Towards Precision Top Quark Mass Measurements

Pedro A. Movilla Fernández
Lawrence Berkeley National Laboratory

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Outline

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- Experimental Challenges
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- Improving Measurements (I)
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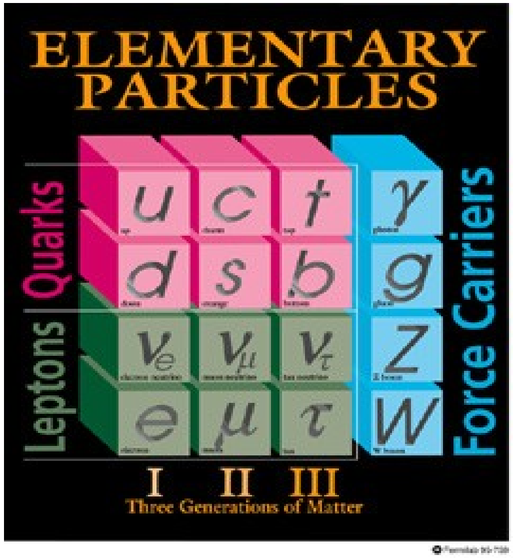
- Improving Measurements (II)
  Calorimeter Simulation | Jet Energy Scale
- Towards Precision Top Quark Mass
- Conclusions

Motivation



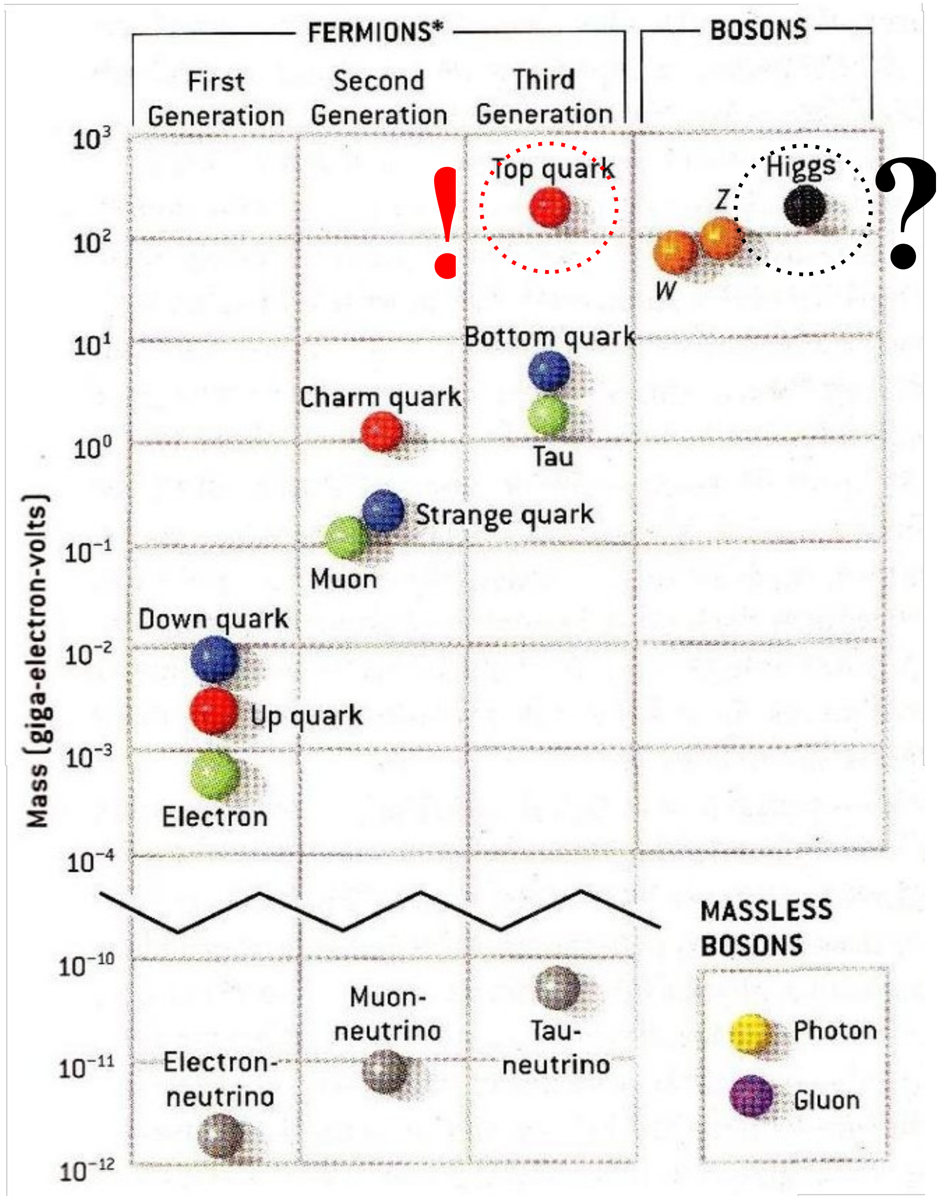
ELEMENTARY PARTICLES
Quarks
Leptons
Force Carriers
u
c
t
d
s
b
ν_e
ν_μ
ν_τ
e
μ
τ
γ
g
Z
W
I II III
Three Generations of Matter

The Top Quark in the Standard Model

- The top quark was just discovered in 1995 by CDF and DØ.
- It is required in the Standard Model (SM) as weak isospin partner of the bottom quark.

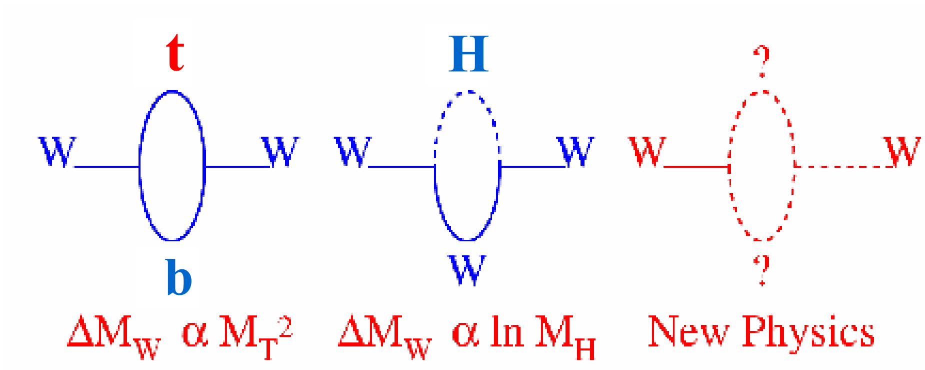
Striking property: the top quark mass is surprisingly large:
- Indicates Yukawa coupling ~ 1
- A key to understand electroweak symmetry breaking?

- The Higgs boson is also required by the SM but unfortunately not seen directly as yet.
- Direct searches at Tevatron ongoing...



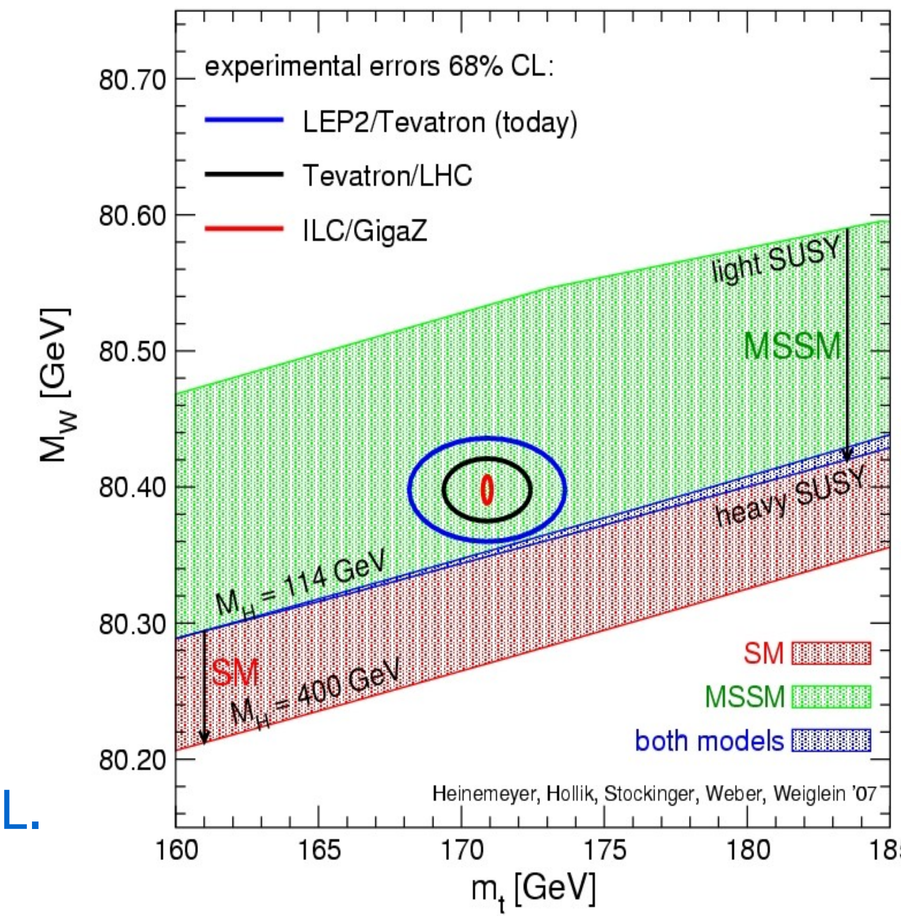
Why Measure the Top Quark Mass?

- It is a fundamental parameter.
- It is correlated to other SM parameters via electroweak corrections.



- Top quark and W boson mass predict the Higgs boson mass.
- Allow to impose constraints for physics beyond the SM.

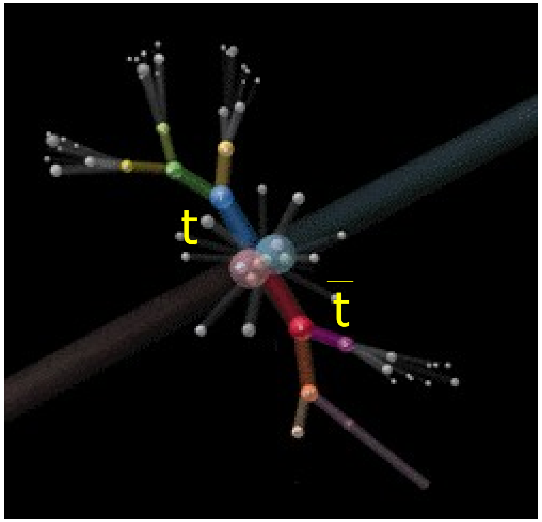
Heinemeyer et al. ,
JHEP 0608:052 (2006)
Update March 2007



- LEP limit: $m_{Higgs} > 114$ GeV/c^2 @ 95% C.L.
- Electroweak fit: $m_{Higgs} = 76^{+33}_{-24}$ GeV/c^2

- Very active field in Tevatron CDF & DØ collaborations ...

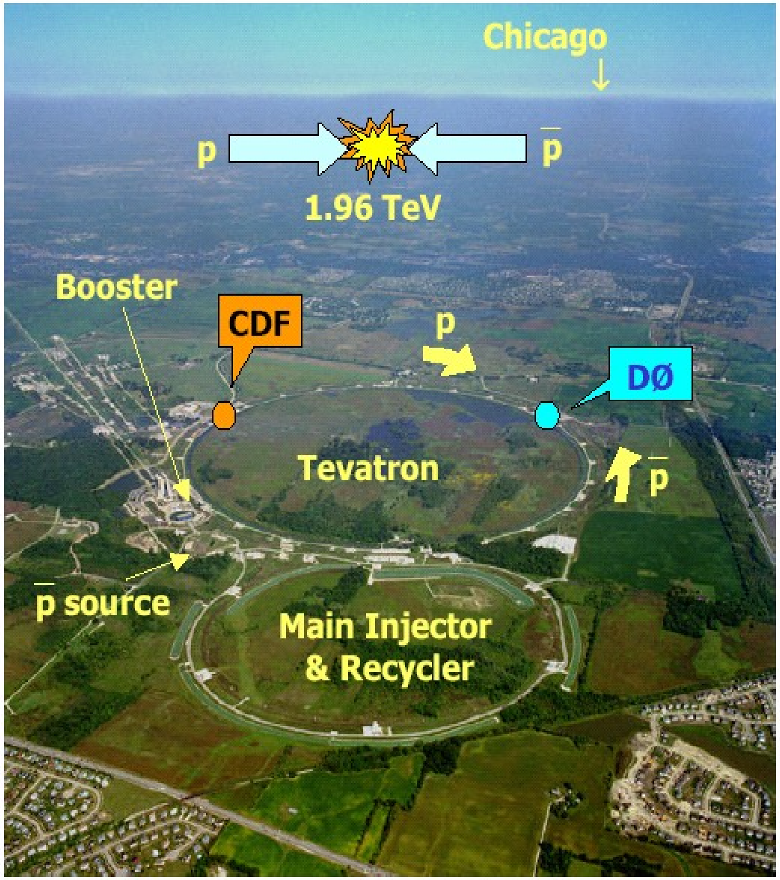
Experimental Challenges



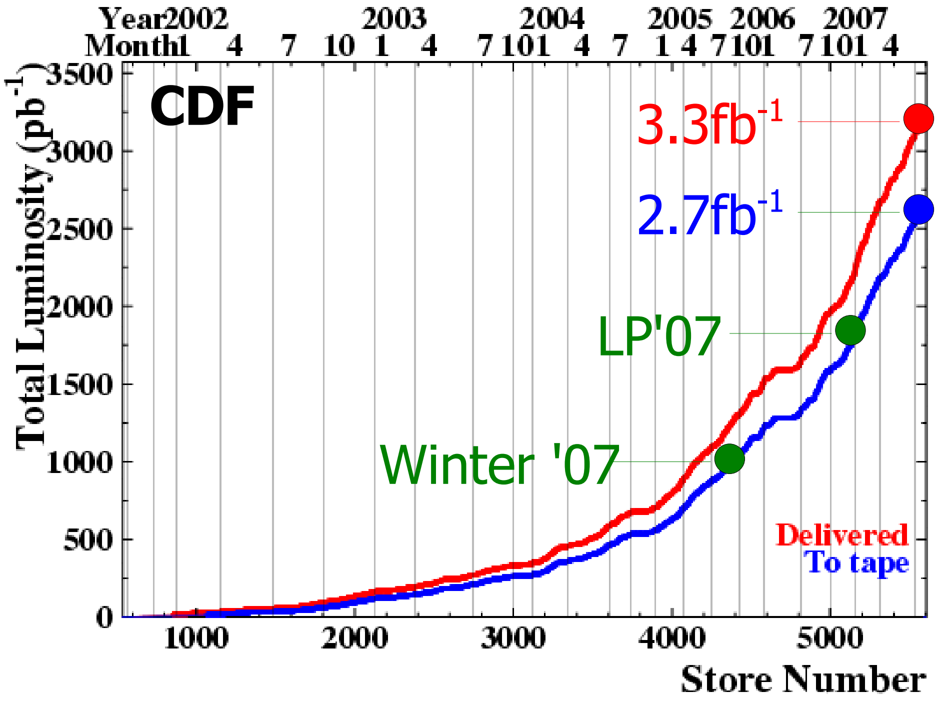
Top Quark Signatures

CDF Detector

Tevatron @ Fermilab

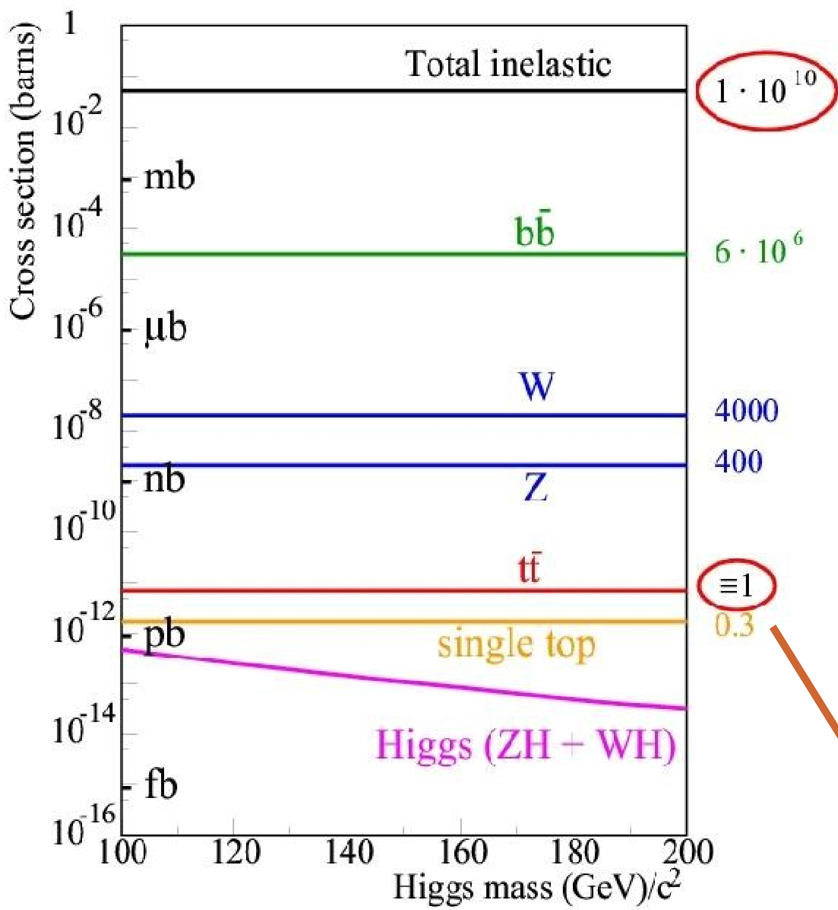


- Run-II (since 2001): proton-antiproton collisions at $\sqrt{s}$=1.96TeV
- Steadily increasing luminosity
  - peak record: $2.86 \times 10^{32} cm^{-2}s^{-1}$
  - on tape: 2.7/fb
  - FY09 estimate: 6-8/fb

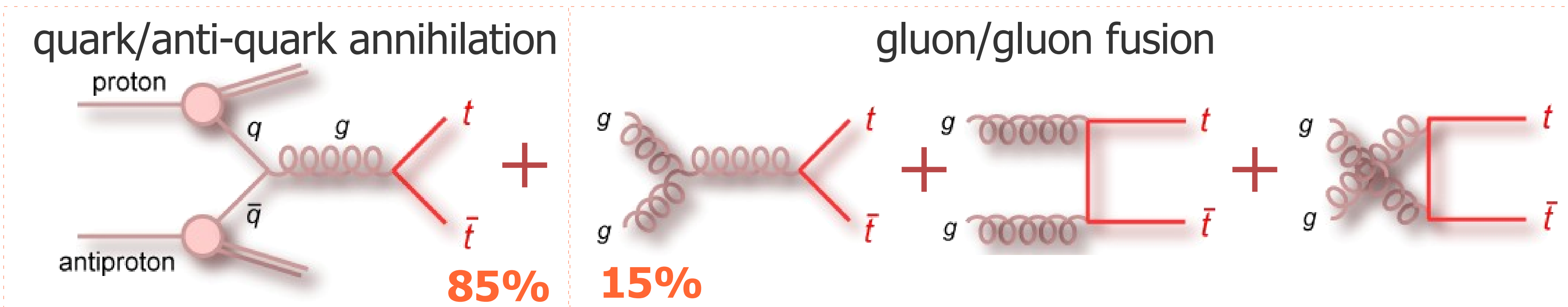


- Currently the only top quark production machine until LHC turns on (2008/9)

Top Quark Production



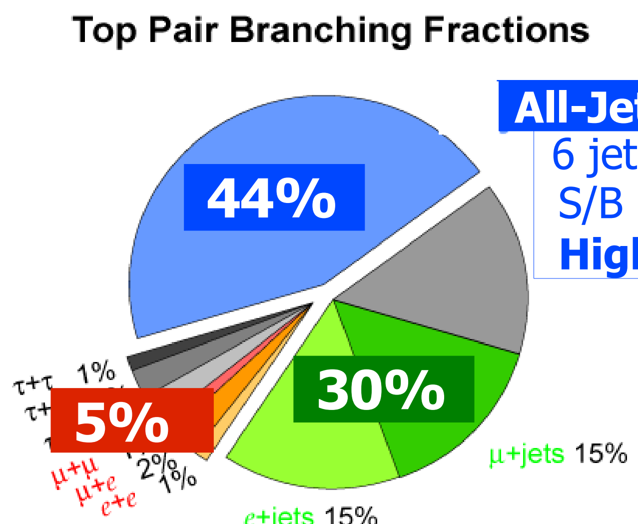
- Top quarks are mainly produced in pairs via quark/antiquark annihilation, and gluon/gluon fusion:
  σ_{tt}(1.96TeV)=6.1pb
- Single top production:
  $\sigma_{t\text{-channel}}$(1.96TeV)=1.98 pb
  $\sigma_{s\text{-channel}}$(1.96TeV)=0.88 pb
  ...ignored in mass analyses
- 1 top quark pair each 10^{10} inelastic collisions ...
  ... a needle in a haystack



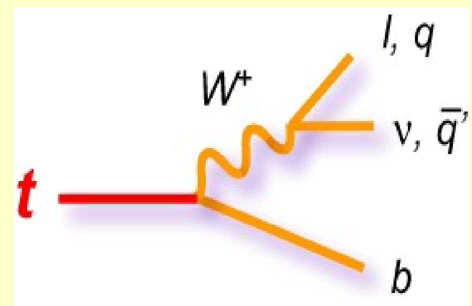
Top Quark Signatures

- SM top quark decays weakly before hadronization
  $\rightarrow$ Can measure its properties directly: Mass, Spin, Charge ...
- BR ($t \rightarrow Wb$)=99.9% (CKM matrix)

- W decay determines experimental signature:



All-Jets
6 jets (2 b)
S/B = 1/23-1/6
High background

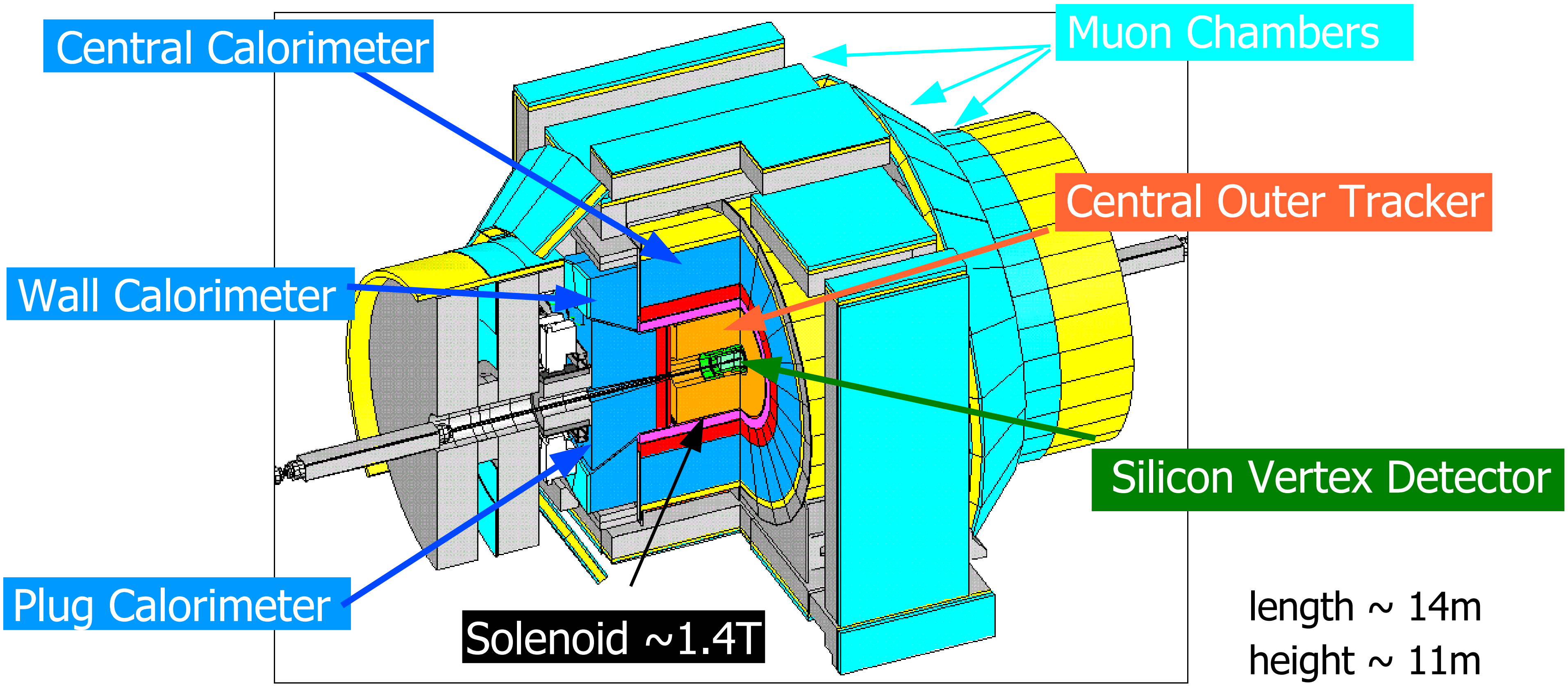


Di-leptons
2 e/μ
2 neutrinos
2 b-jets
S/B = 2-20
Pure samples

Lepton+jets
1 e/μ
1 neutrino
4 jets (2 b)
S/B = 1/2-11/1
Golden Channel

← most precise results obtained in this channel

The CDF Detector



length ~ 14m
height ~ 11m

Hermetic multipurpose design:

- Silicon vertex detector → heavy flavor I.D.
- Tracking system → charged particle momenta/I.D.
- EM and HAD calorimetry → e, γ, jet energies
- Muon system → μ I.D.

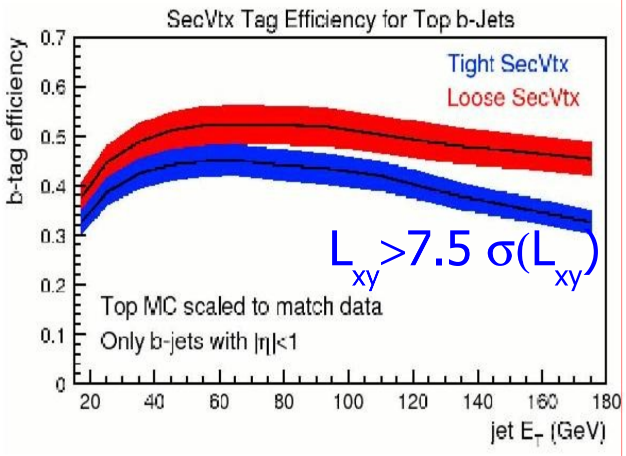
Challenges of Top Quark Physics

Requires full detector capabilities:

- Clean identification of electrons and muons
  → charged leptons from W decay
- Undetected ("missing") energy
  → neutrino reconstruction
- Secondary vertex tagging
  → quark flavor (b or light)
- Calorimeter clusters ("jets")
  → quark reconstruction

...crucial for reduction of background and jet-quark combinatorics

- $t\bar{t}$ tagging efficiency ~ 55%
- $t\bar{t}$ fake rate ~ 0.5 %



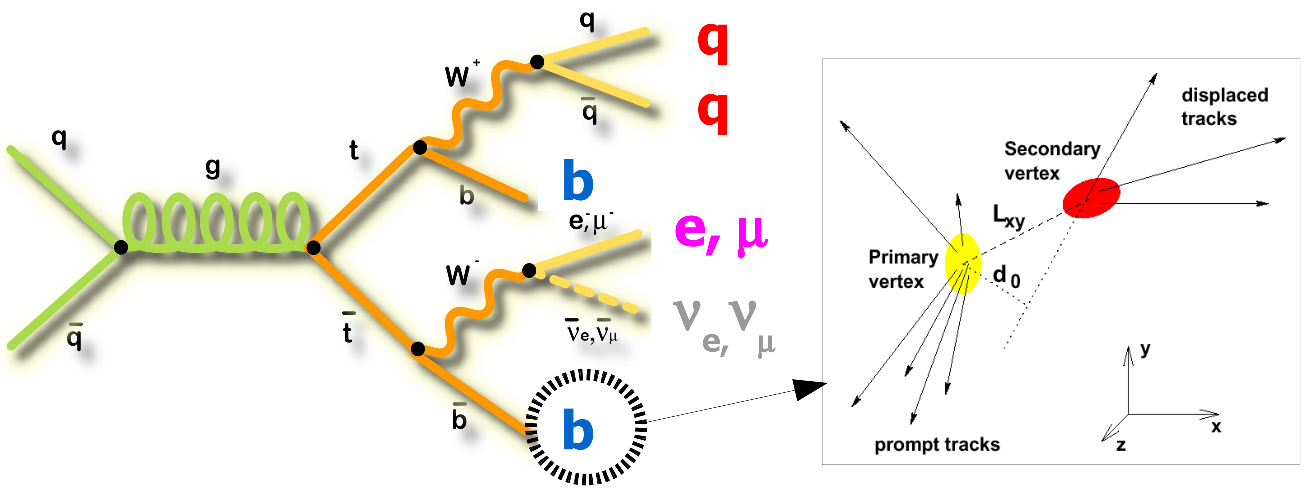
fraction of tagged b jets vs. jet transverse energy

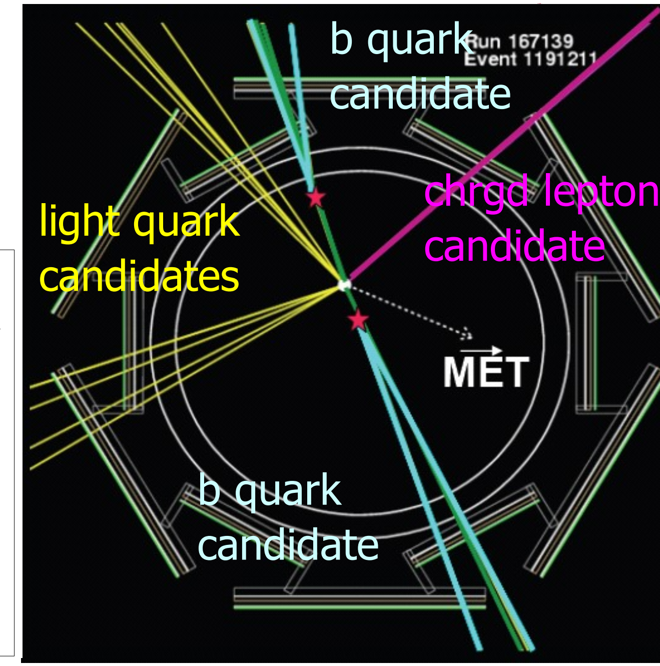
Determination of the jet energy scale (JES)

- Correction of jet energies for detector effects, hadronization, multiple interactions, ...
  → momenta of hadronic top decay products!
- JES currently known at **~3%** level → dominant uncertainty in all top quark mass measurements!

