KinFit/ME and top quark physics

- Compare kinematic fitting tools with ME tools
- Several topics in top quark physics

(I toke some slides from others ☺ , thanks M.Begel and P.Van Mulders)

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Les Houches 2007

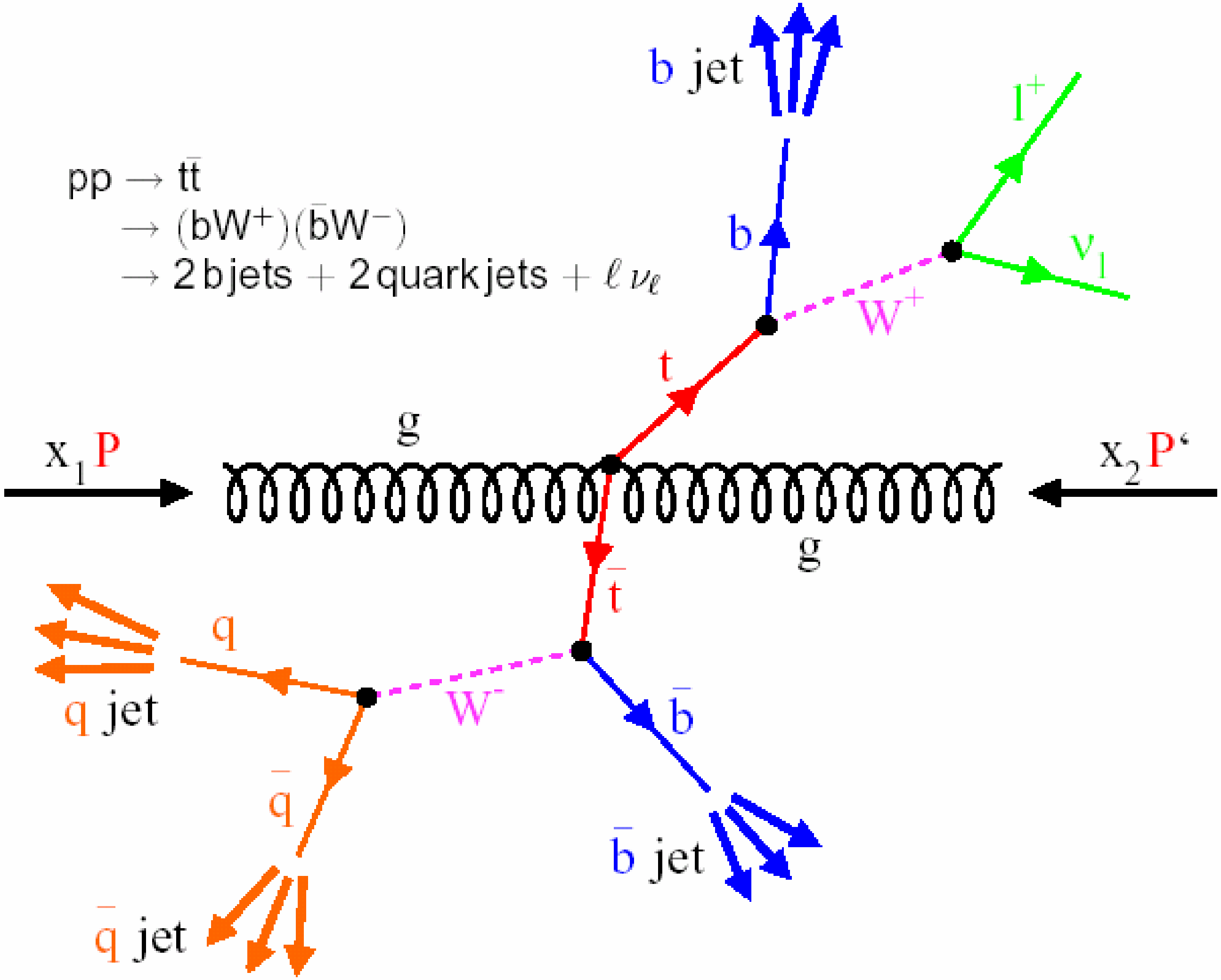
Method

- **Our knowledge of the observed event comes from measured objects in the final state (i = jets, lepton, 'neutrino').**
  - this can be summarized as $\mathbf{p}_i = \{ E_i, \theta_i, \varphi_i, 1/p \}$ (for example)
  - together with the covariance matrix $\mathbf{V}_i$ for each object i
- **Extend this knowledge $\mathbf{p}_i$ and $\mathbf{V}_i$ by assuming some hypothesis for the event**
  - for example : $m_{jj} = m_W$ & $m_{l\nu} = m_W$ & $\Sigma p_x = 0$ & $\Sigma p_y = 0$
- **Add Lagrange multipliers λ_k in the χ^2 equation to incorporate these hypothesed constraints in our knowledge of the event ($\Delta \mathbf{p} = \mathbf{p}^{fit} - \mathbf{p}^{measured}$)**

$$\chi^2(\mathbf{p}^{fit}) = \Delta\mathbf{p}^T \mathbf{V}^{-1} \Delta\mathbf{p} + 2 \sum_{k=1}^{m} \lambda_k f_k(\mathbf{p}^{fit}, \mathbf{a})$$

  - where we have the *m* constraint functions f_k and unmeasured parameters $\mathbf{a}$
  - for the true measured and unmeasured parameters → $f_k(\mathbf{p}_{true}, \mathbf{a}_{true}) = 0$
- **If the constraints are non-linear an iterative procedure is used to solve them**
  - the equation $f_k(\mathbf{p}, \mathbf{a})=0$ are linearized in each iteration step (*Taylor expansion*)
  - the χ^2 equation is minimized ($\partial\chi^2/\partial\mathbf{p}=0$, $\partial\chi^2/\partial\mathbf{a}=0$, $\partial\chi^2/\partial\lambda_k=0$) and solved
  - the iteration stops when some pre-defined convergence criteria are fulfilled

Top quark events good for this!

