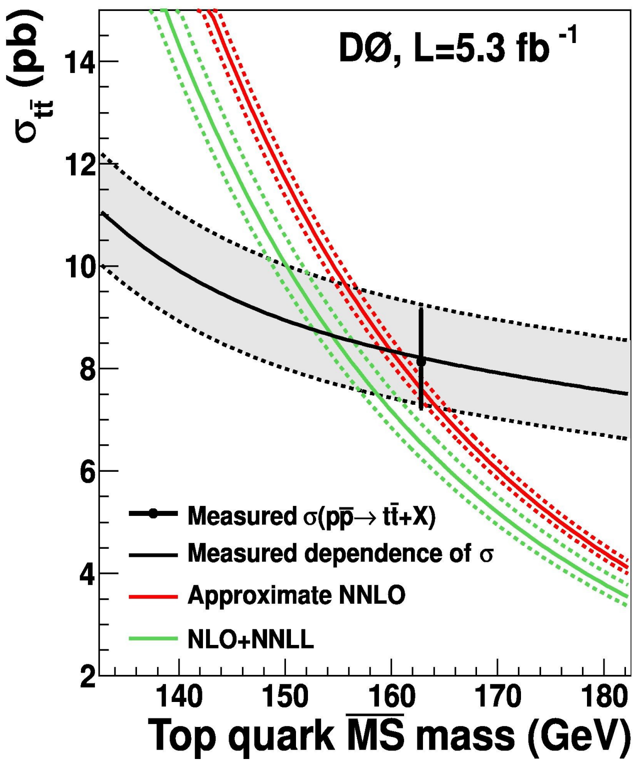
Top mass world average interpreted as pole mass M_t

Difference between $\overline{MS}$ and pole mass about 10GeV

Top Quark Mass: Be aware

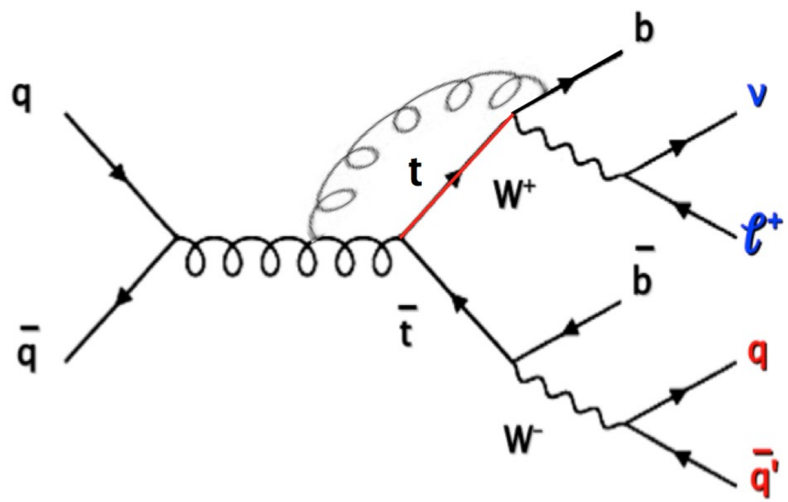
- Alternative method: Extract m_t from cross section measurement
  - Assuming pole or $\overline{MS}$ mass
    - For parameter in MC; For theory calculation
- Pole mass: $m_t = 167.5^{+5.2}_{-4.7}\,GeV$
- Assuming $\overline{MS}$ mass leads to ~7 GeV smaller value
- World average more compatible with pole mass





NLO MC

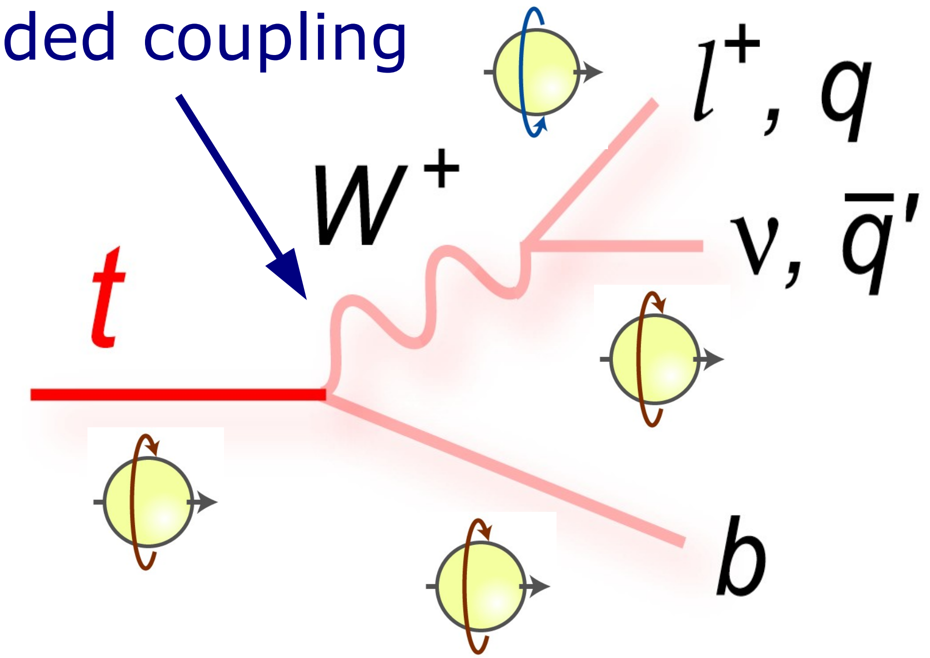
- By now some MC gets on the market with all necessary diagrams
  - No on-shell top quark only
  - So far only dilepton final state
- Should be possible to soon get a better feeling of what it is that we measure



$t\bar{t}$ Spin Correlations

- Short lifetime of top quarks (~0.5*10^{-25}s)
  → Top quarks decay before fragmentation
  - Spin information of top is preserved

Left-handed coupling



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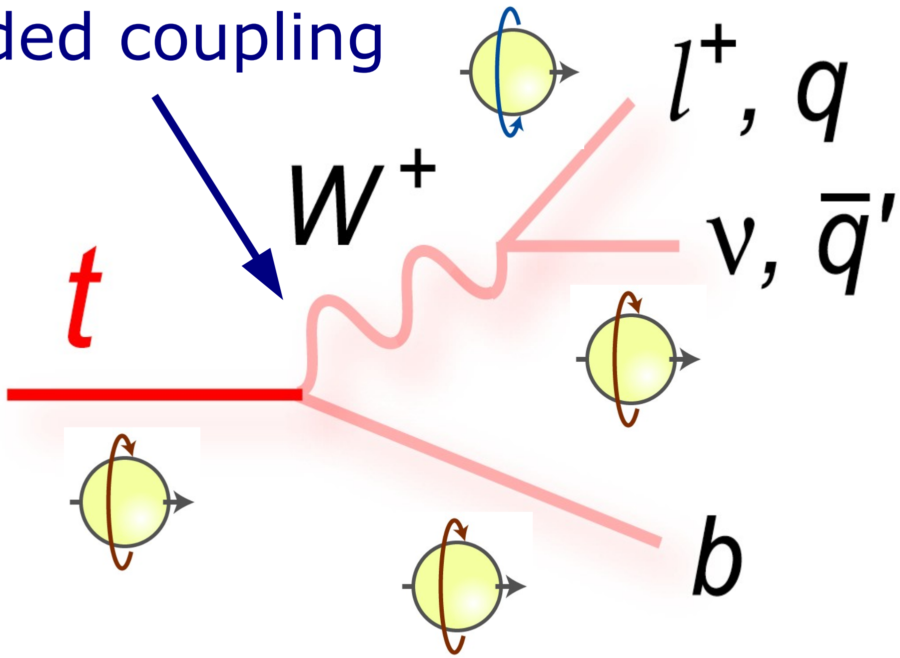
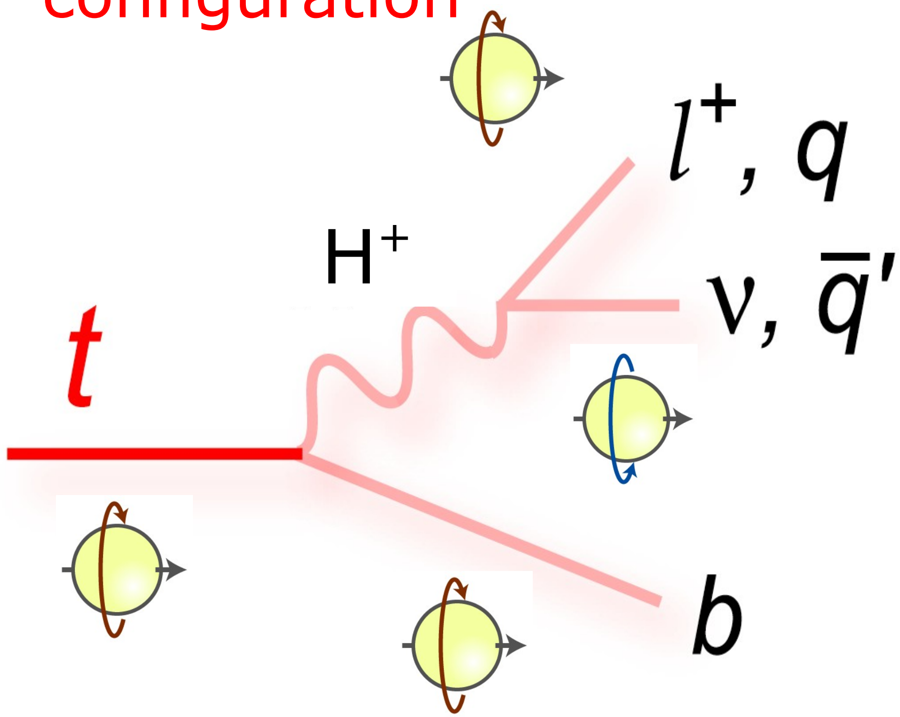


