# Top physics in LHC-D

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**2nd Annual Workshop of the Helmholtz Alliance**
**Physics at the Terascale, Aachen, Nov. 2008**

With W. Bernreuther, F.P. Schilling and **P. Uwer**

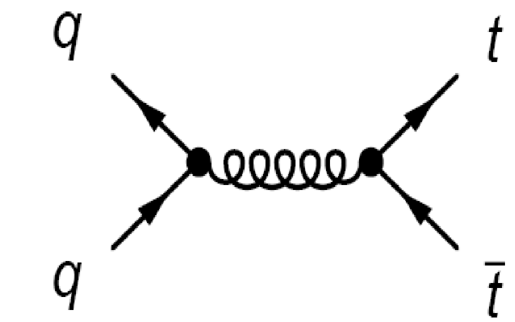
# Top physics at LHC

- Signal will be established with less than a $fb^{-1}$
  - <20% syst. and very small stat. error
- Precise measurement of properties possible

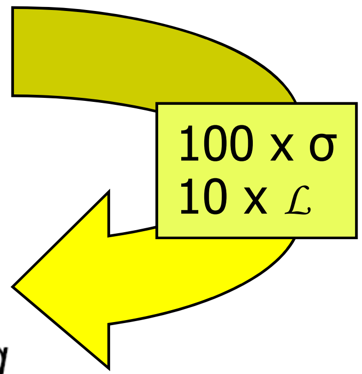
- With first mass measurement
  - Feedback to detector performance
  - Calibration of jet energy scales
- Beyond Standard Model
  - New particles may decay into top pairs
- Background in searches for new physics

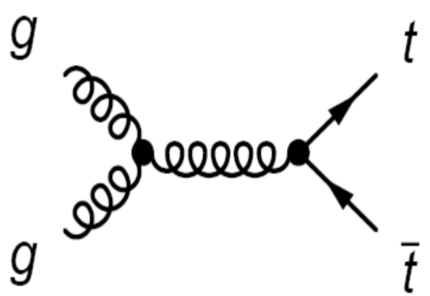
→ Good understanding of top quark physics essential

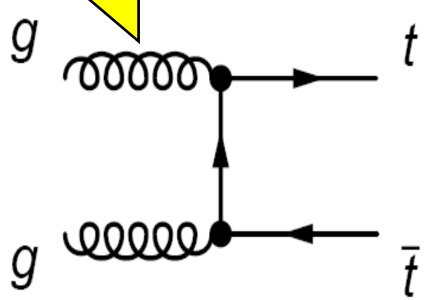
# Top pair production




85% of total cross section
~5 top per hour
analysis reduction to O(100)

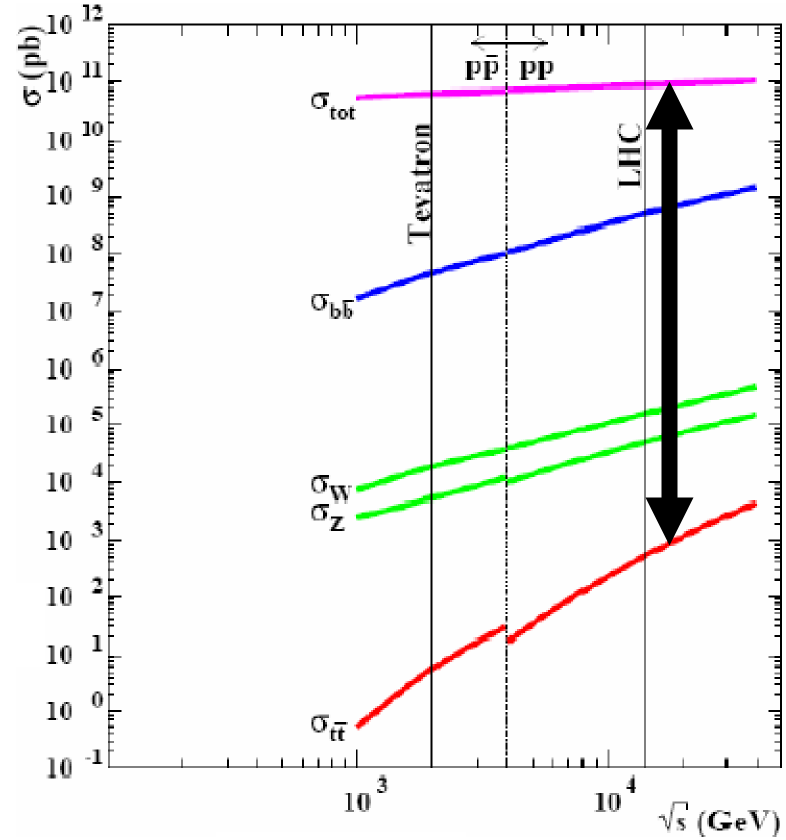


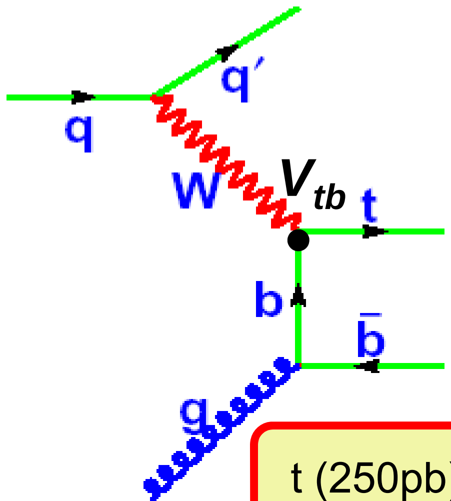




90% of total cross section
~1 top per second

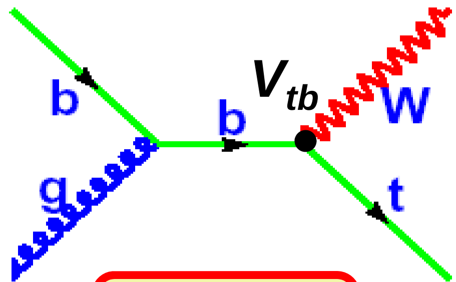
- LHC is a top factory
  - 8M tt/yr at $10^{33}$ $cm^{-2}$ $s^{-1}$
  - still, bckgnd suppression $O(10^8)$ needed



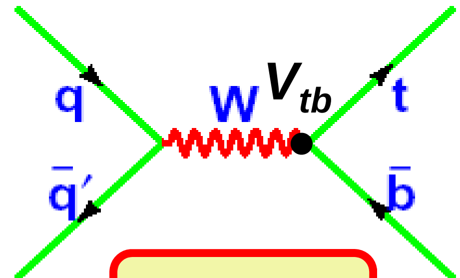
# Electroweak production




t (250pb)

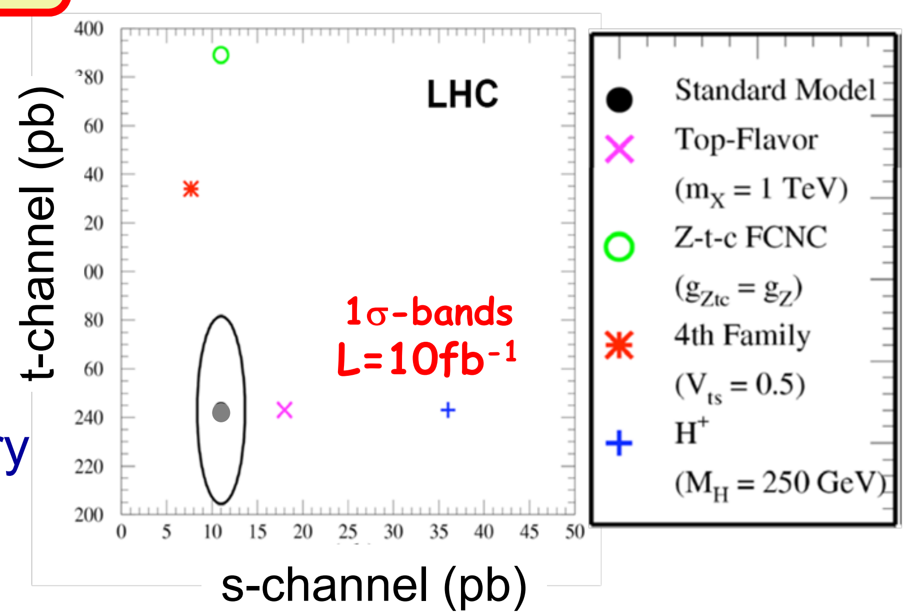



Wt (60pb)



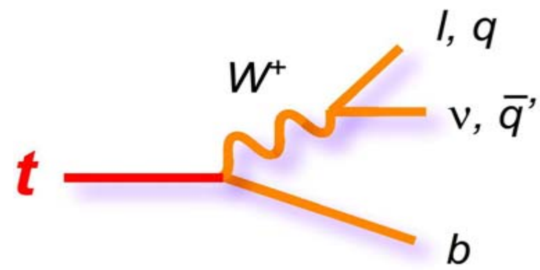

s (10pb)

- Single top complementary to $t\bar{t}$ production : $\sigma_t/\sigma_{tt} \approx 1/3$
- Cross-section → $|V_{tb}|$
- Potential for BSM physics discovery

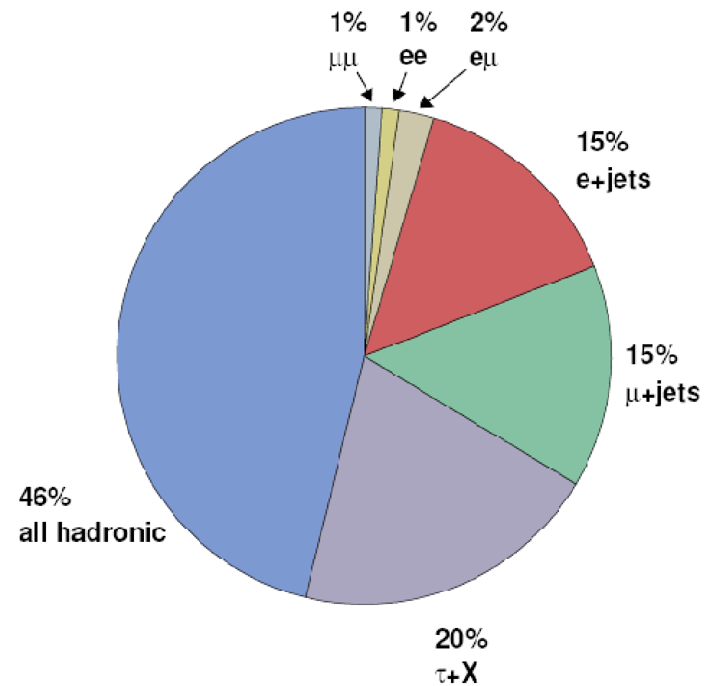


# Top quark decay

- Top quarks decay to Wb ~ 100%




- Pair production signatures
  - dilepton ( $2b + 2\ell + 2\nu$ )
  - lepton + jets ( $2b + 2q + \ell + \nu$ )
  - all hadronic ( $2b + 4q$ )




- Single top signatures
  - t - channel ( $b + q + \ell + \nu$ )
  - Wt - channel ( $1b + 2q + \ell + \nu$ )
  - s - channel ( $2b + \ell + \nu$ )