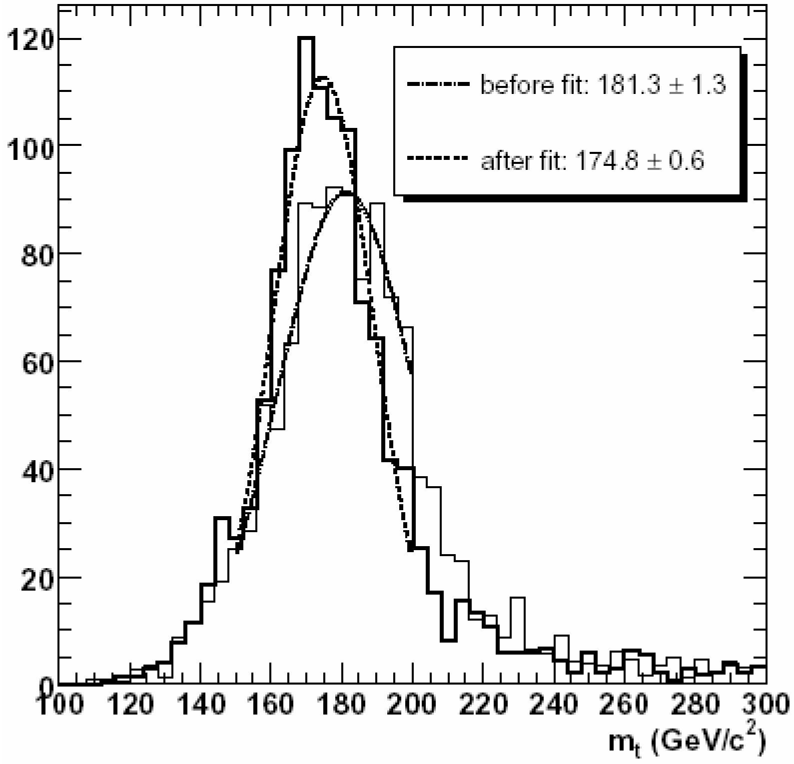


$$\begin{aligned} pp &\to t\bar{t} \\ &\to (bW^+)(\bar{b}W^-) \\ &\to 2\,\text{b jets} + 2\,\text{quark jets} + \ell\,\nu_\ell \end{aligned}$$

Examples in top quark physics

Kinematic fit method was introduced within CMS in CMS Note 2006/023

- **Several parametrizations of the reconstructed four-momenta are applied**
- **Several use cases are considered**



Improving the resolution of the top quark mass by fitting the W boson mass to its generated value (= world average).

Distribution after event selection. Covariance matrices differentiated as a function of the p_T of the jets.

To obtain the same precision without the fit, one needs 5 times more data and also the bias wrt 175GeV is reduced.

Search analyses: test the kinematic hypothesis of the event (*stop decays*)

Definition of parametrizations

(E_T,η,φ) parametrization

The η variable has a non trivial connection with the mass constraints

probably more difficult for the fit

massless jets

(E_T,θ,φ) parametrization

The θ variable has a more natural place within the mass constraints

massless jets

(a,b,c,d) parametrization

Three-momentum as

$$\vec{p}_f = a|\vec{p}_m|\vec{u}_1 + b\vec{u}_2 + c\vec{u}_3$$

with unit vectors :

$$\vec{u}_1 = \frac{\vec{p}_m}{|\vec{p}_m|};$$

$$\vec{u}_2 = \frac{\vec{u}_3 \times \vec{u}_1}{|\vec{u}_3 \times \vec{u}_1|},$$

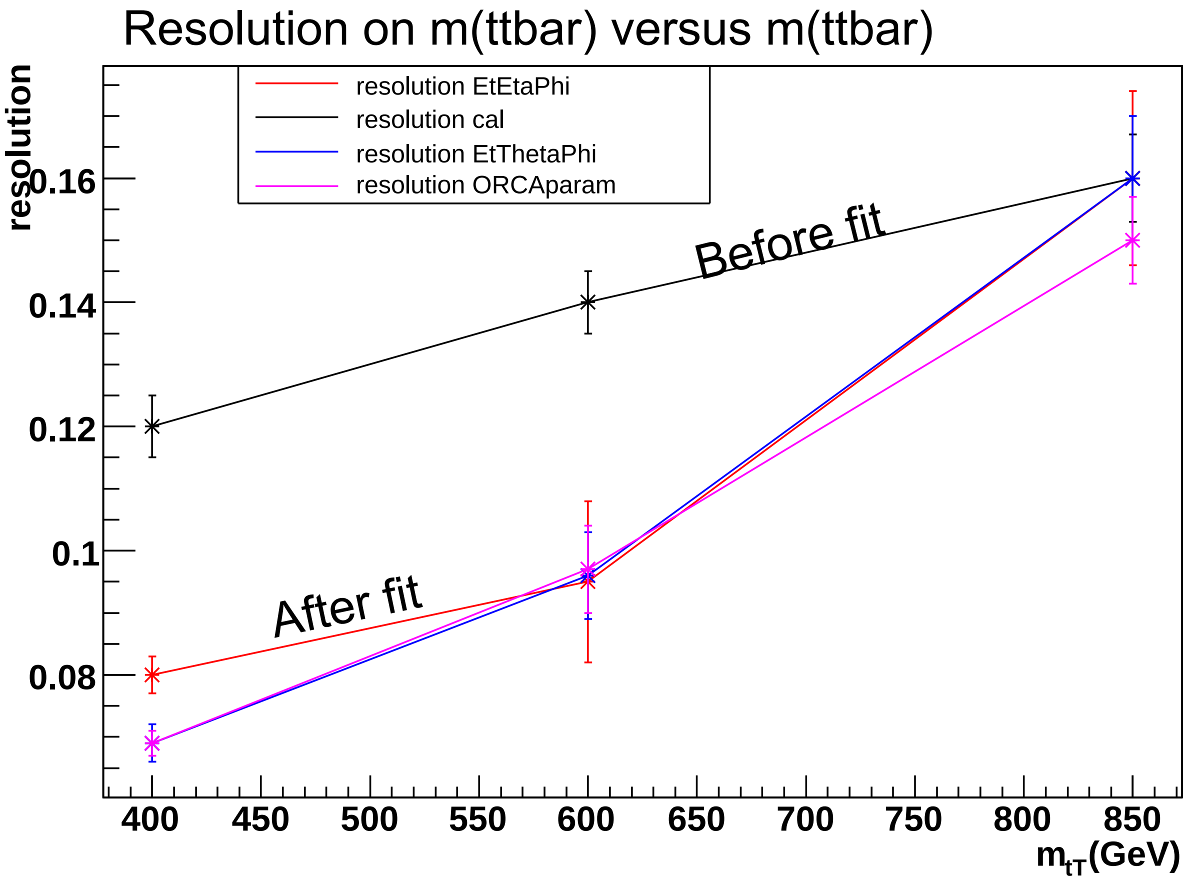
$$\vec{u}_3 = \frac{\vec{u}_z \times \vec{u}_1}{|\vec{u}_z \times \vec{u}_1|}.$$