More details in 2^{nd} part of talk

Lepton+Jets Analysis





- Standard analysis cuts in "Multivariate Method":
  - Exactly one central e/μ with p_T >20 GeV, |η|<1.0
  - Exactly four jets with E_T >15 GeV, |η|<2.0
  - Undetected ("missing") energy > 20GeV
  - At least one SecVtx tag

very similar in other to lepton-jets analyses

- Channel is compromise between statistics and purity:
  - BR~30%, S/B=1/4–11/1
- Moderate combinatorial quark/jet ambiguity:
  - 2-12 permutations

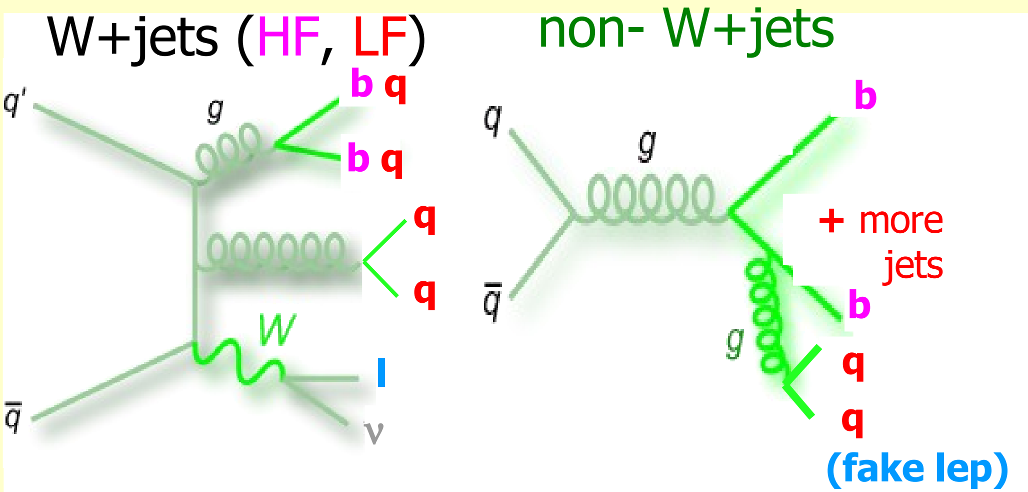
depending on b-tag requirement

- Neutrino momentum partly derived from missing MET
  - two-fold ambiguity

S/B in Multivariate Method

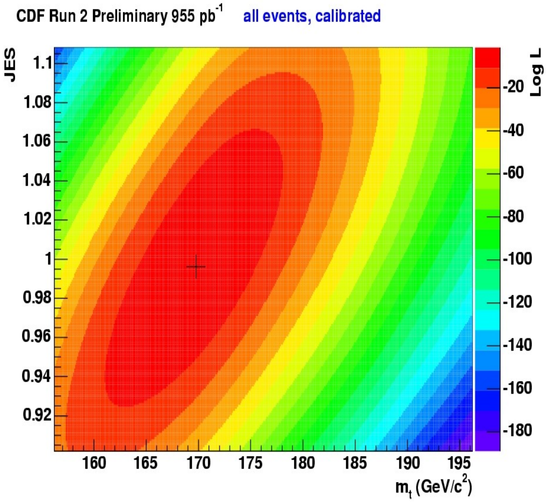
- Found **179** candidate events in **955/pb** of data.
- Background contributions:
  - non-W+jets containing fake leptons ~22% ← Estimated using data with relaxed lepton isolation requirement
  - W+light jets containing mistags ~ 40%
  - W+heavy flavor Wbb, Wcc, Wc ~ 33%
  - Di-Boson WW, ZZ, WZ (small contribution)
  - Single top (small contribution)

  } Estimated using MC



	955 pb^{-1}, 4 jets	
Background	1 tag	2 tags
non-W QCD	5.5±1.1	0.13±0.07
W+light (mistag)	9.5±1.6	0.65±0.32
$W + b\bar{b}$	4.3±1.6	0.90±0.25
$W + c\bar{c}$, $W + c$	2.9±1.0	0.13±0.07
Single top	0.6±0.1	<0.1
Di-boson (WW, WZ, ZZ)	1.4±0.3	0.07±0.02
Total Background	24.1±3.4	1.88±0.48
Events observed	132	47

Improving Measurements (I)



Analysis Techniques

Multivariate Method

Measurement Strategies (1)

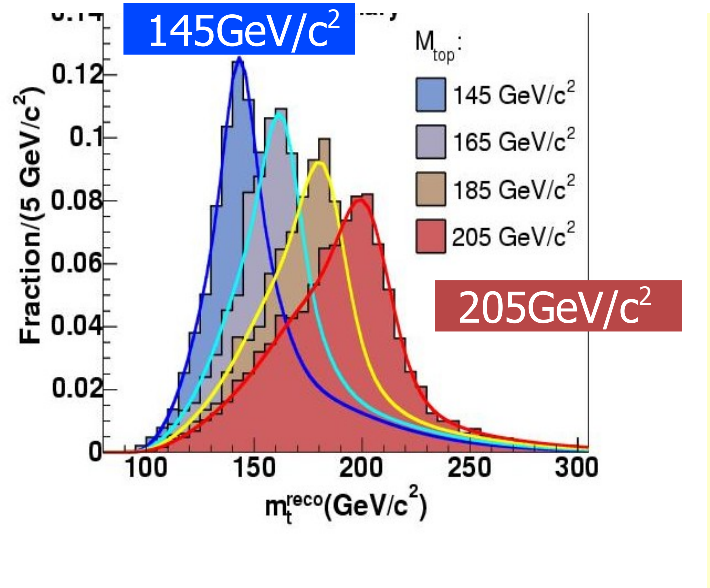
Template Method (TM):

- Classical Run-I strategy
- Calculate <u>one observable</u> per event correlated with M_{top}.
- Compare simulated distributions for signal+ background with varying M_{top} with data to obtain M_{top}.

\+ computationally simple

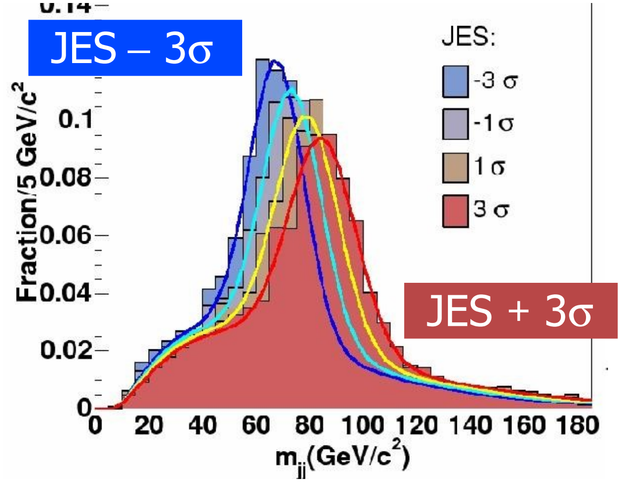
– limited kinematic information, just <u>one number</u> per event

Example: "reconstructed" top mass



- Important extensions developed in Run-II, e.g. use of a 2nd variable for JES calibration.

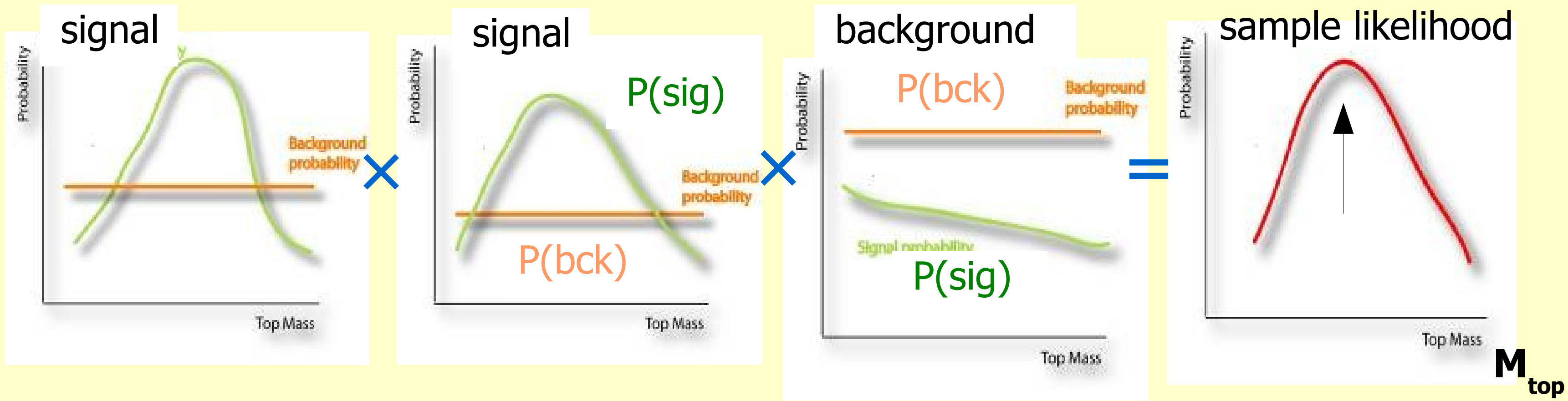
Example: "reconstructed" W mass



Measurement Strategies (2)

Matrix Element Method (ME):

- Calculate a per-event probability density curve (from matrix element calculations) for signal and background as function of M_{top}.
- Multiply probabilities to extract most likely M_{top} for the whole data sample.



\+ per-event probability curve enhances statistical power

– extremely CPU intensive numerical integrations

- ME Method extended using 2-dimensional likelihoods (M_{top}, JES)
- Additional event weighting using S/B discriminants, b-tagging information etc.

Multivariate Method Basics

Event-by-event probability density

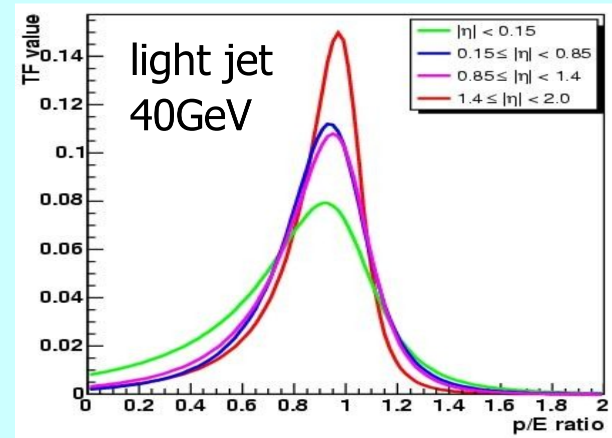
detector level observables | jet-quark combinations | proton-parton density functions | transfer functions

$$\mathcal{P}_{t\bar{t}}(\mathbf{y}|m_t,\mathrm{JES}) \propto \sum_{i=1}^{N\mathrm{perm}} w_i \int d\Phi_6(\mathbf{x})\, f_{\mathrm{pdf}}(q_1)\, f_{\mathrm{pdf}}(q_2) \times |M_{\mathrm{eff}}(m_t,\mathbf{x})|^2 \times W(\mathbf{y}|\mathbf{x},\mathrm{JES})$$

b-tag weight | phase space | leading order signal matrix element

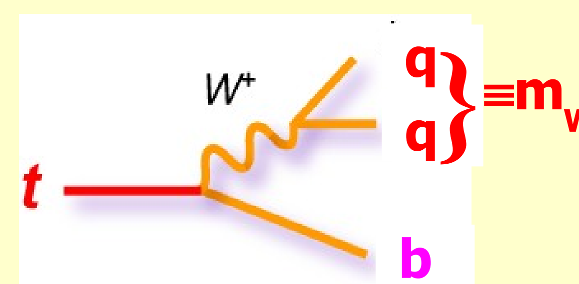
Transfer Functions

- Probabilities for a set of detector variables y to be measured given parton configuration x and JES.
- Smooth function of p(jet)/E(parton), dependent on quark flavor and jet η



In-Situ JES Calibration

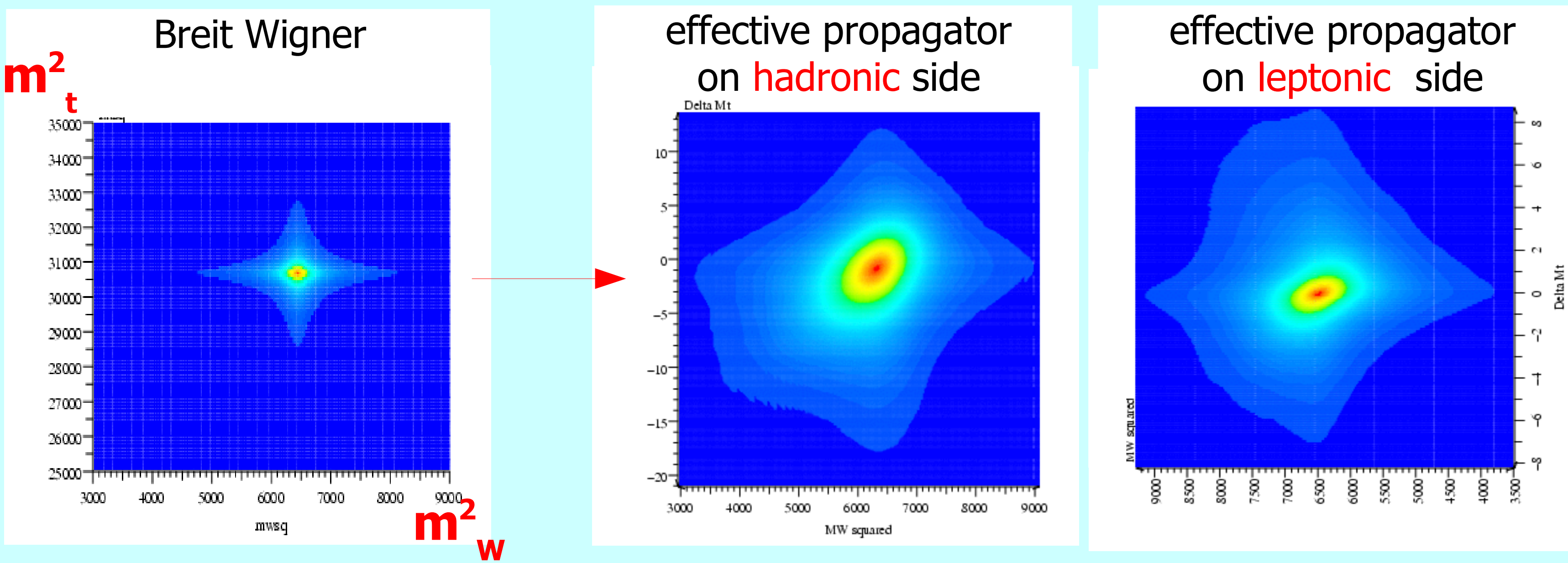
- JES hypothesis giving W mass inconsistent with world average value/width penalizes the event probability.
  $\rightarrow$ Part of ΔJES becomes statistical component of Δm_t and scales down with integrated luminosity!



Integration

- Integration over full phase space in 22 dimensions intractable, make simplifying assumptions:
  - quark angles / charged lepton momentum are perfectly measured
  - quark / charged lepton / neutrino masses are known
- Seven integration variables remaining:
  m^2_W(had), m^2_t(had) , m^2_W(lep), m^2_t(lep) , $\log(p_1/p_2)$ (light quarks), $p_x(t\bar{t})$, $p_y(t\bar{t})$

- Effective propagators are used when integrating over mass variables
  → corrects for mismatch between ME, MC and integration assumptions



Matrix Elements & Background Fraction

- Signal matrix elements: R. Kleiss and W.J. Stirling, Z.Phys. C40 (1988) 419
  - contains both qq→tt and gg→tt tree level amplitudes
  - include effects of finite width of the W, top quark
  - consider non-zero b-quark masses
  - includes complete spin correlations between top production and decay
- More consistent approach given the assumptions made in the effective propagators and transfer functions (both derived from MC)

Multivariate aspect

- Background fraction estimated from Monte Carlo
- Signal probability is weighted using a specially designed S/B discriminant.
- Requirements for the second variable
  - minimum top quark mass dependence
  - minimum JES dependence
  - maximum S/B discrimination

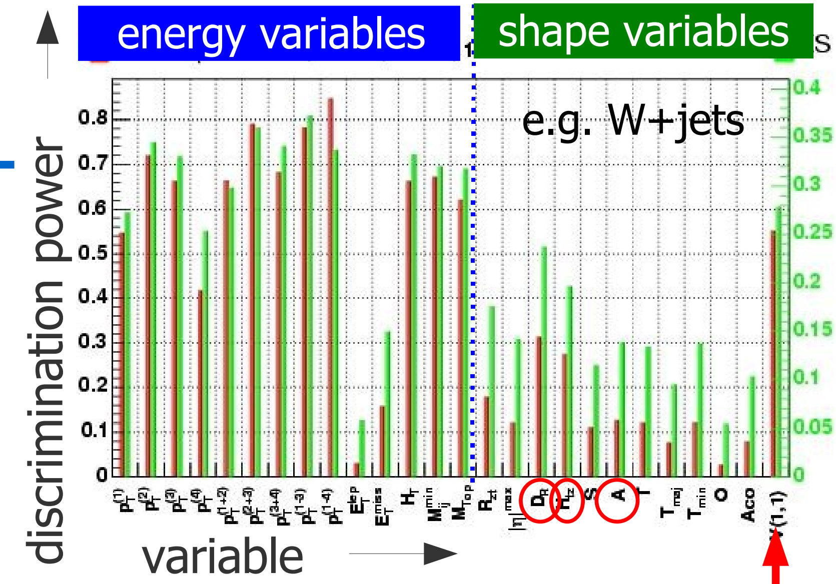
  } essential to allow multiplication of per-event likelihoods (applies to the first two requirements)

... difficult to fulfill all simultaneously

S/B Discriminant

Many candidates to choose from:

- **Energy variables** (e.g. jet transverse energy sum) higher S/B discrimination but also largely correlated with m_t/JES
- **Shape variables** (e.g. aplanarity) lower S/B but smaller m_t/JES dependence



- Linear combination of variables
  $\rightarrow$ m_t / JES systematics mutually cancel

$$A = 1.5 Q_1 \quad \text{(aplanarity)}$$

$$Q_1 < Q_2 < Q_3 \ \text{ EV of } T_{\alpha\beta} = \sum_i p_\alpha^{(i)} p_\beta^{(i)} / (p^{(i)})^2$$

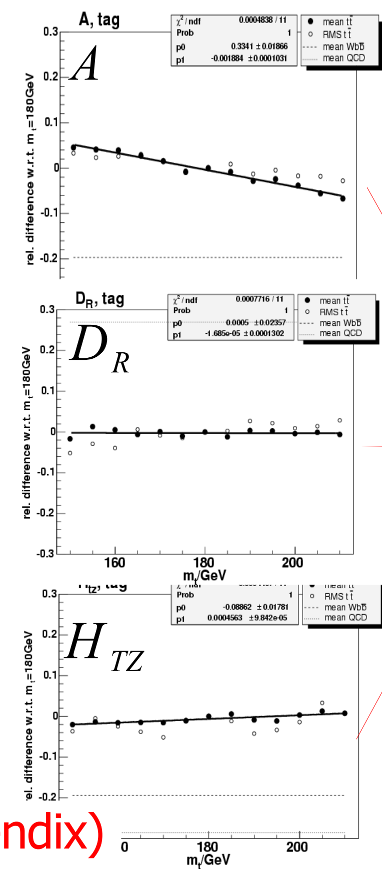
$$D_R = \min(\Delta R_{ij}) \times p_T^{(\min)} / E_T^{\text{lep}}$$

$p_T^{(\min)}$: smaller p_T of the min. separation pair

$$H_{TZ} = \sum_{i=2..4} p_T^{(i)} / \left(\sum_{i=1..4} |p_z^{(i)}| + |p_z^{(\text{lep})}| + |p_z^{(\nu)}| \right)$$

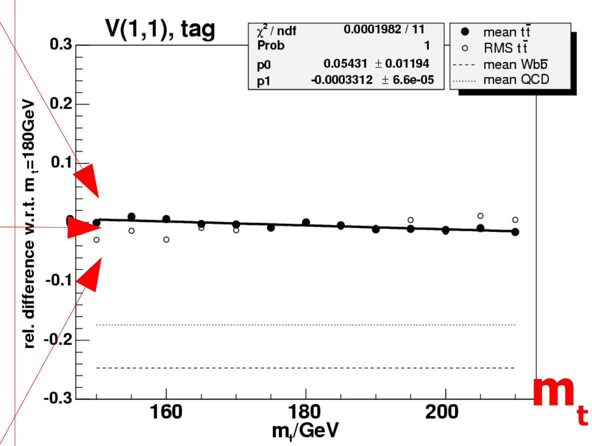
$|p_z^{(\nu)}|$: smallest of neutrino $|p_z|$ solutions

$$V = \left(\hat{c}_1 A + \hat{c}_2 D_R + \hat{c}_3 H_{TZ} \right) \times N$$



Hybrid variable

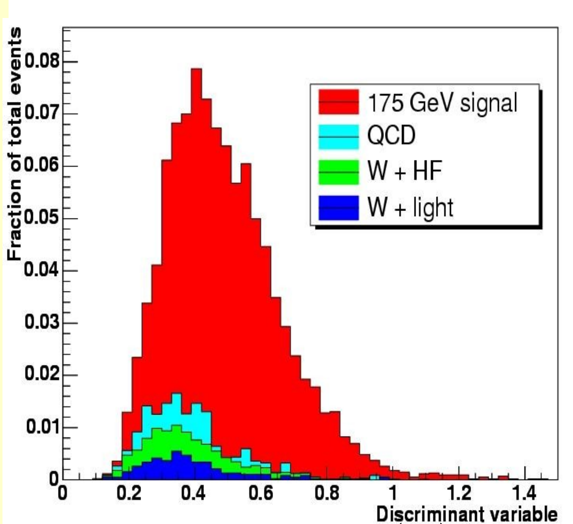
rel. change mean&r.m.s.



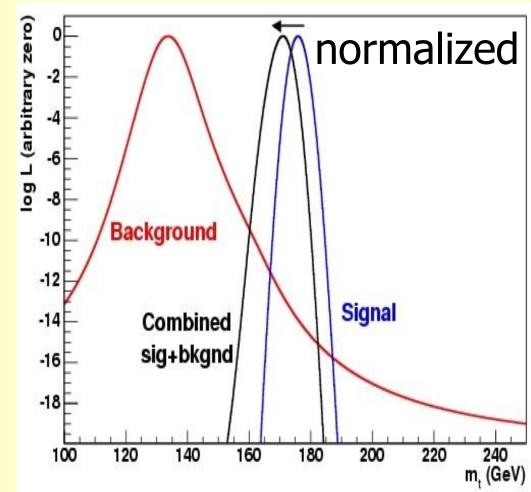
default $(c_1,c_2)=(1,1)$

...systematic fine tuning of coefficients (appendix)

Background Treatment



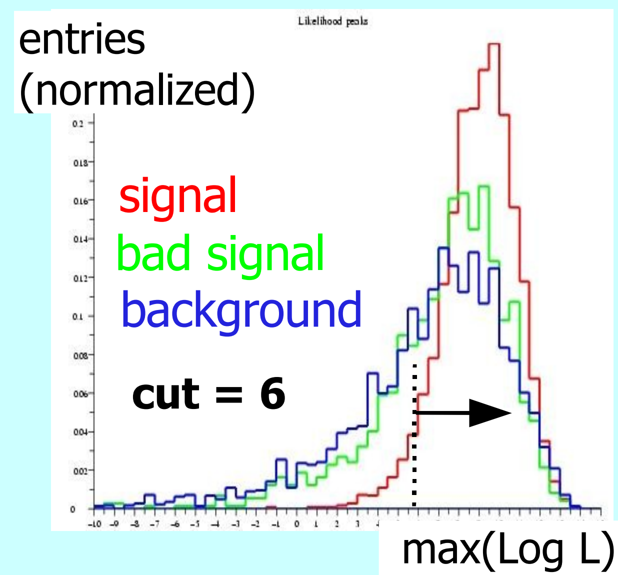
- Adding background shifts signal likelihood curve
- Subtract average log background weighted by background probability



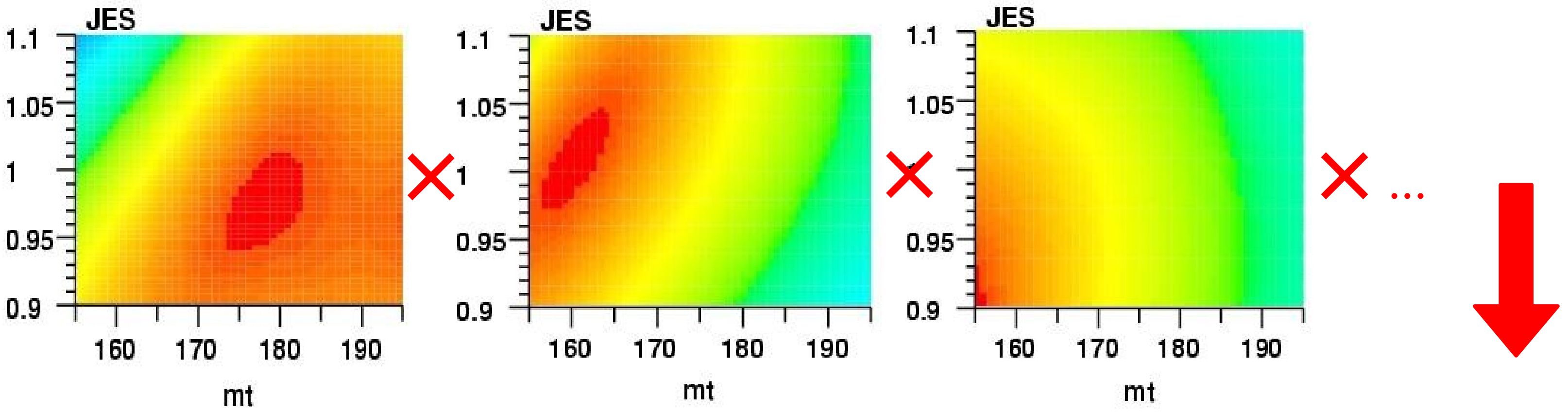
$$f_{bg}(q) = \frac{B(q)}{B(q)+S(q)} \longrightarrow \log(L_{tot}) = \sum_i \log L_{sig,i} - f_{bg}(q_i) \langle L_{bg} \rangle$$

- Additional likelihood cut applied to clean up background and bad signal (ISR/FSR,W→τν…)
- Improves bias and resolution
- Number of candidates: 179 → 149

Type of event	1-tag	>1-tag
Good signal	94.7%	94.1%
Bad signal	73.7%	80.2%
Background	63.1%	57.5%



Extracting the Top Quark Mass



- Build the total 2-dim. likelihood and extract the profile likelihood:

$$L_{\text{prof}}(m_t) = \max_{\text{JES}}\{L_{\text{tot}}(m_t, \text{JES})\}$$

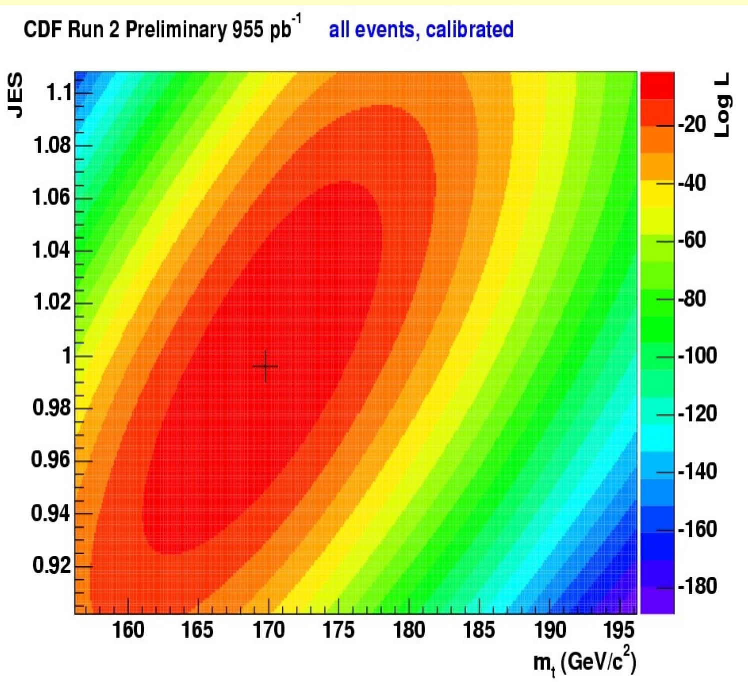
- Peak of 1-dim. profile likelihood gives most probable sample top quark mass

$$L_{\text{prof}}(\hat{m}_t) = \max_{m_t} L_{\text{prof}}(m_t)$$

- Statistical uncertainty is $\sigma = ½(\sigma_+ + \sigma_-)$

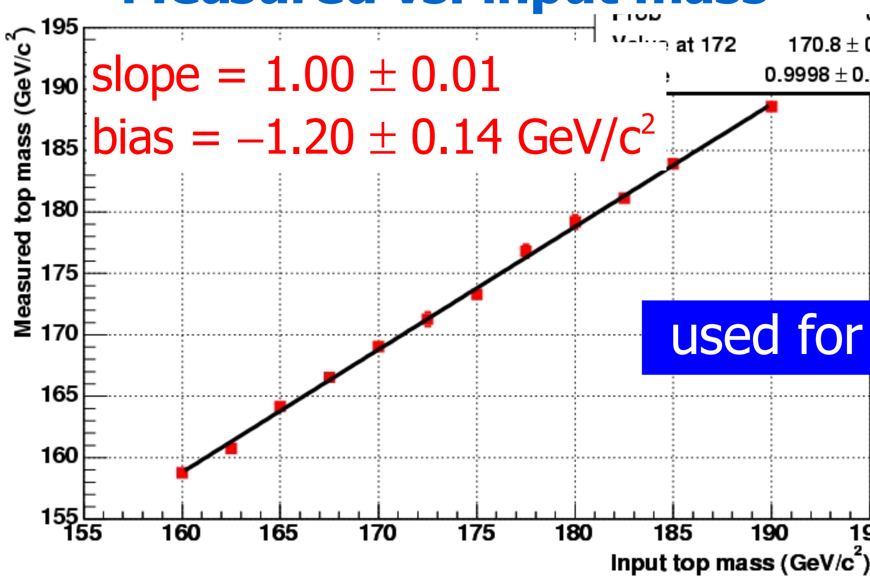
$$L_{\text{prof}}(\hat{m}_t + \sigma_+) = L_{\text{prof}}(\hat{m}_t - \sigma_-) = e^{1/2} L_{\text{prof}}(\hat{m}_t)$$