# Yesterday's LHC-D top session

| | |
|---|---|
| Top-quark pair production beyond next-to-leading order | UWER, Peter |
| ttbar cross section (ATLAS) | RADICS, Balint |
| Top rediscovery / cross section (CMS) | CHWALEK, Thorsten |
| ttbar differential cross section (ATLAS) | BUNSE, Moritz |
| Differential cross section (mtt) at production threshold | STEINHAUSER, Matthias |
| Calibration with ttbar events (CMS) | Mr. NAUMANN-EMME, Sebastian |
| Top Montecarlo at LHC | HUSEMANN, Ulrich |
| Single Top Production in MC@NLO | MOTYLINSKI, Patrick |
| Single top (ATLAS) | KHORIAULI, Gia |
| Single top (CMS) | WEINELT, Julia |
| Top mass and other properties (CMS) | Dr. WOLF, Roger |
| Top mass (ATLAS) | Dr. KROENINGER, Kevin |
| The potential of top invariant mass measurements at the LHC | MALTONI, Fabio |
| Resonances decaying into ttbar (CMS) | STEGGERMANN, Jan |
| ttbar resonances with Herwig++ | MECHTEL, Markus |

**15 talks**

# Top quark pair production

- Top quark pair production beyond NLO Peter Uwer
- ttbar cross section (ATLAS) Balint Radics
- Top rediscovery / cross section (CMS) Thorsten Chwalek
- ttbar differential cross section (ATLAS) Moritz Bunse
- Calibration with ttbar events (CMS) Sebastian Naumann-Emme

# Top-quark production beyond NLO

**Peter Uwer**

- Why do we need to go beyond NLO ?
  - NLO prediction has scale dependence of ~12%
  - Uncertainty due to PDFs is much smaller: < 4%

→ Go beyond NLO to improve theoretical prediction

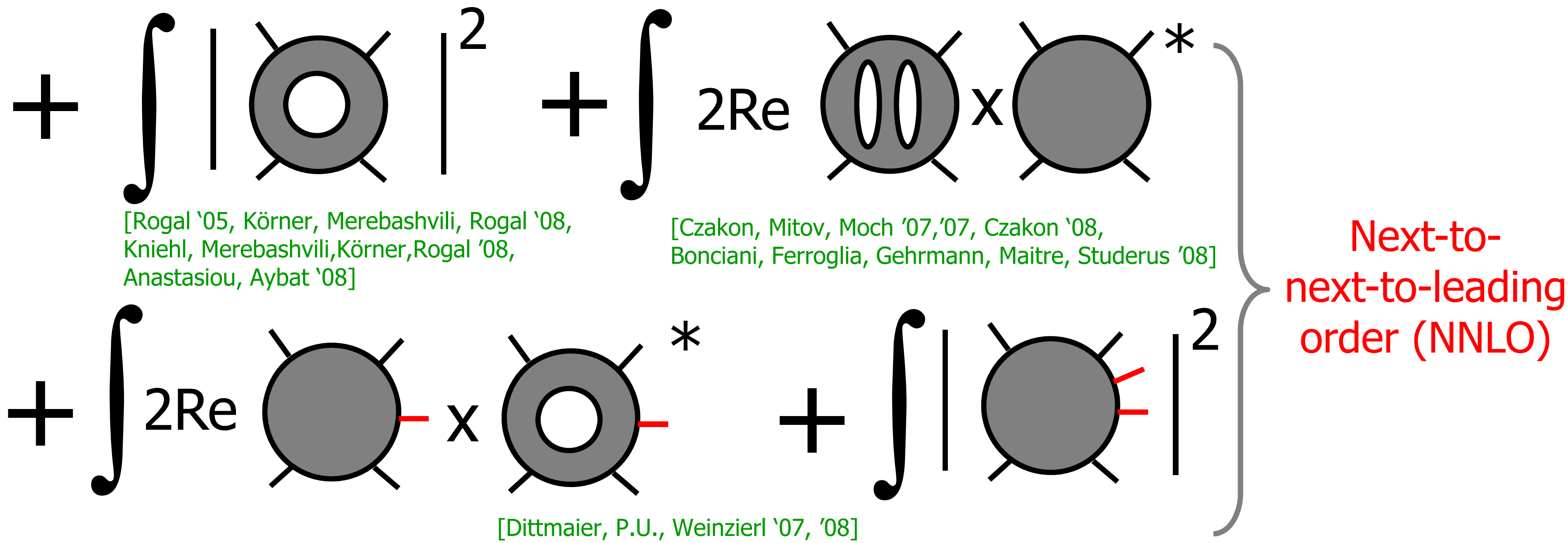
Large contribution to NLO due to (universal) threshold logs

→ Resummation possible (LL, NLL, NNLL)

NEW!

→ Shift of a few percent and slight improvement of scale dependence

# Progress towards complete NNLO




Almost all the building blocks available, combination of the results highly non-trivial due IR singularities

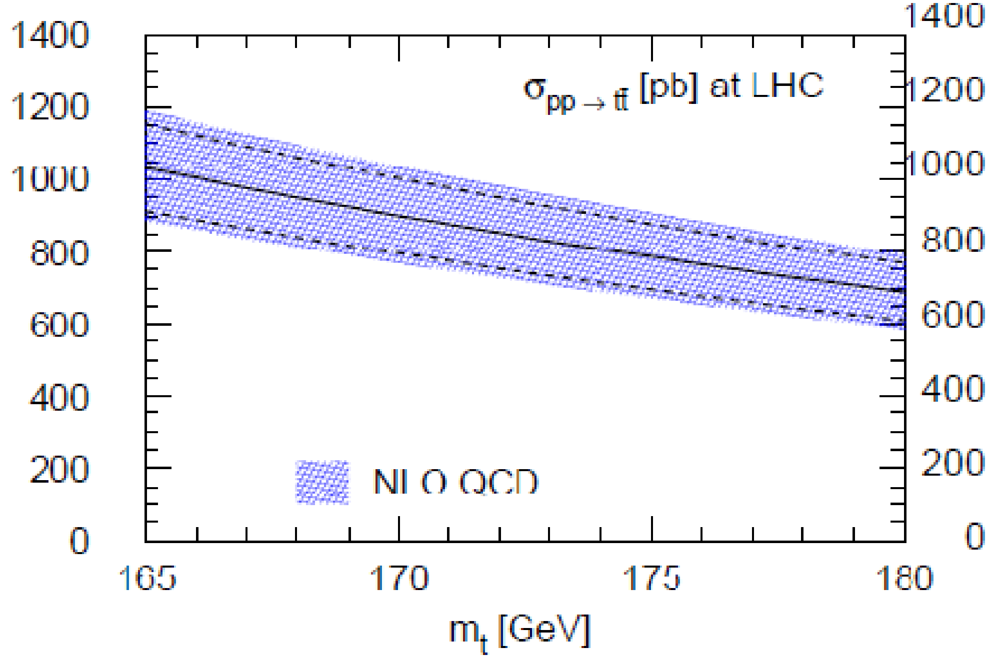
# Approximate NNLO

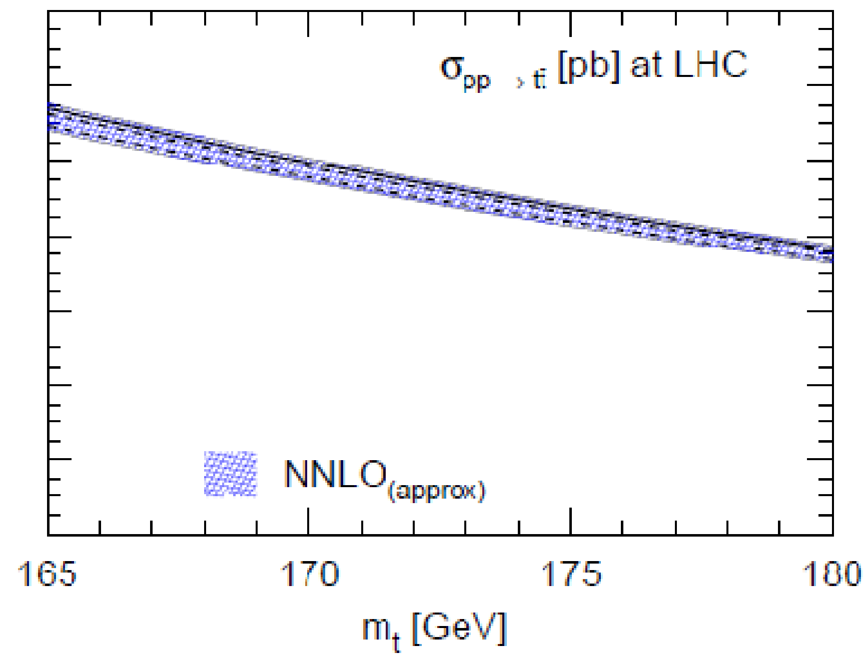
Use existing knowledge to produce approximate NNLO
- all threshold logs at NNLO from NNLL resummation
- Coulomb singularity at NNLO
- Full scale dependence at NNLO from RGE analysis

**[Moch, Uwer arXiv:0804.1476]**

→ Shift of ~5%, important reduction of scale dependence down to 3%

**[Moch, Uwer arXiv:0804.1476]**




Similar analysis done by Kidonakis and Vogt **[Kidonakis, Vogt arXiv: 0805.3844]**

# Experiments: top pair selection

- Large sample will be (eventually) quickly available
  - Mostly concerned with systematic uncertainties
  - Cross section measurement
  - Can be used to calibrate the detector
  - Need to be well understood for searches
- Backgrounds to deal with
  - W + jets, Z + jets
  - Single top
  - Diboson
  - QCD multi-jet events
- Initial strategies
  - Simple selection
  - Do not use b-tagging information or $E_T^{miss}$

# Common systematic uncertainties

- Luminosity estimation
  - Assume initially 20-30%
  - Reduced to 3-5% with dedicated runs and detectors
- Lepton efficiency
  - Initial identification (1%) and trigger efficiency with Z events (1%)
  - fake rate uncertainty for muons (20%) and electrons (50%)
- Jet energy scale
  - Challenging! Assume 5%, ultimate goal is 1%

CERN-OPEN-2008-020
to appear

# Common systematic uncertainties

- B-tagging
  - $t\bar{t}$ will be used to calibrate b-tagging
  - Efficiency known to 5%, mistag rate to 50%
- Parton density functions
  - PDF error sets CTEQ6 and MRST used
  - Evaluation expensive → reweight events
- W+jets normalisation
  - Large theoretical uncertainty
  - Could be determined from data (~20% with $1 fb^{-1}$)

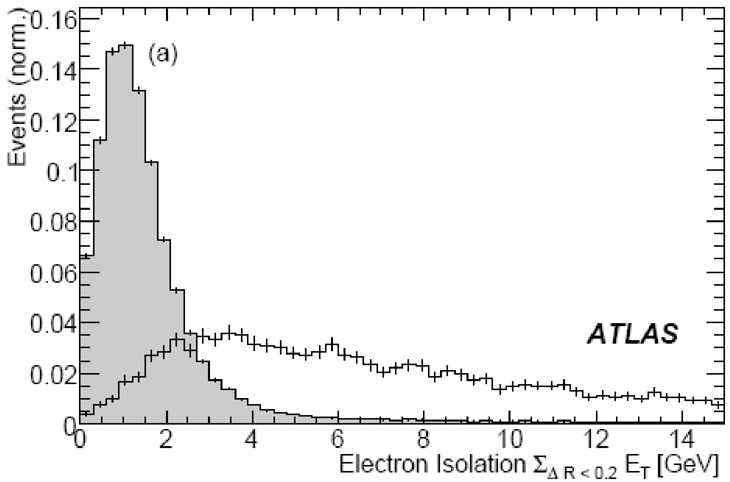
# Dileptonic $t\bar{t}$ cross section

- Smallest background, high trigger efficiency (>96%)
- Sub-channels (ee, μe, μμ) optimized separately

$$\sigma = \frac{N_{observed} - N_{background}}{\epsilon_{trig} \cdot A_{sig} \cdot \int \mathcal{L}dt}$$

Three approaches considered:

- Cut and count
  - Determine optimal cuts
    - $E_T^{miss}$ > 30GeV, 2 jets, 2 os leptons
    - Z veto cut for same flavor
- Inclusive template
- Likelihood method

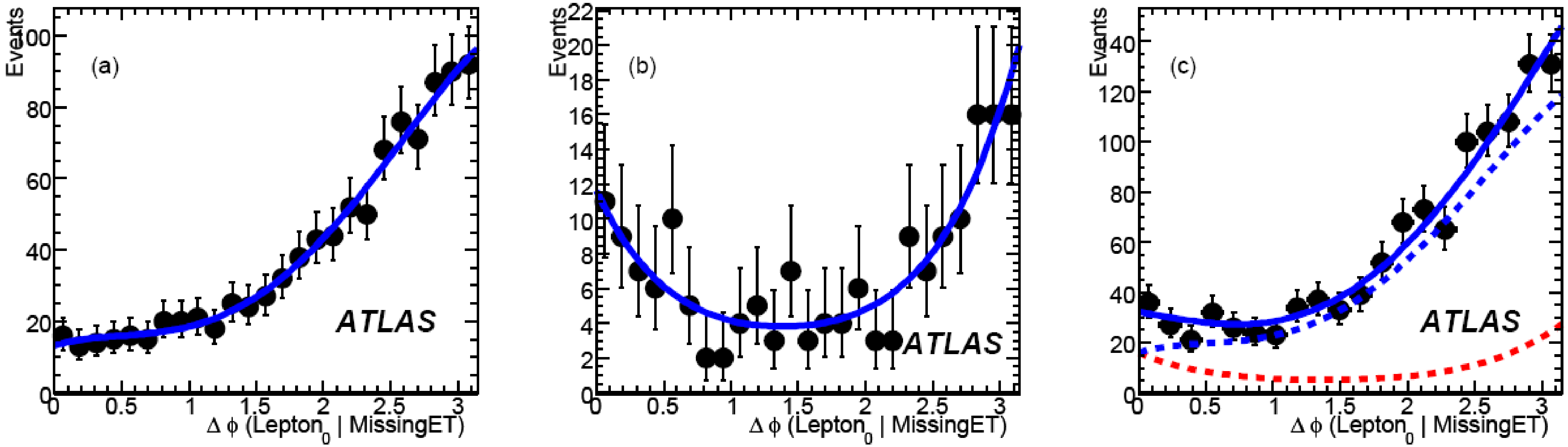



**Balint Radics**

# Dilepton channel

- Likelihood method

100pb$^{-1}$




$$\text{Cut and Count method:} \quad \Delta\sigma/\sigma = \quad (4(\text{stat})^{+5}_{-2}(\text{syst}) \pm 2(\text{pdf}) \pm 5(\text{lumi}))\%$$

$$\text{Template method:} \quad \Delta\sigma/\sigma = \quad (4(\text{stat}) \pm 4(\text{syst}) \pm 2.(\text{pdf}) \pm 5(\text{lumi}))\%$$

$$\text{Likelihood method method:} \quad \Delta\sigma/\sigma = \quad (5(\text{stat})^{+8}_{-5}(\text{syst}) \pm 0.2(\text{pdf}) \pm 5(\text{lumi}))\%$$

# $t\bar{t}$ lepton+jets analysis

event Selection: 1 lepton Pt > 20 GeV, Missing Et > 20 GeV,
at least 4 Jets with Pt > 20 GeV, of which at least 3 Jets Pt > 40 GeV

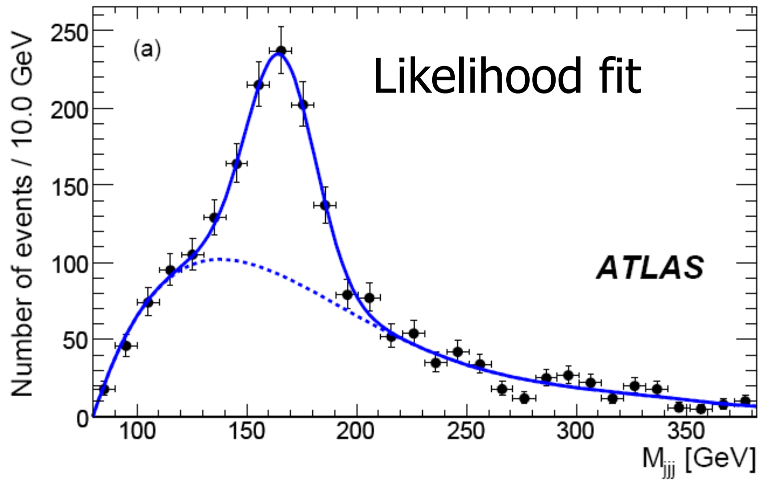
hadronic top candidate: 3 Jet combination leading to highest Pt

hadronic W candidate: 2 Jet combination from hadronic top Jets, leading to highest Pt

$100 pb^{-1}$

W constraint: W candidate has an invariant mass of the reconstructed W mass ± 10 GeV

- Main backgrounds are single boson plus jet production and QCD fakes
- Plans for data driven background estimation:
  - W/Z+jets
  - QCD fakes

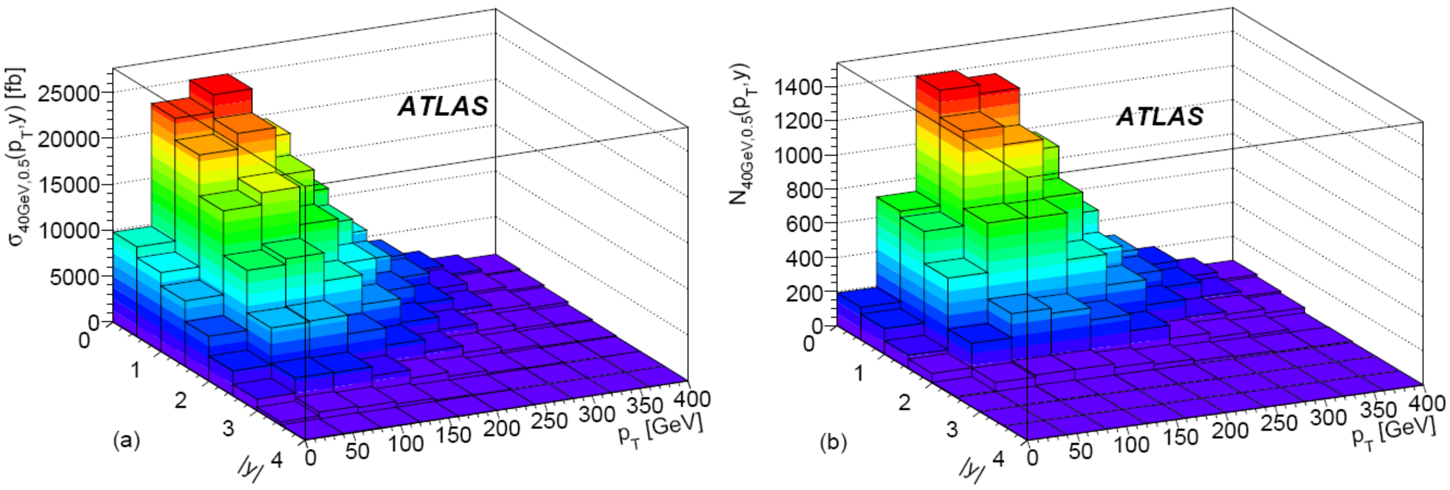



$$\text{Likelihood method:} \quad \Delta\sigma/\sigma = (7(\text{stat}) \pm 15(\text{syst}) \pm 3(\text{pdf}) \pm 5(\text{lumi}))\%$$

$$\text{Counting method:} \quad \Delta\sigma/\sigma = (3(\text{stat}) \pm 16(\text{syst}) \pm 3(\text{pdf}) \pm 5(\text{lumi}))\%$$

# Differential cross-section

Feasibility study of double differential $t\bar{t}$ cross-section $f(p_T,y)$




Truth, generated with MC@NLO

Reconstructed, 1fb$^{-1}$

New: employ TMVA to distinguish correct pairing of jets from combinatorial background

**Moritz Bunse**

# $t\bar{t}$ μ+jets

Thorsten Chwalek



PAS-TOP-08-005

## Early data analysis ($10 pb^{-1}$)

Tight cuts on muons to reduce QCD

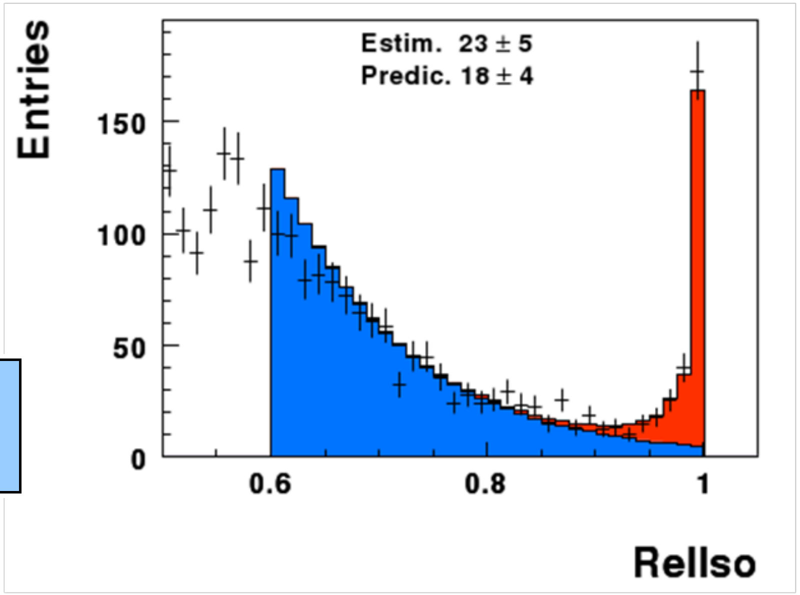
No $E_T^{miss}$ cut, no b-tagging

With this selection we find in $10\ pb^{-1}$:

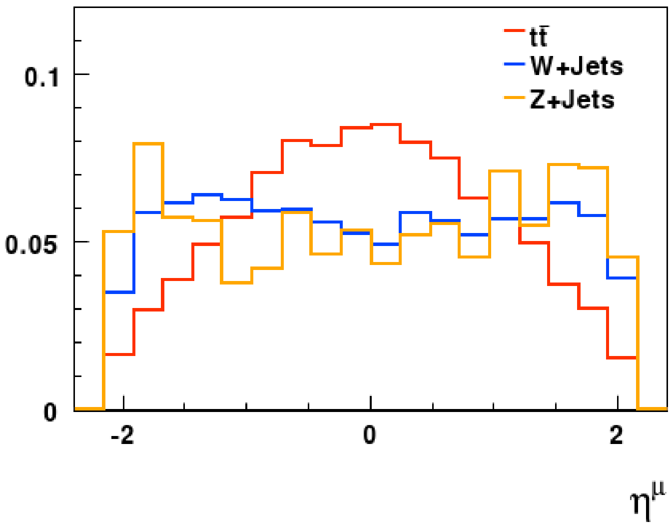
**128 ttbar signal events**
**25 ttbar other events**
**63 BG events**