and for the energy :

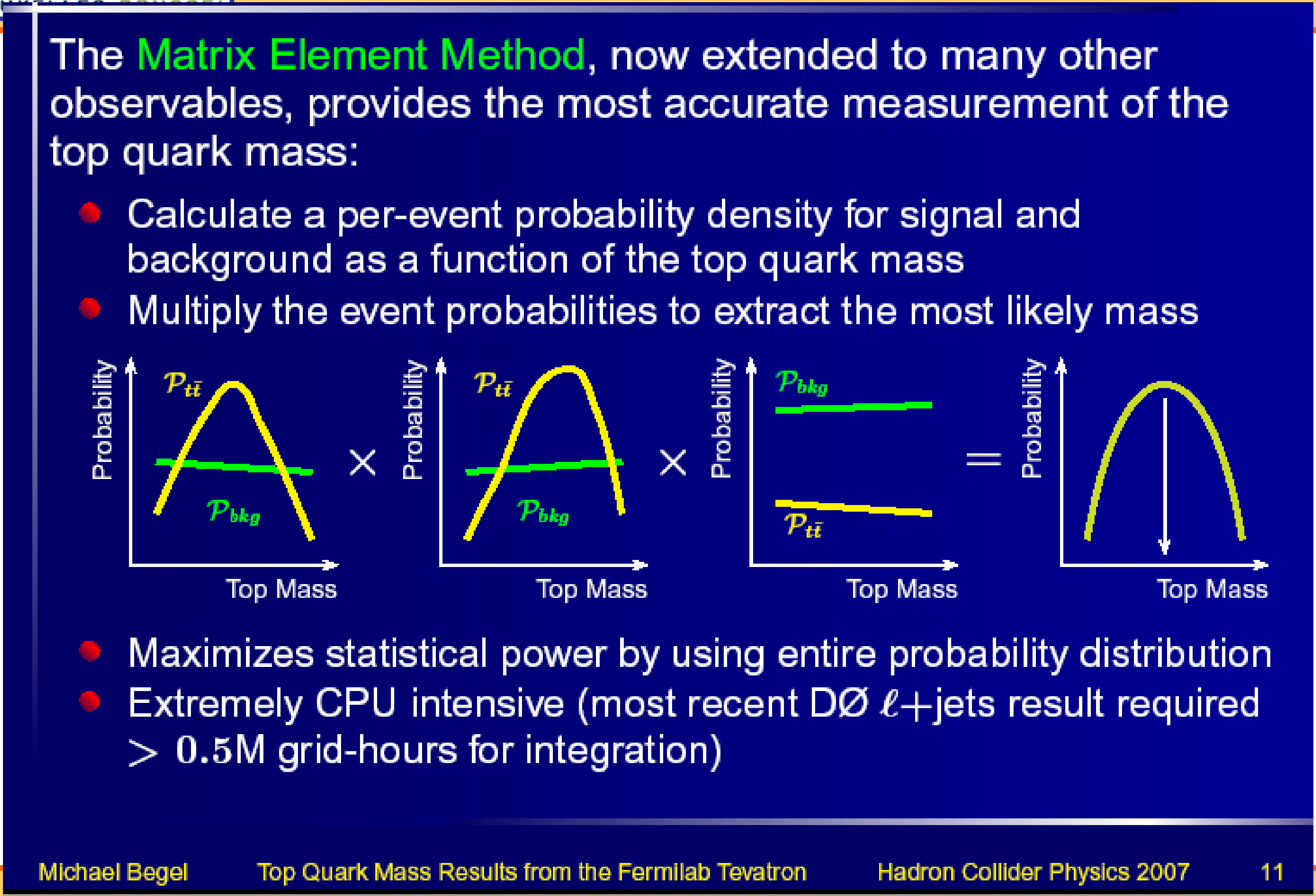
$$E_f = d \cdot E_\mathrm{m}$$

Case studies

- Top quark physics
- Stop decays in SUSY models
- Resonances decaying into ttbar systems
- ...