- Correct mass and uncertainty value using calibration obtained from pseudo-experiments

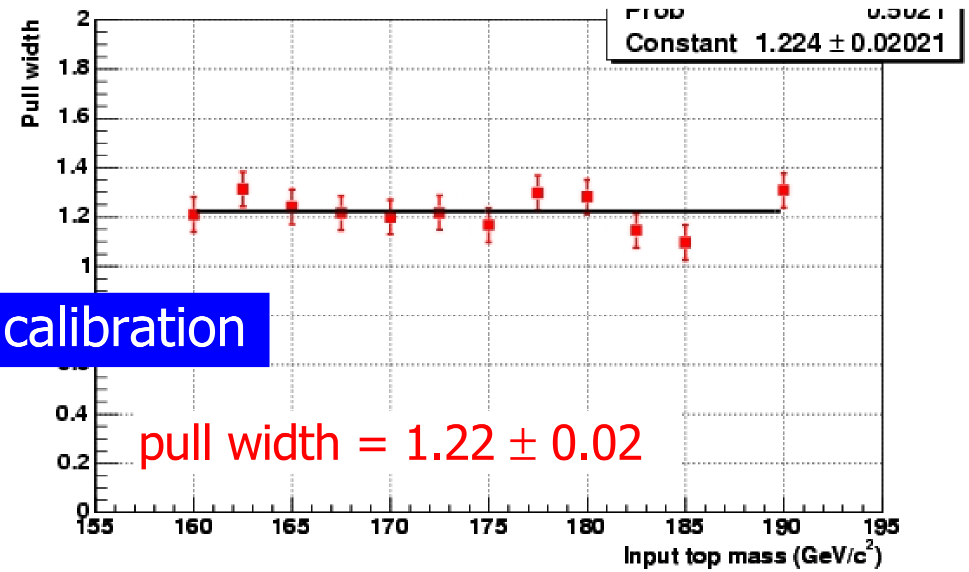


Calibration & Checks

Measured vs. input mass

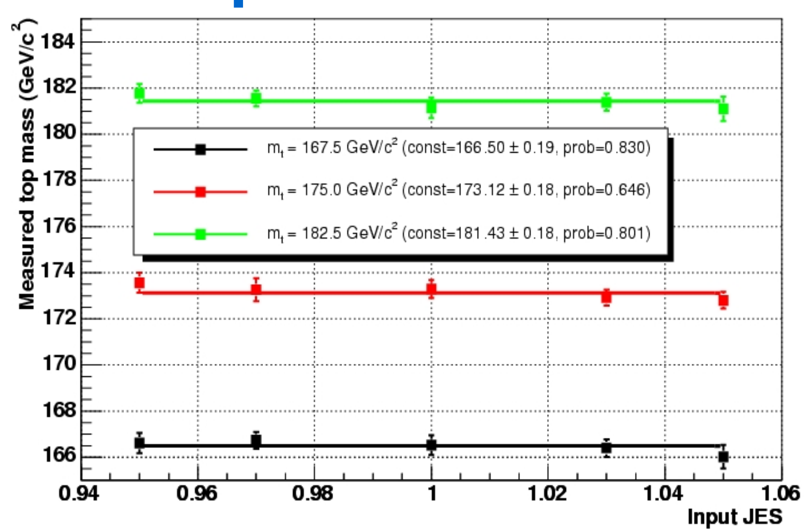


Pull Widths



used for calibration

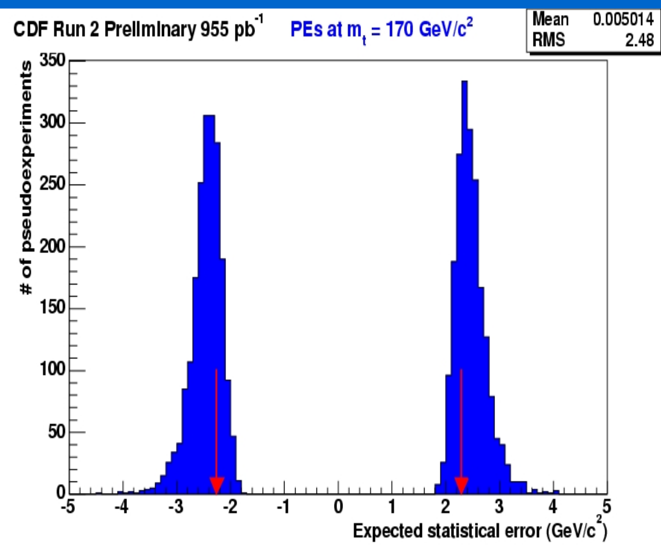
Input JES Variation



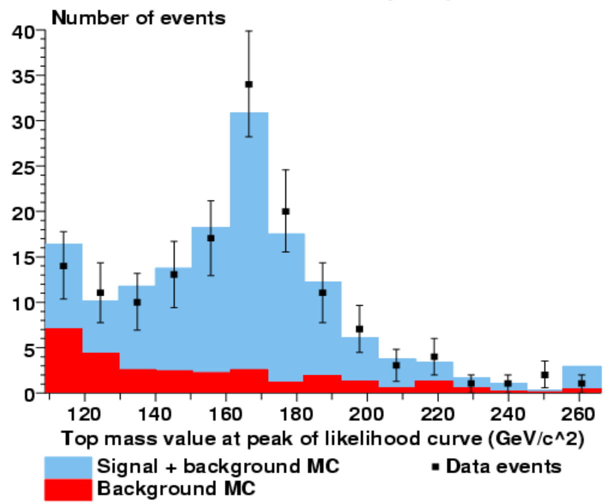
- Calibration corrects for simplifying assumptions
- Measured top quark mass very stable under ±5% variation of input JES

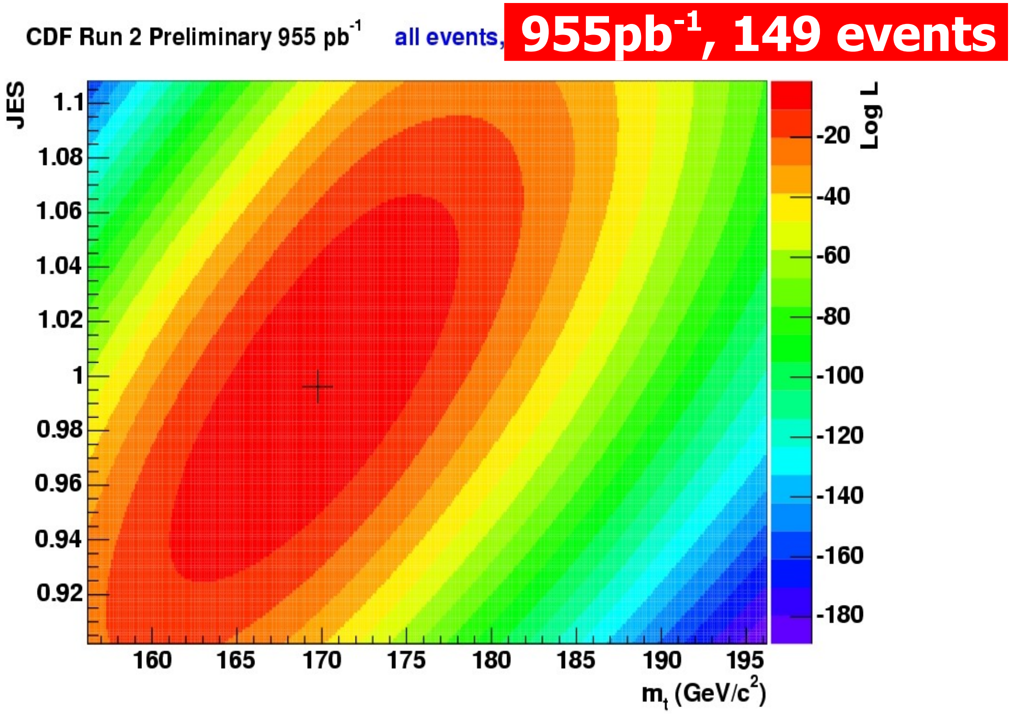
Numerical Result

expected vs. measured statistical error



peak likelihood mass data vs. MC





$$M_{top} = 169.8 \pm 2.3\,(\text{stat.} + \text{JES}) \pm 1.4\,(\text{syst.})\ \text{GeV/c}^2$$

$$M_{top} = 169.8 \pm 2.7\,(\text{tot.})\ \text{GeV/c}^2$$

$$\text{JES} = 0.996 \pm 0.018\,(\text{stat.})$$

- Only 0.1 GeV/c^2 less precise than world's single best 1fb^{-1} measurement (Winter '07, used in current world average)!

Uncertainties

Systematic source	Systematic uncertainty (GeV)
Residual JES	0.28
PDFs	0.46
ISR	0.75 ± 0.36
FSR	0.67 ± 0.40
MC generator	0.44 ± 0.43
Gluon fraction	0.05
Background: fraction	0.20
Background: composition	0.39
Background: average shape	0.29
Background: Q^2	0.30
Calibration	0.14
b-JES	0.23
b-tag E_T dependence	0.02
Permutation weighting	0.06
Multiple interactions	0.05
Lepton P_T	0.05
Total	1.39

- Total systematic:
  ΔM_{top}(syst.) = 1.4 GeV/c^2
- Largest contribution from modeling of the initial and final state gluon radiation:
  ΔM_{top}(ISR+FSR) = 1.0 GeV/c^2
- Statistical component:
  ΔM_{top}(stat.+JES)
  = 2.3 GeV/c^2
  = 1.6(stat.) + 1.7(JES) GeV/c^2.
- Residual JES uncertainty:
  $\Delta M_{top}(JES_{res})$ = 0.3 GeV/c^2.

  (η/p_t dependence of jet corrections)

Future Improvements

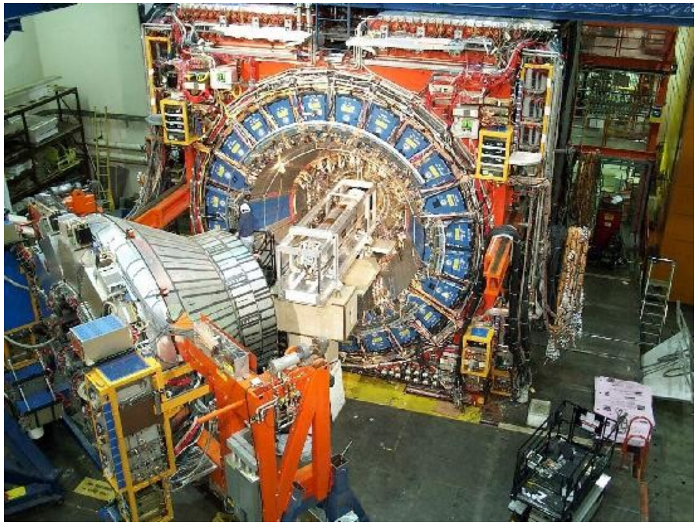
- Major problem is the presence bad signal:
  - wrong jet-to-parton assignment
  - ISR/FSR jets among the four leading jets: contamination is highest in least energetic jet

hurts resolution, causes bias, causes pull widths $\neq 1$

- Possible remedy:
  - consider also a signal probability which ignores 4^{th} leading jet
  - introduce a bad signal discriminant (ANN)

- Get rid of simplifying integration assumptions and effective propagators:
  - Requires expansion of integration phase space (up to 19 dimensions)
- Improve background discrimination:
  - ANN discriminant with no top quark mass and JES dependence?
- Introduce a-priori JES constraint

Improving Measurements (II)

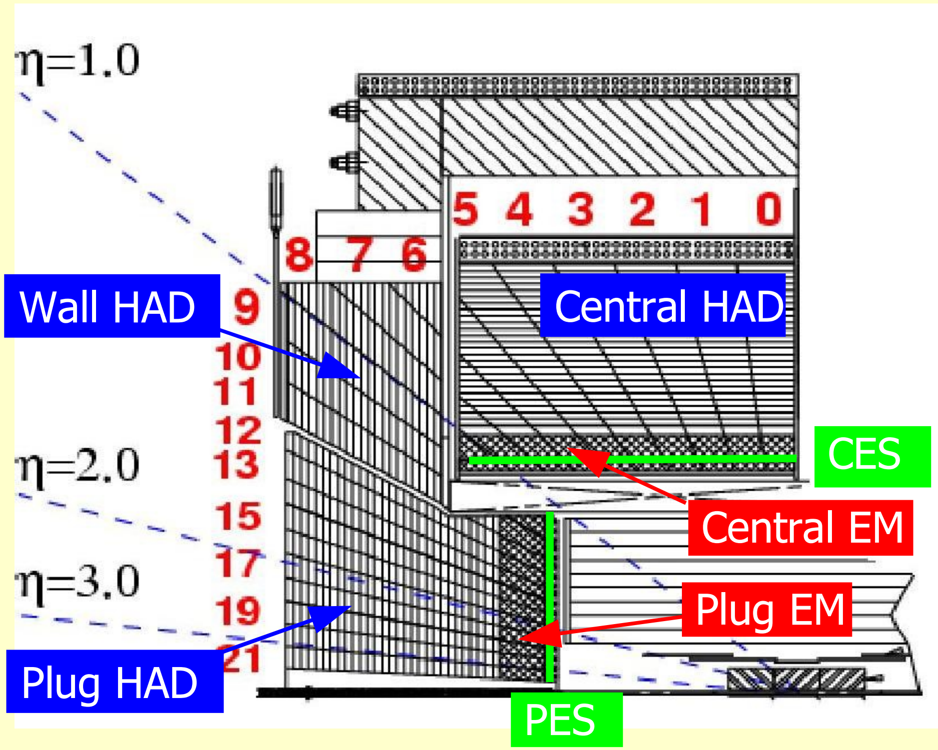


Calorimeter Simulation

Jet Energy Scale

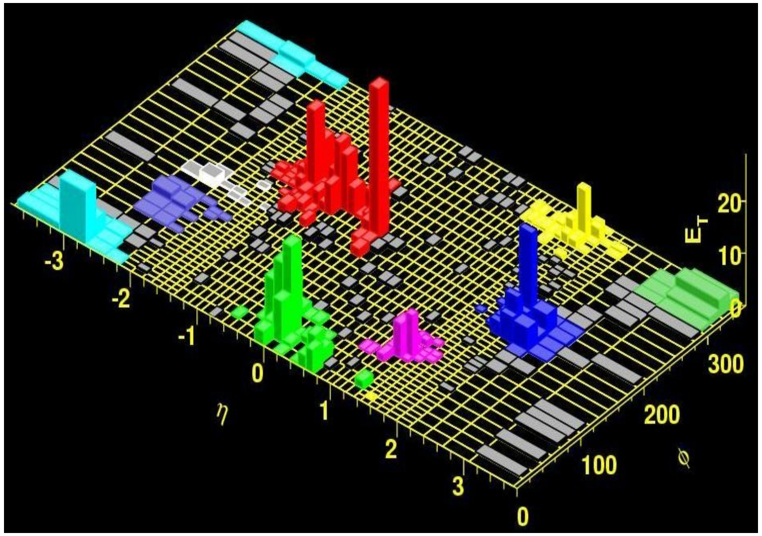
The CDF Calorimeter

- Sampling calorimeter:
  - scintillating tiles
  - lead/iron absorbers
  - projective tower geometry
- Partition in Central/Plug/Wall:
  - Blind zones between Wall/Plug (“Crack”)
  - Instrum. between towers (“Phi-Cracks”)
- Pseudorapidity coverage: $|\eta| < 3.6$
- Granularity: 24(48) wedges/ring
- Pre-shower & shower maximum detectors



		Central	Plug
EM	thickness	$19\,X_0$, 1λ	$21\,X_0$, 1λ
	sample(Pb)	$0.6\,X_0$	$0.8\,X_0$
	sample(scint.)	5 mm	4.5 mm
	resolution	$\frac{13.5\%}{\sqrt{E}} \oplus 2\%$	$\frac{14.5\%}{\sqrt{E}} \oplus 1\%$
HAD	thickness	$4.5\,\lambda$	$7\,\lambda$
	sample(Fe)	25-50 mm	50 mm
	sample(scint.)	10 mm	6 mm
	resolution	$\frac{50\%}{\sqrt{E}} \oplus 3\%$	$\frac{70\%}{\sqrt{E}} \oplus 4\%$

Determination of the Jet Energy Scale

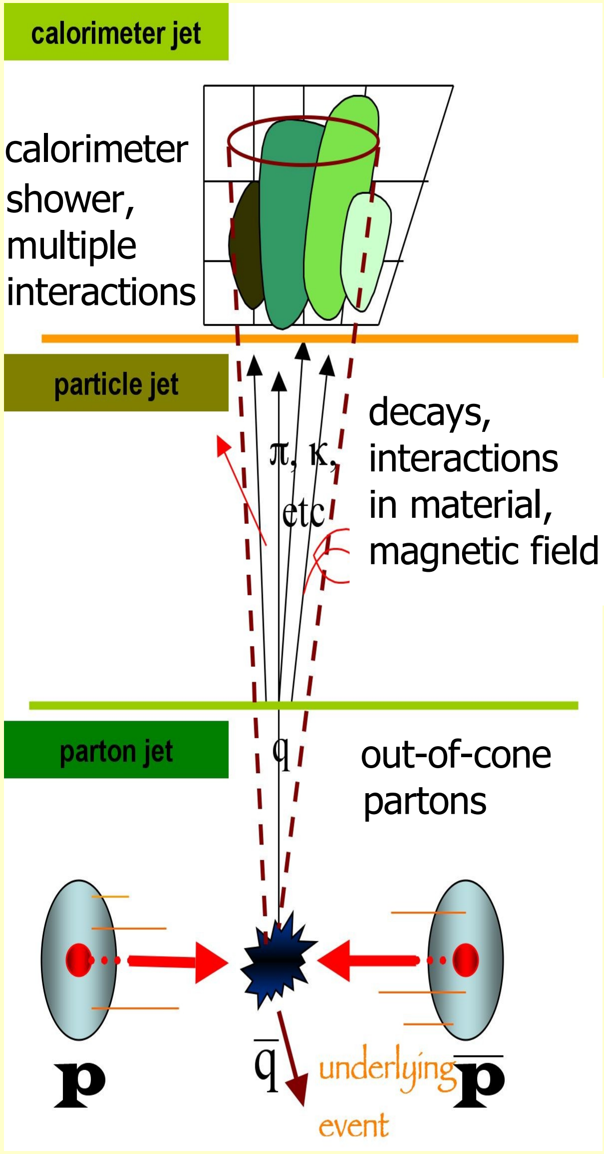


A very complex task involving

- Jet clustering:

$$R=\sqrt{(\eta-\eta_{jet})^2+(\phi-\phi_{jet})^2}$$

- Multistep correction based on data and MC
- Tuning of the calorimeter simulation and of physics models



Detector effects:

- particle losses due to passive material
- non-linear energy response
- threshold effects, noise
- uninstrumented regions
- sampling fluctuations

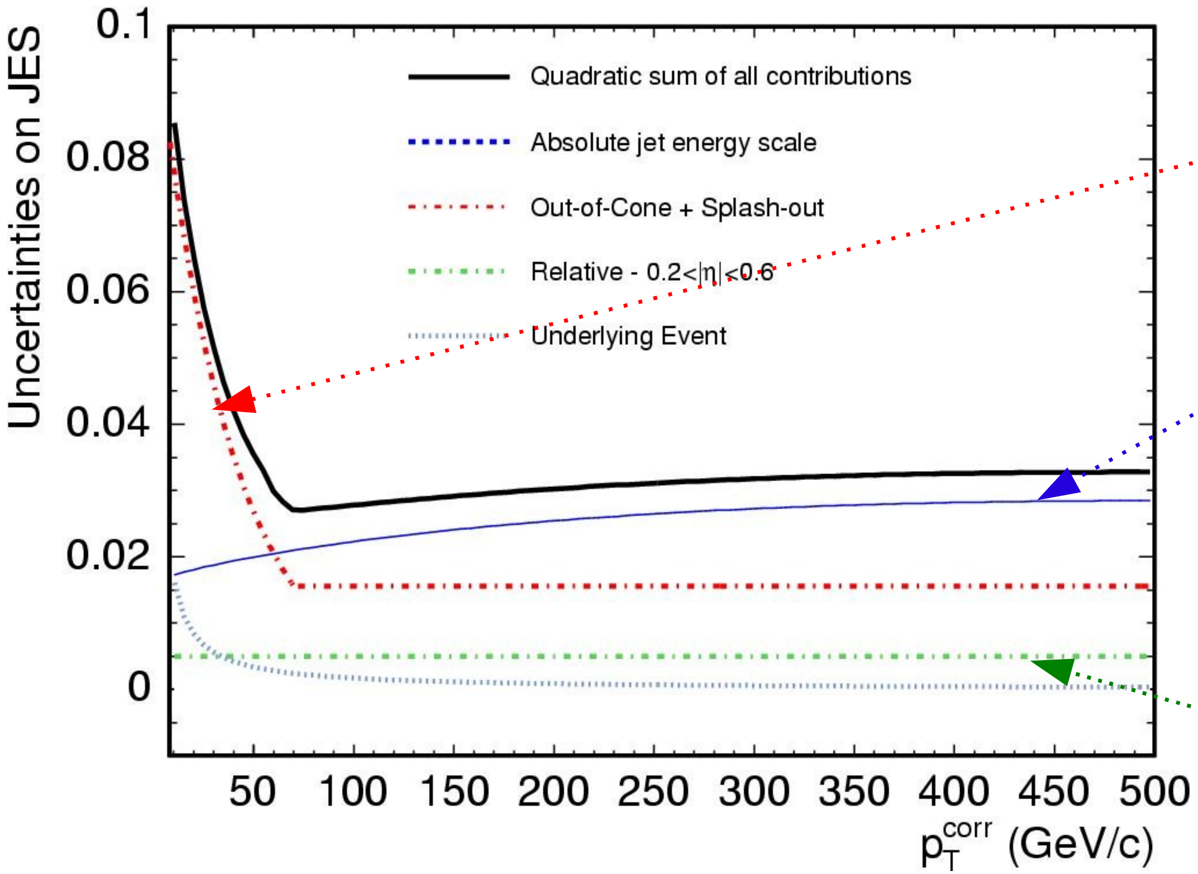
Jet algorithm effects:

- energy threshold
- out-of-cone losses

Physics effects:

- hadronization
- multiple interactions
- spectator partons
- initial and final state gluon radiation
- flavor of parent parton

Total JES Uncertainty



Out-of-Cone correction
- MC/data mismatch of energy flow outside the jet cone
- direct contribution from lateral E/p shower profile

Absolute correction
- contribution from absolute E/p response simulation

Relative Correction
- contribution from imperfection of Plug/Wall simulation

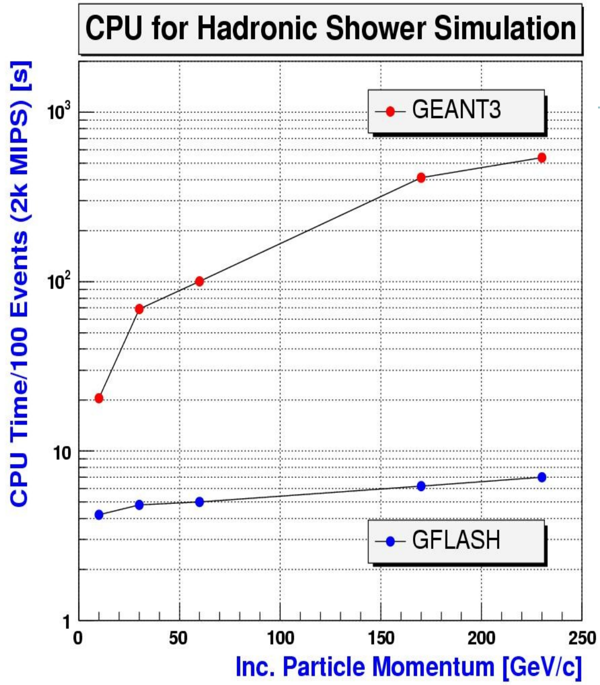
- Above plot reflects simulation performance of CDF-II publications (excluding recent improvements)
- Calorimeter simulation uncertainties are the dominant source of uncertainty (specially if no JES in-situ calibration possible).

CDF Calorimeter Simulation

CDF Run II simulation is based on GEANT3

- Encodes detector geometry/material composition
- Propagates particle from interaction point through detector volume up to the first inelastic interaction

control is passed to ...