New Physics in decay could change configuration



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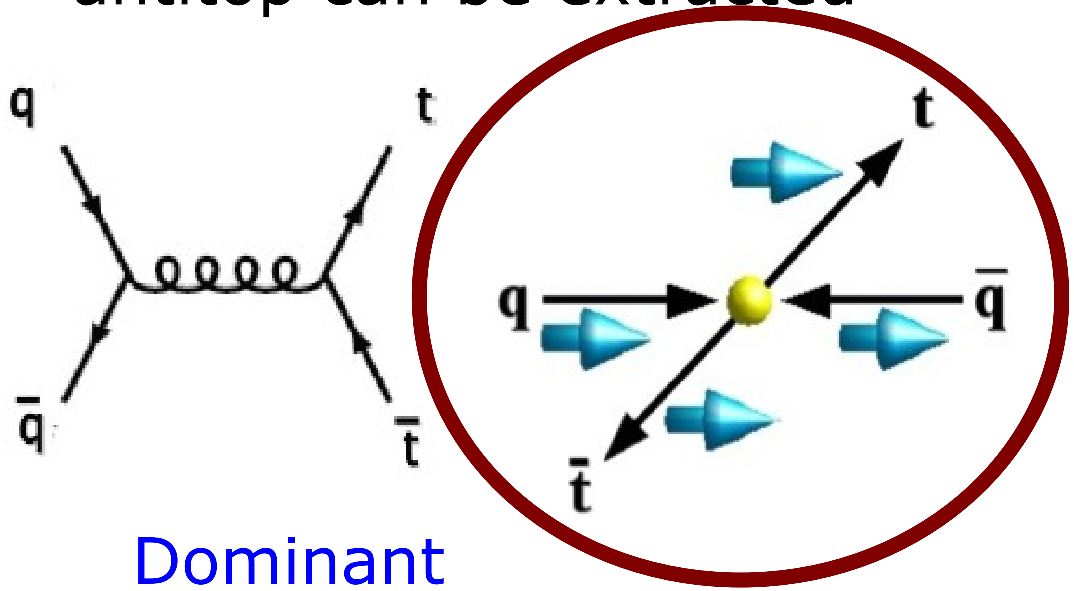
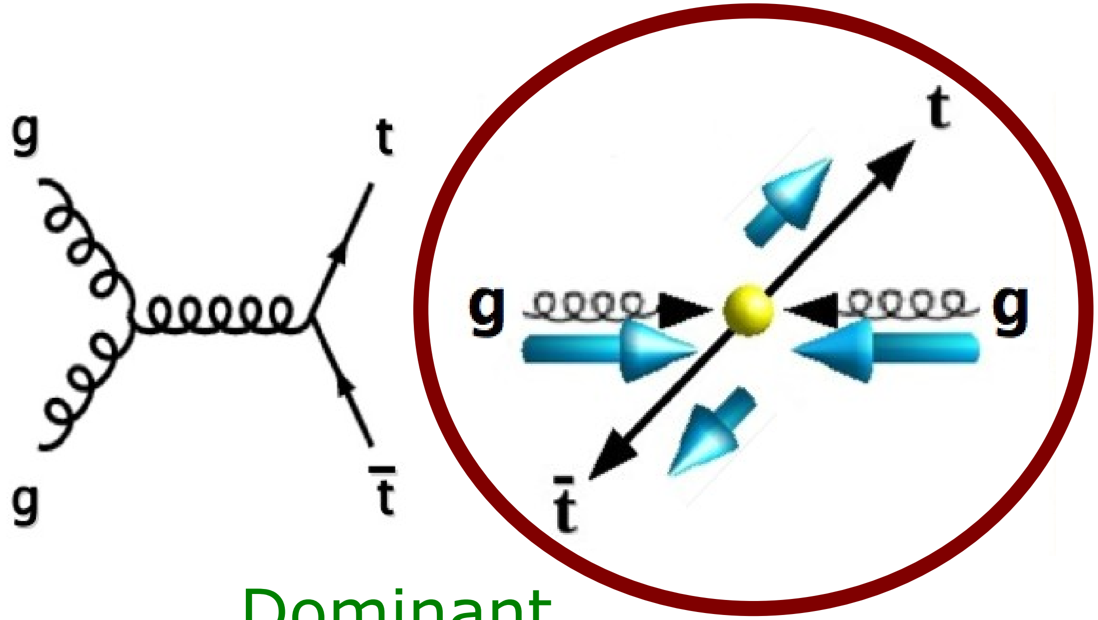
- Top Quarks produced unpolarized
  → but spin correlation of top and antitop can be extracted



Dominant
spin correlation at Tevatron



Dominant
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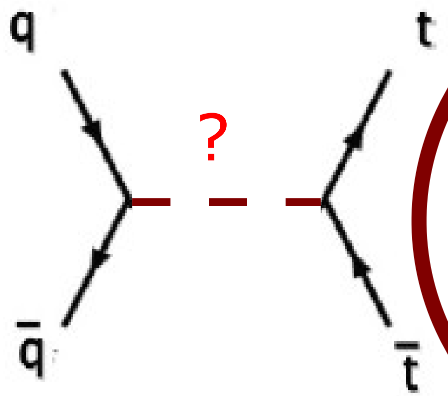