Matrix elements



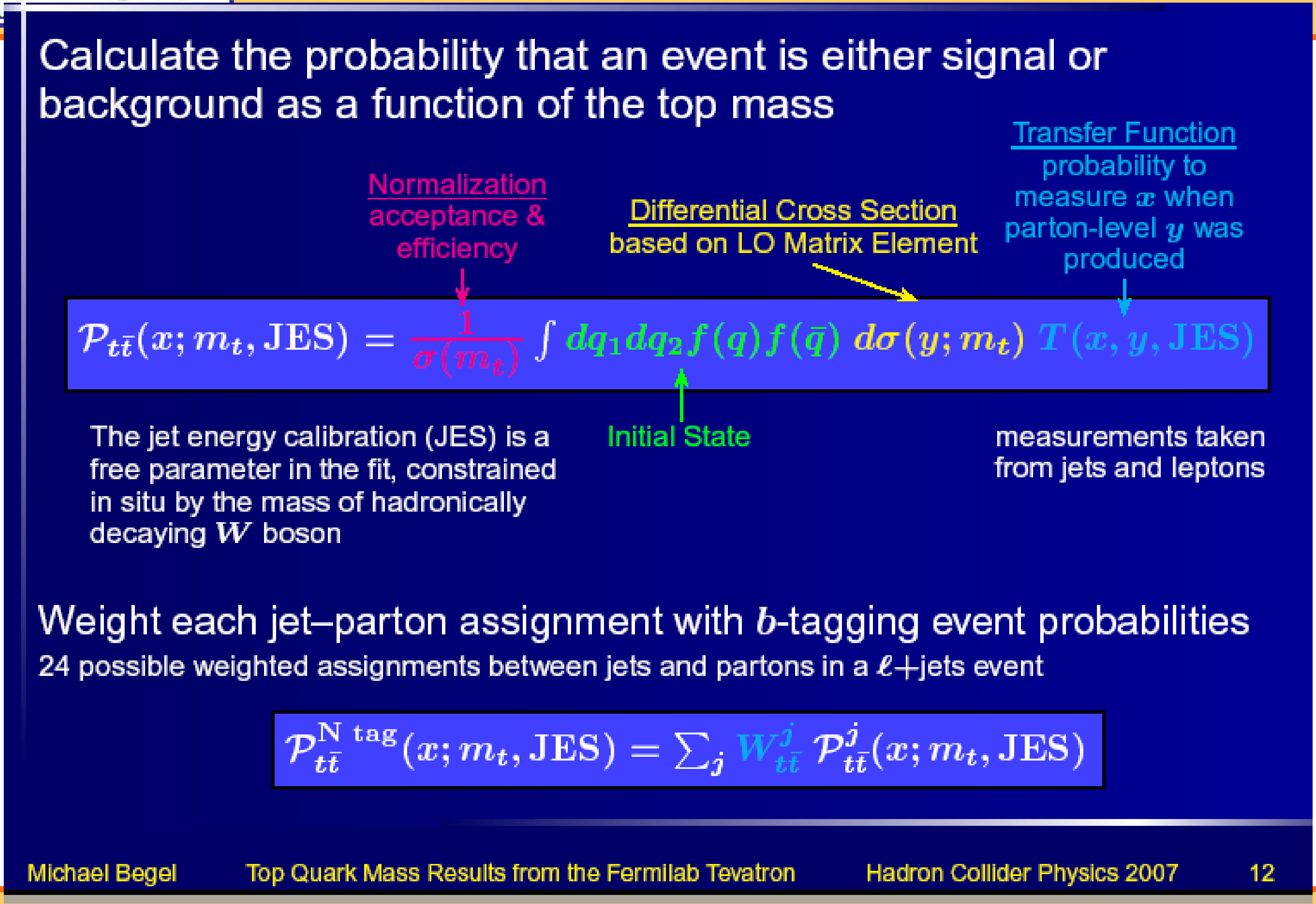
The **Matrix Element Method**, now extended to many other observables, provides the most accurate measurement of the top quark mass:

- Calculate a per-event probability density for signal and background as a function of the top quark mass
- Multiply the event probabilities to extract the most likely mass

- Maximizes statistical power by using entire probability distribution
- Extremely CPU intensive (most recent DØ ℓ+jets result required > 0.5M grid-hours for integration)

Michael Begel Top Quark Mass Results from the Fermilab Tevatron Hadron Collider Physics 2007 11

Matrix elements



Calculate the probability that an event is either signal or background as a function of the top mass

<u>Normalization</u>
acceptance &
efficiency

<u>Differential Cross Section</u>
based on LO Matrix Element

<u>Transfer Function</u>
probability to
measure x when
parton-level y was
produced

$$\mathcal{P}_{t\bar{t}}(x; m_t, \mathrm{JES}) = \frac{1}{\sigma(m_t)} \int dq_1 dq_2 f(q) f(\bar{q})\, d\sigma(y; m_t)\, T(x, y, \mathrm{JES})$$

The jet energy calibration (JES) is a free parameter in the fit, constrained in situ by the mass of hadronically decaying W boson

Initial State

measurements taken from jets and leptons

Weight each jet–parton assignment with b-tagging event probabilities

24 possible weighted assignments between jets and partons in a ℓ+jets event

$$\mathcal{P}_{t\bar{t}}^{\mathrm{N\ tag}}(x; m_t, \mathrm{JES}) = \sum_j W_{t\bar{t}}^{j}\, \mathcal{P}_{t\bar{t}}^{j}(x; m_t, \mathrm{JES})$$