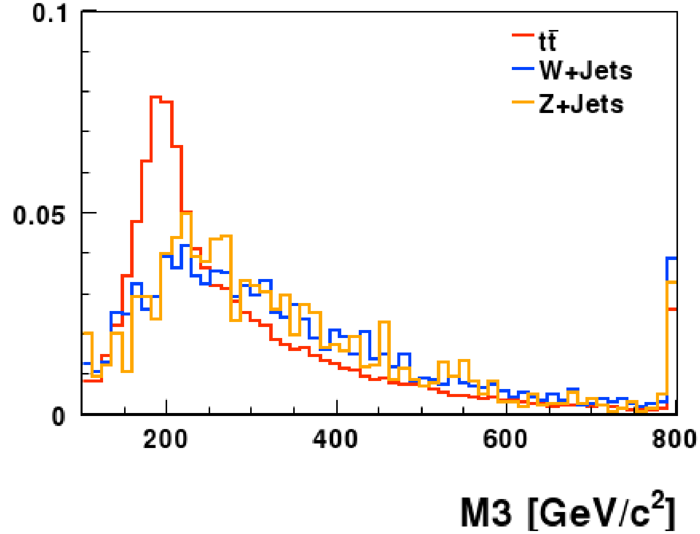
- Data driven QCD background estimate
  - Exponential fit + template
  - Select RelIso > 0.95

$$RelIso = \frac{p_T^{\mu}}{p_T^{\mu} + CalIso + TrackerIso}$$

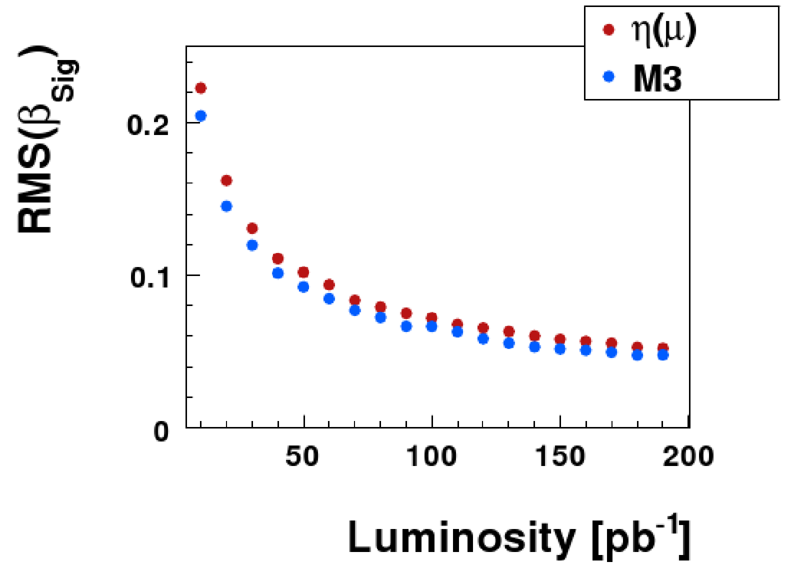


- Discriminating variables η and M3




- Perform binned likelihood fit
  - Luminosity dependence of statistical uncertainty

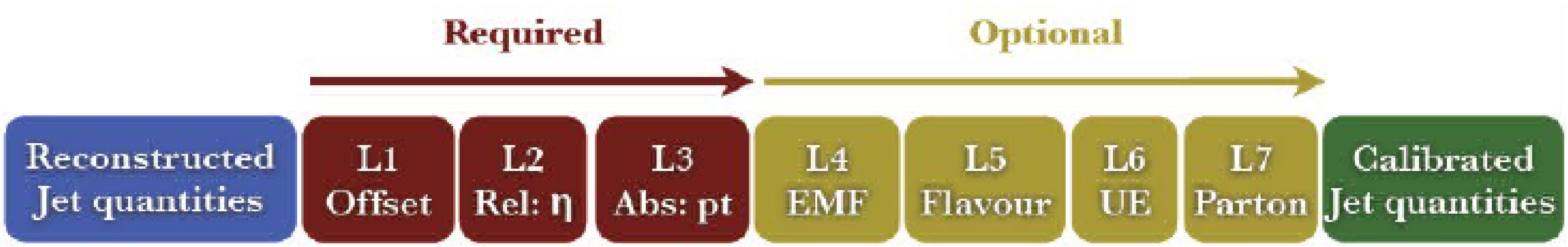



- Systematics
  - Important contribution from JES
- Improve with overall likelihood
  - 12 input variables

# Top quark as a calibration tool

- Top quark suitable to calibrate JES and b-tagging
- Two approaches for jet correction: factorized and global fit

- CMS is developing a factorized jet correction in 7 steps:




*Level 1*: correction for pile-up, electronic noise and jet energy lost by thresholds
*Level 2*: relative correction for variations in jet response with pseudo-rapidity
*Level 3*: absolute correction as a function of jet $p_T$

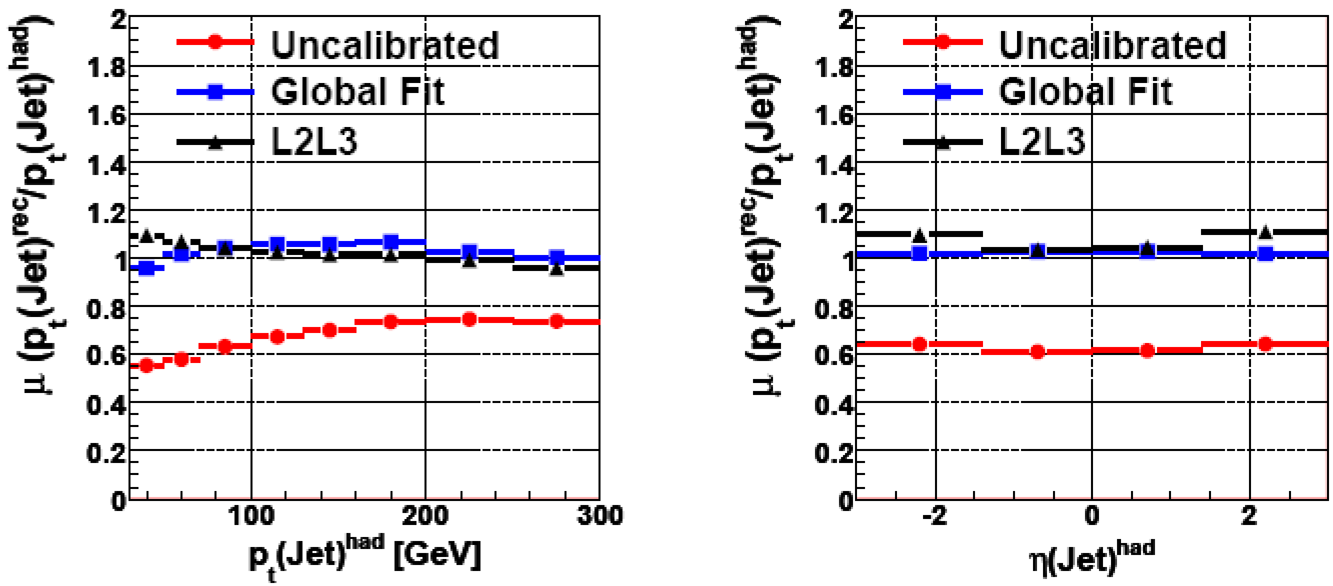
**Sebastian Naumann-Emme**

# Top quark as a calibration tool

- Global fit
  - takes correlations into account
  - recalibrate on tower level and calibrate on jet level
  - combine orthogonal samples

$$\chi^2_{\text{global}} = \chi^2_{\gamma/Z+\text{jet}} + \chi^2_{\text{dijet}} + \chi^2_{\text{track-tower}} + \chi^2_{\text{top}} + \dots$$

- Proof of principle with $t\bar{t}$ events



# Monte Carlo for top quark physics

- Type I: leading order (LO) matrix element (ME) + parton shower (PS)
  - ME for hard process (2→1 or 2→2) at tree level
  - PS: radiation of other partons (e.g. gluon splitting) → resummation of leading logarithms
- Type II: Leading order ME + PS + merging
  - MEs for hard processes including 2→*n* (e.g. $t\bar{t}$ + jets)
  - PS with LO generator (PYTHIA or HERWIG) or internally (SHERPA)
  - Mechanism to remove phase-space overlap between jets from 2→*n* ME and PS ("merging", e.g. CKKW, MLM)
- Type III: Next-to-leading order (NLO) ME + PS
  - Hard process to NLO accuracy (real & virtual corrections)
  - Mechanism to remove phase-space overlap between jets from NLO ME and PS (HERWIG for MC@NLO)

**ME+PS**

Herwig
Pythia
SingleTop, TopRex
Phantom
AcerMC
GRAPPA
CompHEP

**ME+PS+merging**

Alpgen
MadGraph
Sherpa

**NLO+PS**

MC@NLO
POWHEG

**Ulrich Husemann**

# Monte Carlo for top quark physics

- Tevatron (Pythia) $\rightarrow$ LHC (more sophisticated generators)
- $t\bar{t}$ production
  - MC@NLO seem to fit requirements, new: Powheg
- Single top
  - MadGraph or AcerMC. Now also MC@NLO
- Backgrounds
  - W/Z+jets in Alpgen (LO not sufficient)
- Underlying event
  - Tunable in generators
  - Important to do it right
- Don't underestimate the infrastructure of experiments
  - Long turn-around time, validations, …

# Top mass and properties

- Top mass and other properties (CMS) Roger Wolf
- Top mass (ATLAS) Kevin Kröninger

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Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

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| process | lumi | group(s) |
|---|---|---|
| $\sigma(top+\gamma)$ | $>10\ fb^{-1}$ | AC |
| $t\to bW,\ V_{tb}=1$ | $>1\ fb^{-1}$ | AC/KA |
| direct meas. | $>1\ fb^{-1}$ | HH/Desy |
| spin correl. | $>10\ fb^{-1}$ | AC/Desy |
| $\sigma(gg\to ttbar)$ | $0.1\ fb^{-1}$ | KA/HH |

# Top mass & properties

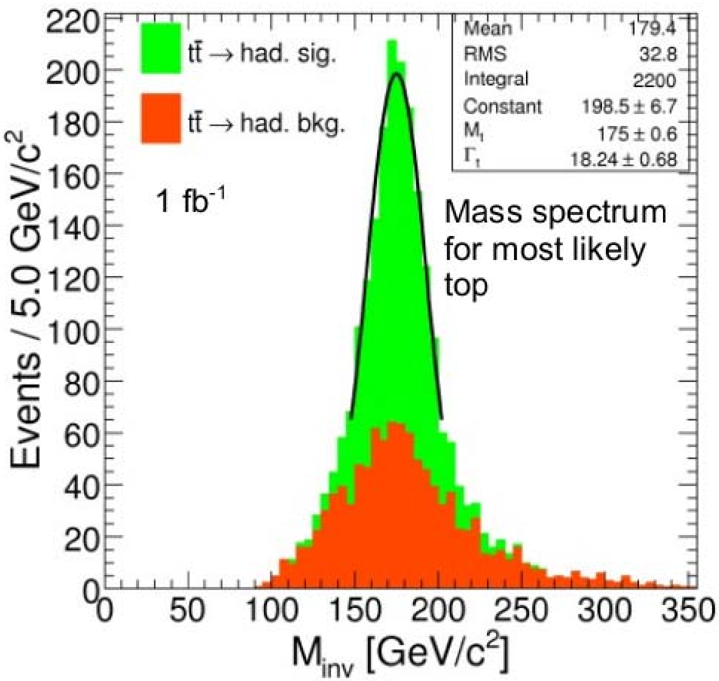
Presented study in full hadronic mode (Aachen)

- Combinatorics
- QCD

- Classes of diff. matching quality

- With likelihood obtain
  - S/B = 2/3
- Dominating systematics
  - QCD background
  - ISR/FSR
  - JES