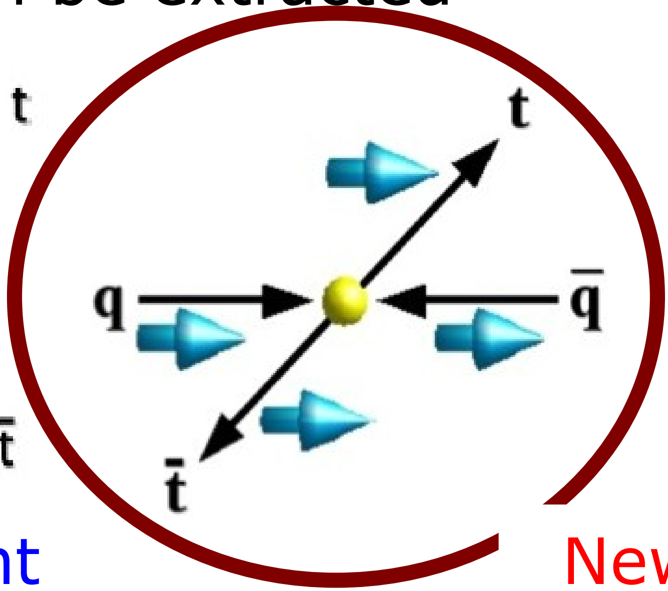

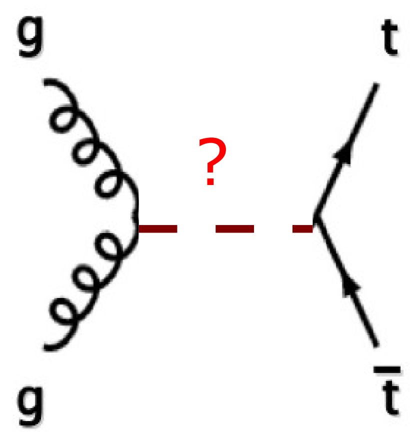

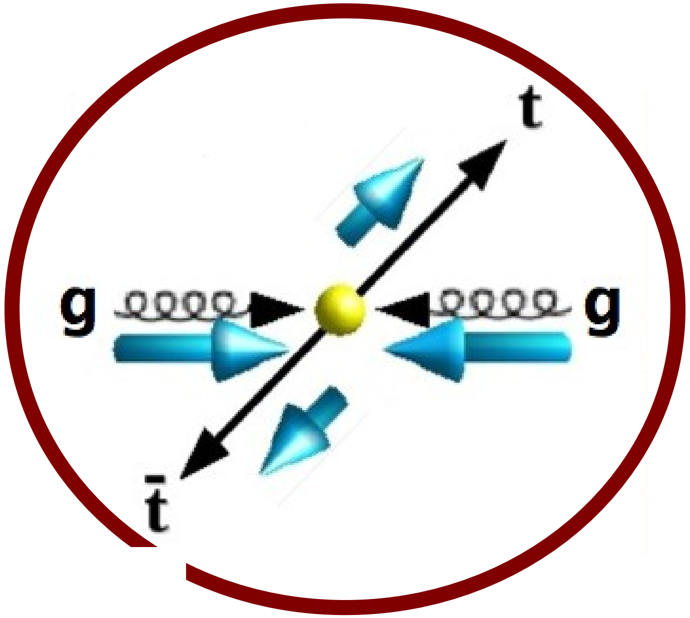

Dominant
spin correlation at Tevat

New Physics in
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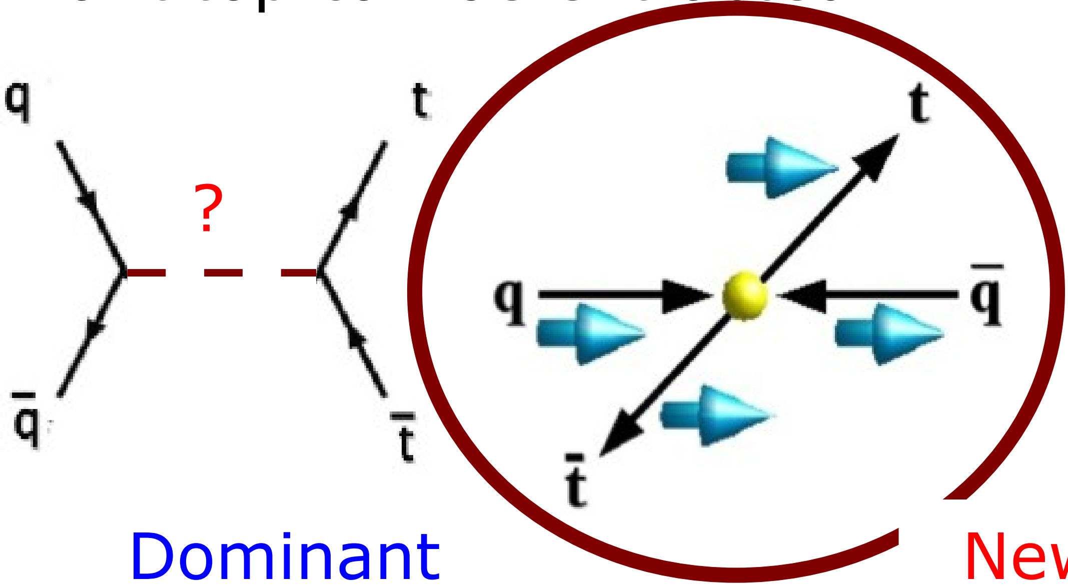
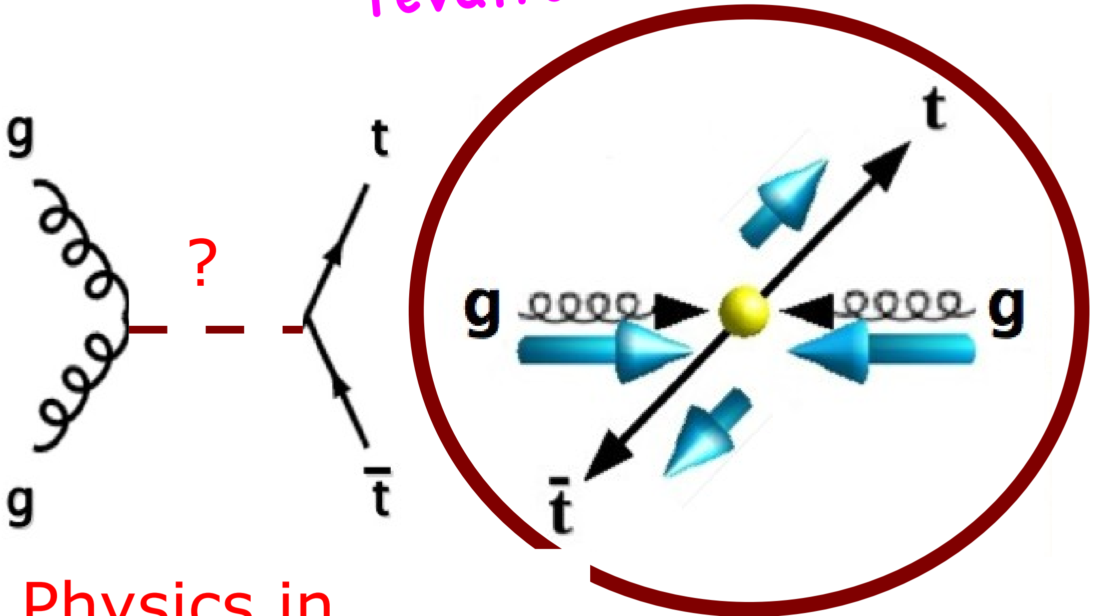
Complementary between Tevatron and LHC





Dominant
spin correlation at Tevat

New Physics in
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- Test full chain from production to decay

$t\bar{t}$ Spin Correlations

- Various methods on the market
  - Template methods
  - Matrix element methods

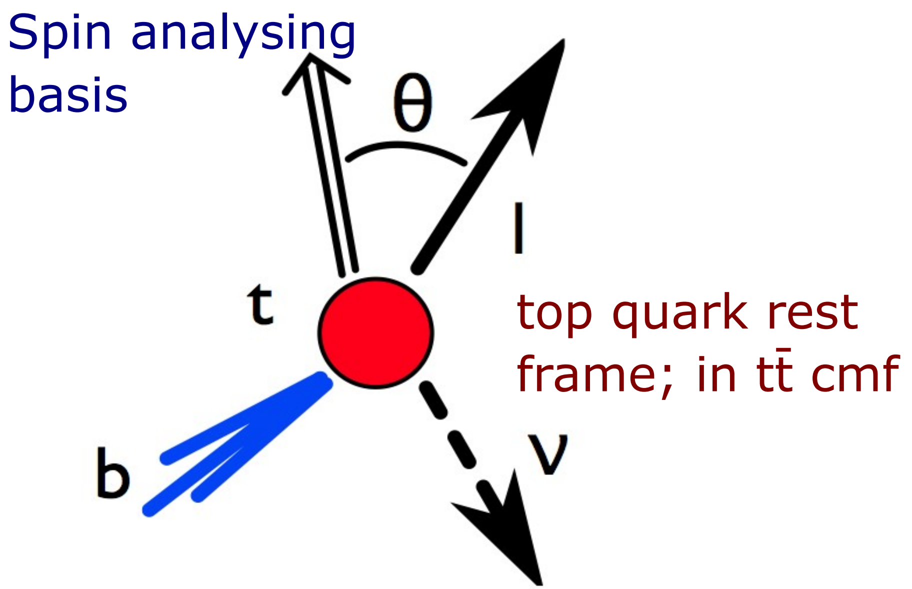
$t\bar{t}$ Spin Correlations

- Various methods on the market
  - Template methods
  - Matrix element methods
- Differential cross section:

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1 \, d\cos\theta_2} = \frac{1}{4}(1 - C\cos\theta_1\cos\theta_2)$$

  - Dilepton: Angle of (anti)lepton wrt. spin axis in (anti)top rest-frame
  - C: spin correlation strength
  - NLO SM: C≈0.78

$$C = \frac{N(\uparrow\uparrow)+N(\downarrow\downarrow)-N(\uparrow\downarrow)-N(\downarrow\uparrow)}{N(\uparrow\uparrow)+N(\downarrow\downarrow)+N(\uparrow\downarrow)+N(\downarrow\uparrow)}$$



$t\bar{t}$ Spin Correlations

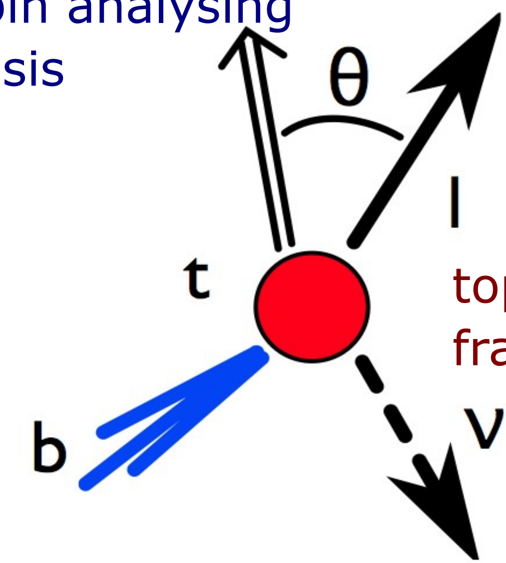
- Various methods on the market
  - Template methods
  - Matrix element methods
- Differential cross section:

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1\, d\cos\theta_2}=\frac{1}{4}(1-C\cos\theta_1\cos\theta_2)$$

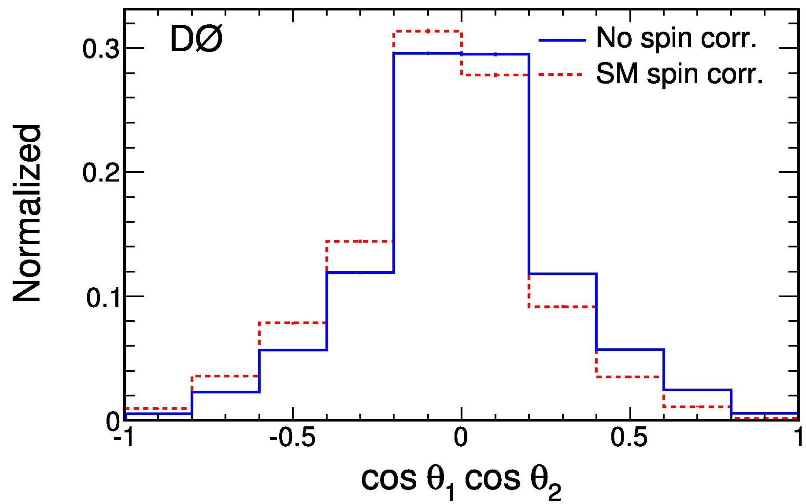
  - Dilepton: Angle of (anti)lepton wrt. spin axis in (anti)top rest-frame
  - C: spin correlation strength
  - NLO SM: C≈0.78

$$C=\frac{N(\uparrow\uparrow)+N(\downarrow\downarrow)-N(\uparrow\downarrow)-N(\downarrow\uparrow)}{N(\uparrow\uparrow)+N(\downarrow\downarrow)+N(\uparrow\downarrow)+N(\downarrow\uparrow)}$$

Spin analysing basis



top quark rest frame; in $t\bar{t}$ cmf



$t\bar{t}$ Spin Correlations

- Various methods on the market
  - Template methods
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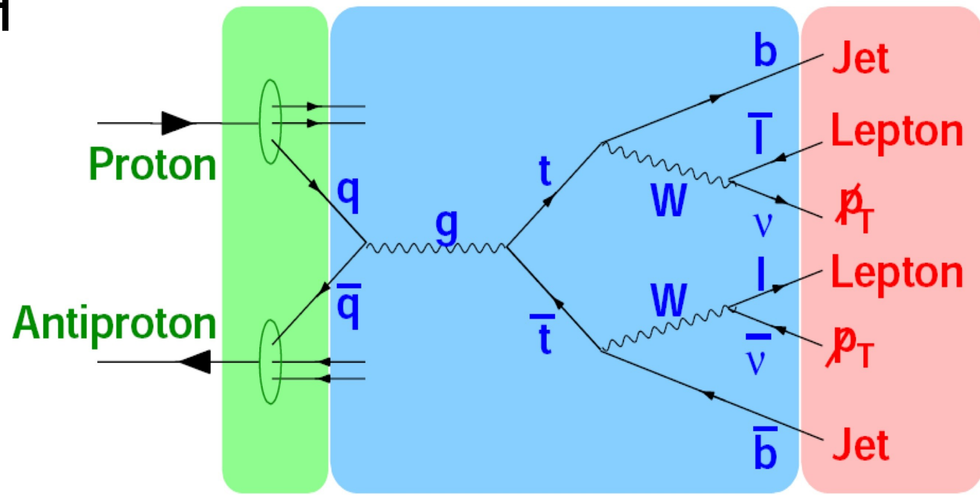
$t\bar{t}$ Spin Correlations

- Various methods on the market
  - Template methods
  - Matrix element methods
- For each event calculate probability to belong to certain hypothesis H
  - Similar strategy as for top quark mass



$$P_{sig}(x;H) = \frac{1}{\sigma_{obs}} \int \sum_{flavors} dq_1 dq_2 dy\, f(q_1) f(q_2) \sigma(y;H) W(x,y)$$

Matrix Elements for Spin

- (y,H) depends on sum over final colors and spins of matrix elements squared

Calculation taken from Mahlone,Parke

$$\sum |\mathscr{M}|^2 = \frac{(1+H)}{2} \frac{g_s^4}{9} F\overline{F} \left(2 - \beta^2 s_{qt}^2\right) - H \frac{g_s^4}{9} F\overline{F} \Delta$$

Matrix Elements for Spin

- (y,H) depends on sum over final colors and spins of matrix elements squared

Kinematics of top and antitop quark decay

Calculation taken from Mahlone,Parke

$$\sum |\mathscr{M}|^2 = \frac{(1+H)}{2}\frac{g_s^4}{9} F\overline{F}(2-\beta^2 s_{qt}^2) - H\frac{g_s^4}{9}F\overline{F}\Delta$$

This makes the difference between the matrix element with and without spin correlations taken into account