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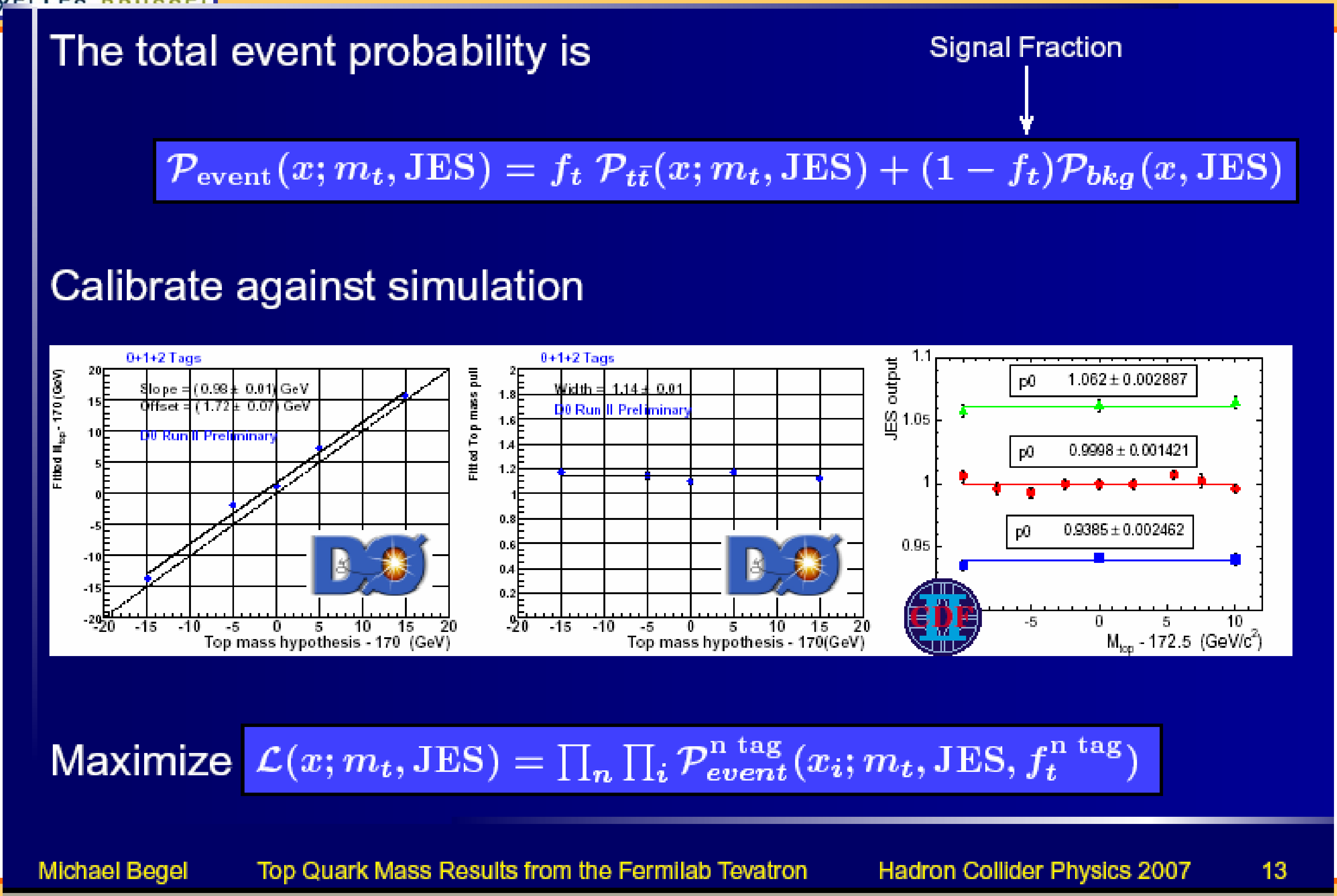
Matrix elements



The total event probability is

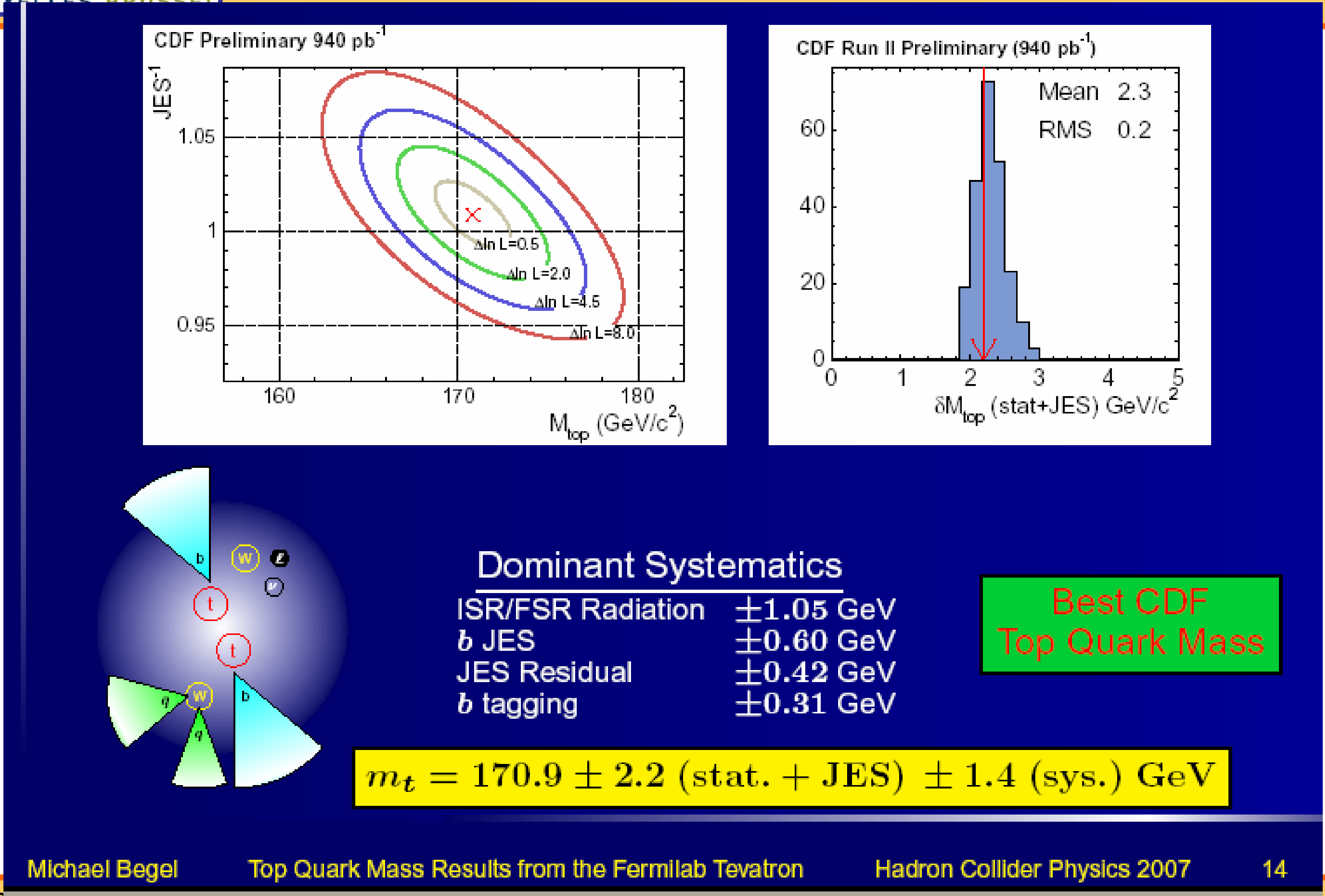
Signal Fraction

$$\mathcal{P}_{\text{event}}(x; m_t, \text{JES}) = f_t\, \mathcal{P}_{t\bar{t}}(x; m_t, \text{JES}) + (1 - f_t)\mathcal{P}_{bkg}(x, \text{JES})$$