CPU time increases with E:

GEANT ∝ E

GFLASH ∝ log(E)

GFLASH G.Grindhammer, M.Rudowicz and S. Peters, NIM A290 (1990) 469

- Fast simulation of electromagnetic and hadronic showers (developed by H1 Coll.)
  - in CDF up to 100 times faster than detailed G3 shower
  - ideal for simple geometry with repetitive sampling structure
  - very robust and flexible (tunable)
- Generates sophisticated longitudinal and lateral shower profiles
- Distributes energy spots according to profiles and sampling fluctuations

GFLASH in a Nutshell

- GFLASH treats calorimeter as a single effective medium.
- EM and HAD responses are related to MIP response

Sampling structure/spatial energy distribution:

$$d\,E_{vis}(\mathbf{r}) = E_{inc}\,\hat{m}\sum_{\hat{k}} \frac{\hat{k}}{\hat{m}}\, c_{\hat{k}}\, f_{\hat{k}}(\mathbf{r})\, d\,\mathbf{r}$$

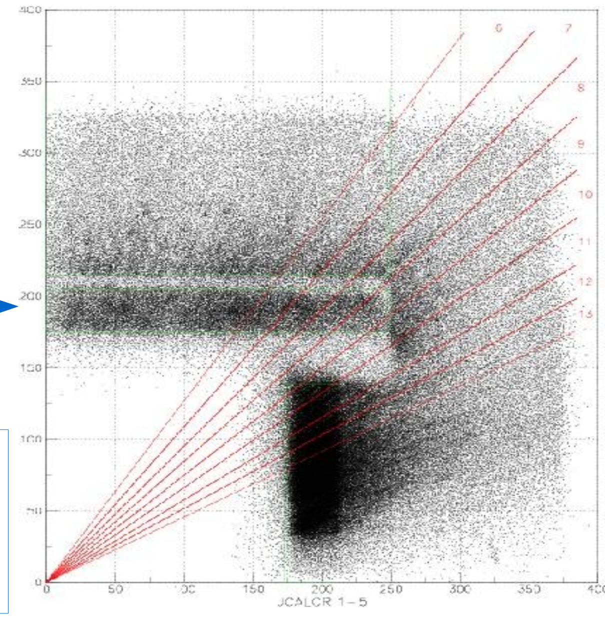
$\hat{k} = EM, HAD$

- $\hat{m}$: MIP response
- $\hat{k}/\hat{m}$: response relative to MIP
- $c_{\hat{k}}$: relative fraction EM/HAD

Profile:

$$f(\mathbf{r}) \propto L(z)\, T(r, z)$$

$L(z)$: longitudinal; $T(r,z)$: lateral



longitudinal profile: interval step energy $E_{inc} \int L(z)\, dz$ → smear # of energy spots → lateral profile: distribute spots according to T(r,z) → integrate spots → sampling fractions: $\hat{m}, \frac{\hat{k}}{\hat{m}}$

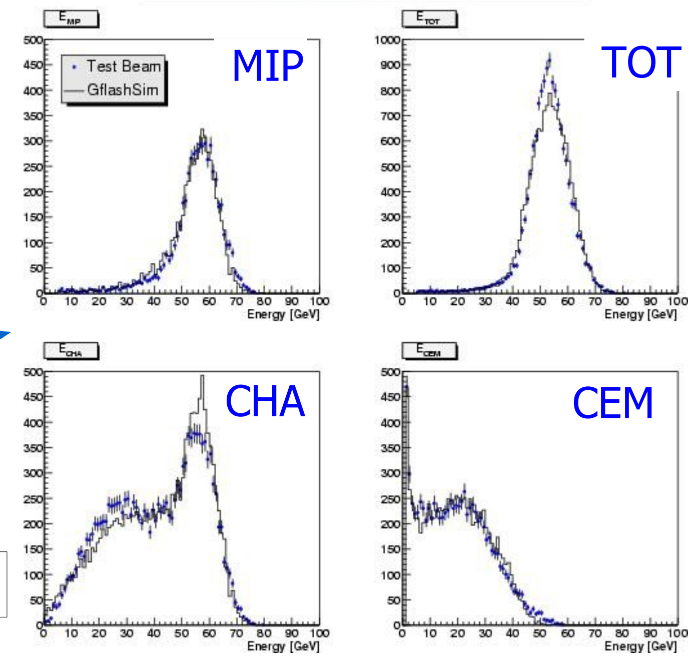
incident energy → sampling fluctuations resolution effects → deposited energy → visible energy

Tuning Overview (Hadronic Only)

Test beam data

...used to fix many longitudinal shower details:

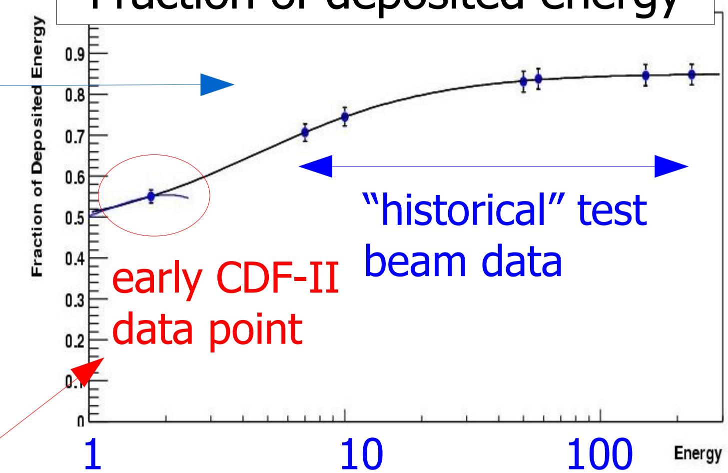
- **"MIP peak":**
  Response of minimum ionizing particles in EM
- **Hadronic energy scale:**
  Shape of the EM and HAD response,
  TOT=EM+HAD, MIP=HAD (EM<670MeV)



57 GeV pion test beam

In-situ Run-II data (plus test beam data)

- **Energy dependence:**
  Interpolate energy dependence of parameters using ⟨E/p⟩ response in EM and HAD
- **Lateral profile:**
  Adjust ⟨E/p⟩ profile in EM and HAD

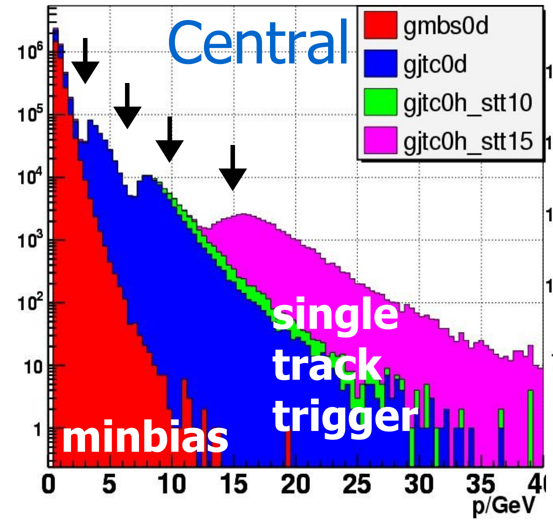


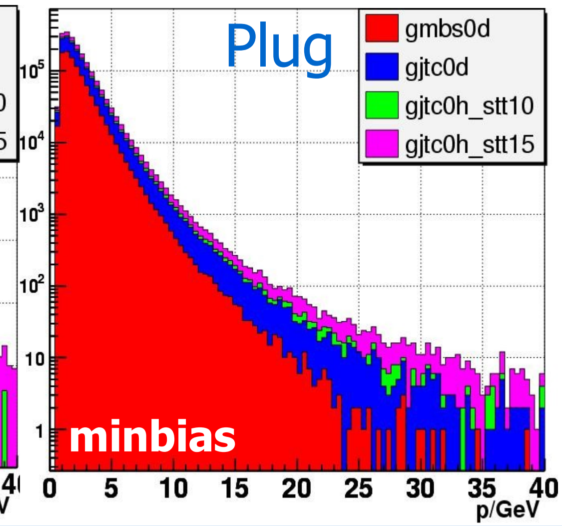
- Early Run-II: Poor in-situ control up to 2.5 (5) GeV

In Situ Tuning Approach

Run-II improvements

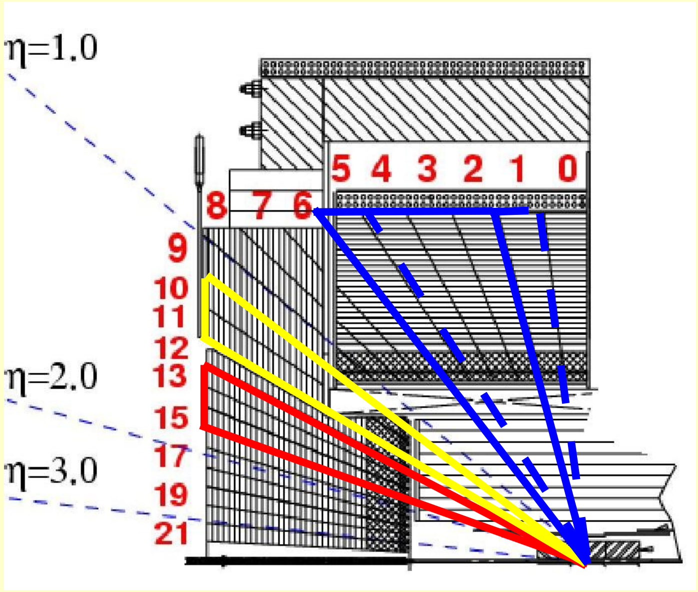
- Single track triggers with thresholds up to 15 GeV/c.
- Single charged particle response analysis.
- In-situ tuning extended up to 40(20) GeV/c in Central (Plug)





Tuning Basics

- Performed separately for Central/Crack/Plug
- Flavor-mixed particle gun | background model | detector simulation
- High quality tracks | η range limited by availability of COT tracks



Lateral profiles (to do first)	EM | HAD
Fractional energy deposits Relative sampling fractions	TOT MIP

Lateral Profile

$$T(r) = \frac{2 r R_0^2}{(r^2 + R_0^2)^2}$$

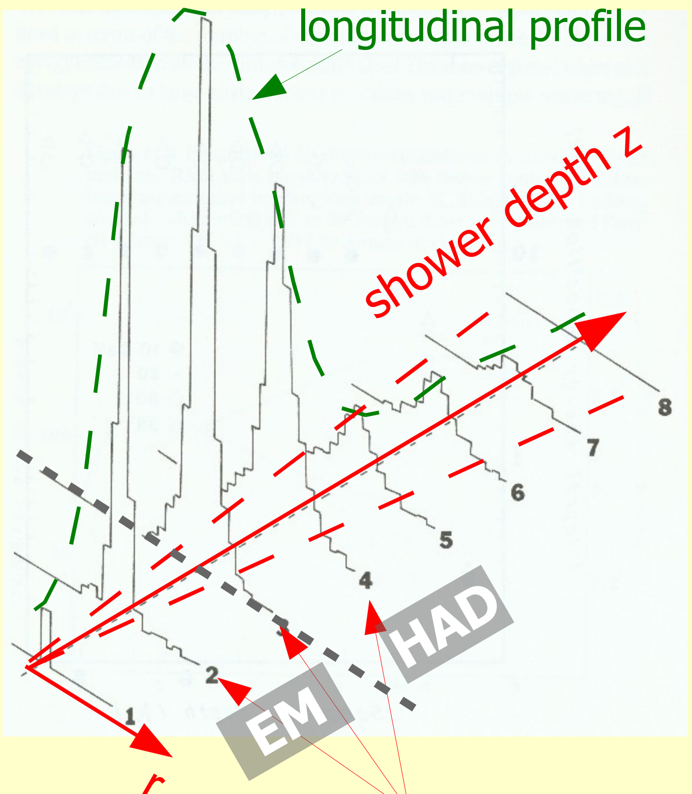
- r: radial distance from shower center
- z = shower depth

- R_0: log-normal distribution
  (in units of Moliere radius or absorptions lengths)
- Mean & width of R_0:

$$\langle R_0(E,z) \rangle = \left[R_1 + (R_2 - R_3 \log E)\, z \right]^n$$

$$\frac{\sigma_{R_0}(E,z)}{\langle R_0(E,z) \rangle} = \left[(S_1 - S_2 \log E)(S_3 + S_4 z) \right]^2$$

hadrons: n=1
photons, electrons: n=2

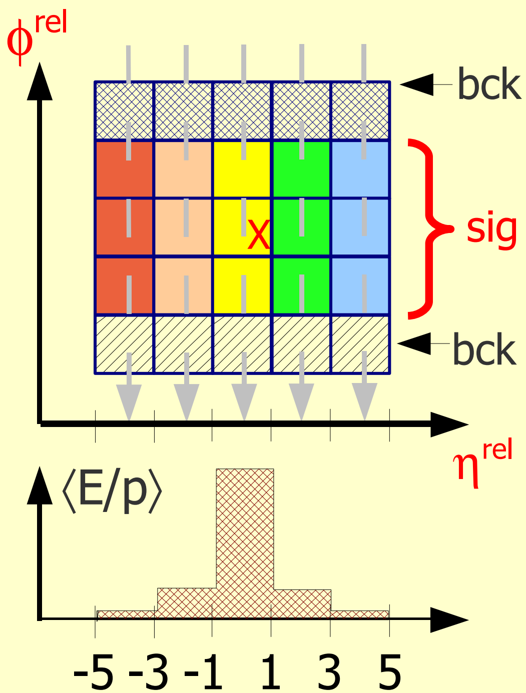


- Hadronic showers: linear dependence on shower depth
- Logarithmic dependence on incident particle energy

7 parameters

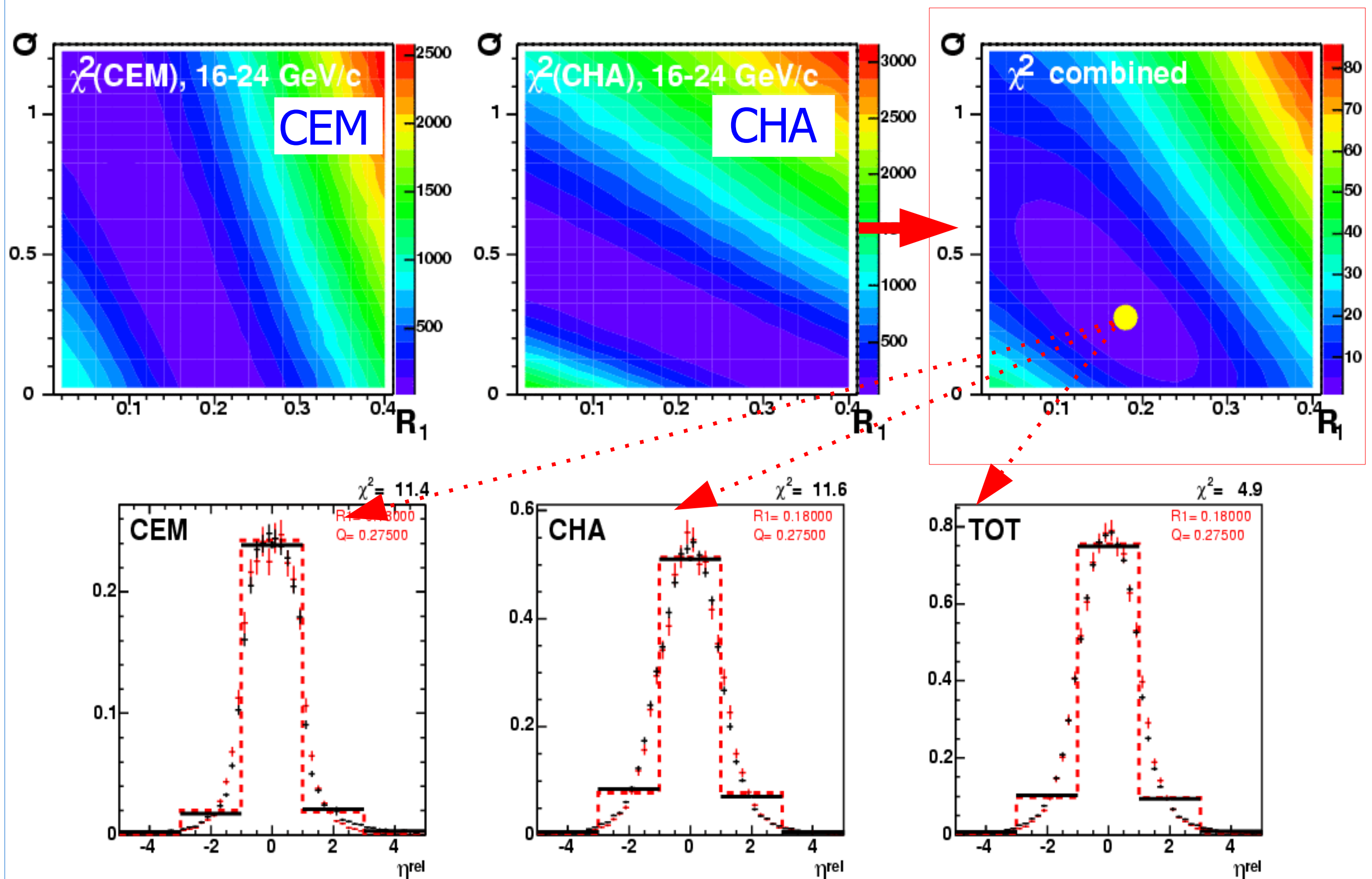
Lateral Profile Tuning

X extrapol. track impact point



$$\eta^{rel} = \frac{\eta - (\eta^{max} + \eta^{min})/2}{(\eta^{max} - \eta^{min})/2}$$

Example: 20 GeV profile (Central)



Parameter scan

$$\langle R_0(E_{inc}, z) \rangle = [R_1 + (R_2 - R_3 \ln E_{inc}) z]^n$$

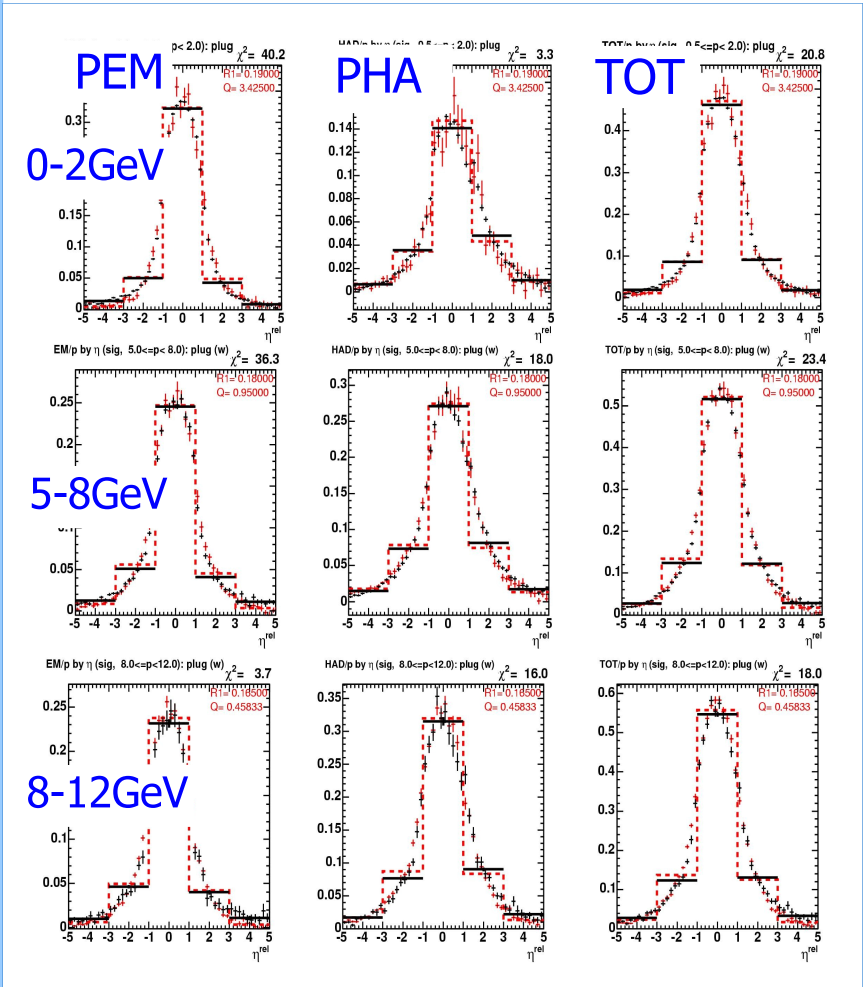
core term R_1

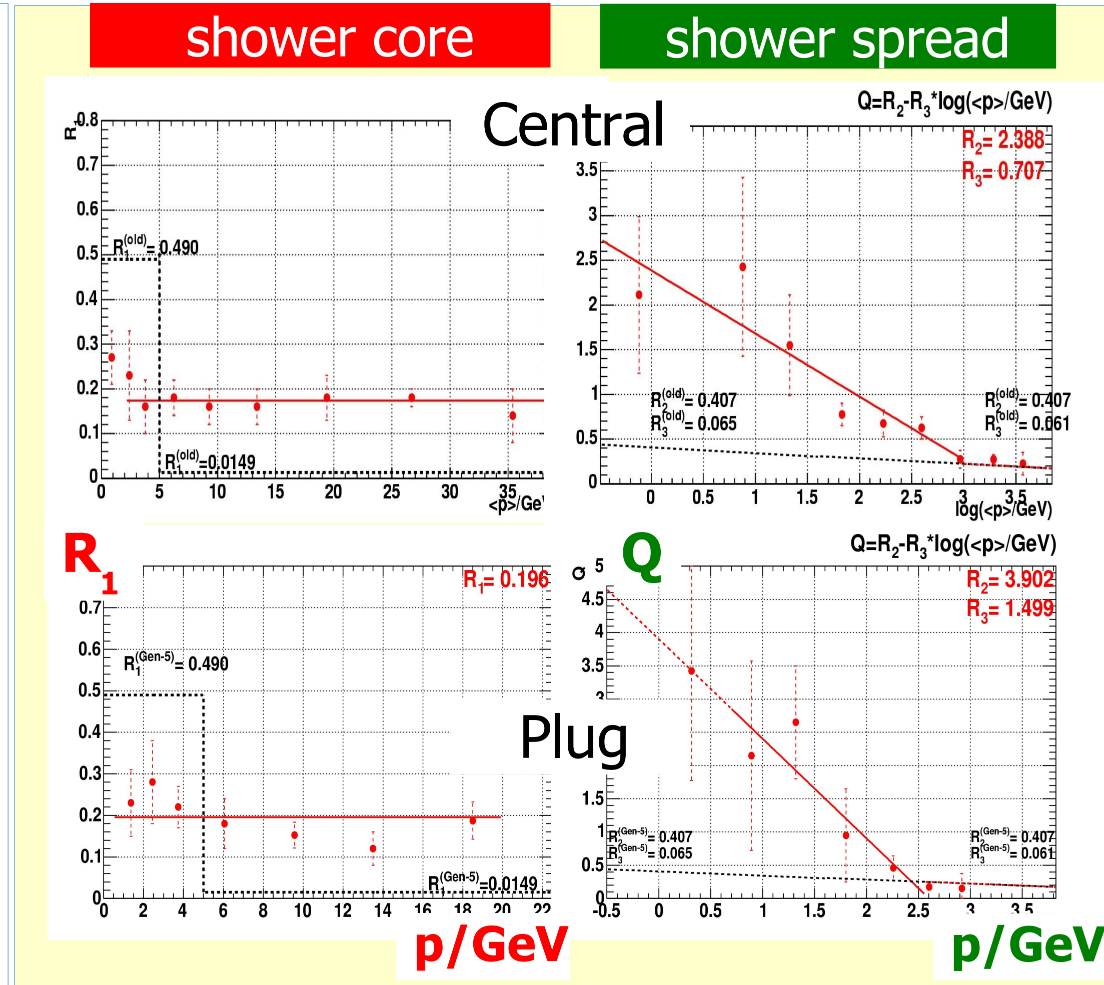
spread term Q
- shower depth
- incident particle energy

- EM and HAD probe different stages of shower development.
- Normalization to absolute data response decouples tuning from longitudinal profile details.

Pedro A. Movilla Fernández, LBNL

Lateral Profile Tuning (2)





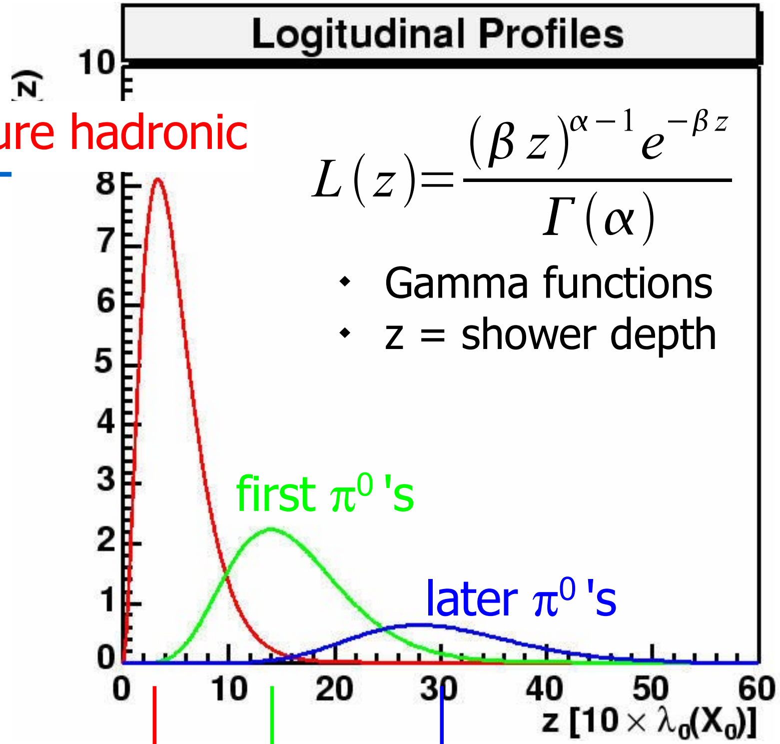
- Consistent global tuning in Central and Plug
- Lateral profiles must match as perfectly as possible to avoid bias in absolute response tuning

Longitudinal Profile

$$dE_{vis}(\boldsymbol{r}) = E_{inc}\,\hat{m}\sum_{\hat{k}} \frac{\hat{k}}{\hat{m}} c_{\hat{k}}\, f_{\hat{k}}(\boldsymbol{r})\,d\boldsymbol{r}$$

- Hadrons: superposition of 3 shower classes:

$$L \propto f_{dep}(E)\left[c_h H_h(x) + c_f H_f(y) + c_l H_l(z)\right]$$



$$L(z) = \frac{(\beta z)^{\alpha-1} e^{-\beta z}}{\Gamma(\alpha)}$$

- Gamma functions
- z = shower depth

$$H_h(x) = \frac{(\beta_h x)^{\alpha_h-1} e^{-\beta_h x}}{\Gamma(\alpha_h)}, \quad c_h = 1 - f_{\pi^0}(E)$$

$$H_f(y) = \frac{(\beta_f y)^{\alpha_f-1} e^{-\beta_f y}}{\Gamma(\alpha_f)}, \quad c_f = f_{\pi^0}(E)(1 - f^l_{\pi^0}(E))$$

$$H_l(z) = \frac{(\beta_l z)^{\alpha_l-1} e^{-\beta_l z}}{\Gamma(\alpha_l)}, \quad c_l = f_{\pi^0}(E) f^l_{\pi^0}(E)$$

- Incident particle energy dependence of fractions

$$f_i(E) = a + b\tanh(c\log E + d)$$ (typically)

...primary switches for Run-II tuning improvements!

Total of 20 parameters:
means & widths of
- the class fractions f's,
- the α's and β's

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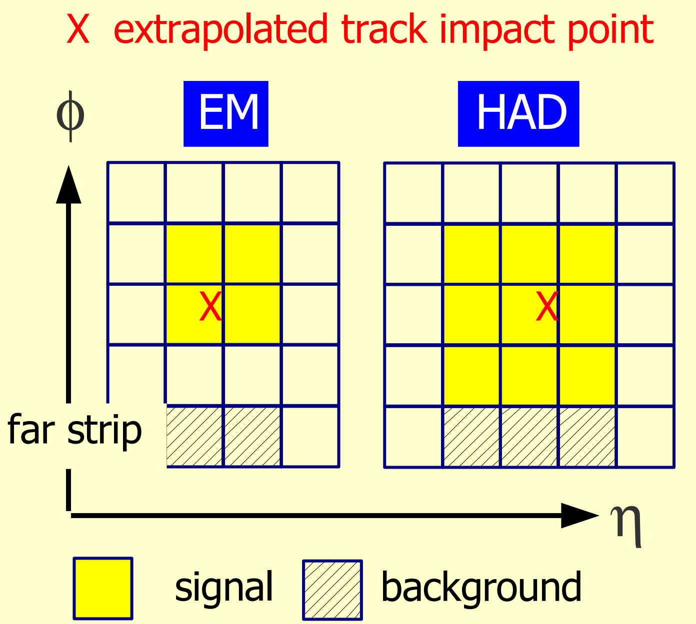
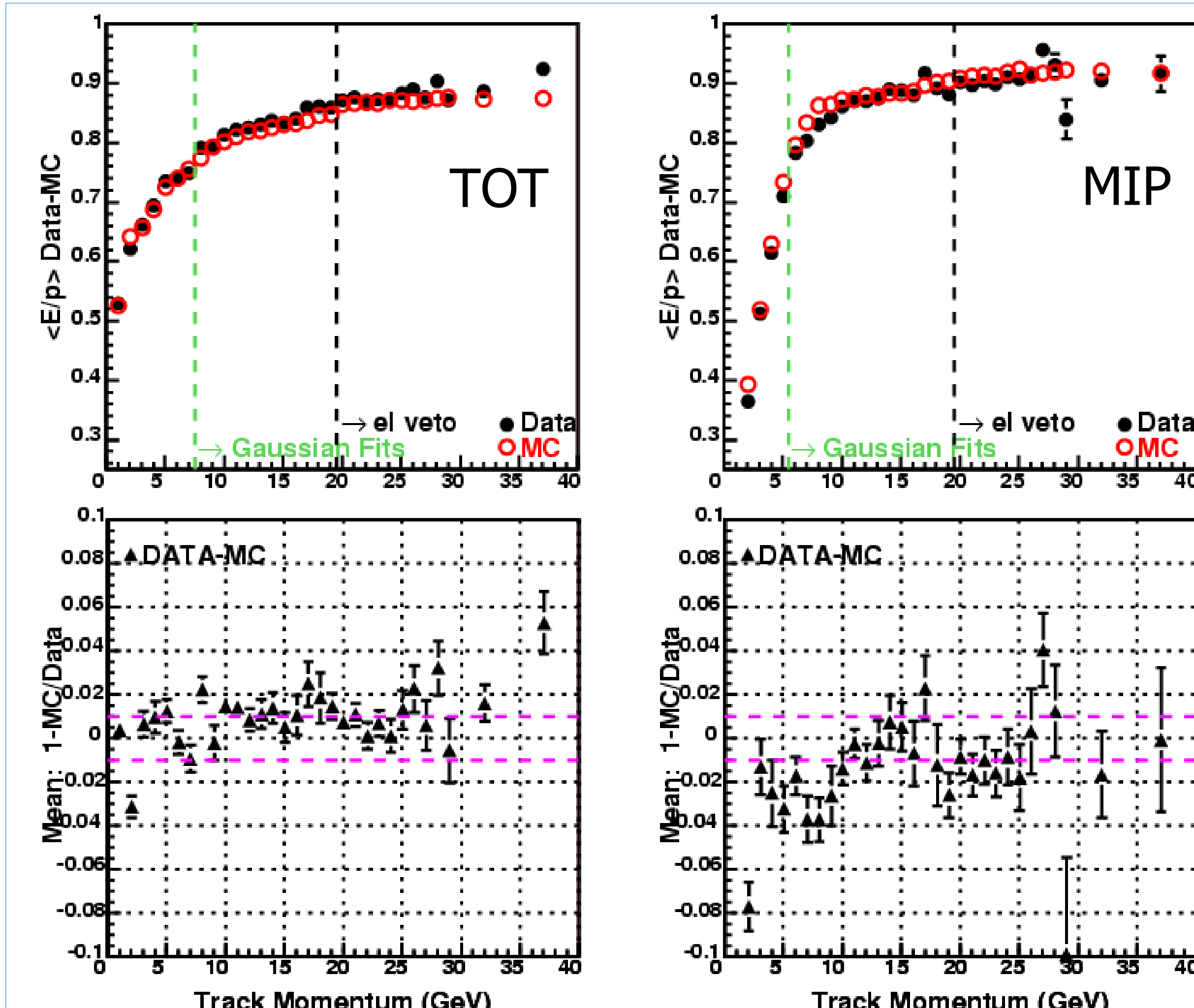
Absolute Response Tuning (Central)