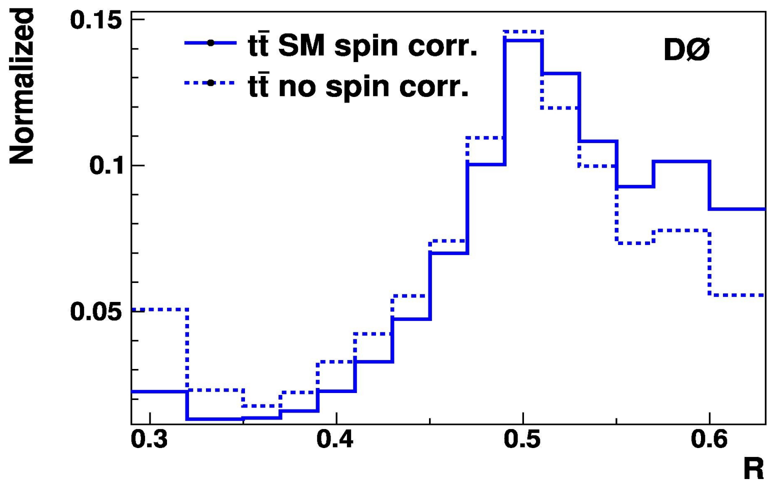
$$\Delta = \frac{(1-c_{\bar{\ell}q}c_{\ell\bar{q}}) - \beta(c_{\ell\bar{t}} + c_{\bar{\ell}t}) + \beta c_{qt}(c_{\bar{\ell}q} + c_{\ell\bar{q}}) + \frac{1}{2}\beta^2 s_{qt}^2(1-c_{\bar{\ell}\ell})}{\gamma^2(1-\beta c_{\bar{\ell}t})(1-\beta c_{\ell\bar{t}})}$$

Transformation to Templates

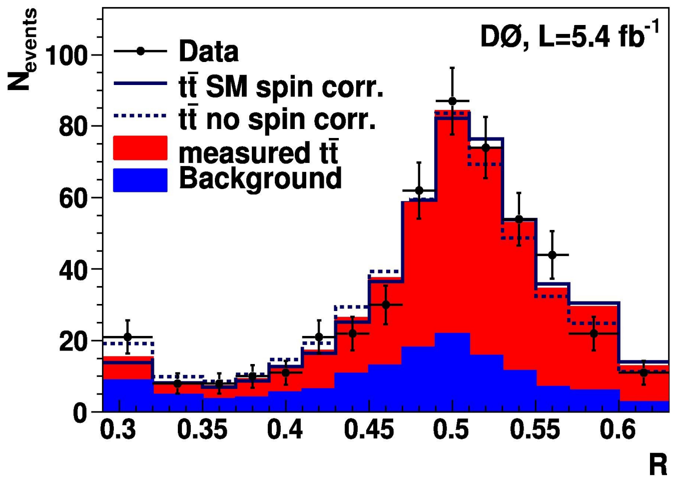
- Calculate probability with the two matrix elements and define a discriminator R:

$$R = \frac{P_{\mathrm{sgn}}(H=1)}{P_{\mathrm{sgn}}(H=0) + P_{\mathrm{sgn}}(H=1)}$$

Melnikov, Schulze

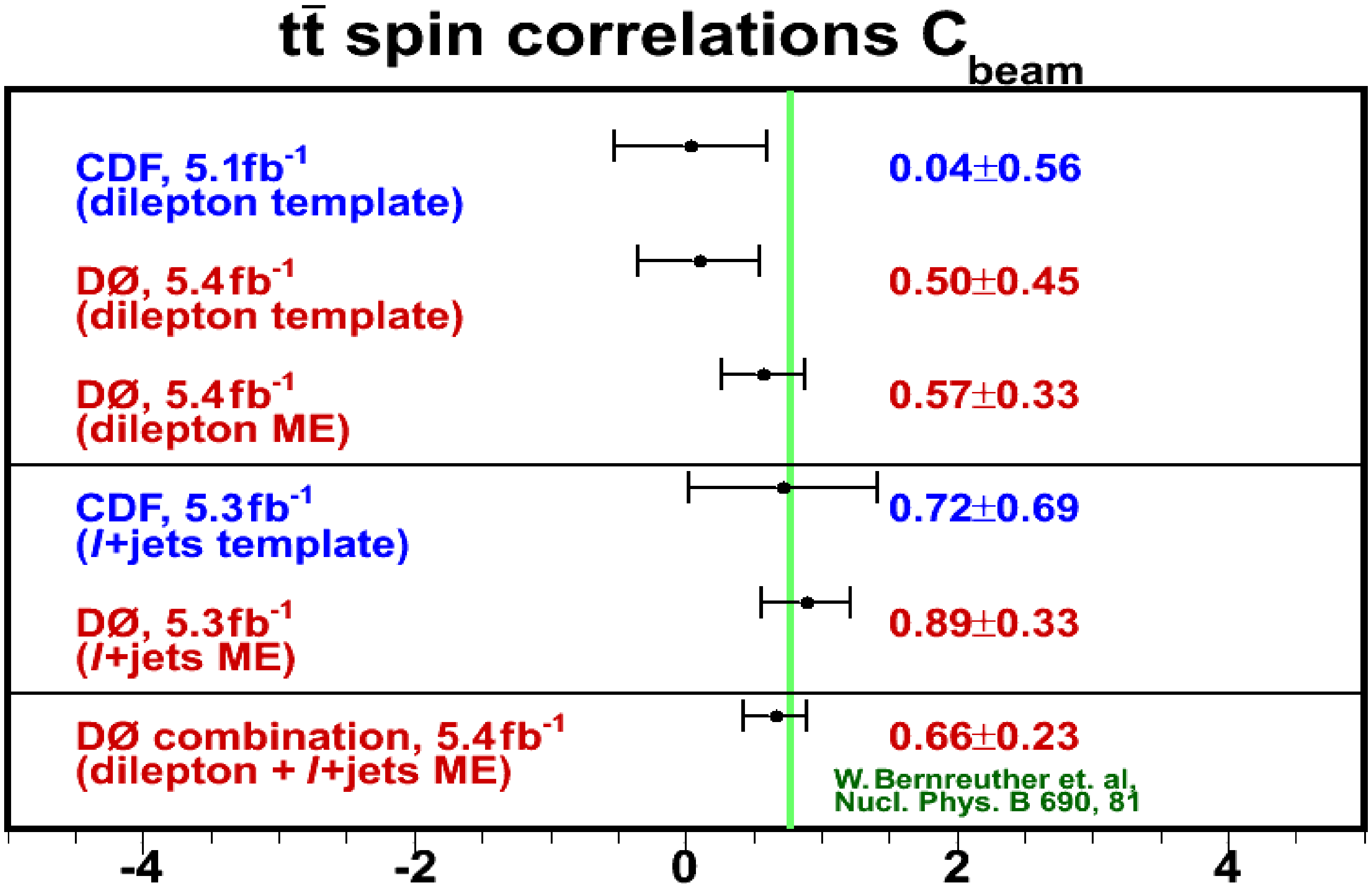


- Templates based on MC@NLO MC, defining R with and without spin correlation
- ~30% improvement over template method!



$t\bar{t}$ Spin Correlations

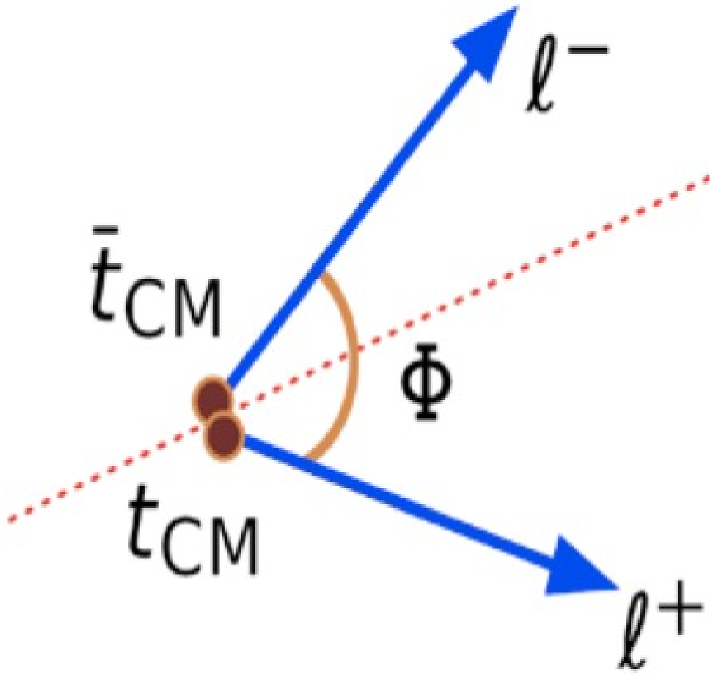
- In recent years, enough data was collected to be sensitive to spin correlations