Calibrate against simulation

Maximize $\mathcal{L}(x; m_t, \text{JES}) = \prod_n \prod_i \mathcal{P}^{n\ \text{tag}}_{event}(x_i; m_t, \text{JES}, f_t^{n\ \text{tag}})$

Matrix elements



Dominant Systematics

ISR/FSR Radiation	±1.05 GeV
b JES	±0.60 GeV
JES Residual	±0.42 GeV
b tagging	±0.31 GeV

Best CDF
Top Quark Mass

$$m_t = 170.9 \pm 2.2\ (\text{stat.} + \text{JES})\ \pm 1.4\ (\text{sys.})\ \text{GeV}$$

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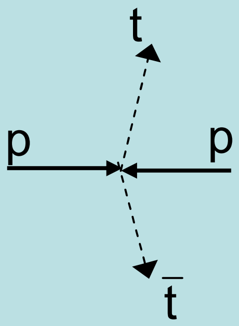
Matrix elements versus KinFit

Kinematic fit and matrix elements tools serve the same purpose. A thorough comparison between them on for example top quark events is essential. Also we have to test the use of these methods at the LHC prior to data taking (we will have to deal with many other issues when real data is coming)

- event-by-event comparison (KinFit includes mass constraints, ME includes the full kinematics of the event)
- theoretical issues in the calculation of the ME
- systematic uncertainties due to the use of Leading-Order ME's
- using ME's for other measurements and other topologies

Top quark physics issues

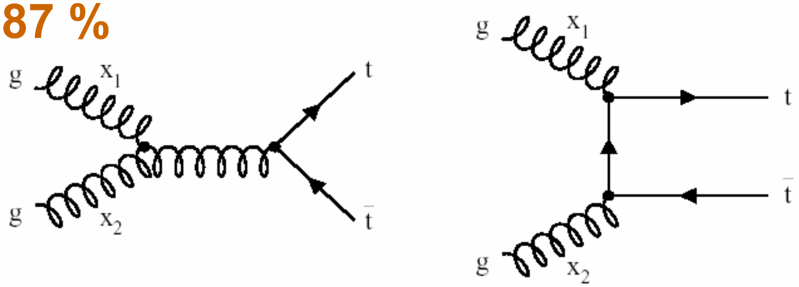
top pairs

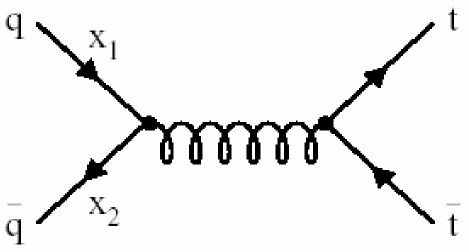


10 tt pairs per day @ Tevatron ⇨ 1 tt pair per second @ LHC

qq →tt : 85% *gg→tt : 87%*

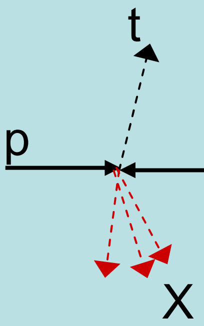
~87 %



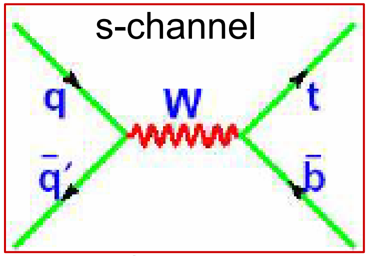


- ❖ NLO cross-section σ^{NLO} = **833** pb ⇨ ~8M events/10fb^{-1}

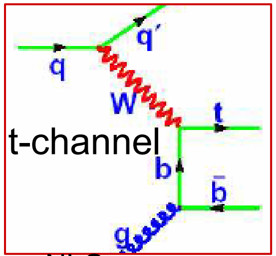
single-top



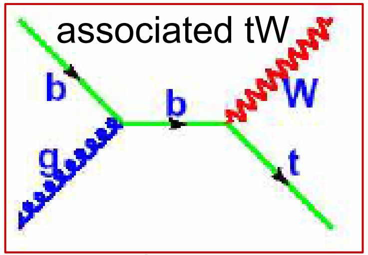
? single-top @ Tevatron ⇨ 30 single-tops per minute @ LHC