M. Duda (AC)



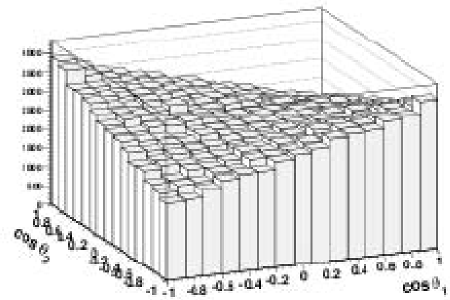

**Roger Wolf**

- $\Delta m_{top}$ (1fb$^{-1}$) = ± 1(stat) ± 3(syst) GeV

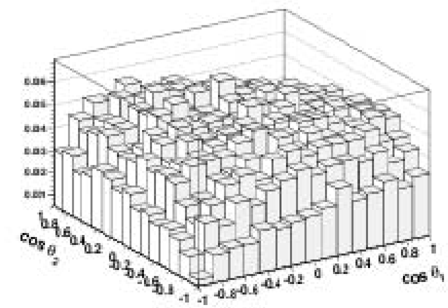
# Spin Correlations (Reconstruction)

Hamburg

Before reconstruction:



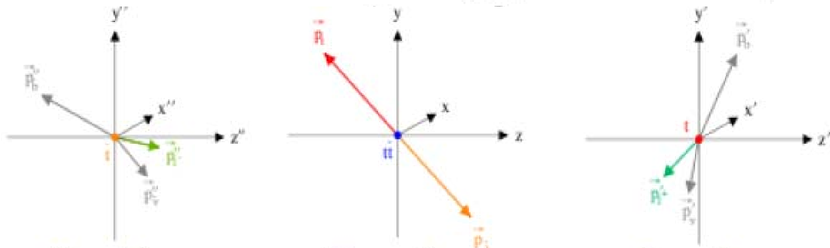

After reconstruction:



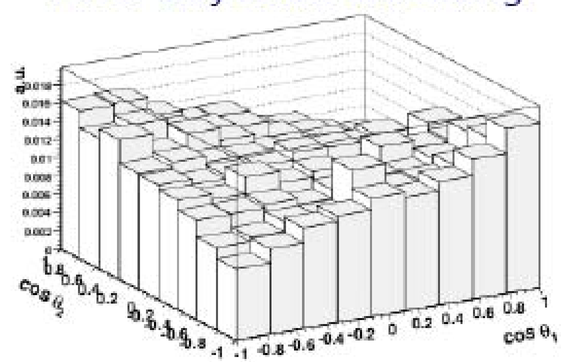

$$\cos\theta^*_{l^-} = \frac{\vec{p}''_{l^-}\cdot\vec{p}_{\bar{t}}}{|\vec{p}''_{l^-}||\vec{p}_{\bar{t}}|}$$

$$\cos\theta^*_{l^+} = \frac{\vec{p}'_{l^+}\cdot\vec{p}_{t}}{|\vec{p}'_{l^+}||\vec{p}_{t}|}$$

- helicity basis -




After bayesian unfolding:




$$\frac{1}{N}\frac{d^2N}{d\cos\theta^*_{l+}d\cos\theta^*_{l-}} = \frac{1}{4}(1 - \mathcal{A}\kappa_1\kappa_2\cos\theta^*_{l+}\cos\theta^*_{l-} + p_+\cos\theta^*_{l+} + p_-\cos\theta^*_{l-})$$

$A$=0.3 ... 0.4

A (10 fb$^{-1}$)=0.414±0.002(stat.)±0.024(syst.)

B. Hegner (Desy)

15

# Top mass

- Similar selection as top pair with cuts to enhance purity, e.g.
  - Use b-tagging for ultimate precision
  - W mass constraint
  - Cut on other invariant mass combinations

- Methods under investigation
  - Top reconstruction with likelihood fitter
  - Use of templates
  - Extract ratio $m_{top}/m_W$
  - Matrix element method
  - B decay length technique

# Matrix-Element method

- **Idea:** interpret differential cross-section as pdf for top mass.
- Includes *physics process* (ME-element) and *detector parameterization*
- Uses all available kinematic information

$$P(x;M_t) = f_s P_s(x;M_t) + (1-f_s) P_{bkg}(x)$$

$$P_s(x|M_t) = \frac{1}{\sigma(M_t)} \int d\Phi \; |M_{t\bar{t}}(q_i,p_i;M_t)|^2 \; W(p,x) \; f_{PDF}(q_1) f_{PDF}(q_2)$$

Propability to measure x

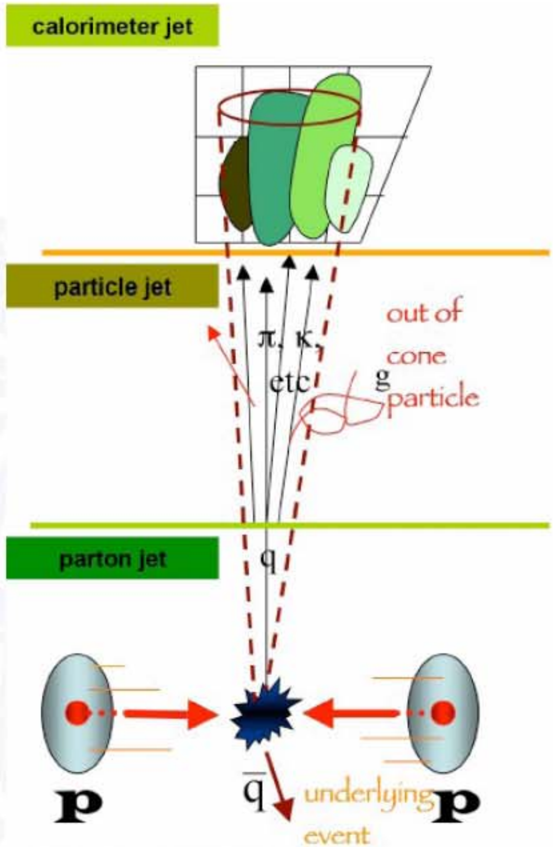
normalisation: production croos section

phase space

matrix element: dynamic: Parton/parton → ttbar

transfer function: Maps the physical p to the detectable observable x

PDFs

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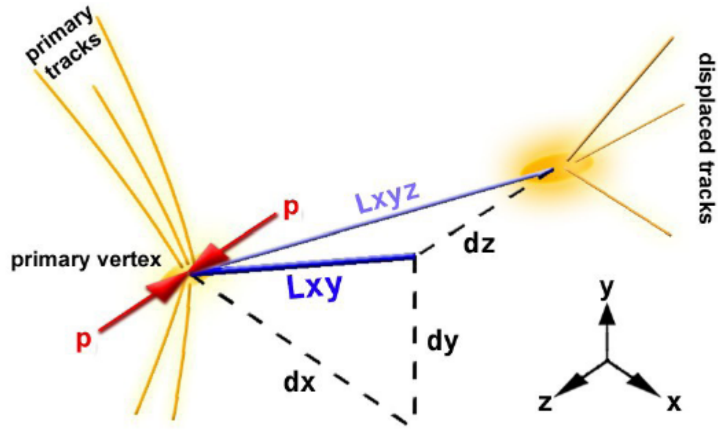
**Kevin Kröninger**

# B decay length method

- **Idea:** Top mass correlated to momentum of b-hadron
- Measure $<L_{xy}>$ to infer $m_{top}$
- Motivation: ***JES-independent***




top mass → *b*-quark momentum → *B*-hadron momentum

kinematic two-body decay:
→ if top decays at rest:
$E_b \approx 0.6\, m_{top} c^2 - 36.8$ GeV

fragmentation:
$E_B = X_b \cdot E_b$
$\langle X_b \rangle = 0.7193 \pm 0.0016^{+0.0038}_{-0.0033}$
(measured at OPAL)

The decay length of the *B*-hadrons is given by:

$$\boxed{L = \beta\gamma c\tau = p_B\, \tau / m_B}$$

with $\beta = v/c$, $\gamma\tau =$ lifetime in laboratory system

- Need:
  - Tracking
  - *b-tagging*

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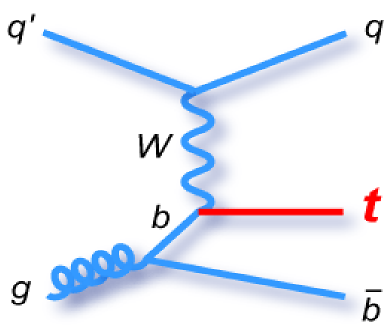
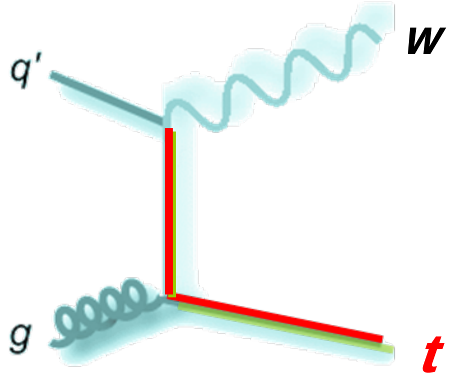
# Single top

- Single top production in MC@NLO Patrick Motylinski
- Single top (ATLAS) Gia Khoriauli
- Single top (CMS) Julia Weinelt