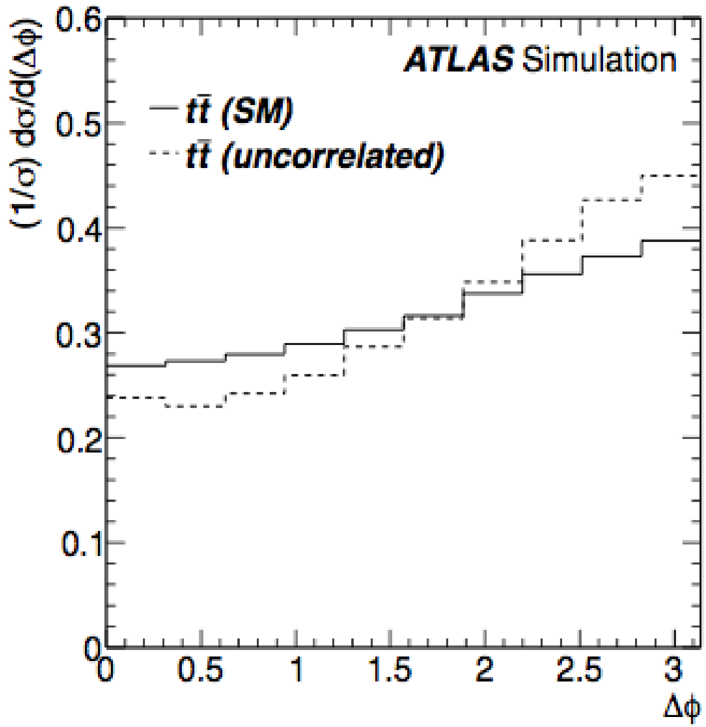


First evidence for non-vanishing $t\bar{t}$ spin correlations!

Spin Correlations at LHC

- LHC: 85% gg → $t\bar{t}$: dominated by like helicity gluons at low √s
- Simple variable in dilepton channel: $\Delta\phi = |\phi_{l+} - \phi_{l-}|$
  - No reconstruction of $t\bar{t}$ system needed!





Spin Correlations at LHC

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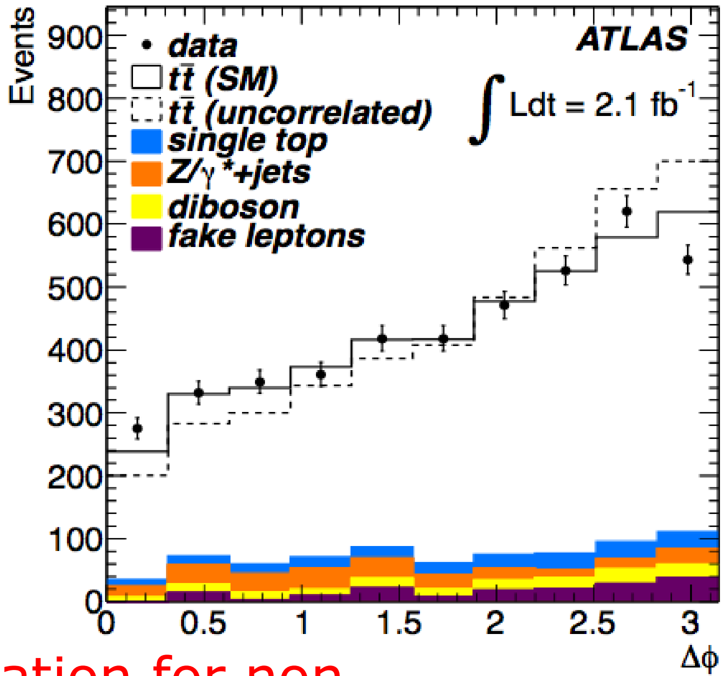
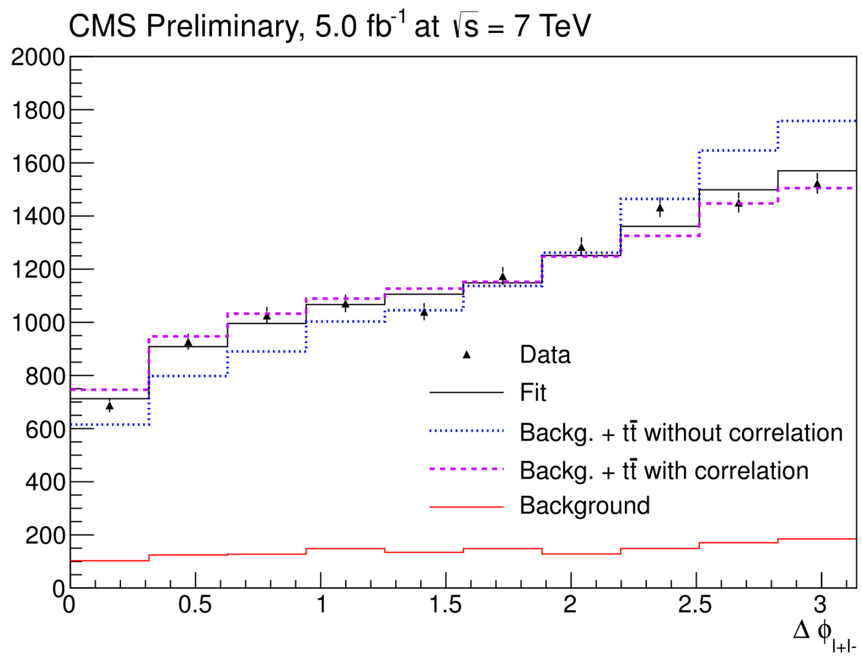
Complementary between Tevatron and LHC





Atlas:
First observation for non-vanishing $t\bar{t}$ spin correlations!

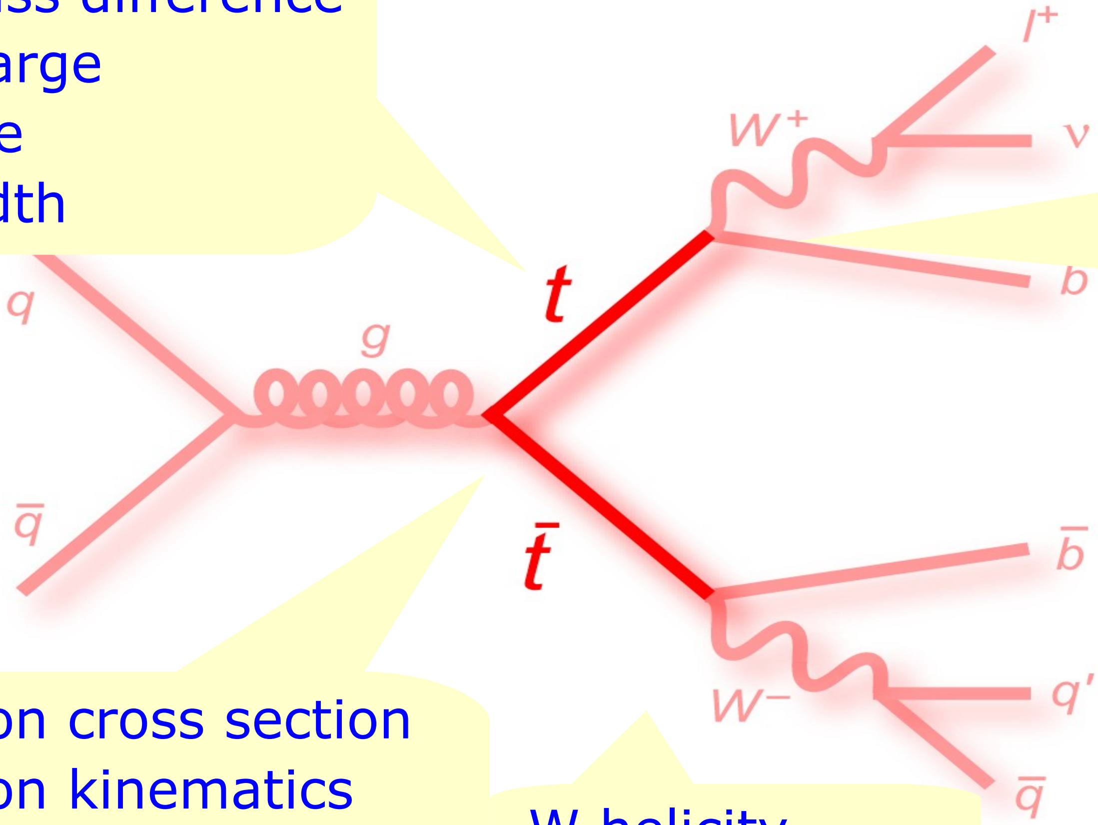
Overview other Properties Analyses

- Mass and spin correlations just two examples of top properties analyses
- To understand whether the particle discovered in 1995 is really the SM top: all possible properties need to be considered
  - Top quark charge
  - Decay properties
  - Correlations
  - ...