σ^{NLO} = 6.6 pb
σ^{NLO} = 4.1 pb



σ^{NLO} = 153 pb
σ^{NLO} = 90 pb



σ^{NLO} = 60 pb
σ^{NLO} = 60 pb

σ_{top} & $\sigma_{anti\text{-}top}$ not equal

σ^{NLO}(total) = **373** pb
⇨ ~3.7M events/10fb^{-1}

- ✸ top production
- ✸ anti-top production

Top quark physics issues

PRODUCTION

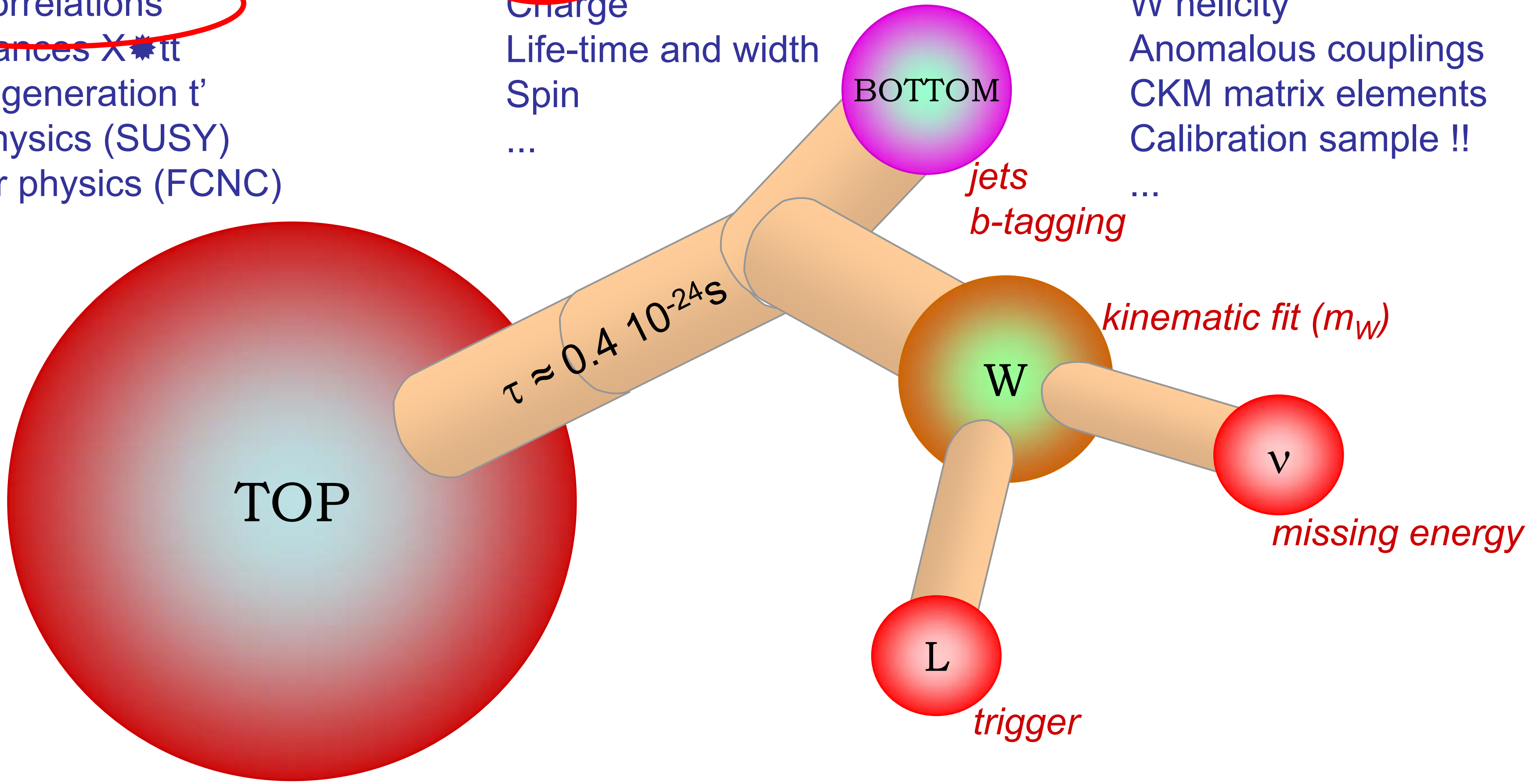
Cross section
Spin-correlations
Resonances X✸tt
Fourth generation t’
New physics (SUSY)
Flavour physics (FCNC)
...

PROPERTIES

Mass (matter vs. anti-matter)
Charge
Life-time and width
Spin
...

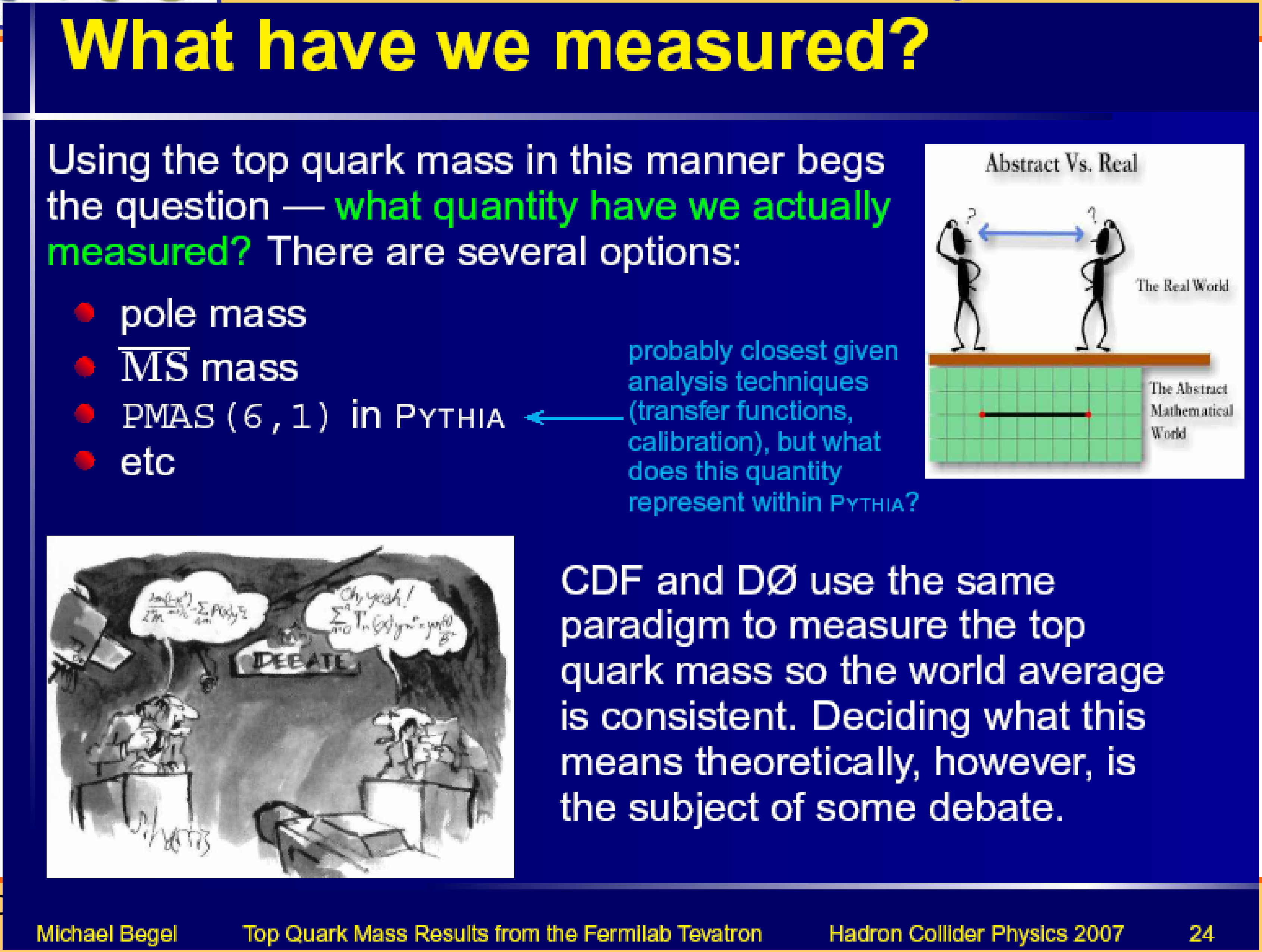
DECAY

Charged Higgs
W helicity
Anomalous couplings
CKM matrix elements
Calibration sample !!
...