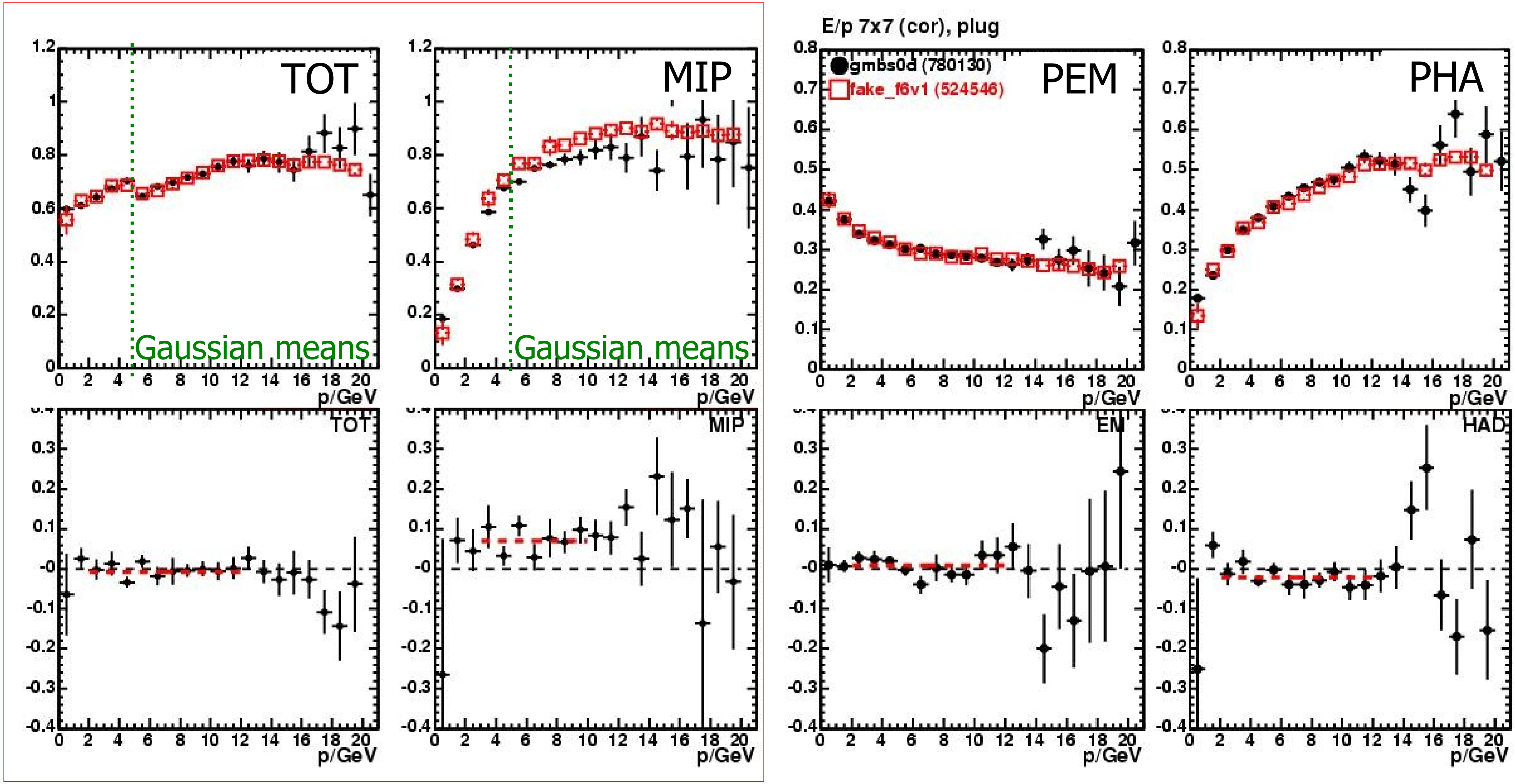


sig: EM=2x2 blocks
HAD=3x3 blocks
bck: EM=2x far strip
HAD=3x far strip



- TOT and MIP is primary reference: shower almost fully contained → response less dependent on shower starting point & particle flavor (appendix)
- TOT is basis for JES uncertainty determination

Absolute Response Tuning (Plug)

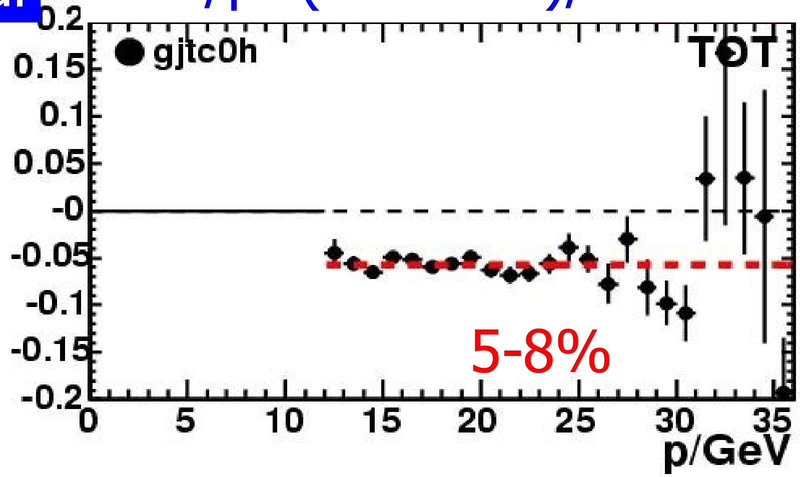


- Priority to get TOT right
- Moderate discrepancy in MIP

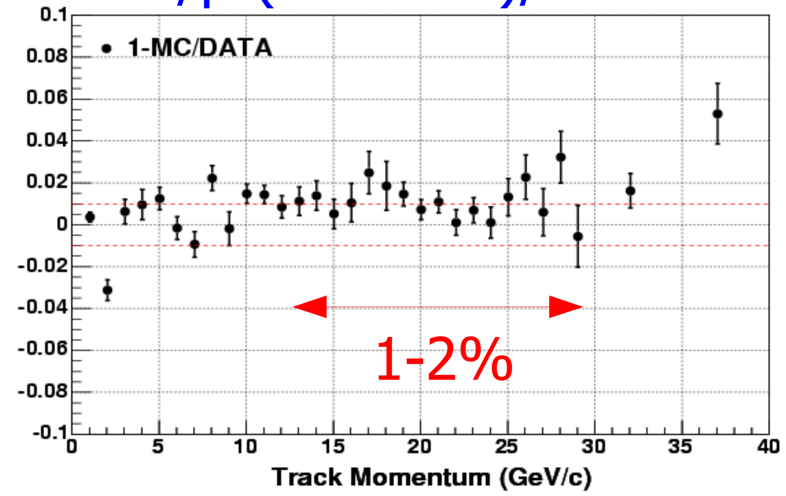
Changes

Central

E/p: (Data-MC)/Data



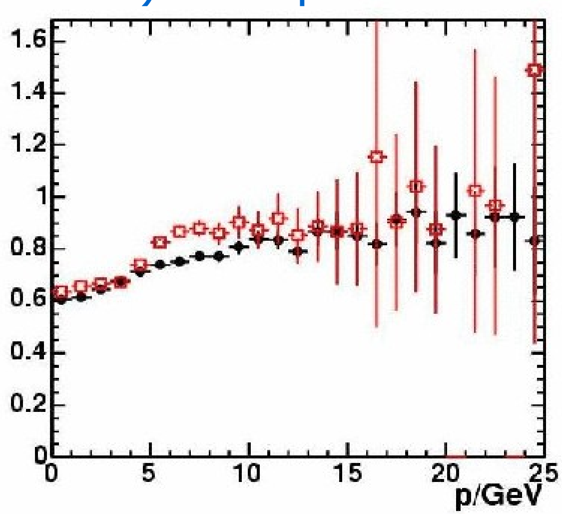
E/p:(MC-Data)/Data



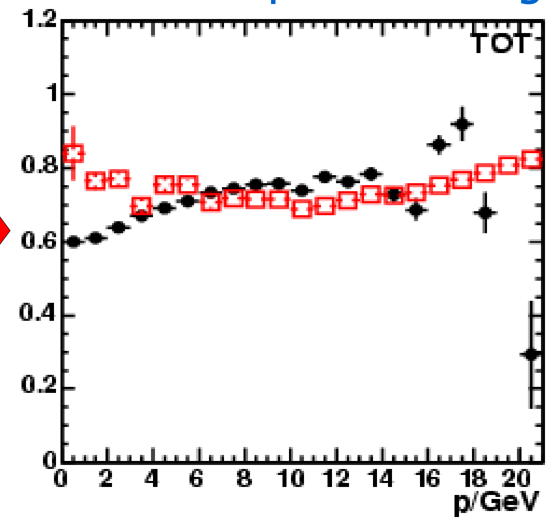
Plug

E/p (total response)

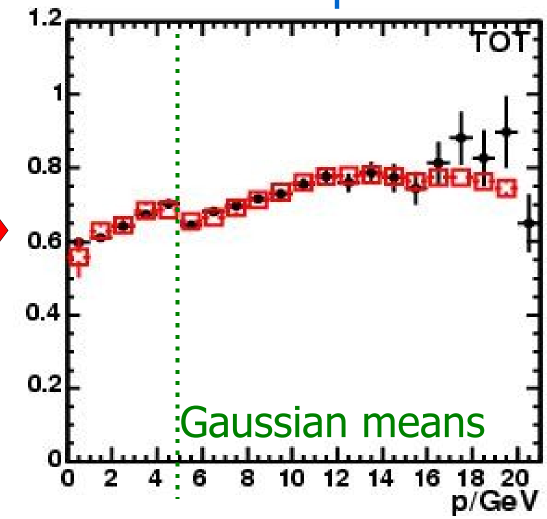
a) initial picture



b) after lateral profile tuning



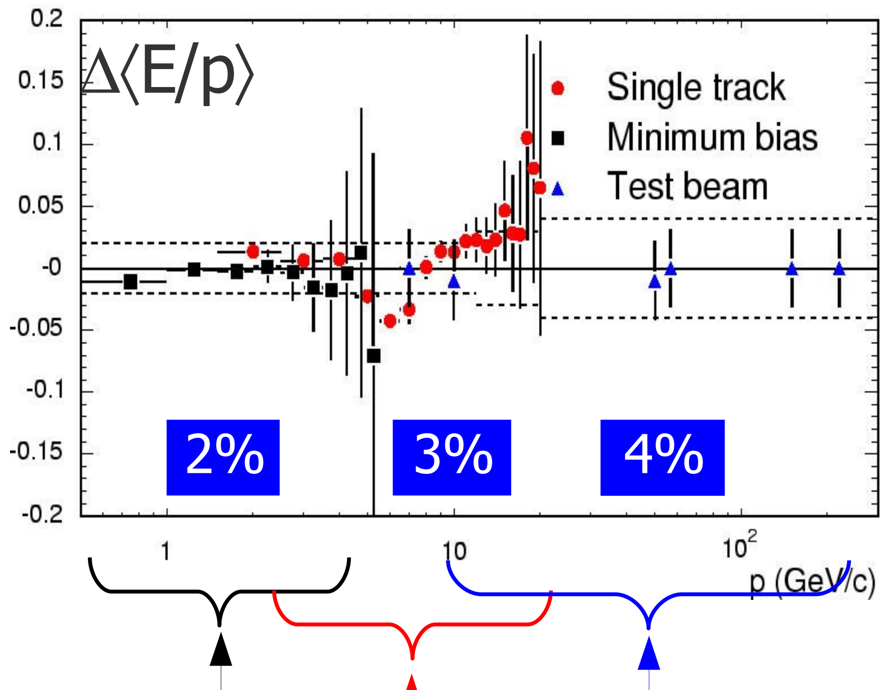
c) after absolute response tuning



- Have gained substantial in-situ control up to 40 (20) GeV in Central (Plug)

Simulation Performance

Performance early Run-II effective in past/ongoing CDF publications:

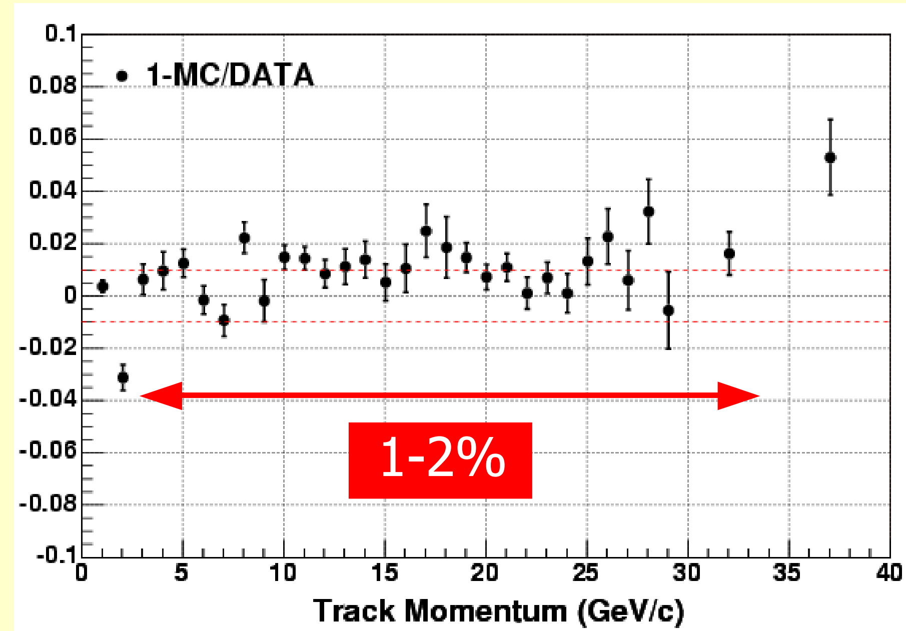


in-situ tuning
p<2.5(5) GeV/c

test beam data
p>20GeV/c
(conservative errors)

later in-situ validation
2.5<p<20GeV/c
(poor statistics)

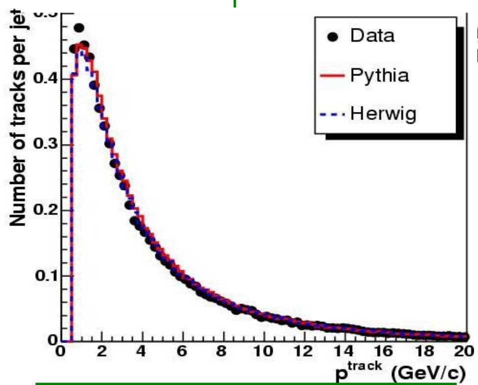
now



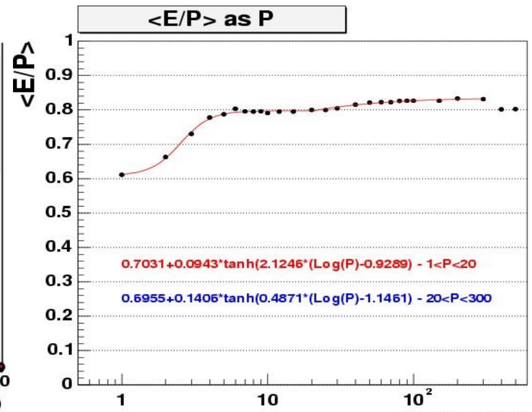
- Better and consistent tuning.
- Percentages directly translate into JES uncertainties (next page)

Jet Energy Scale Uncertainties

e.g. jet p_T=50-60GeV

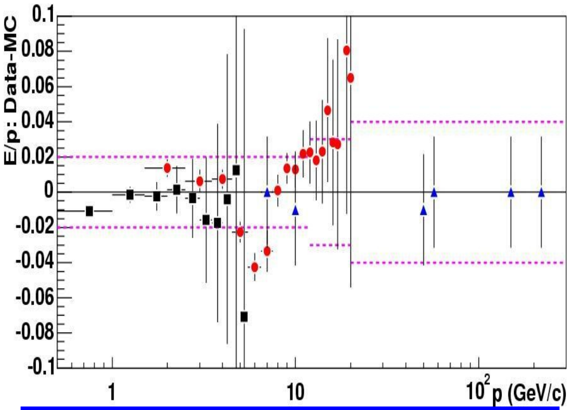


particle spectrum



$\langle E/p \rangle$ (had)

$\langle E/p \rangle(e,\gamma)$ = 1 (30% fraction)

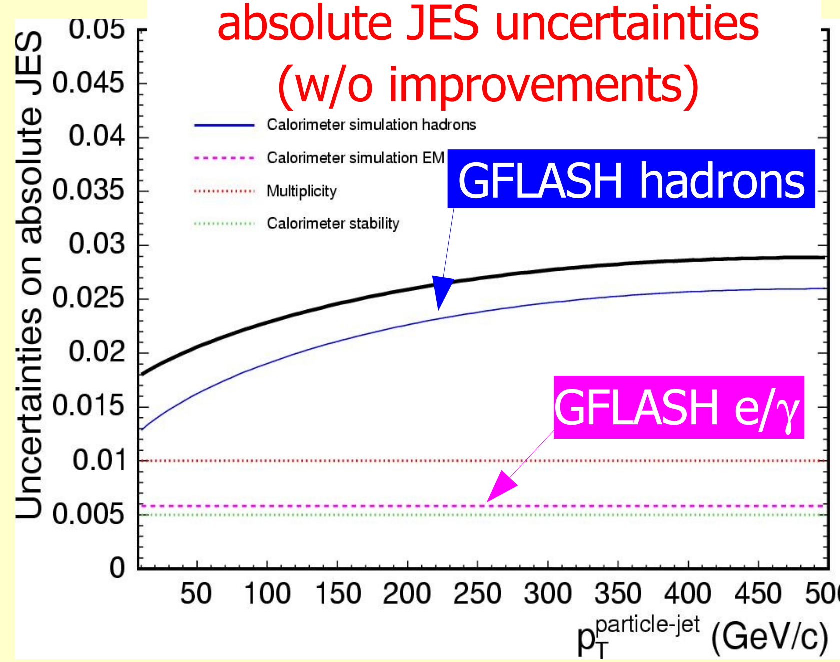


$\Delta \langle E/p \rangle$

$$\frac{\Delta E}{E} = \frac{1}{E} \sum_i p_i \left\langle \frac{E_i}{p_i} \right\rangle \Delta \left\langle \frac{E_i}{p_i} \right\rangle$$

- Derived from "first principles" :
- Convolution of MC/data difference with the jet's particle spectrum and E/p response

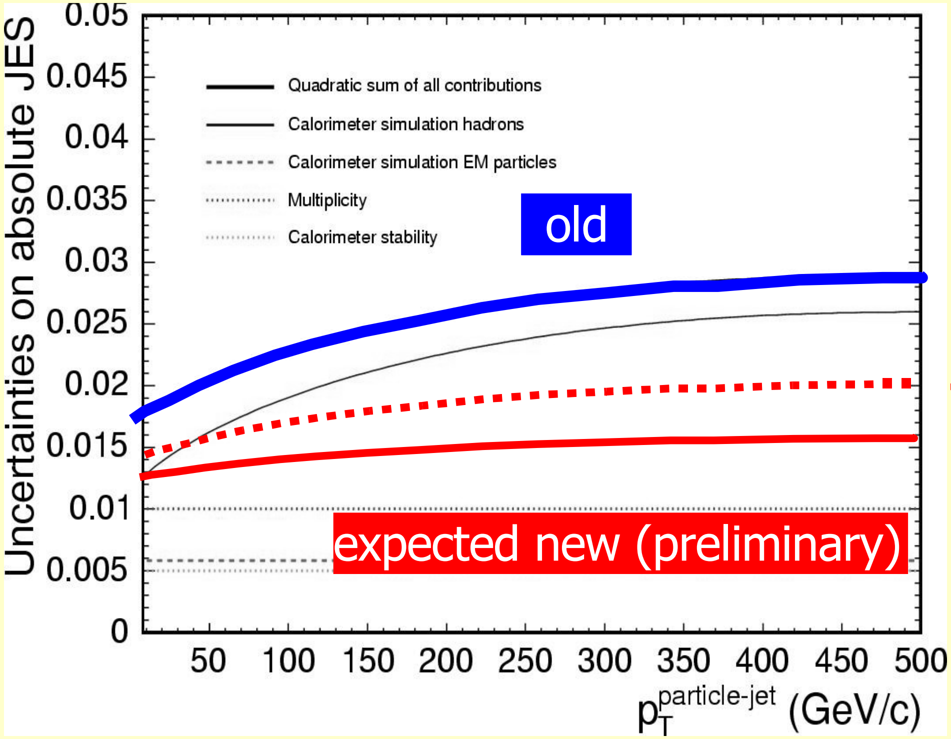
→ absolute JES uncertainty



Absolute JES Uncertainty

- We can get rid of old test beam based conservative high p estimates
- Have better agreement at low and medium p
- Absolute E/p uncertainty reduced by a factor of ~2:

  estimated new JES uncertainty:
  1.8-2.8% → 1.4% (preliminary)



Impact to performance top quark mass measurements:

- w/o in situ JES: e.g. di-lepton
- w/ in situ JES but a-priori JES constraint: e.g. all-jets
- reduction of residual JES uncertainties

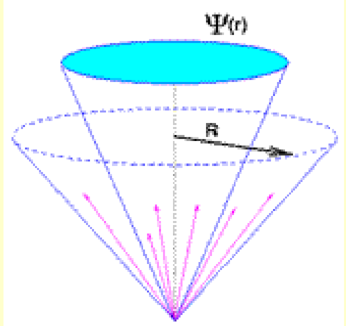
→ Reduction of ΔM_{top}(Absolute), $\Delta M_{top}(JES_{stat})$?

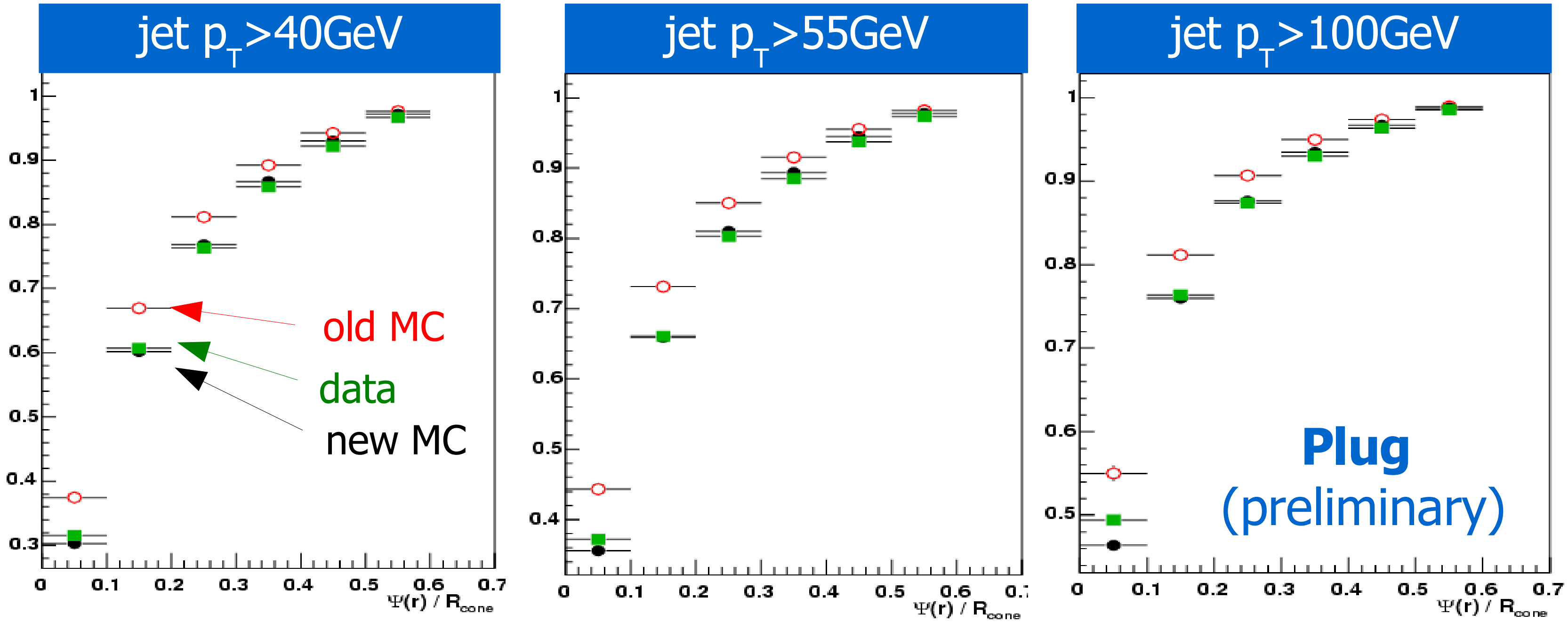
... more comments later!

Jet Shapes

- For example: Integrated jet energy flow

$$\Psi(r) = \frac{1}{N_{jets}} \sum_{jets} \frac{p_T(0,r)}{p_T(0,R)}$$

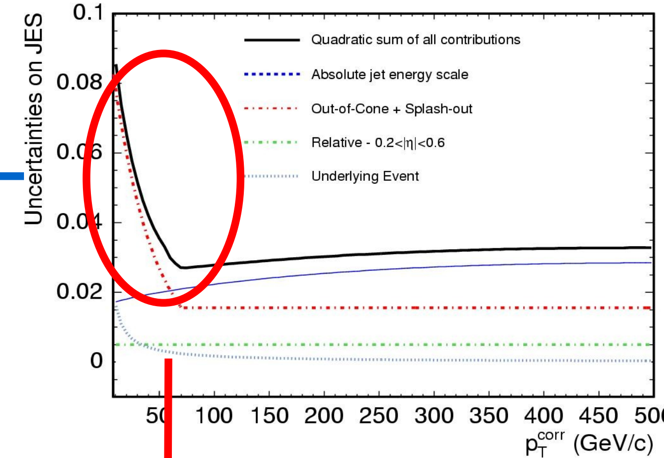




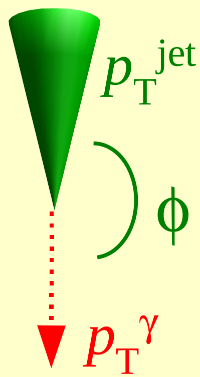
- Much better agreement
  - → reduces bias in relative correction Plug to Central
  - → impact to OOC uncertainties

(next slides)

OOC Uncertainties



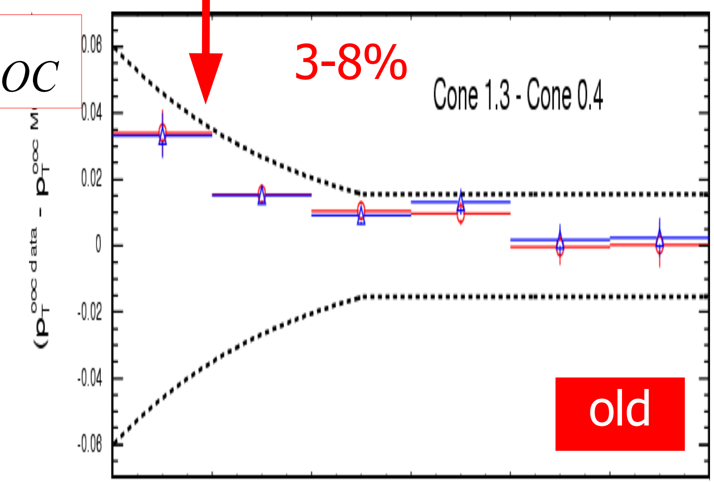
- Photon-jet balance technique: validate the probe jet using well measured photon energy



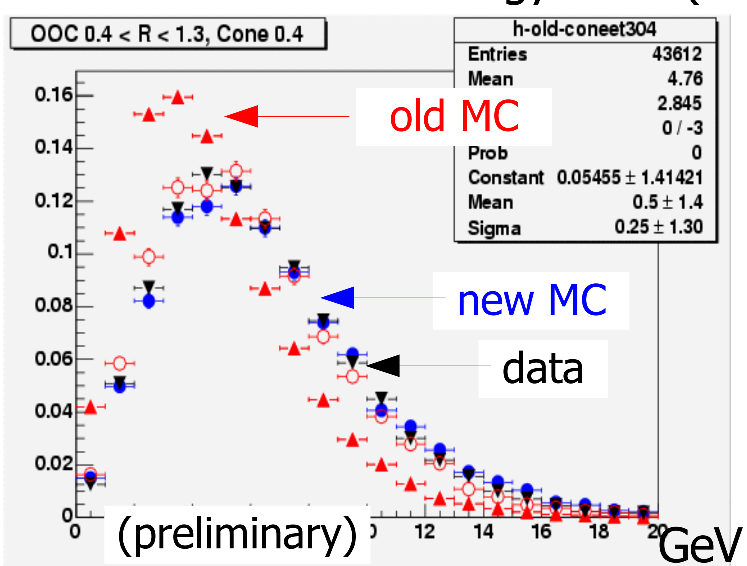
$$f_{\gamma} = 1 - \frac{p_T^{jet}}{p_T^{\gamma}}$$

$$\delta_{OOC} = f_{\gamma}^{data,\, cor} - f_{\gamma}^{MC,\, cor}$$

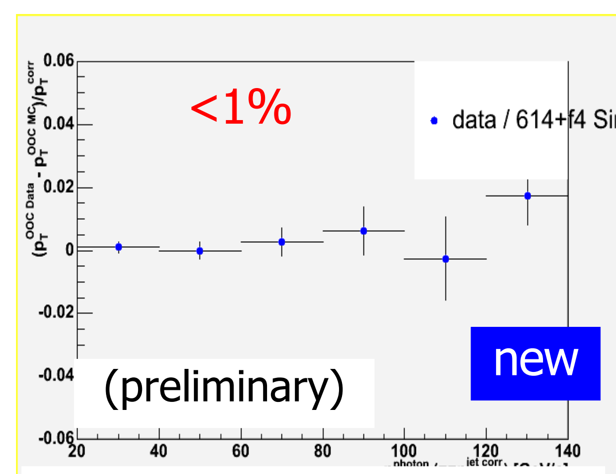
δ_{OOC}



OOC transverse energy flow (R=0.4...1.3)



δ_{OOC}

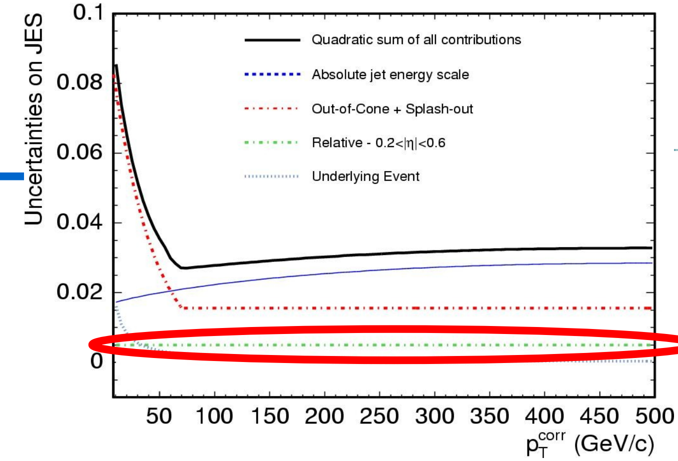


corrected jet p_T(GeV/c)

→ Reduction of ΔM_{top}(OOC)?