All we (did and do) study about the Top

Top mass
Top mass difference
Top charge
Lifetime
Top width

Branching ratios
$|V_{tb}|$
Anomalous coupling
New/Rare decays



Spin correlation
Charge asymmetry
Color flow

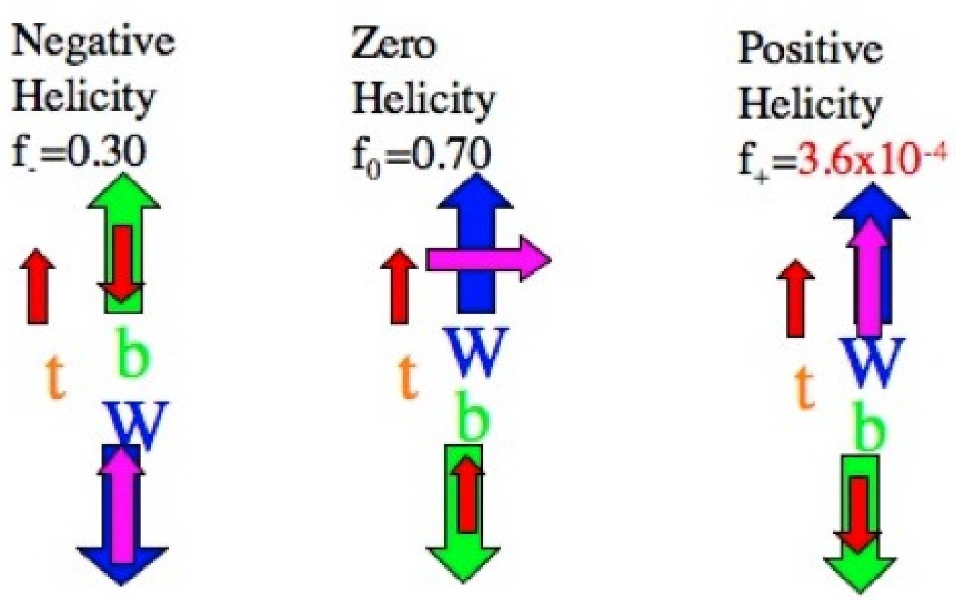
Production cross section
Production kinematics
Production via resonance
New particles

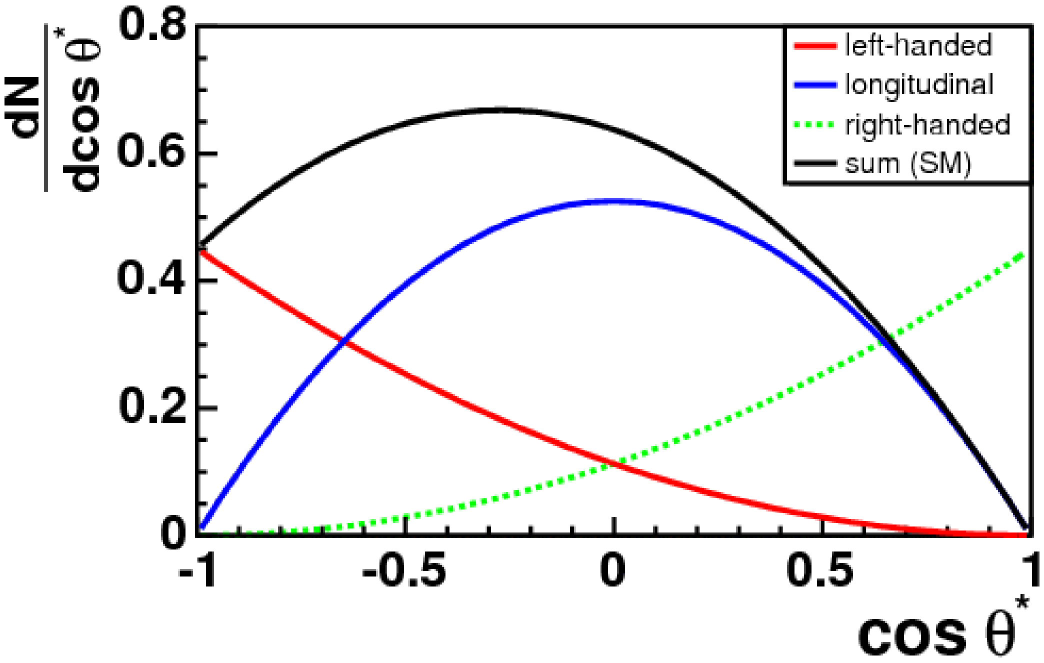
W helicity

s- & t- channel production, properties and searches in single top events

All we (did and do) study about the Top

- W helicity:
  Left handed coupling of W-boson to fermions:
  Not every combination of spin for W and b-quark is allowed





Production kinematics
Production via resonance
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W helicity

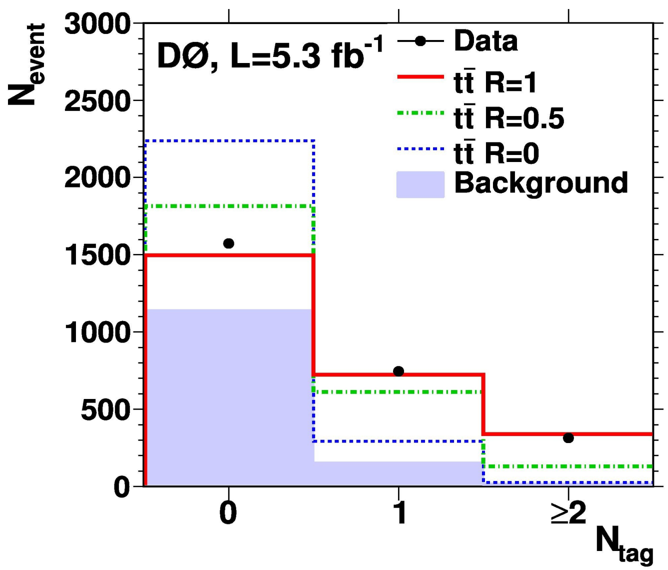
s- & t- channel production, properties and searches in single top events

All we (did and do) study about the Top

- SM: R=1, constrained by CKM unitarity

$$R = \frac{B(t \to Wb)}{B(t \to Wq)} = \frac{|V_{tb}^{2}|}{|V_{td}^{2}| + |V_{ts}^{2}| + |V_{tb}^{2}|}$$