In the long run the data will extend the Tevatron precision reach.

Top quark physics issues



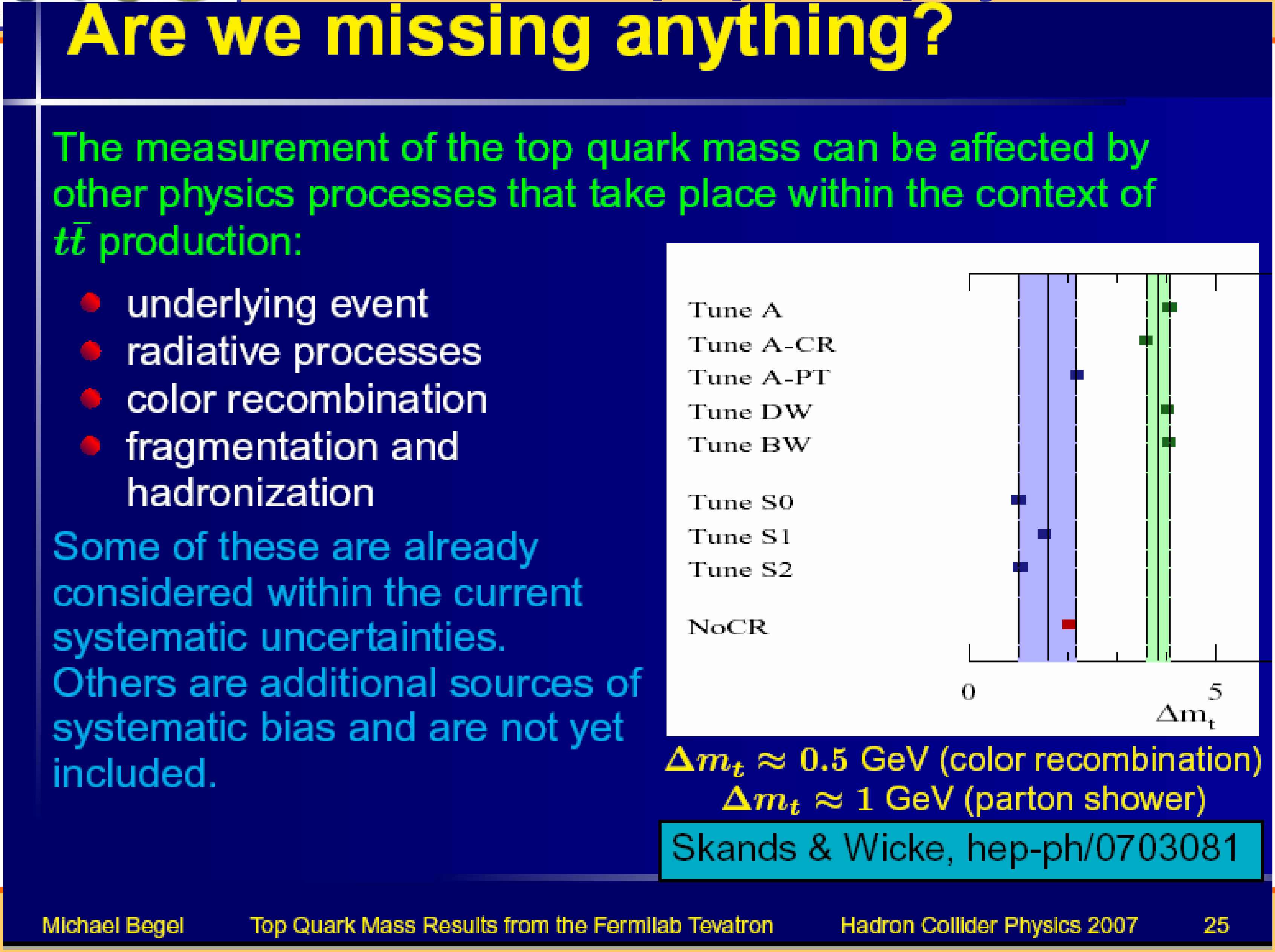
What have we measured?

Using the top quark mass in this manner begs the question — what quantity have we actually measured? There are several options:

- pole mass
- $\overline{\text{MS}}$ mass
- `PMAS(6,1)` in PYTHIA ← probably closest given analysis techniques (transfer functions, calibration), but what does this quantity represent within PYTHIA?
- etc

CDF and DØ use the same paradigm to measure the top quark mass so the world average is consistent. Deciding what this means theoretically, however, is the subject of some debate.

Top quark physics issues



Are we missing anything?

The measurement of the top quark mass can be affected by other physics processes that take place within the context of $t\bar{t}$ production:

- underlying event
- radiative processes
- color recombination
- fragmentation and hadronization

Some of these are already considered within the current systematic uncertainties.
Others are additional sources of systematic bias and are not yet included.

$\Delta m_t \approx 0.5$ GeV (color recombination)
$\Delta m_t \approx 1$ GeV (parton shower)

Skands & Wicke, hep-ph/0703081

Top quark sessions

We will have a specific top quark session on :

- **General WG2 Brainstorm this afternoon (14:00 - Library)**
  → setting up the workflows...
- **Friday 15th (9:00 - main auditorium): top physics**

Strong connection between top quark physics and the jet algorithm sessions however.