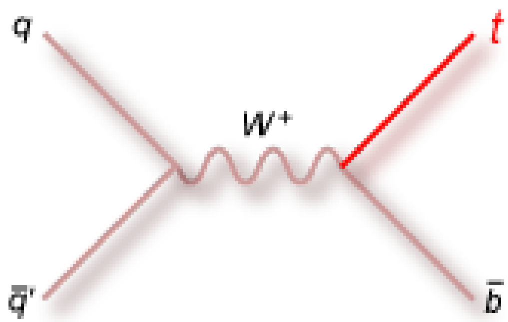

*t-channel*

***σ = 240pb***




*tW production*

***σ = 60pb***

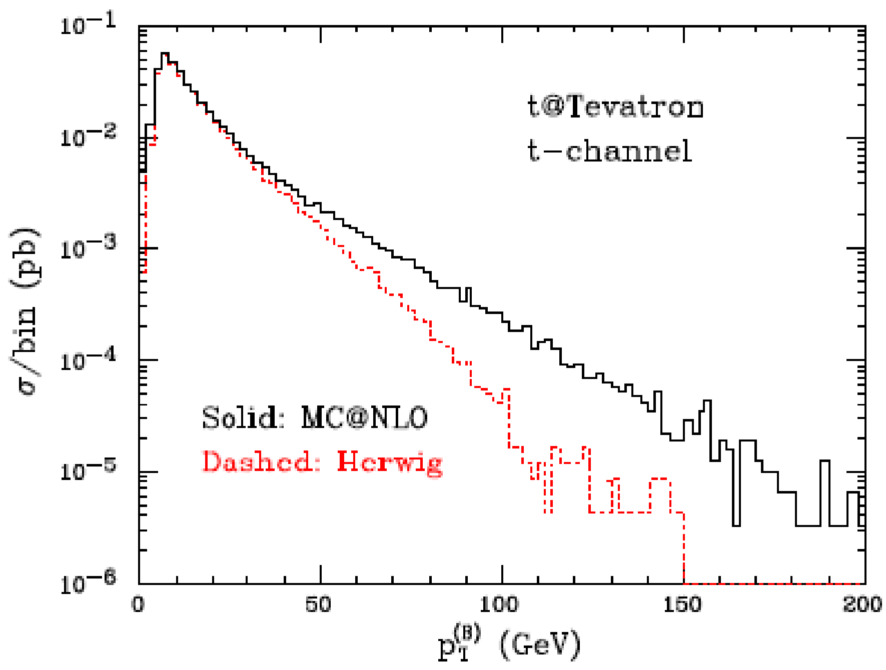



*s-channel*

***σ = 10pb***

# Single Top Production in MC@NLO

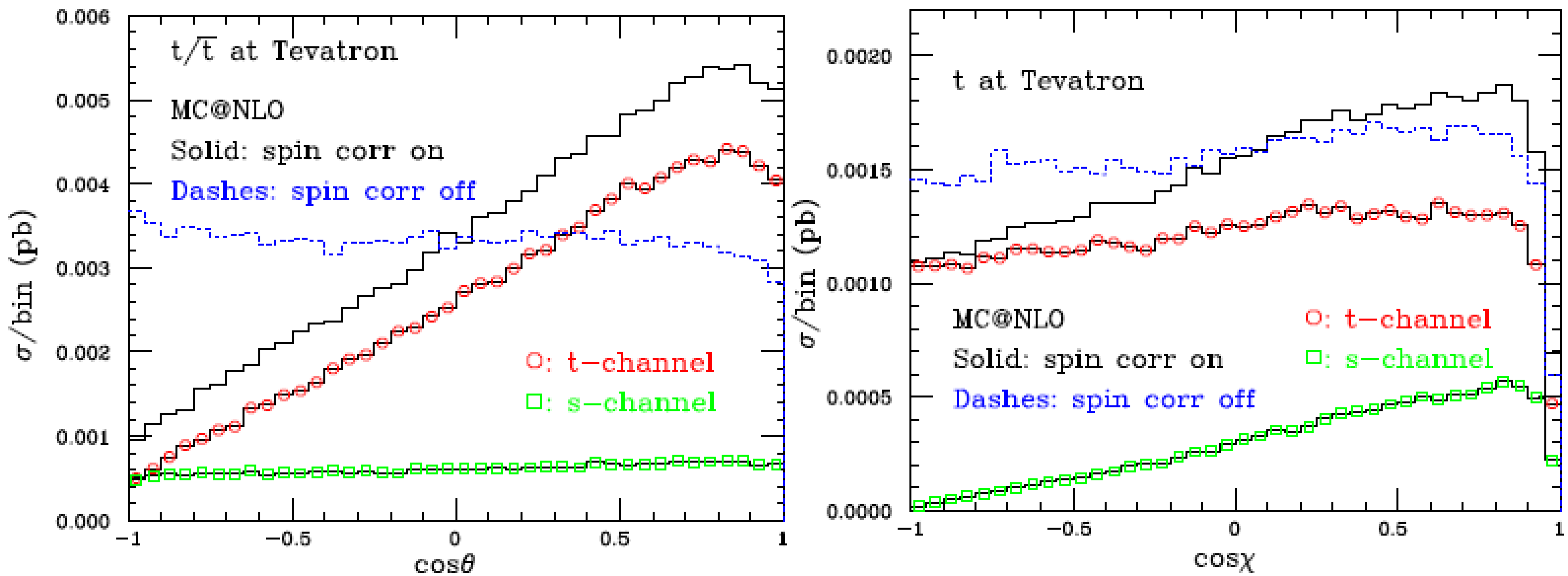
- $p_T$ of additional b-jet (not from top) is sensitive to NLO effects
  - Consistent treatment important to cover full phase space




**Patrick Motylinski**

- Until recently t-channel and s-channel, now also Wt channel

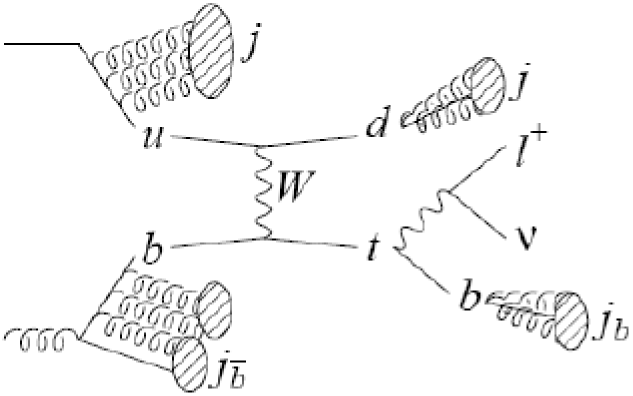
# EFFECTS OF SPIN CORRELATIONS




where
$\theta$ is the angle between the direction of flight of the lepton (from top decay) and the hardest non-$b$ jet
$\chi$ is the the angle between the direction of flight of the lepton (from top decay) and the anti-proton beam.

# Single top event topology

- Single top like other processes has its **background**
- Background is suppressed using cuts determined by the single top **event topology**




universitätbonn

## Pre-selection:

Exactly one lepton, $n_{jets}$ in [2,4], b-tagged jet, $E_T^{miss}$

26-Nov-08

**Gia Khoriauli**

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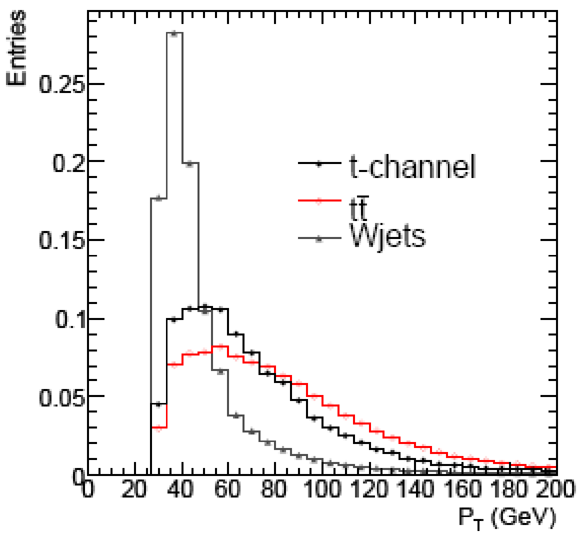
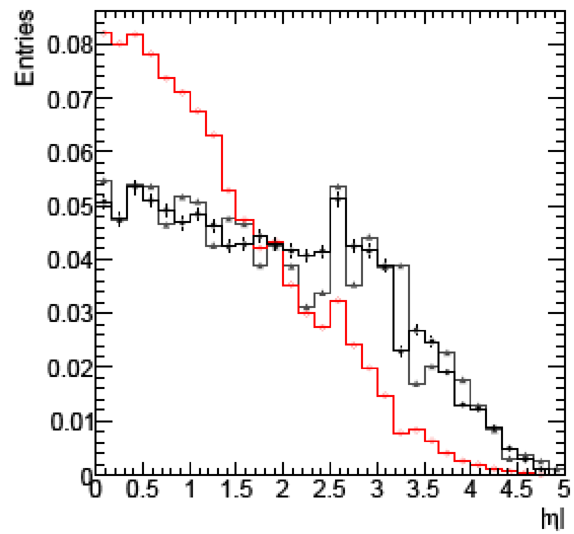
# Background suppression

- Specific for t-channel
  - $p_T$ of b-jet > 50 GeV — forward leading non-b jet

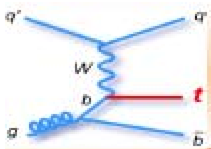



- Ultimately use likelihood and boosted decision trees

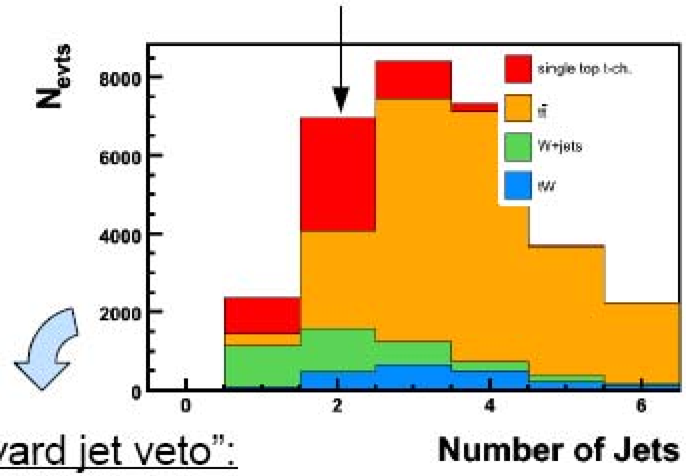
**$\Delta\sigma/\sigma$ - single-top cross section measurement uncertainty**
(multivariate analysis)

| | 1fb$^{-1}$ | 10fb$^{-1}$ |
|---|---|---|
| t-channel: | $\pm 5.7\%_{stat}$ $\pm 21.7\%_{sys}$ | $\pm 1.8\%_{stat}$ $\pm 9.8\%_{sys}$ |
| Wt-channel: | $\pm 20.6\%_{stat}$ $\pm 48.0\%_{sys}$ | $\pm 6.6\%_{stat}$ $\pm 19.4\%_{sys}$ |
| s-channel: | $\pm 64.0\%_{stat}$ $\pm 95.0\%_{sys}$ | $\pm 20.0\%_{stat}$ $\pm 48.0\%_{sys}$ |

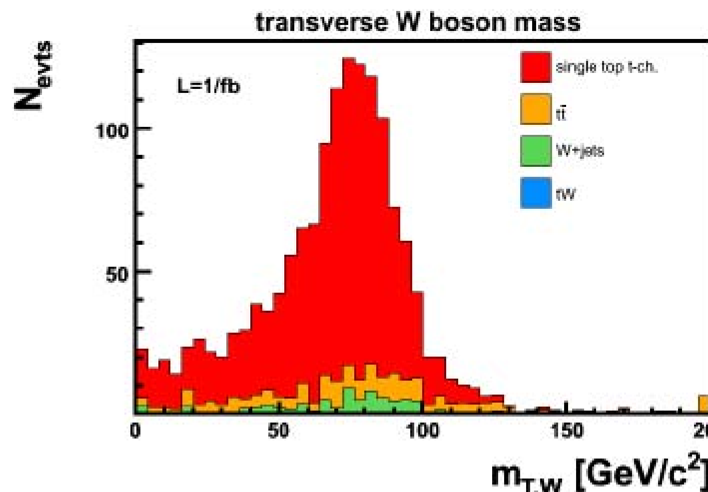


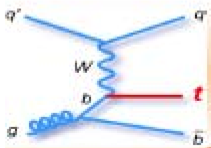

# Event Yield @ 1/fb

| process | $N_{exp}$ |
|---|---|
| t-channel | 1226 |
| ttbar | 199 |
| tW | 48 |
| W+jets | 117 |
| Z+jets | 4 |
| diboson | 8 |
| Wbb | 8 |
| Wcc | 2 |
| Zbb | 3 |
| Zcc | 0 |
| QCD | 571 |
| ΣB | 960 |
| S/B | 1.3 |
| S/sqrt(S+B) | 26.3 |




+ “forward jet veto”:



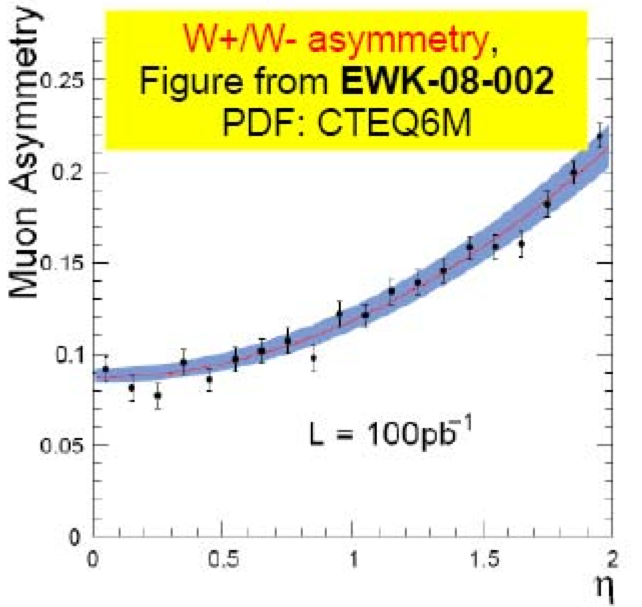



# BG Estimation Strategies

**W+jets:**

is charge-asymmetric (pp-collider)
- ttbar and QCD BGs are not

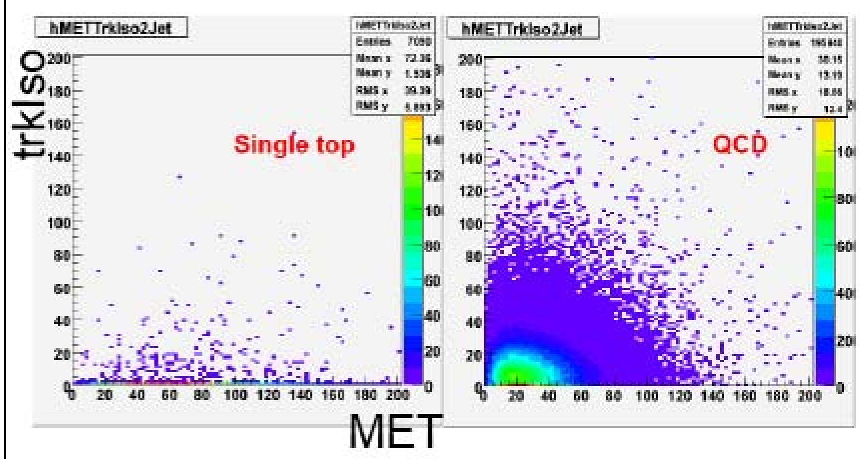
W+/W- asymmetry will be measured pretty well with <100/pb, in the high-statistics 0j sample




**QCD:**

At the moment (*):
Demonstrate the feasibility for ST of the methods being worked out for semileptonic ttbar analyses

→ Working on ABCD method
e.g. MET vs track isolation




(* different strategies are in preparation)

# $m_{t\bar{t}}$

- Top-quark pair production near threshold, Matthias Steinhauser
- The potential of top invariant mass, Fabio Maltoni
- Resonances decaying into ttbar (CMS) Jan Steggermann
- ttbar resonances with Herwig++ Markus Mechtel

# Differential σ($m_{tt}$) at production threshold

Factorization of cross section

$$M\frac{\mathrm{d}\sigma_{P_1P_2\to T}}{\mathrm{d}M}(S,M^2)=\sum_{i,j}\int_\rho^1 \mathrm{d}\tau\left[\frac{\mathrm{d}\mathcal{L}_{ij}}{\mathrm{d}\tau}\right](\tau,\mu_f^2)\; M\frac{\mathrm{d}\hat\sigma_{ij\to T}}{\mathrm{d}M}(\hat s,M^2,\mu_f^2).$$

Luminosity     Partonic cross section

$$M\frac{\mathrm{d}\hat\sigma_{ij\to T}}{\mathrm{d}M}(\hat s,M^2,\mu_f^2) \;=\; F_{ij\to T}(\hat s,M^2,\mu_f^2)\,\frac{1}{m_t^2}\,\mathrm{Im}\,G^{[1,8]}(M+i\Gamma_t),$$

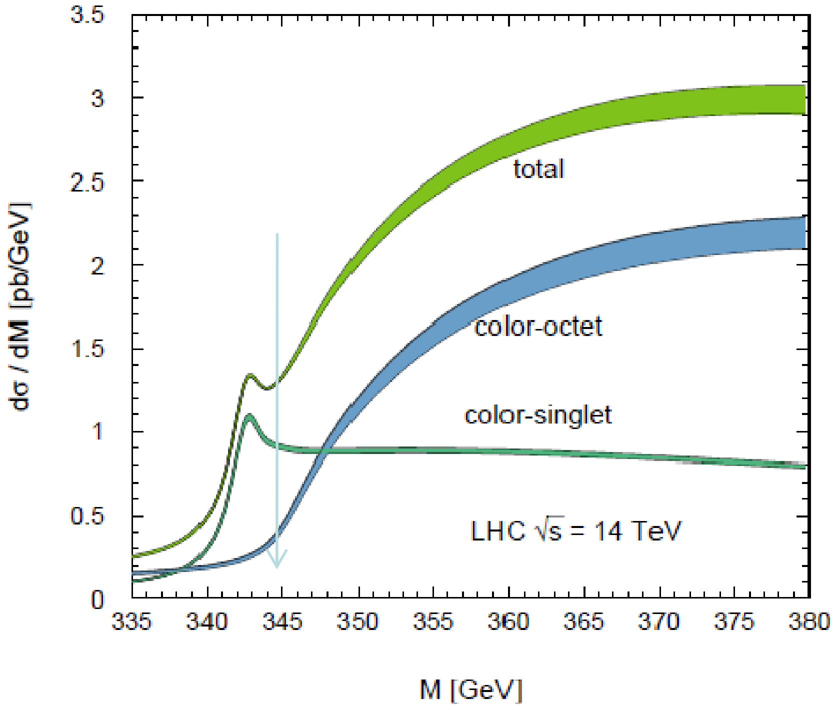
Hard scattering coefficient

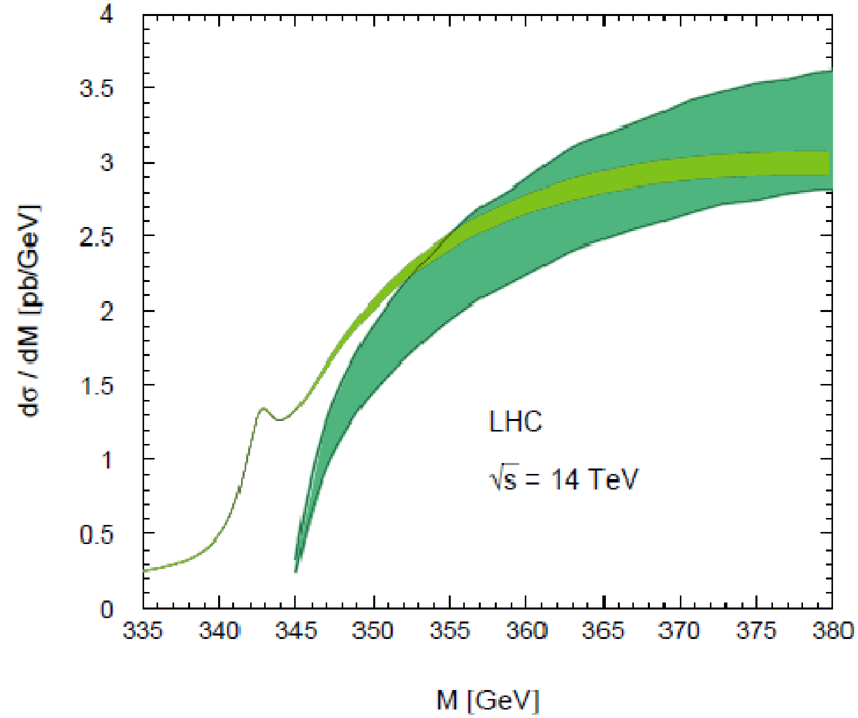
Greens function, Effects of "would-be" Bound state

Extension of recent work by Hagiwara et al:

Complete NLO result for hard scattering coefficient
Resummation of threshold logarithms
All processes included

**Matthias Steinhauser**

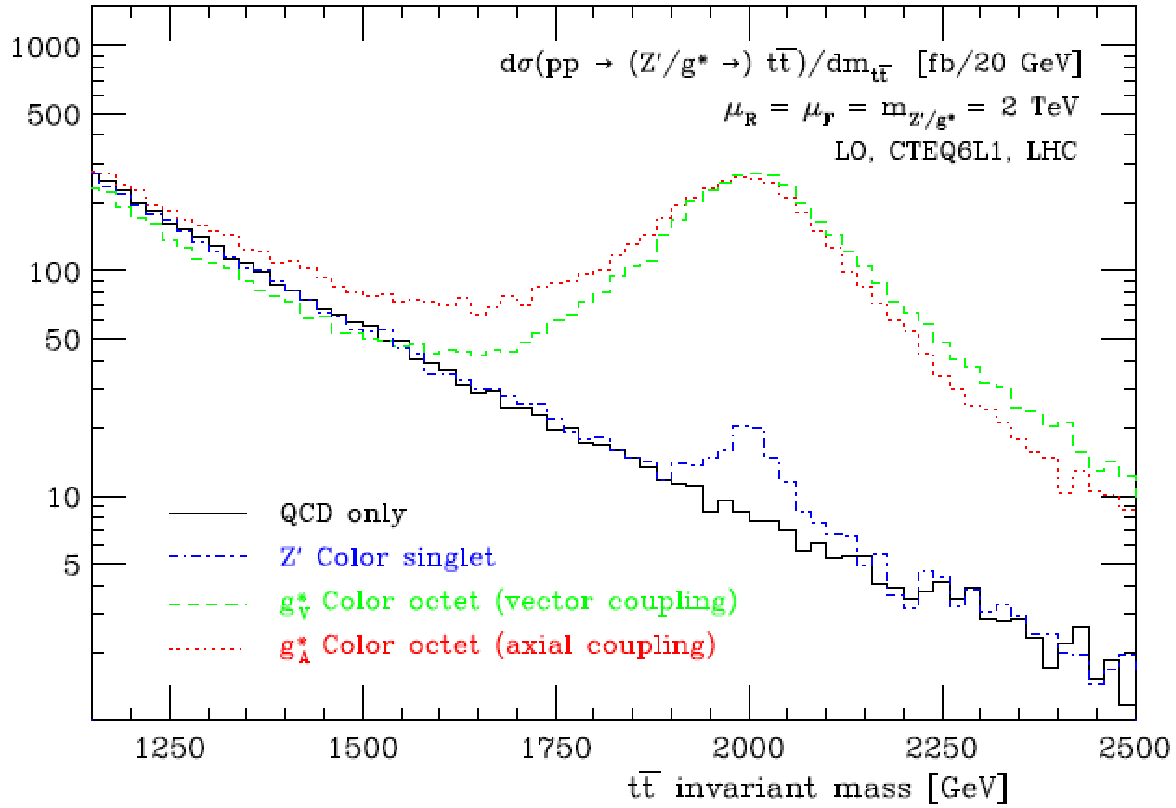



- No sharp resonances due to top width
- Shift of the total cross section (few pb)
- Important modification of $m_{tt}$-distribution in threshold region
  - Peak in singlet channel useful for mass determination ?