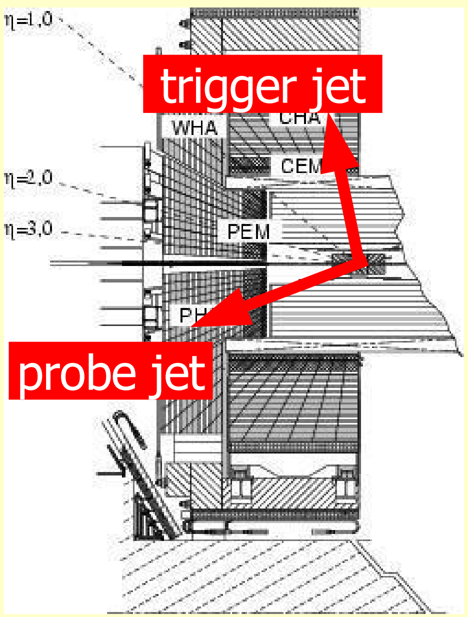
... still under study!

Di-Jet Balance



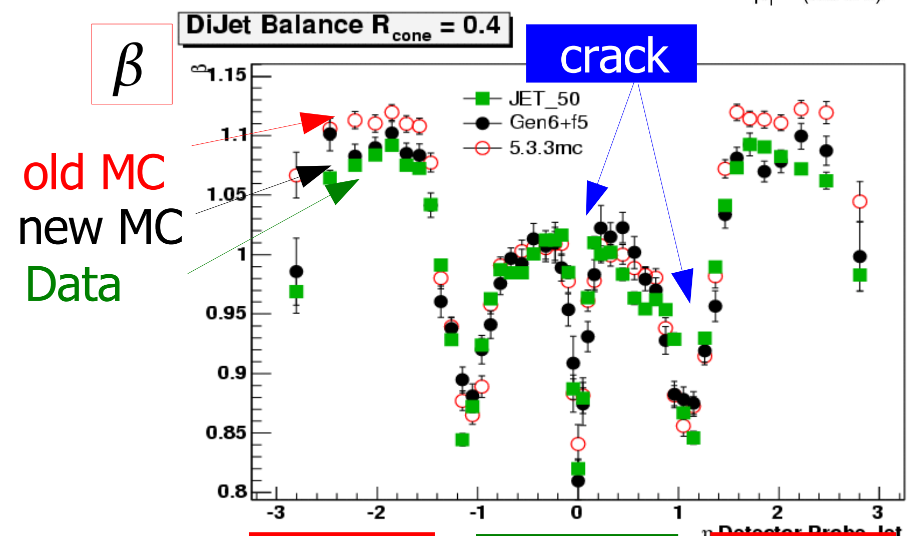
Di-jet balancing technique

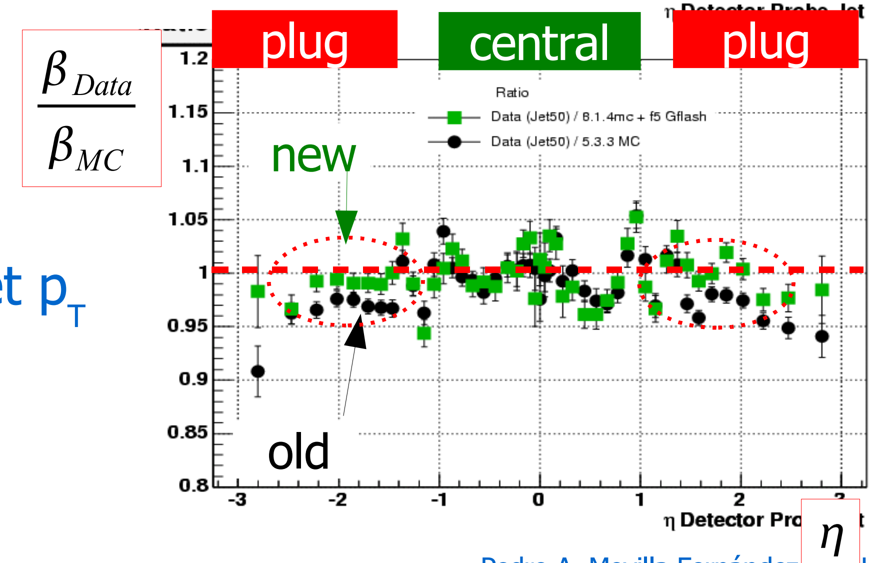
- Monitoring and correction of the inhomogeneous calorimeter response using reference jet p_T in Central part.



$$f = \frac{p_T^{probe} - p_T^{trigger}}{(p_T^{probe} + p_T^{trigger})/2}$$

$$\beta \equiv \frac{2+f}{2-f} = \frac{p_T^{probe}}{p_T^{trigger}}$$

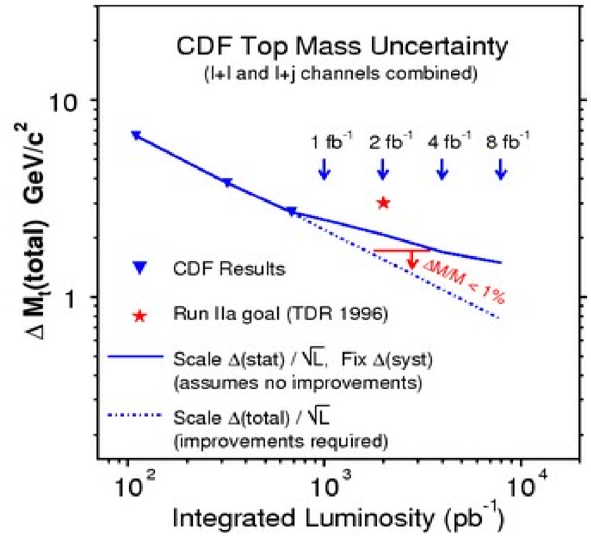




- Improvements for certain cone sizes and jet p_T

→ Reduction of ΔM_{top} (Relative)?

Towards Precision Top Quark Mass



Di-Lepton Channel

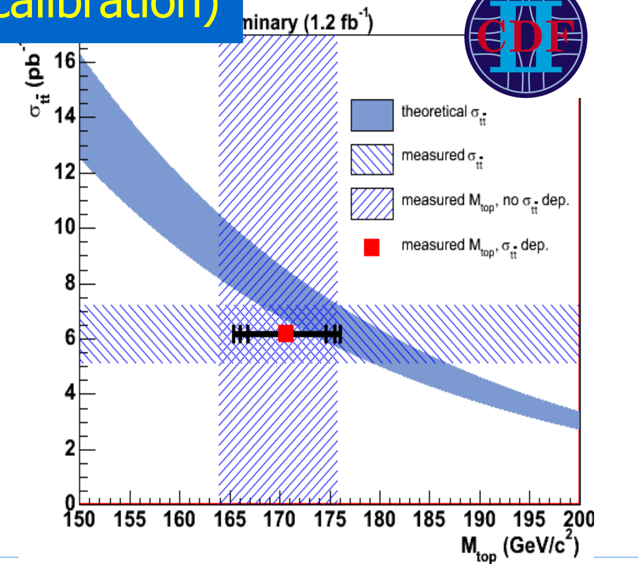
Template Method, $p_z(tt)$ assumption, 1.2fb^{-1} (no in situ JES calibration)

w/ cross section constraint (reduced JES systematics)

$$M_{top} = 170.7 {}^{+4.2}_{-3.9} (\text{stat.}) \pm 2.6 (\text{syst.}) \pm 2.4 (\text{theo.}) \, \text{GeV}/c^2$$

JES_{tot}	b-JES	JES	Relative	Absolute	OOC
GeV/c^2	0.9	1.5	0.3	1.1	1.0

expect to improve



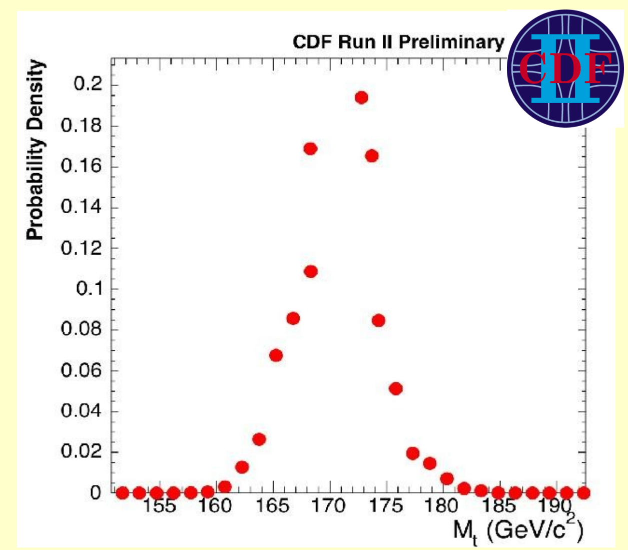
Matrix Element Method, 1.8fb^{-1} (no in situ JES calibration)

$$M_{top} = 170.4 \pm 3.1 (\text{stat.}) \pm 3.0 (\text{syst.}) \, \text{GeV}/c^2$$

JES_{tot}	b-JES	JES	Relative	Absolute	OOC
GeV/c^2	0.2	2.6	0.1	1.8	1.8

expect to improve

$\delta(\Delta m_t)/\delta(\Delta_{JES})$ difficult to assess : 0.9? <0.1?



Best di-lepton measurement.

All-Jets Channel

ME assisted Template Method, 0.94fb^{-1} (in situ JES calibration)

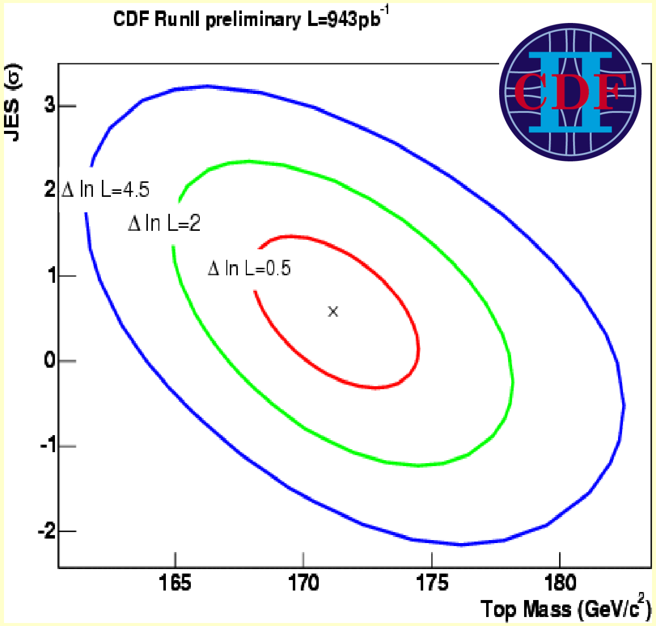
a priori JES constraint

$$L = L_{1\,\mathrm{tag}}(m_t, \mathrm{JES}) \times L_{2\,\mathrm{tag}}(m_t, \mathrm{JES}) \times \exp\left(\frac{-(\mathrm{JES}-\mathrm{JES}_{\mathrm{exp}})^2}{2}\right)$$

$$M_{\mathrm{top}} = 171.1 \pm 3.7\,(\mathrm{stat.+JES}) \pm 2.1\,(\mathrm{syst.})\ \mathrm{GeV}/c^2$$

JES	Stat	b-JES	Residual	Relative	Absolute	OOC
GeV/c^2	2.4	0.4	0.7	0.2	0.5	0.5

expect to improve



- Dominant systematic uncertainties:
  - gluon FSR,
  - background modeling
  - generator

  O(~1GeV/c^2) each

Best all-jets measurement.

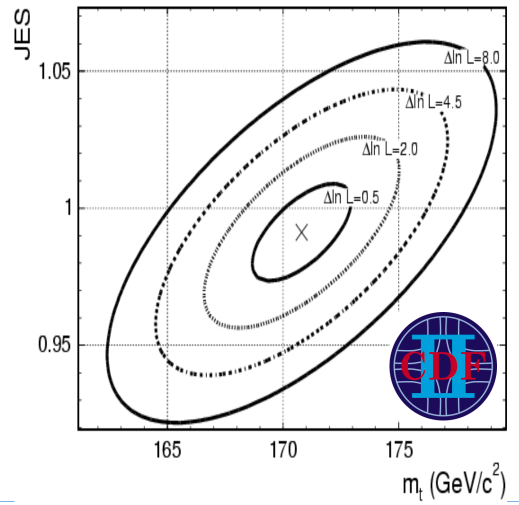
JES Uncertainties (Lepton-Jets)

Matrix Element Method, 0.96fb^{-1} (in situ JES calibration)

$$L(M_{\text{top}}, \text{JES}, C_s) \propto \prod_{i=1}^{\text{events}} \left[C_s P_{t\bar{t}}^{(i)}(M_{\text{top}}, \text{JES}) + (1 - C_s) P_{\text{bck}}^{(i)}(\text{JES}) \right]$$

$$M_{\text{top}} = 170.8 \pm 2.2\,(\text{stat.+JES}) \pm 1.4\,(\text{syst.})\,\text{GeV}/c^2$$

JES	Stat	b-JES	Residual
GeV/c^2	1.5	0.6	0.4



Template Method, 1.7fb^{-1} (in situ JES calibration)

a priori JES constraint

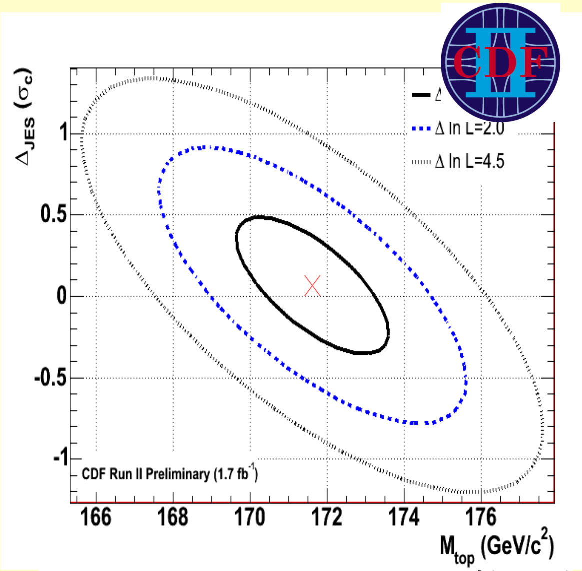
$$L = L_{1\,\text{tag}}(m_t, \Delta_{\text{JES}}) \times L_{2\,\text{tag}}(m_t, \Delta_{\text{JES}}) \times \exp\left(\frac{-\Delta_{\text{JES}}^2}{2\sigma_c^2} \right)$$

$$M_{\text{top}} = 171.6 \pm 2.1\,(\text{stat.+JES}) \pm 1.1\,(\text{syst.})\,\text{GeV}/c^2$$

JES	Stat	b-JES	Residual
GeV/c^2	1.3	0.6	0.6

dominating systematics

- ISR/FSR modeling O(~0.5GeV/c^2)



Best single measurement.

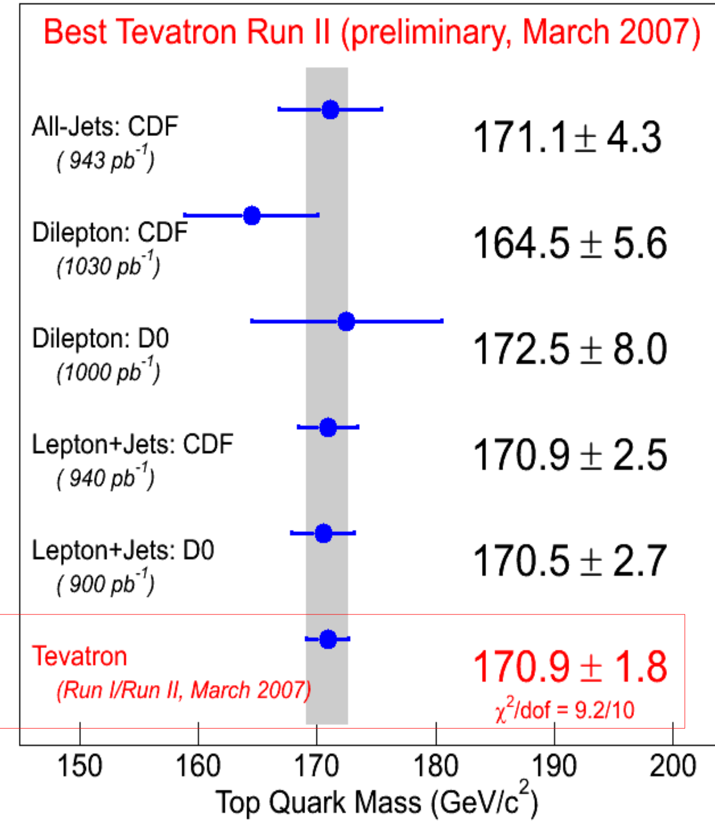
Precision vs. Consistency

Tevatron combination (March '07)

Parameter	Value (GeV/c^2)	Correlations		
all-jets	172.2 ± 4.1	1.00		
lep-jets	171.2 ± 1.9	0.21	1.00	
di-lep	163.5 ± 4.5	0.15	0.30	1.00

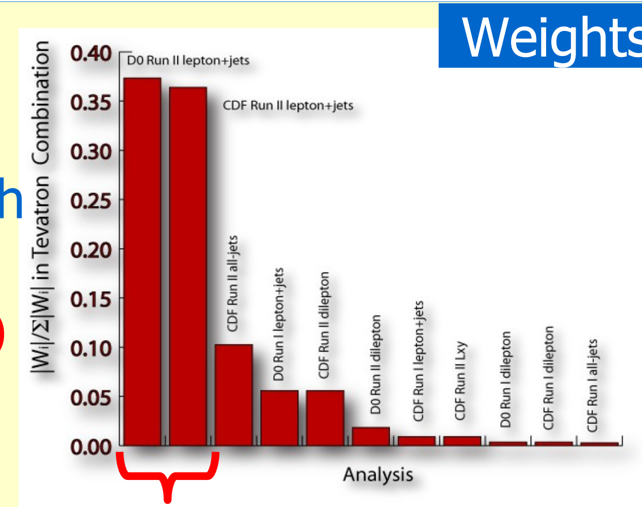
2.4%
1.1%
2.8%
1.1%

p (di-lep/all-jets) = 7%
p (lep-jets/all-jets) = 75%
p (di-lep/lep-jets) = 12%



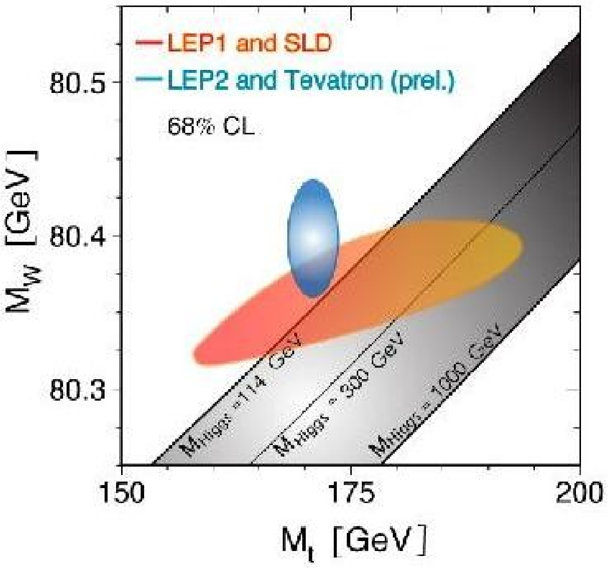
- Can we trust increased precision? Are we biased by unknown systematics (e.g. color reconnection)?
- Need higher precision in non-golden channels with different hadronic activity to verify
  $\rightarrow$ reduction of Δ_{JES} essential (e.g. di-lepton channel)
- Alternate less JES sensitive methods important
  - lepton p_T | decay length technique (appendix)

Weights



Lepton+Jets

Conclusions



Lessons from Run-II

- We have gained confidence through a consistent picture of many excellent top mass measurements at CDF and DØ

1.1%

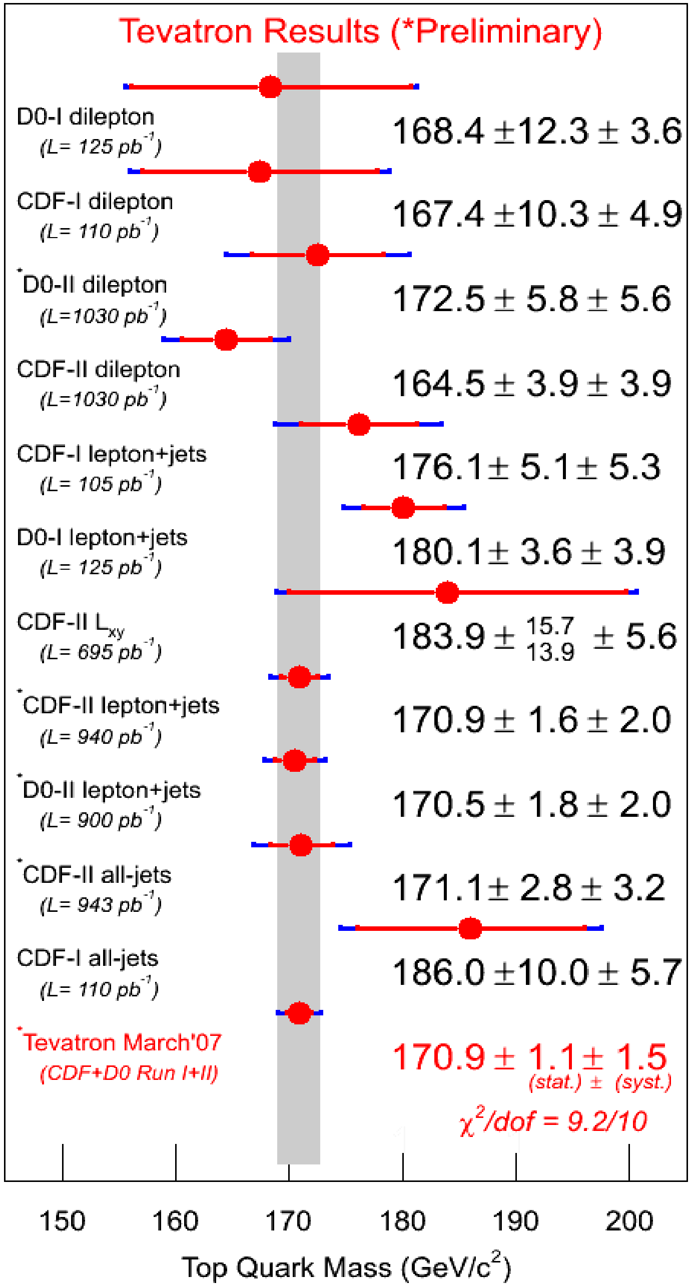
Combined CDF&D0 result (March '07):

$$M_{top} = 170.9 \pm 1.8\ \mathrm{GeV}/c^2$$

- Precision reached is based on
  - High b-tagging efficiency
  - Improved analysis techniques
  - In-situ W-jj calibration of the JES
- Uncertainty squeezed down more than expected by integrated luminosity.

...the end of the story?

- We could do better with improved JES...



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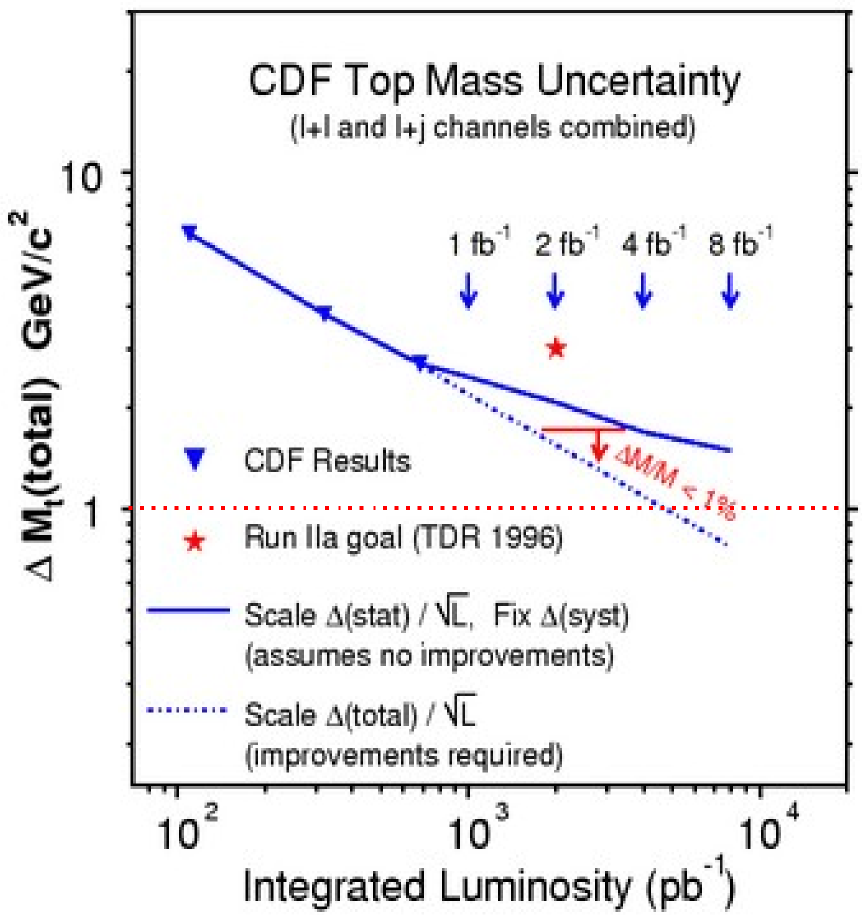
Outlook

- Clearly surpassed TDR Run-IIa goal!
- Enhanced precision requires mutual verification in all channels.
- We are therefore awaiting how future measurements will benefit from reduced JES uncertainties through better calorimeter simulation.
- Limiting factor at the end of Run-II expected to be ISR/FSR (=theoretical).
- With combined efforts we can reach $\Delta M_{top} < 1$ GeV/c^2 at the end of Run-II

...expected after 5-10 years LHC!!!



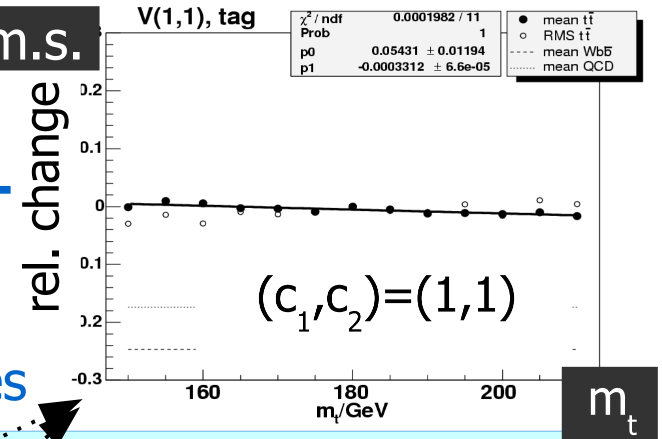
Tevatron might be the lasting legacy for the top quark mass!