- R<1 could indicate new physics



Branching ratios
$|V_{tb}|$
Anomalous coupling
New/Rare decays

Spin correlation
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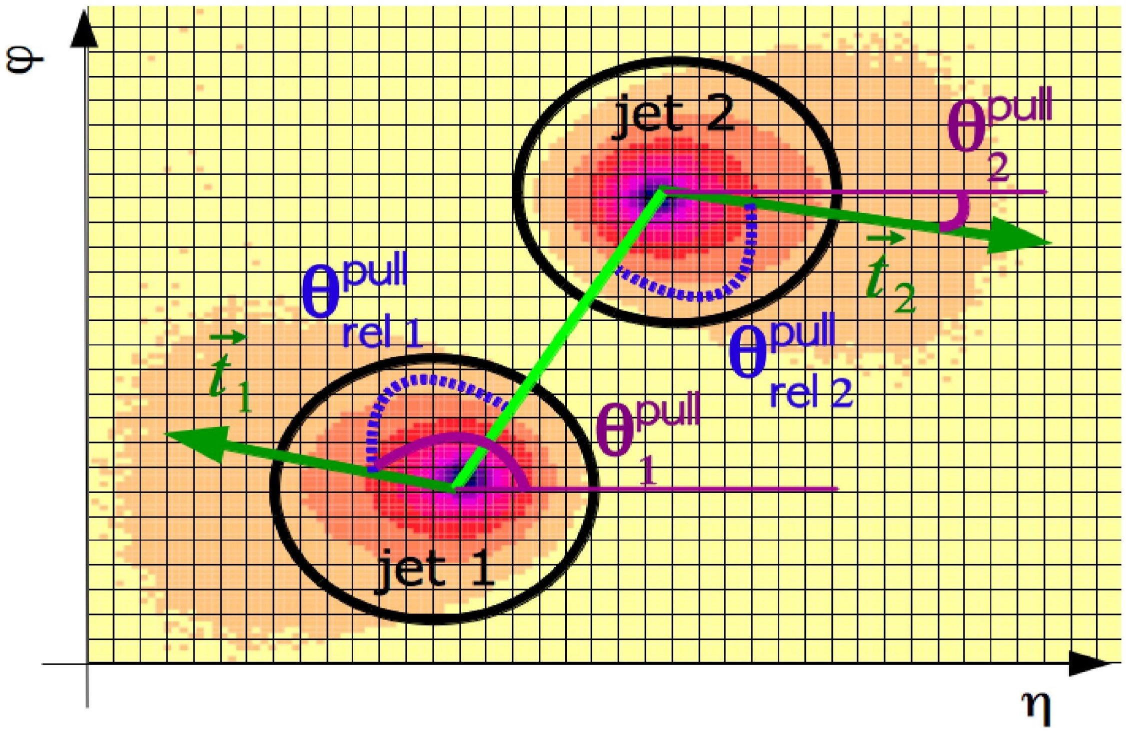
s- & t- channel production, properties and searches in single top events

All we (did and do) study about the Top

- Jets carry color, and are thus color connected to each other
  - Study color flow of decay products from W boson



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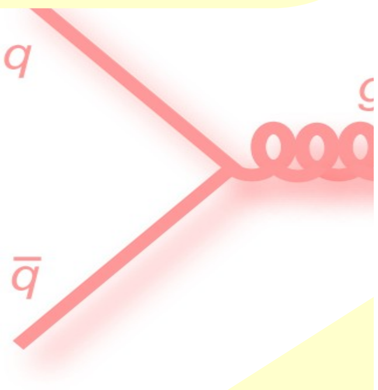
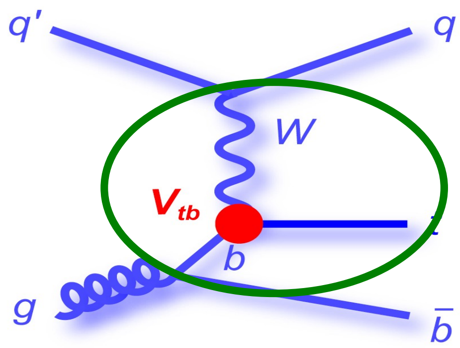
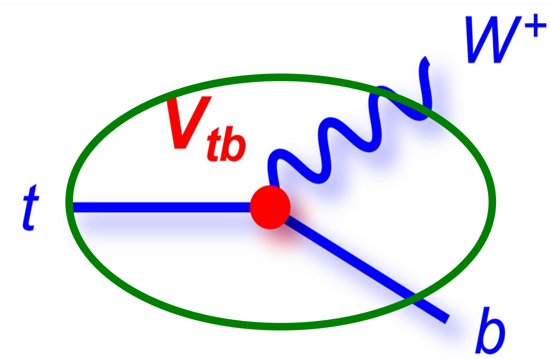


Production cross sectio
Production kinematics
Production via resonan
New particles

- Direct determination challenging due to detector resolution
- Indirect determination: combination of single top cross section measurement and ratio of branching fraction determination

$$\Gamma_t = \frac{\Gamma(t \to Wb)}{B(t \to Wb)}$$





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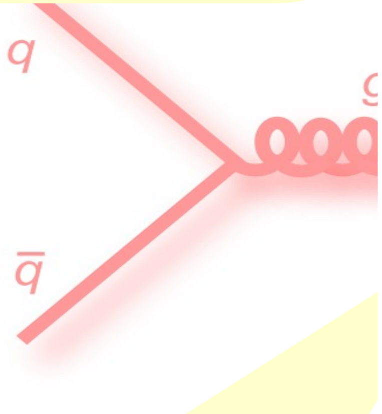
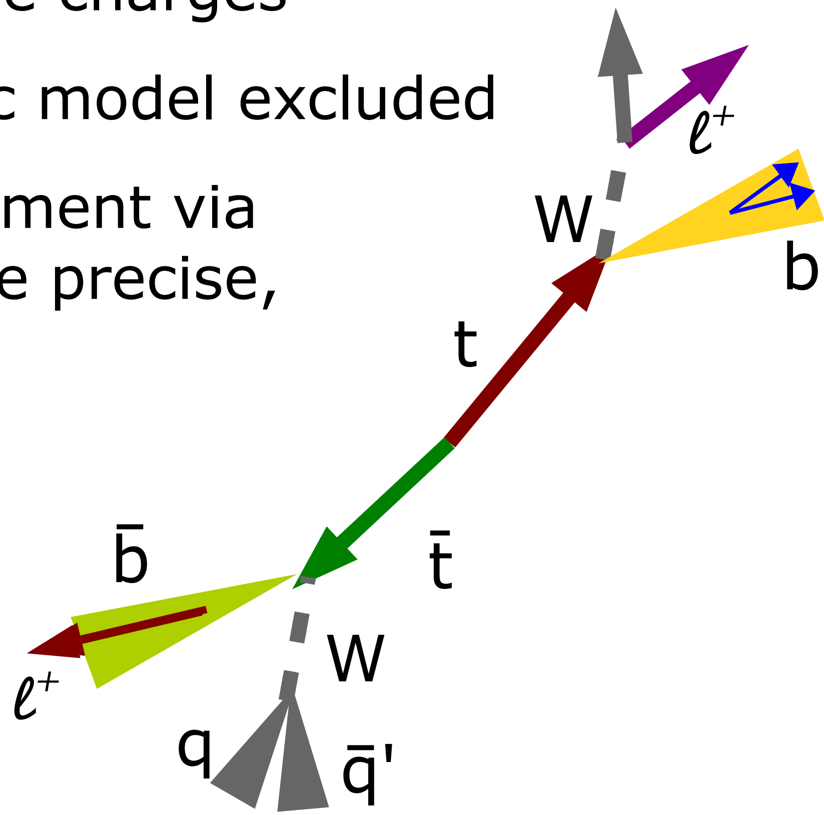


Production cross sectio
Production kinematics
Production via resonan
New particles

- Exotic model with top charge -4/3 e could be possible (SM: +2/3e)
  - Get info on charge of b-jets to distinguish the charges
  - By now exotic model excluded
- Charge measurement via $t\bar{t}$+gamma: more precise, not done yet



Summary Mass & Spin Correlations

- Top quark mass: free parameter in the SM
  $\rightarrow$ precise determination important
- Several methods were developed for a precise top quark mass measurement
  - Many are used for other analyses also (e. g. spin correlation)
- Still ongoing discussion what quantity we measure
  - Pole mass? Close to pole mass?
- $t\bar{t}$ spin correlations: first evidence at DØ and first observation at Atlas
  - Complementary measurements at Tevatron and LHC

BACKUP

The Top Quark

- Heaviest known elementary particle:

$$m_t = 173.3 \pm 1.1 GeV$$

arXiv:1007.3178

- Standard Model:
  - Single or pair production
  - Electric charge +2/3 e
  - Short lifetime 0.5×10^{-24}s
    - Bare quark - no hadronization
  - ~100% decay into Wb
  - Large coupling to SM Higgs boson