# $m_{tt}$ distribution

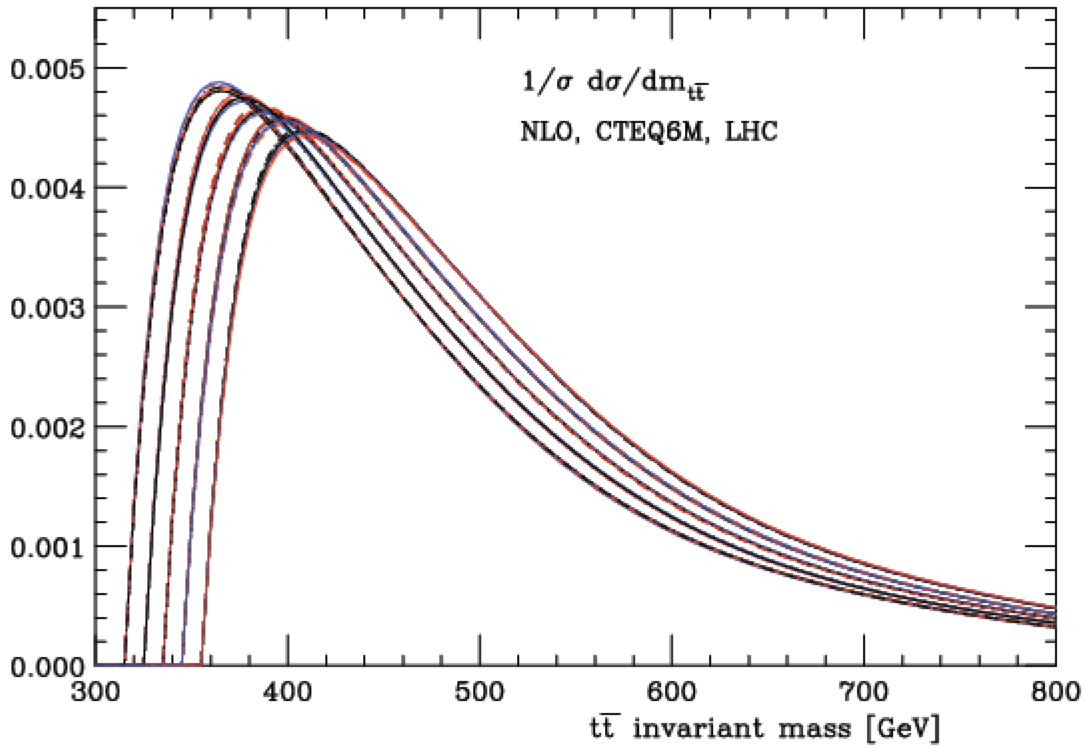
R. Frederix, F. Maltoni , arXiv:0712.2355




- (Model independent) discovery potential
- Now possible in MadGraph

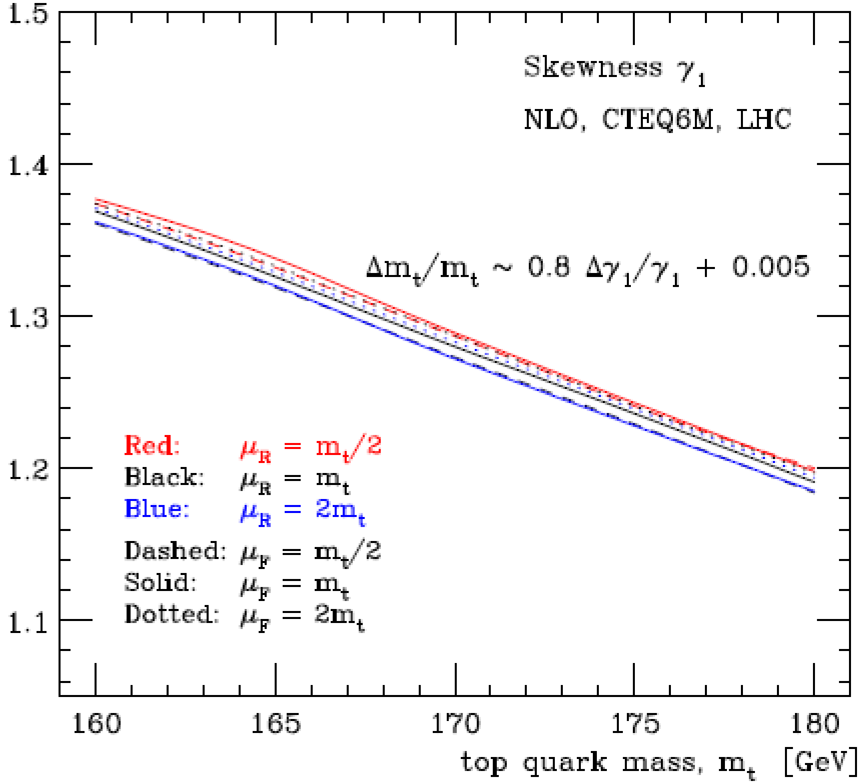
**Fabio Maltoni**

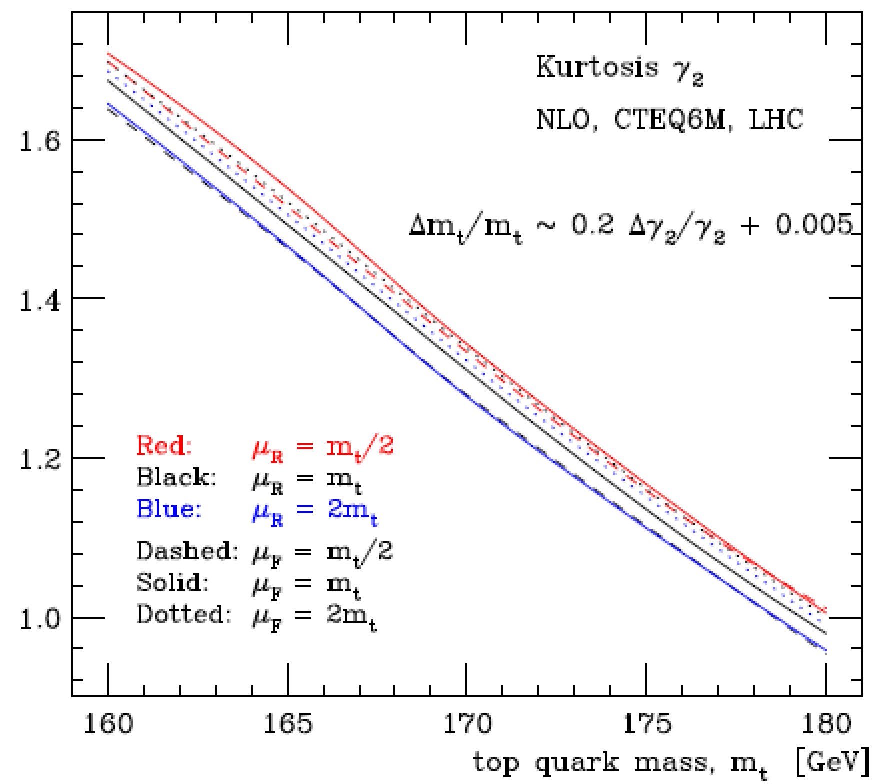
# $m_{tt}$ shape




- Can extract top mass from $m_{tt}$
  - shape stable wrt scale variation
  - shape sensitive to top mass

# Moments

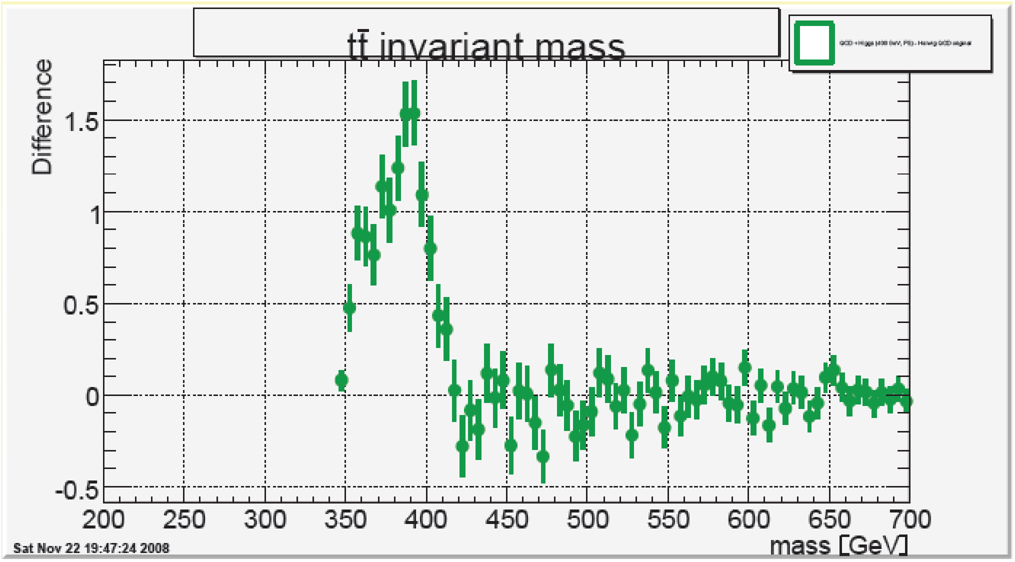


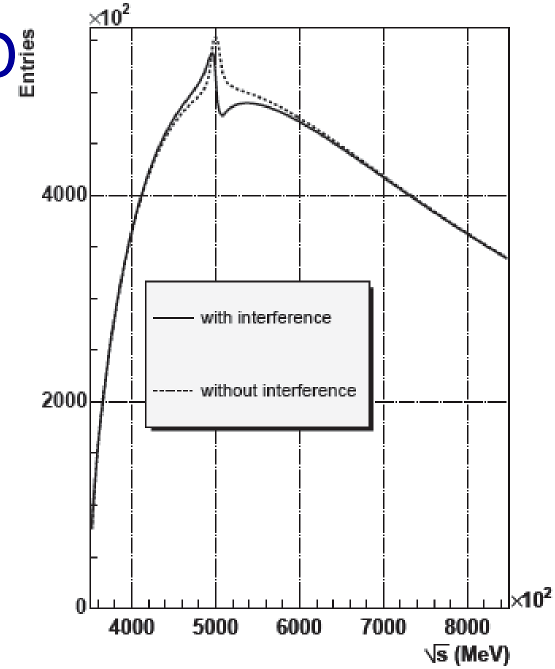




- Additional sensitivity to moments
- Need further studies of systematics from experiment

# $t\bar{t}$ resonances with Herwig++

- Interference between a resonance and QCD
  - Usually neglected
  - Yields characteristic peak/dip structure
- New ME in Herwig++ including interference
  - Just specify resonance parameters
- Example:



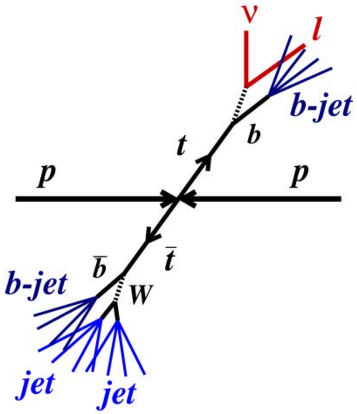

**Markus Mechtel**

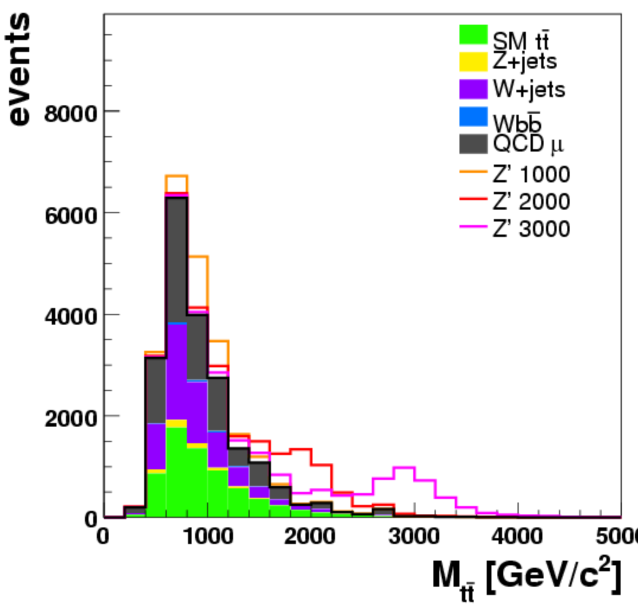
To be studied:
Detector resolution effects

# $m_{t\bar{t}}$ distribution

- Wide field of activities in Germany (AC, HH, KA involved)
- Searches for new physics at different energies
  - Requires new reconstruction strategy at $m_{t\bar{t}}$ > 1 TeV
- Use kinematic fitting, especially at low mass
- Make sure trigger is efficient
- Example:
  - $1fb^{-1}$ of data

  → Good resolution




**Jan Steggermann**

# Conclusion

- Lots of activity in top physics
- Fourth workshop in the LHC-D series, next in Spring 2009
- Lively discussions during workshop
- Key measurements well covered by German groups
- Plan: strengthen common activities

Interested?
Register to
dlhc_top@desy.de