(...at least for a while)

Backup Slides

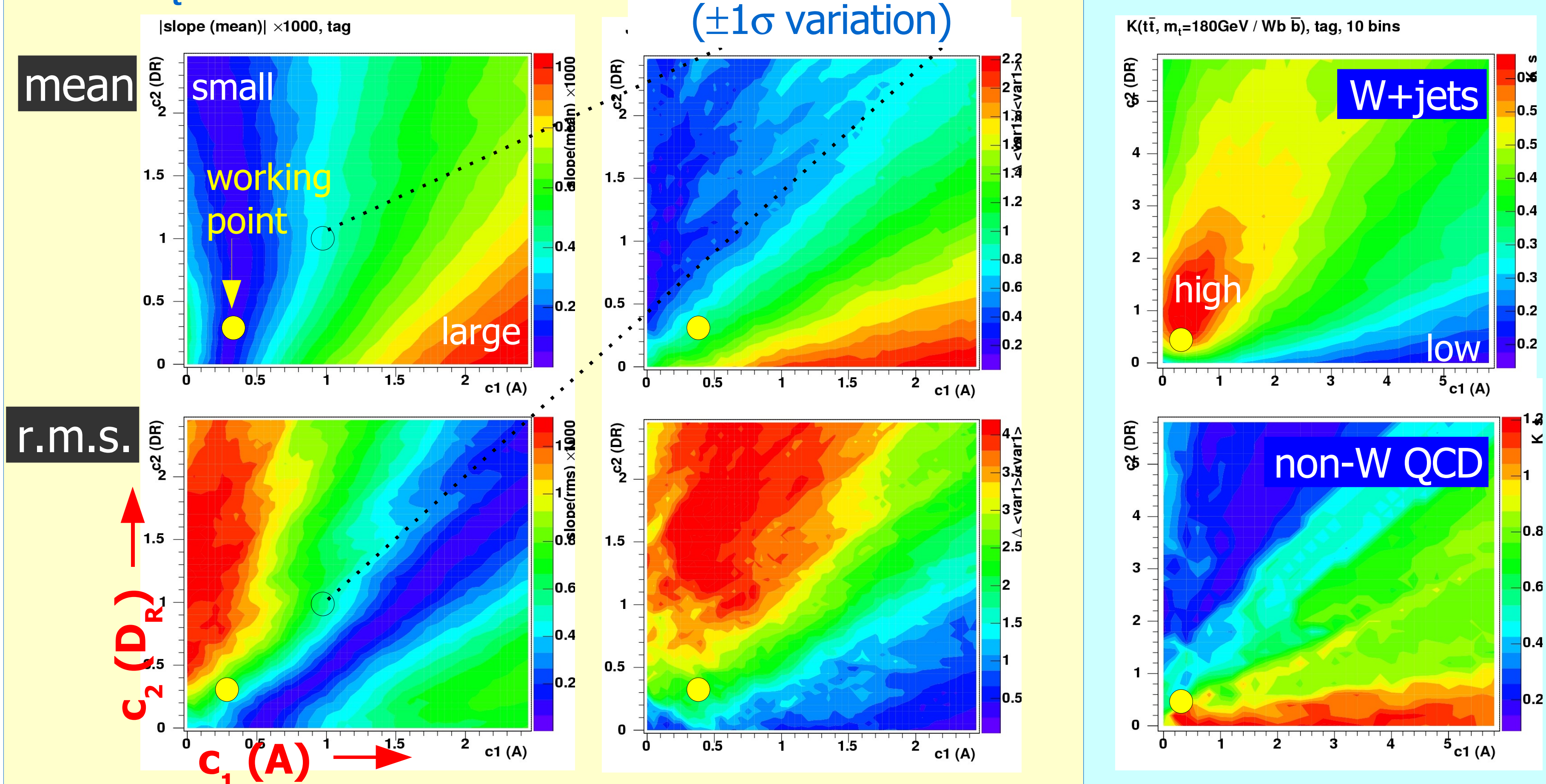
Hybrid Variable

- Fine tuning of two independent coefficients
- Study relative changes w.r.t. reference distribution
- S/B discrimination quantified by divergence measures



$$V=\left(\hat{c}_1 A+\hat{c}_2 D_{\mathrm{R}}+\hat{c}_3 H_{\mathrm{TZ}}\right)\times N$$

m_t dependence [0.1%] **JES dependence** [%] ($\pm1\sigma$ variation) **S/B discrimination**



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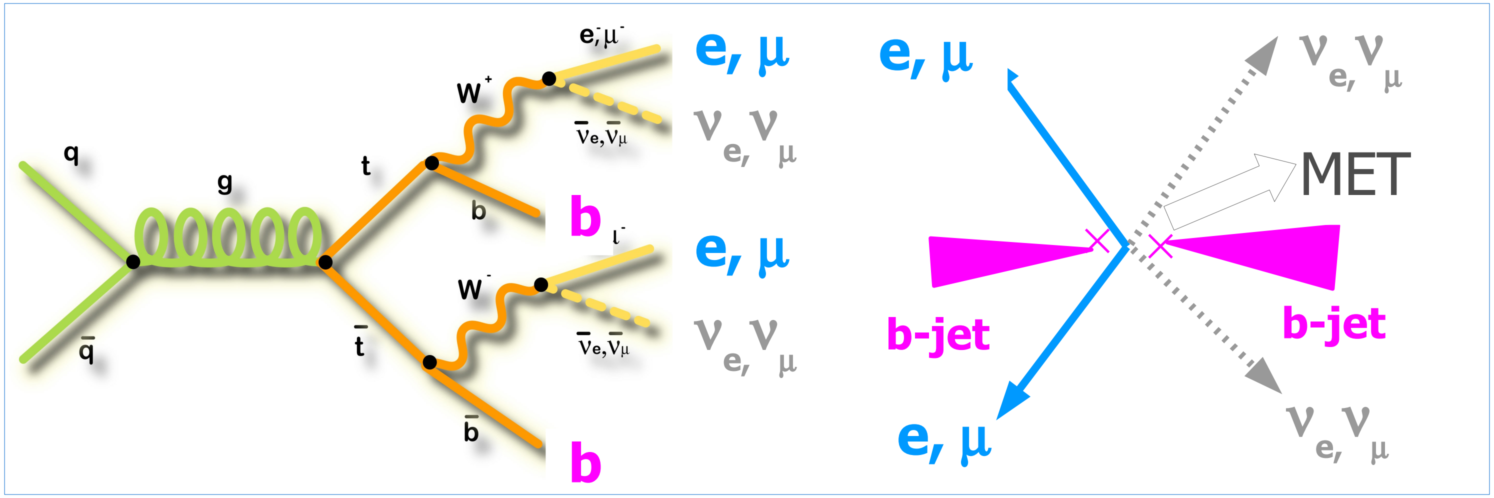
The Di-Lepton Channel

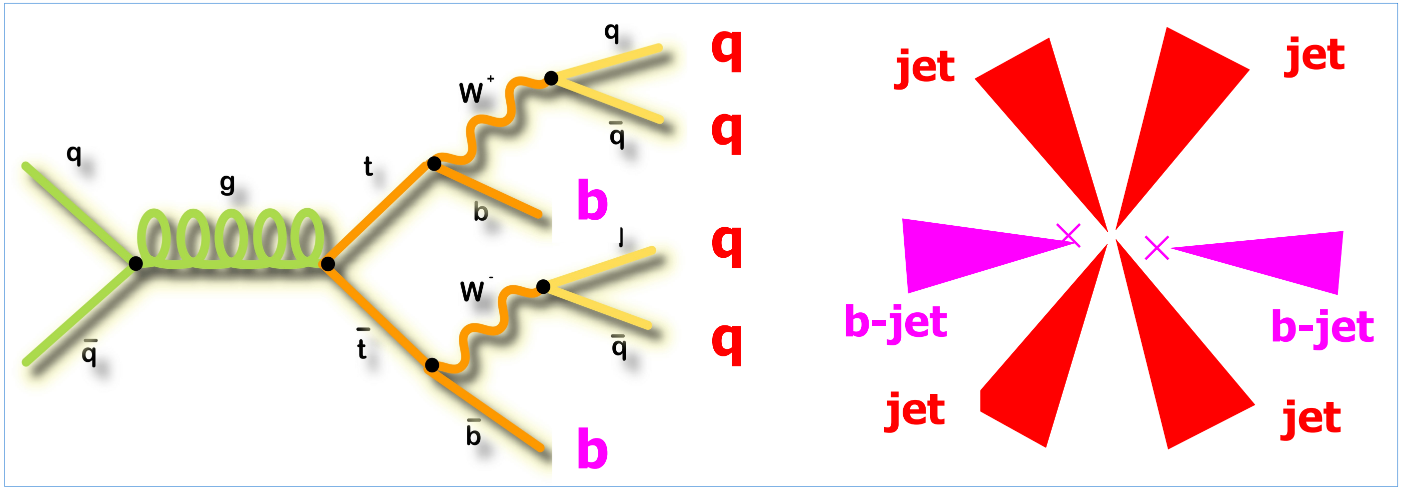


- Typical analysis cuts:
  - 2 OS lepton candidates
  - 2 high E_T jets
  - ≥0 or ≥1 b-tag
  - large missing E_T
  - high total transverse energy

- Major backgrounds:
  Z/γ*+2jets
  WW+2 jets
  W+3jets (fake leptons)

- Clean sample but poor statistics
  BR ~ 5% | S/B ~ 2 (20) for ≥0 (≥1) b-tag
- Small combinatorial ambiguity: 2 jet-quark assignments
- Under-constrained kinematics: 2 neutrinos but 1 missing E_T variable

The All-Jets Channel



- Standard analysis cuts:
  - Exactly 6 high E_T jets
  - lepton veto
  - low missing E_T significance
  - ≥1 or 2 b-tags
  - large total E_T
  - spherical+isotropic topology

- Major backgrounds:
  non-W bb4q (fake leptons)
  non-W 6q (fake leptons + fake b-tags)
- Good statistics but huge background:
- BR~44% | S/B~1/23 (≥0 tag) ~1/6 (≥1 tag)
- S/B was recently pushed to 1/1 due to additional signal ME probability cut (very restrictive but feasible for >1/fb.)

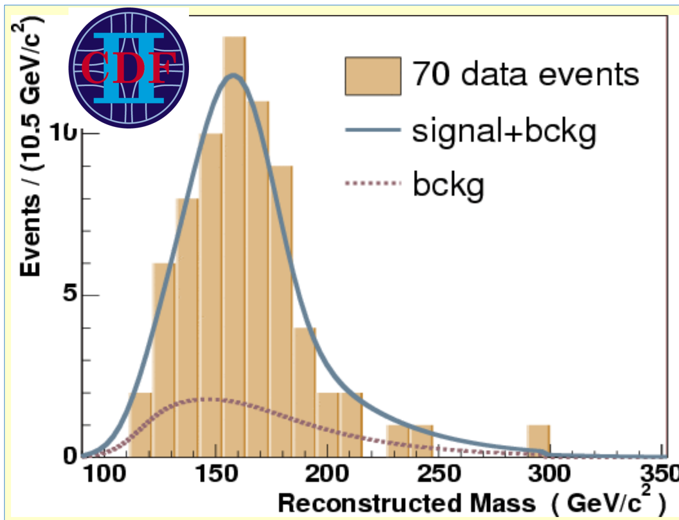
- Large combinatorial jet-quark ambiguity
- Well measurable kinematics (no neutrino)

Template, Di-Lepton, 1.2fb^{-1}

- Under-constrained problem requires assumption for one kinematic variable...

$$
\begin{aligned}
P_{\nu_{1x}} + P_{\nu_{2x}} &= \not{E}_{T_x} \\
P_{\nu_{1y}} + P_{\nu_{2y}} &= \not{E}_{T_y} \\
P_{t_z} + P_{\bar{t}_z} &= P_{t\bar{t}z} \\
M_t &= M_{\bar{t}} \\
M_W &= 80.4 \\
\vec{P}_b + \vec{P}_{W+} &= \vec{P}_t \\
\vec{P}_{\bar{b}} + \vec{P}_{W-} &= \vec{P}_{\bar{t}} \\
\vec{P}_{l+} + \vec{P}_{\nu} &= \vec{P}_{W+} \\
\vec{P}_{l-} + \vec{P}_{\bar{\nu}} &= \vec{P}_{W-}
\end{aligned}
$$

- Assume $P_z(t\bar{t})=0$, $\sigma\{P_z(t\bar{t})\}=180\text{GeV}/c^2$:
  No top mass dependence, same for signal and background
  ...derived from MC and lepton plus jets data
- Solve numerically equations within allowed phase space:
  For each event, dice the two b-quark energies, E_T(miss), and P_z(tt) around their measured/assumed values within their given resolutions.
- Sum up and take the most probable resulting ("raw reconstructed") top quark mass to build the template.

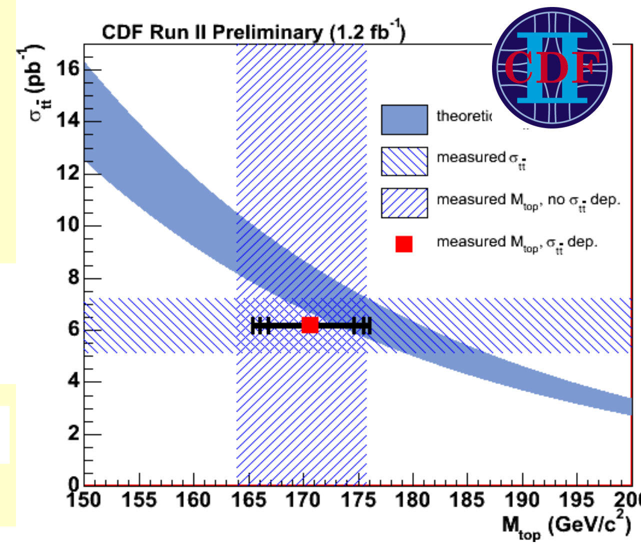


traditional method:

cross section constraint:

70 candidate events (≥0 b-tag)

No in-situ JES calibration.



$$M_{top} = 169.7^{+5.2}_{-4.9}(\text{stat.}) \pm 3.1(\text{syst.})\ \text{GeV}/c^2$$

$$M_{top} = 170.7^{+4.2}_{-3.9}(\text{stat.}) \pm 2.6(\text{syst.}) \pm 2.4(\text{theo.})\ \text{GeV}/c^2$$

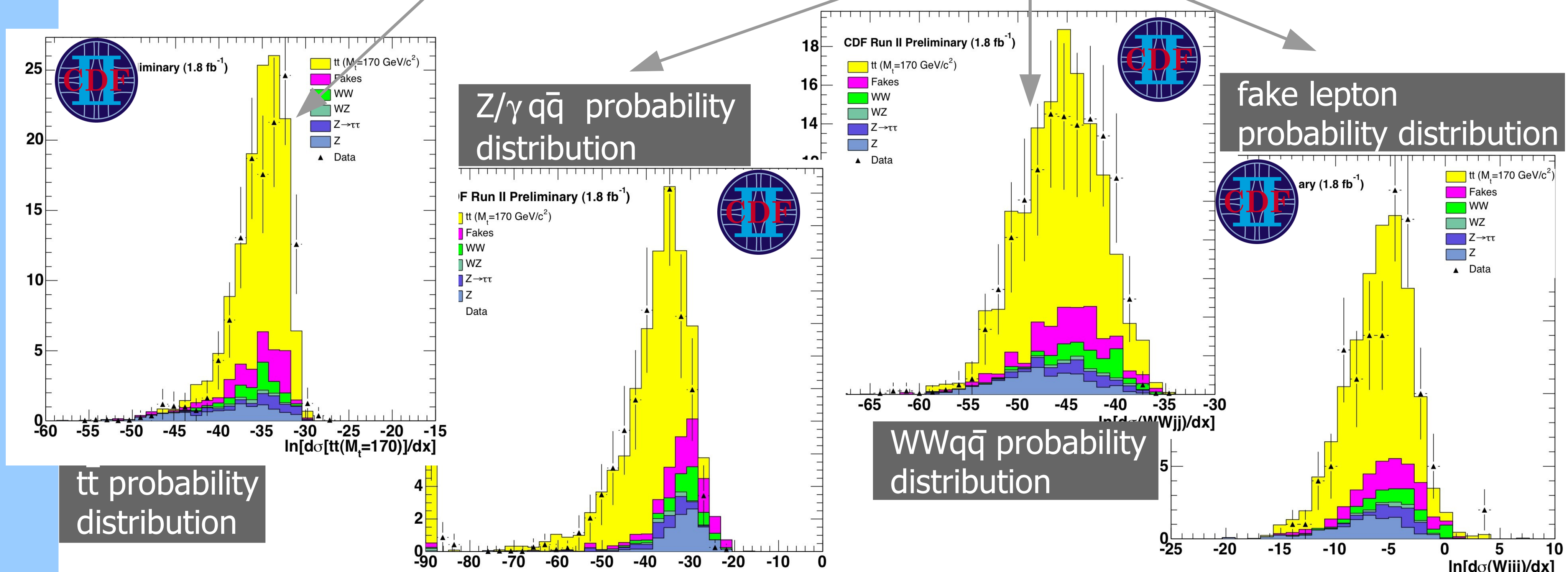
Matrix Element, Di-Lepton, 1.8fb^{-1}

- Event probability is weighted sum of signal and of three major backgrounds

$$P_{t\bar{t}}(\boldsymbol{x};M_{\rm top}) = P_{\rm s}(\boldsymbol{x};M_{\rm top})\,w_{\rm s}(M_{\rm top}) + \sum_{i=1}^{3} P_{\rm b}^{(i)}(\boldsymbol{x})\,w_{\rm b}^{(i)}(M_{\rm top})$$

signal from LO matrix element

background, fixed weights $w_b^{(i)}$

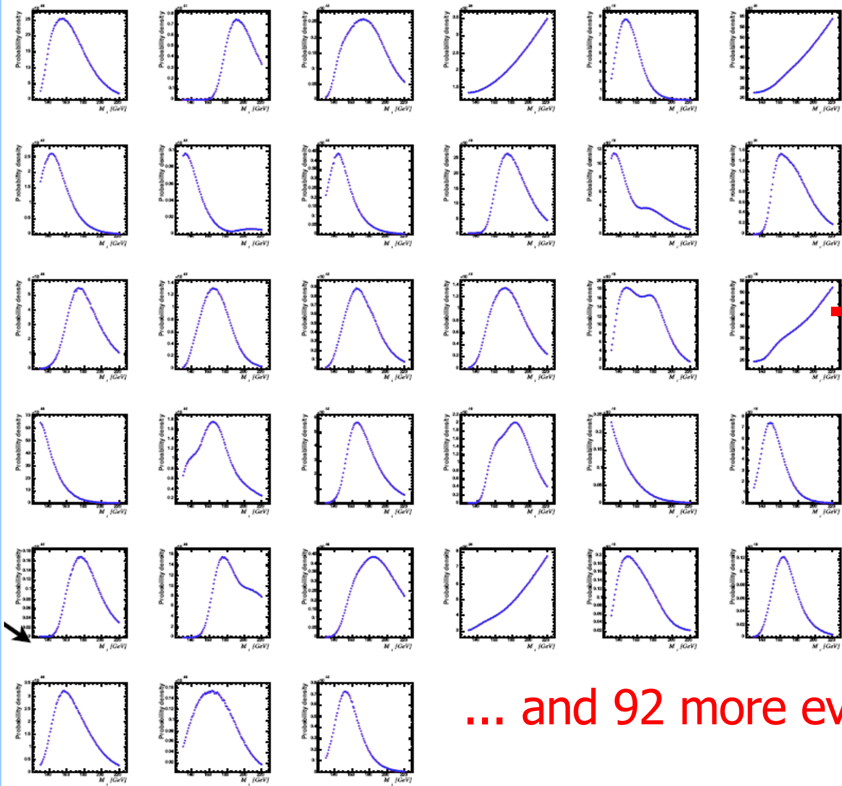


... agree well with data!

Log(dσ/dx)

- Background probabilities reduce M_{top} uncertainty by 15%
- In-situ JES calibration not possible for the signal.

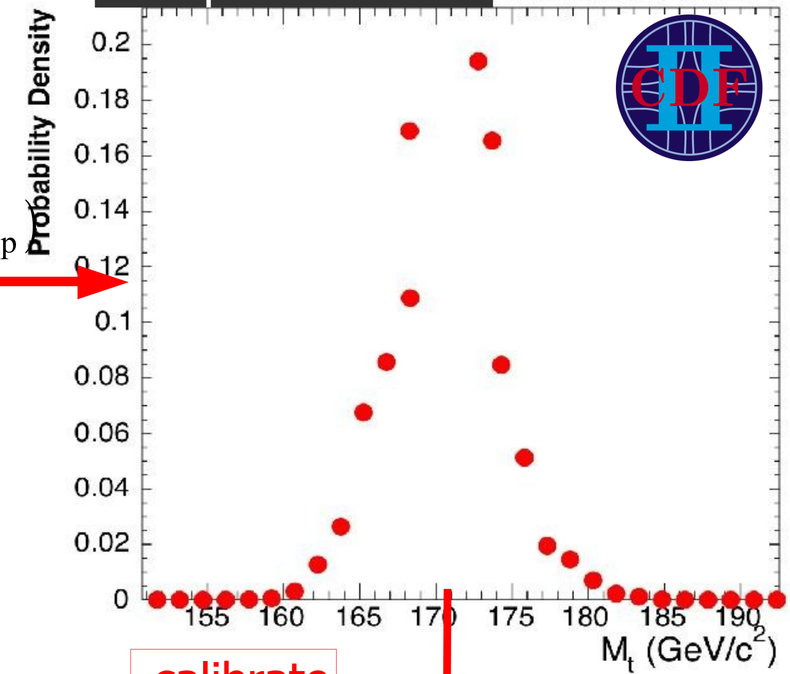
Matrix Element, Di-Lepton, 1.8fb^{-1}



$\prod P_{t\bar{t}}(\boldsymbol{x}; M_{top})$

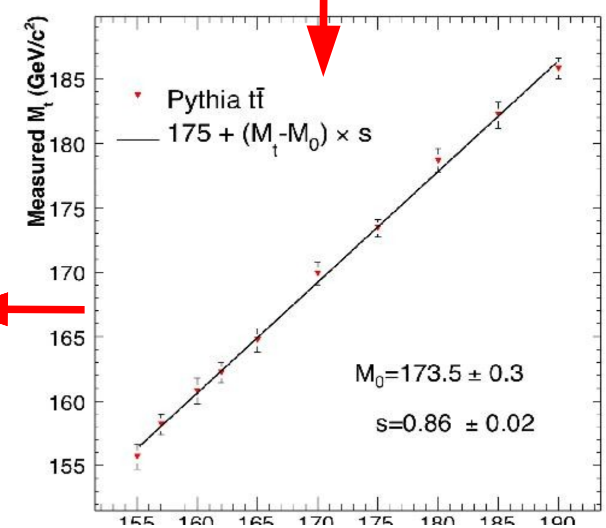
multiply

sample likelihood



... and 92 more events

calibrate



slope <1 due to background

Result using 125 candidate events (≥0 b-tag):

$$M_{top} = 170.4 \pm 3.1(\text{stat.}) \pm 2.6(\text{JES}) \pm 1.5(\text{syst.})\ \text{GeV}/c^2$$

... most precise single di-lepton top quark mass!

Template Method, All-Jets, 943pb^{-1}

- 2-D templates for M_{top} and JES: Signal from ME, background model from data (0 b-tag sample, has negligible signal)

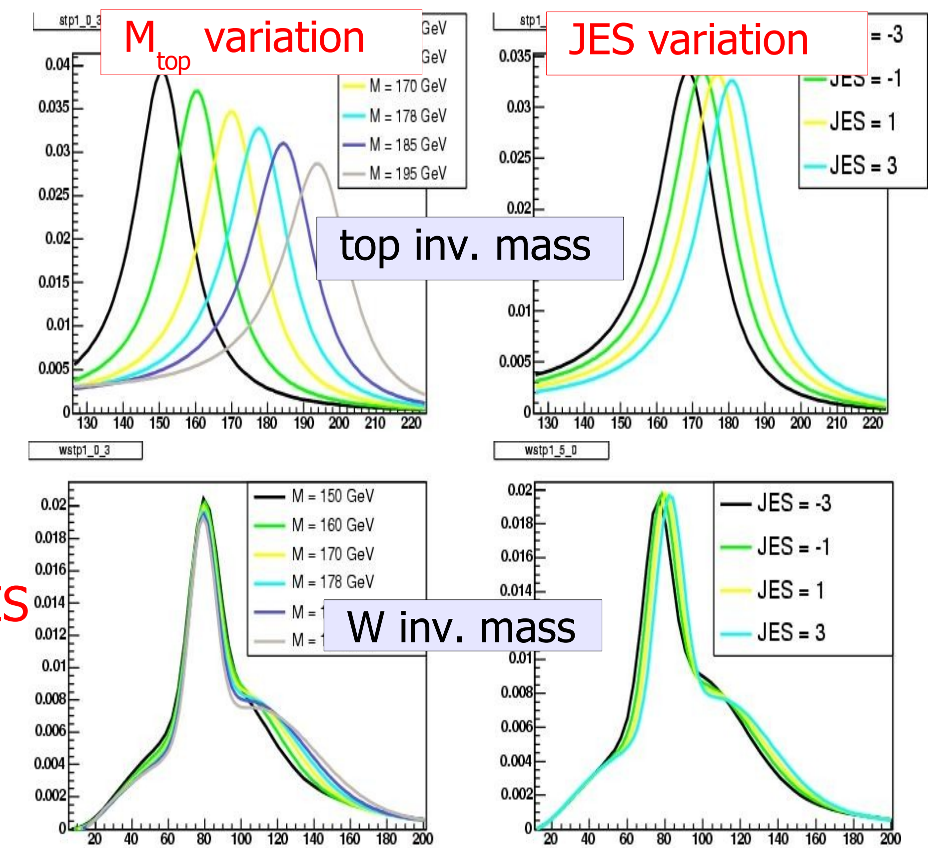
- Signal+background probability densities:

P ($\mathbf{m_t}$ | M_{top}, JES) P ($\mathbf{m_W}$ | M_{top}, JES)

$$L_{1,2\text{ b-tag}} = L^{(\text{top})}_{\text{shape}} \times L^{(W)}_{\text{shape}} \times L_{\text{obs}} \times L_{\text{sig}}$$

constrain to number of observed events

constrain to number of signal events



- Sample likelihood:

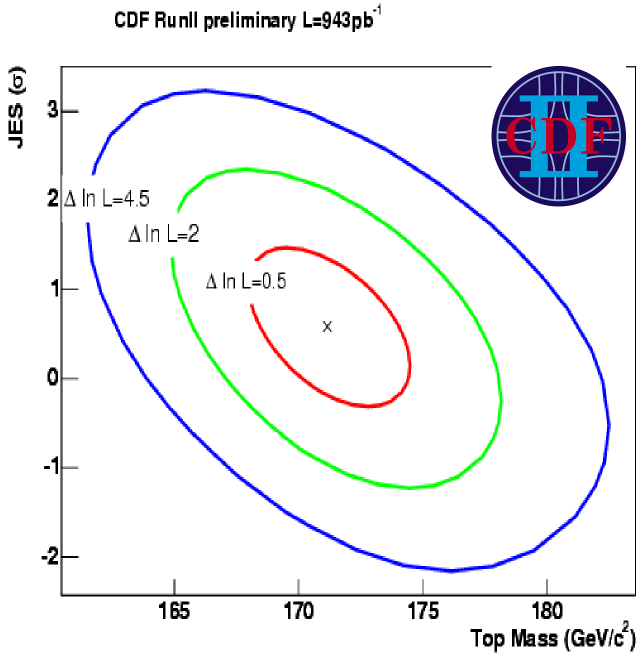
constrain to a priori JES

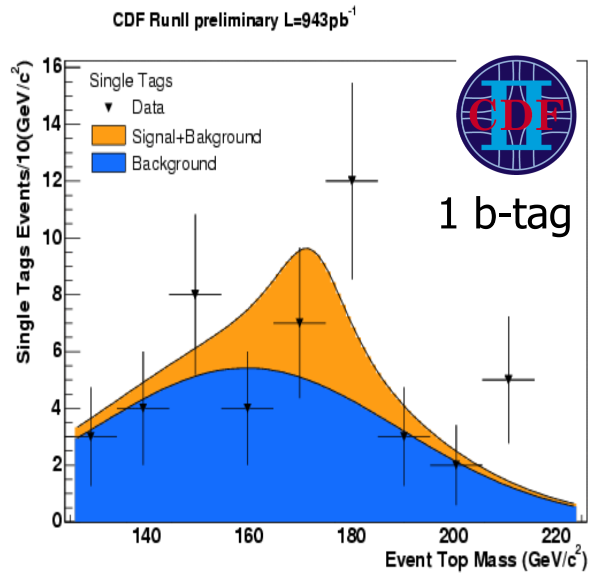
$$L = L_{1\text{ b-tag}} \times L_{2\text{ b-tags}} \times L_{\text{JES}}$$

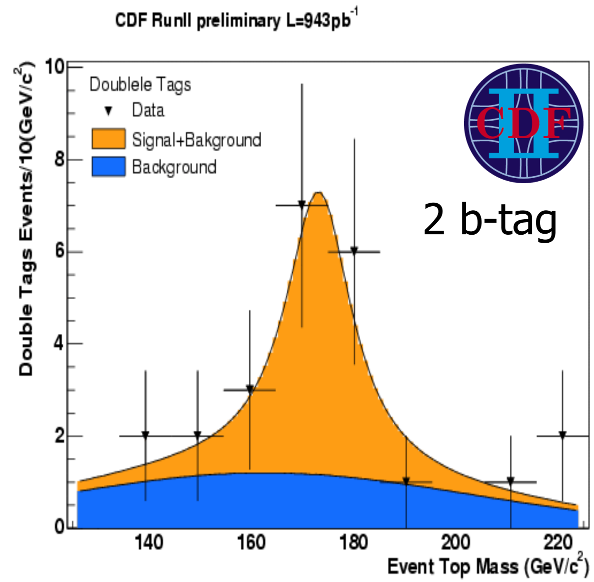
- Likelihood is maximized w.r.t:

M_{top}, JES & number of 1(2) b-tagged signal/back. events respecting constraints (background fraction poorly known in All-Jets channel!)

Template Method, All-Jets, 943pb^{-1}







Result using 64 candidate events (≥ 1 b-tag):

$$M_{top} = 171.1 \pm 2.8(\text{stat.}) \pm 2.4(\text{JES}) \pm 2.1(\text{syst.})\ \text{GeV}/c^2$$

- First All-Jets result with in-situ JES.
- All-Jets channel becomes competitive!

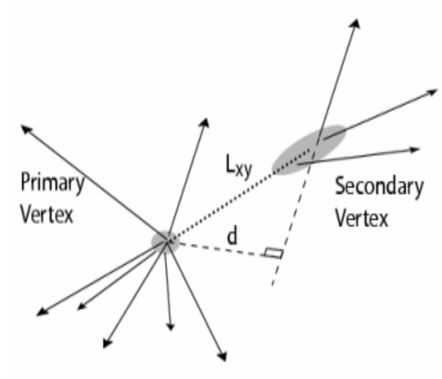
- Result from "traditional" 1-D template method using kinematic mass fitter:
  - no in-situ JES calibration, no restrictive signal probability cut:

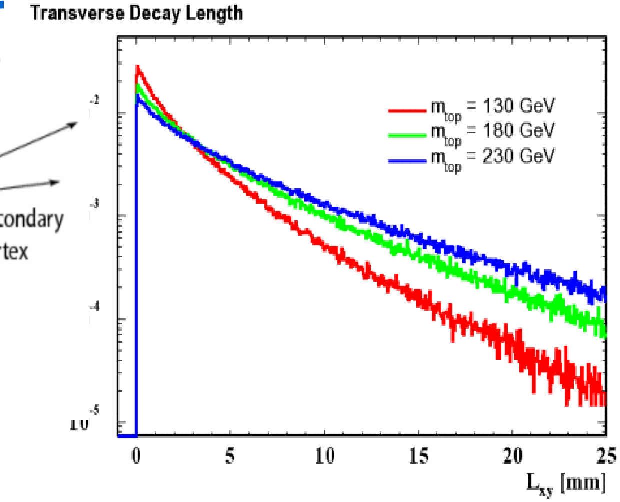
1-D template, 1020pb^{-1}, 772 candidate events (≥ 1 b-tag):

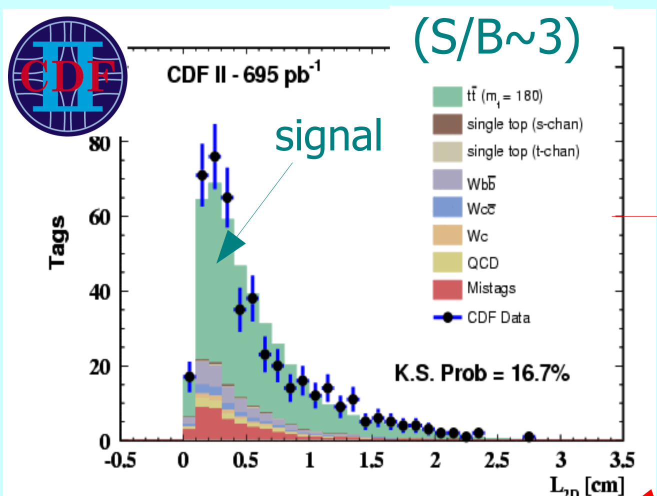
$$M_{top} = 174.0 \pm 2.2(\text{stat.}) \pm 4.5(\text{JES}) \pm 1.7(\text{syst.})\ \text{GeV}/c^2$$

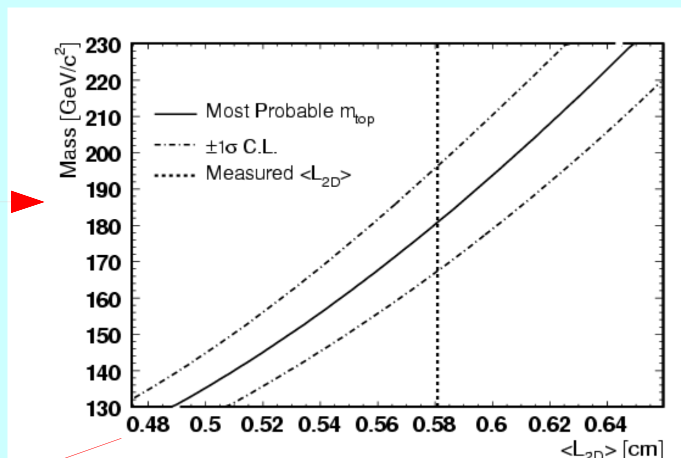
Decay Length Technique, Lepton+Jets 695pb^{-1}

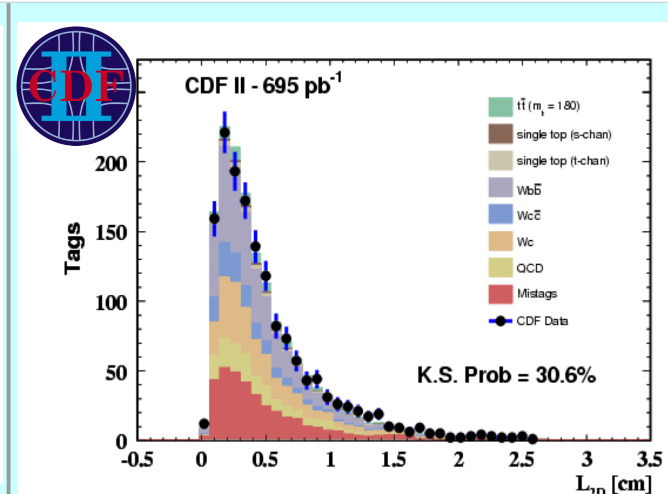
- Lepton+jets (with ≥ 3 jets, ≥ 1 b-tag)
- Template variable is transverse decay length
- Top mass sensitivity comes through slope of an exponential curve (difficult to measure)
- Mean of decay length is converted to most probable top mass (assessed via MC)











Result using 375 candidate events:

$$M_{top} = 183.9^{+15.7}_{-13.4}(\text{stat.}) \pm 0.3\,(\text{JES}) \pm 5.6\,(\text{syst.})\,\text{GeV}/c^2$$

control sample (W+1jet,W+2jets)

- Systematics largely uncorrelated with those of other measurements!
- Statistics limited, but can make significant contribution to LHC

Systematics

(status 03/07/2007)

Uncertainties [GeV/c^2]	Di-Lepton (ME 1030 pb^{-1})	Lepton+Jets (ME 955 pb^{-1})	All-Jets (TM 940 pb^{-1})
Statistical	3.9	1.6	2.8
JES	3.5	1.5	2.4
Residual JES		0.4	0.7
b-JES		0.6	0.4
ISR/FSR	0.4	1.1	1.2
PDF	0.8	0.1	0.5
Generator	0.9	0.2	1.0
MC statistics	0.7	0.2	0.4
Background model	0.2		0.9
Sample composition	0.7		0.1
Lepton p_T	0.1	0.2	
b-tag p_T dep.		0.3	
Multiple interactions	0.2	0.1	
Method	0.6		0.2
Total systematics (excluding JES)	1.7	1.4	2.1

physics model

Lepton+Jets (ME 370 pb^{-1})

Source of Uncertainty	b-Tagging Analysis
Statistical uncertainty and jet energy scale	$+4.1$ -4.5
JES only	3.5
Physics modeling:	
Signal modeling	± 0.46
Background modeling	± 0.40
PDF uncertainty	$+0.16$ -0.39
b fragmentation	± 0.56
b/c semileptonic decays	± 0.05
Detector modeling:	
JES p_T dependence	± 0.19
b response (h/e)	$+0.63$ -1.43
Trigger	$+0.08$ -0.13
b tagging	± 0.24
Method:	
Signal fraction	± 0.15
QCD contamination	± 0.29
MC calibration	± 0.48
Total systematic uncertainty	$+1.2$ -1.8
Total uncertainty	$+4.3$ -4.9

- Non-JES systematics mainly dominated by physics model:
  - amount of FSR gluon radiation, hadronization model,...

... will limit or knowledge of M_{top} in future!

Jet Energy Correction

$$P_T = \{ P_T^{cal}(R) \times f_{rel} - f_{MI} \} \times f_{abs} - f_{UE} + f_{OOC}$$

$f_{rel} = f_{rel}(R, \eta, P_T^{cal})$ **:Relative correction** ← di-jet balance (data, MC)

- makes calorimeter response uniform in η

$f_{MI} = f_{MI}(R)$ **:Multiple Interaction Correction** ← MinBias (data)

- subtracts energy from pile-up ppbar interactions

$f_{abs} = f_{abs}(R, P_T)$ **:Absolute correction** ← di-jets (MC)

- corrects calorimeter jets to particle jets

$f_{UE} = f_{UE}(R, P_T)$ **:Underlying Event Correction** ← MinBias (MC)

- subtracts energy from spectator particles (ISR, beam-beam-remnant)

$f_{OOC} = f_{OOC}(R, P_T)$ **:Out-of-Cone Correction** ← di-jets (MC)

- corrects for particle losses outside the jet cone (FSR, hadronization)

- At each step, systematic uncertainties are estimated by comparing MC and data
- Photon+jets, Z+jets used for validation

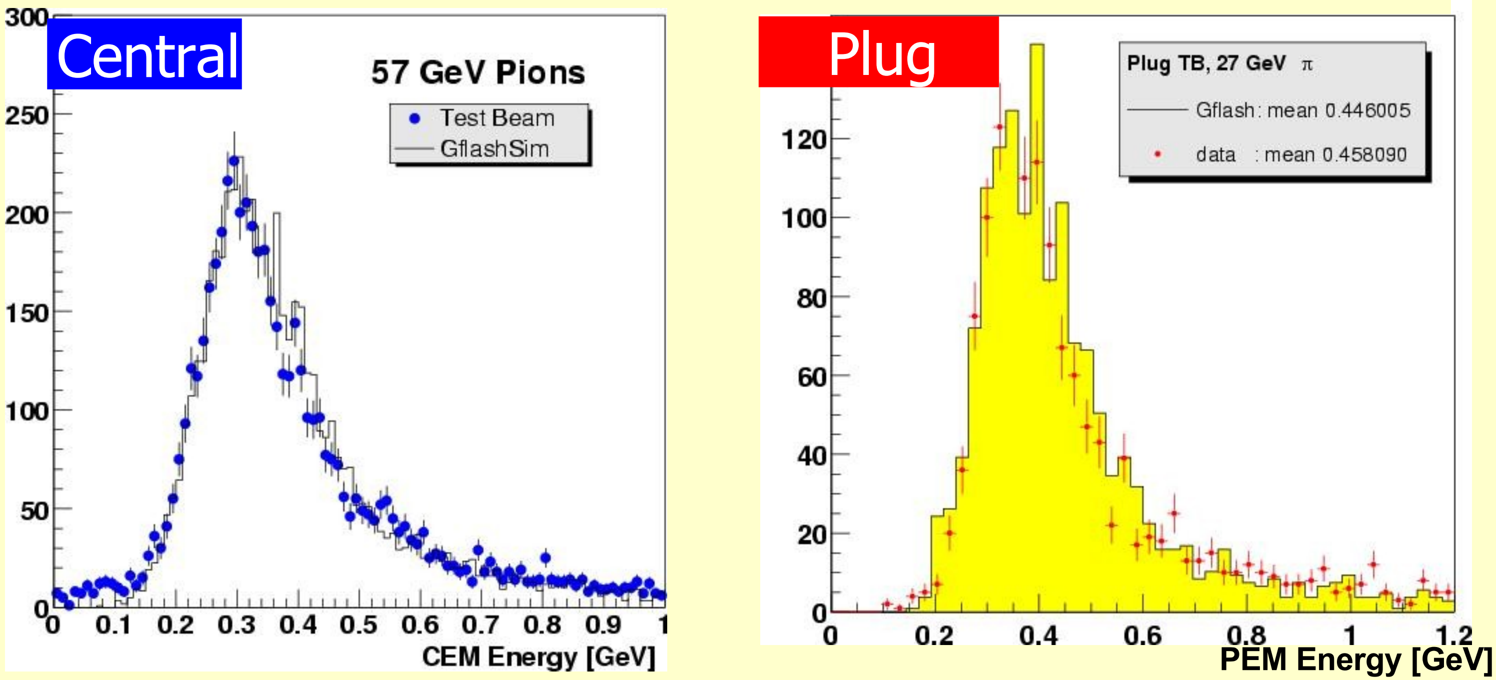
MIP Peak

$$dE_{vis}(\mathbf{r}) = E_{inc}\,\hat{m}\sum_{\hat{k}} \frac{\hat{k}}{\hat{m}} c_{\hat{k}}\, f_{\hat{k}}(\mathbf{r})\, d\mathbf{r}$$

- MIP response theoretically well understood
- Charge collection efficiencies
- Serves as reference for other responses

mean and width of MIP response

test beam pions

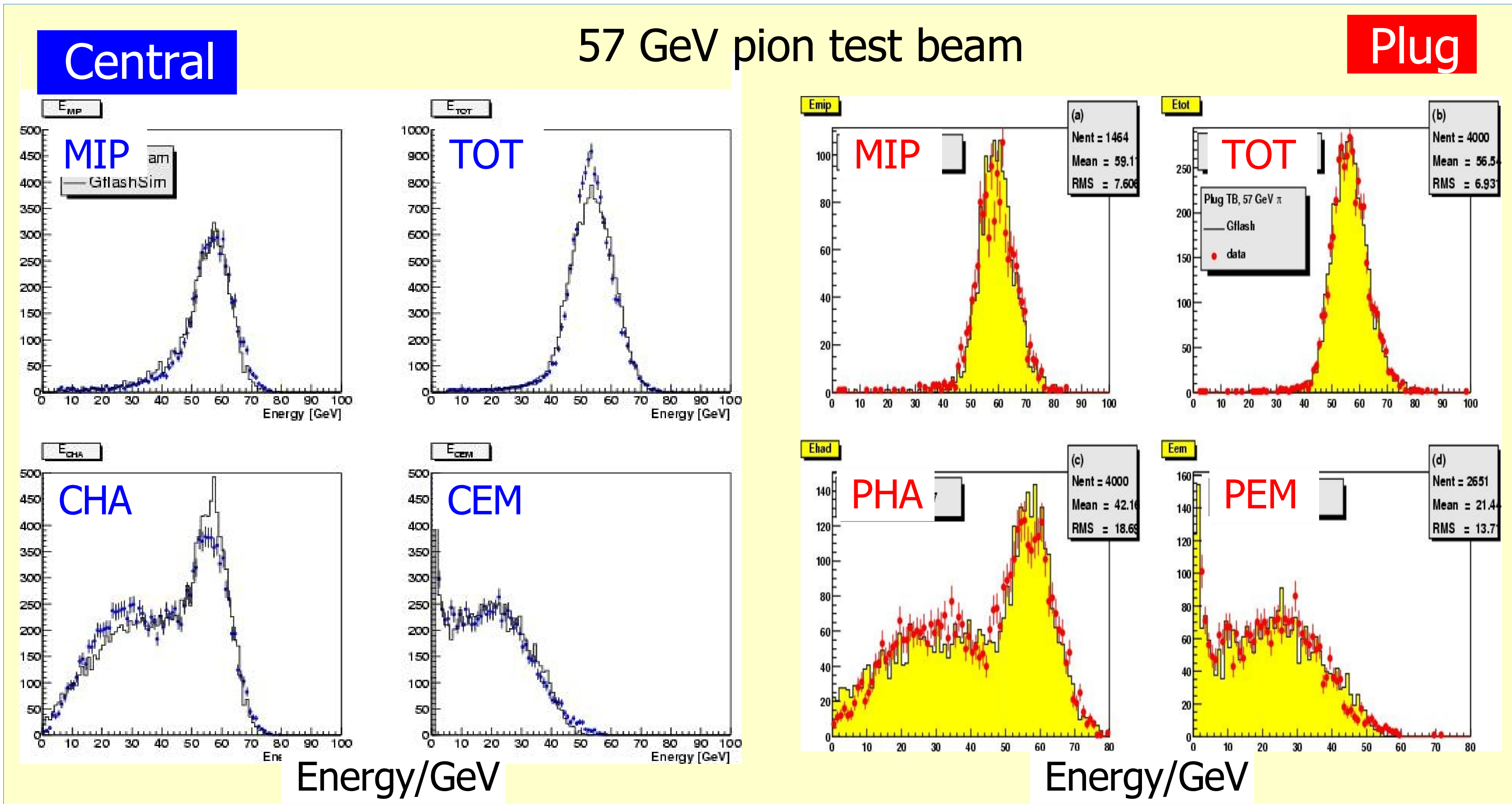


Hadronic Energy Shape

$$d E_{vis}(\mathbf{r}) = E_{inc}\,\hat{m}\sum_{\hat{k}} \frac{\hat{k}}{\hat{m}}\, c_{\hat{k}}\, f_{\hat{k}}(\mathbf{r})\, d\mathbf{r}$$

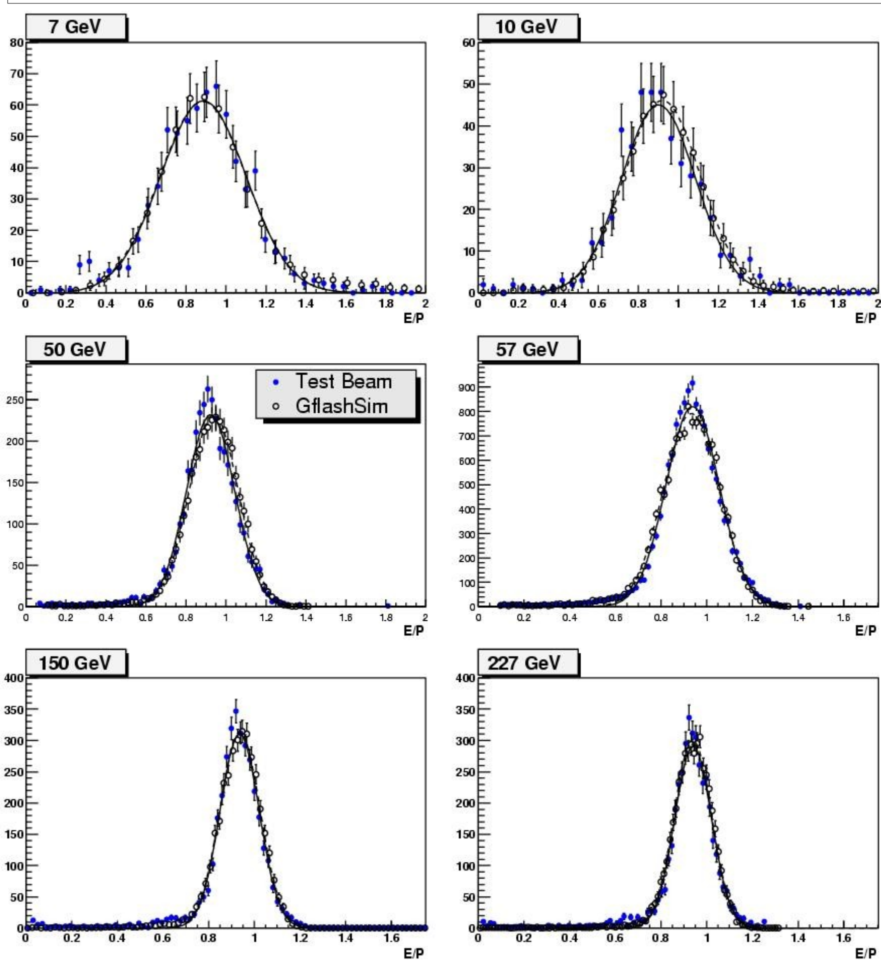
- Iterative procedure to find reasonable parameter set (under-constraint problem)

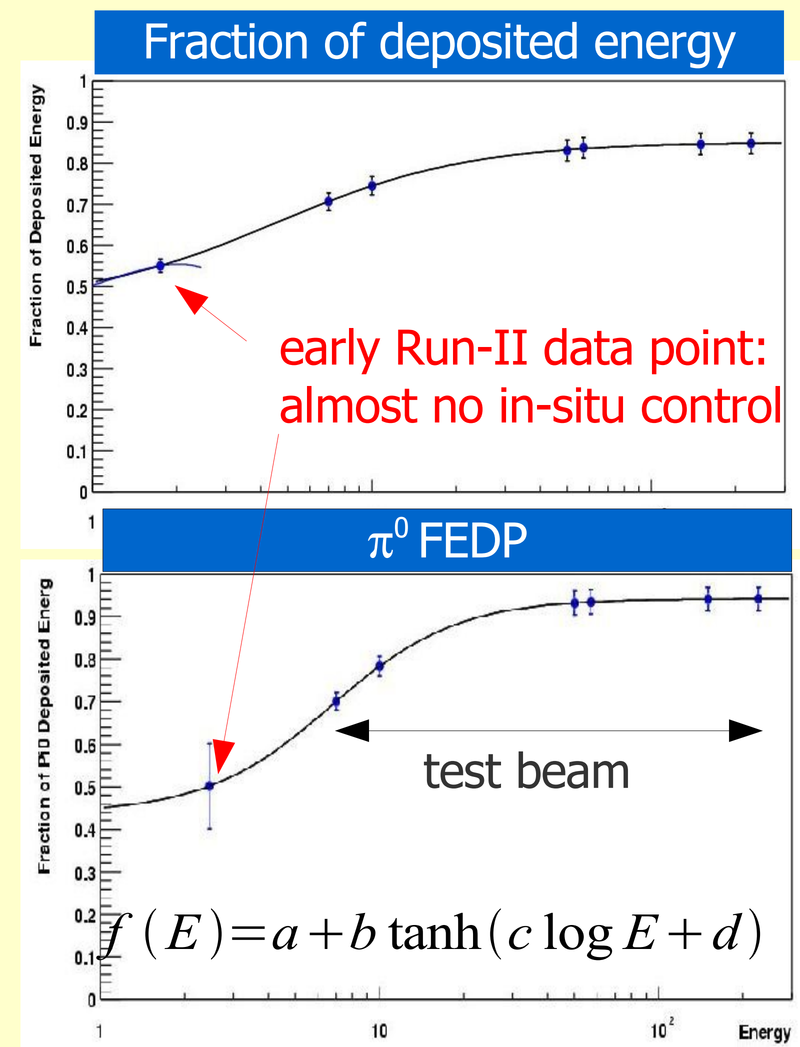
GFLASH switches:
- sampling fractions
- f_{dep}, $f_{\pi 0}$, α_l, β_h, β_l + widths



Energy Dependence (Early Run-II picture)

Test beam E/p distributions (Central)

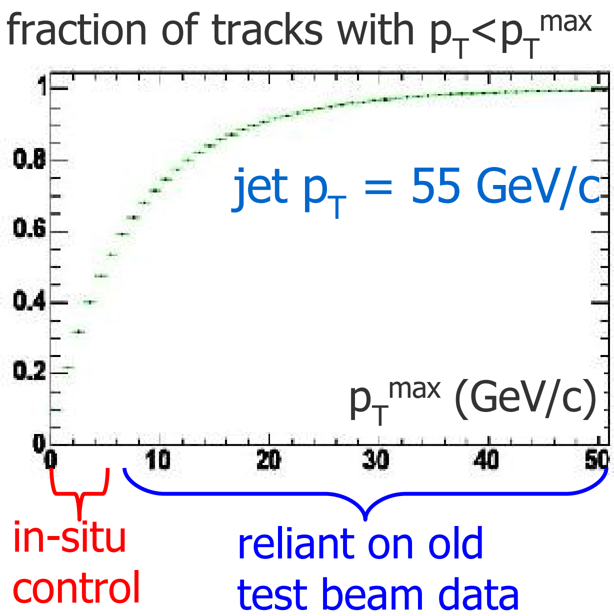




- Many longitudinal details are fixed using 57 GeV pion test beam data.
- Energy dependence adjusted using all available test beam data sets:
  Central: 7-227 GeV/c, Plug: 9-231 GeV/c

In Situ Tuning Approach

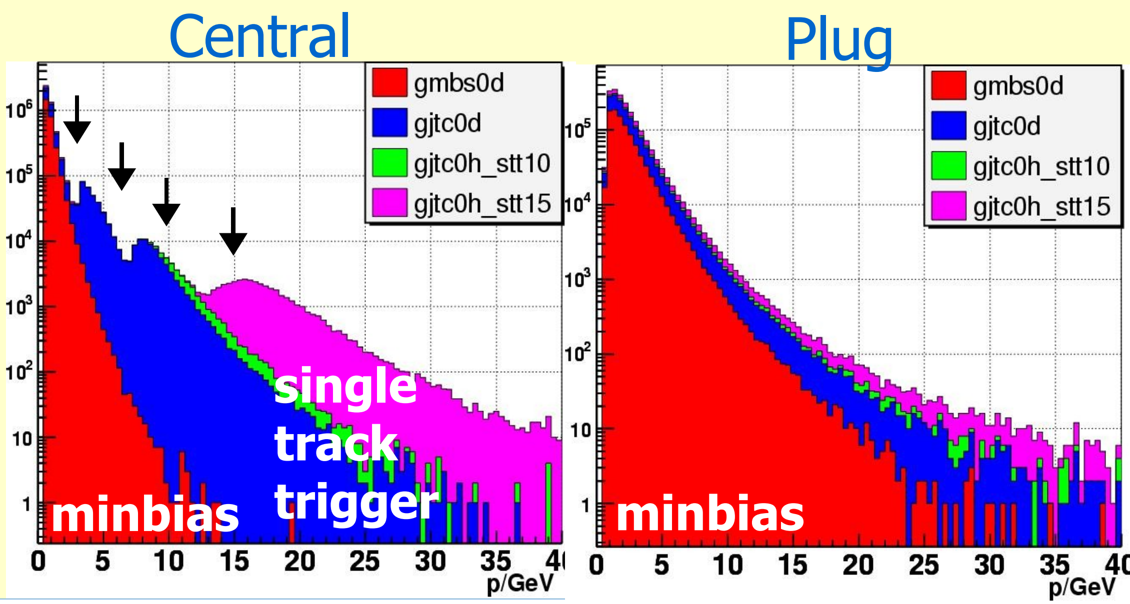
- Tuning is based on isolated charged particle response.
- Early Run-II picture:
  - In-situ tuning up to 2.5 (5) GeV (statistics limited)
  - Problem with test beam: time dependence, different experimental environment



(early Run-II picture)

Run-II improvements

- Single track triggers with thresholds up to 15 GeV/c.
- Single charged particle response analysis.
- In-situ tuning extended up to 40(20) GeV/c in Central (Plug)

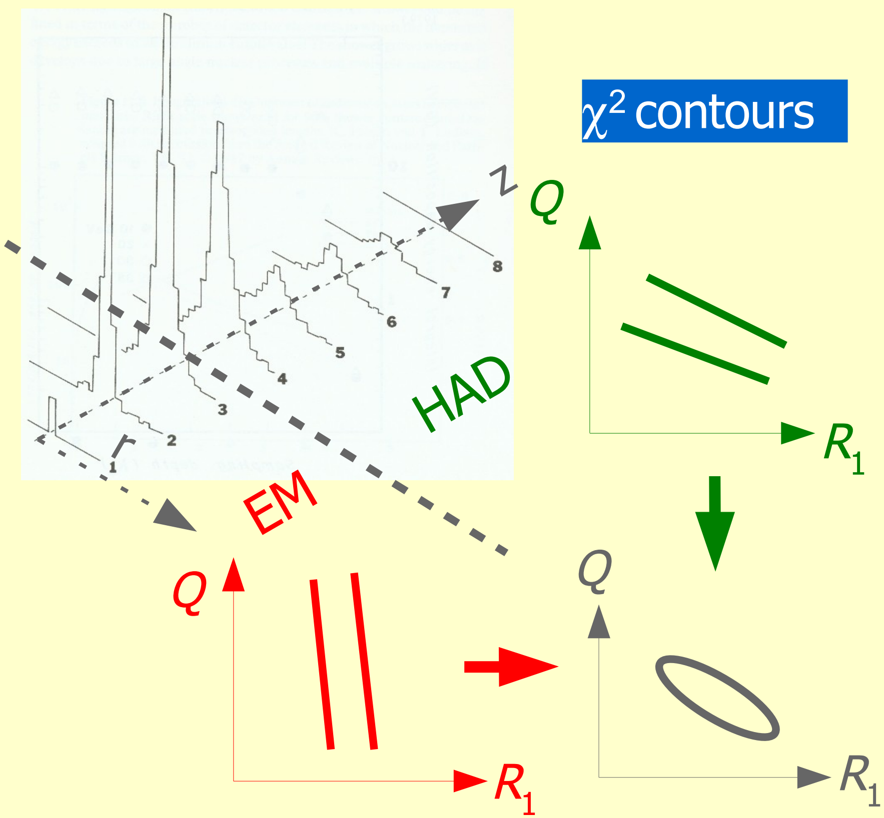


Lateral Profile

$$\langle R_0(E_{inc}, z)\rangle = [R_1 + (R_2 - R_3 \ln E_{inc})\, z]^n$$

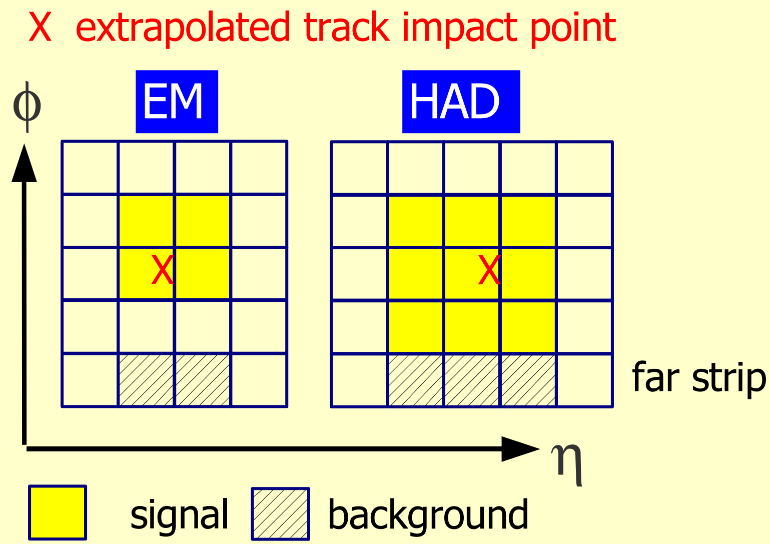
core term R_1

spread term Q
- shower depth
- incident particle energy

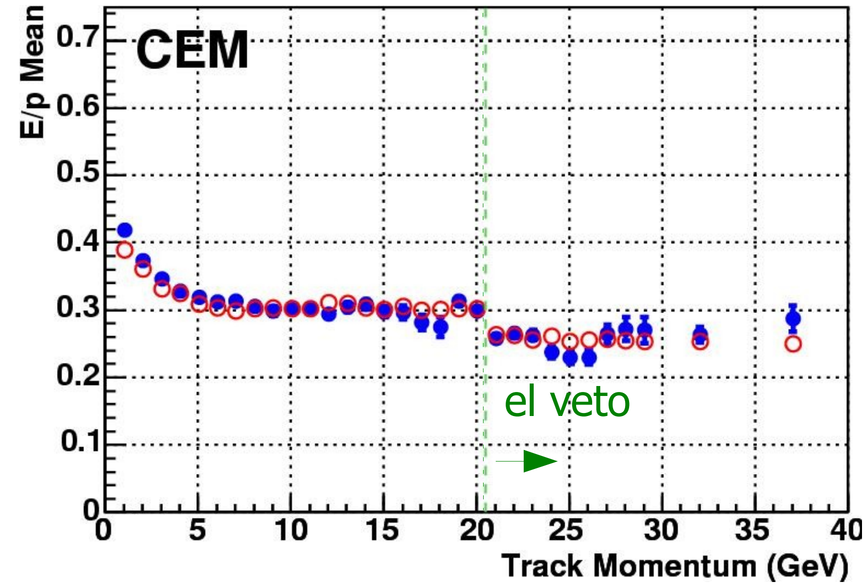


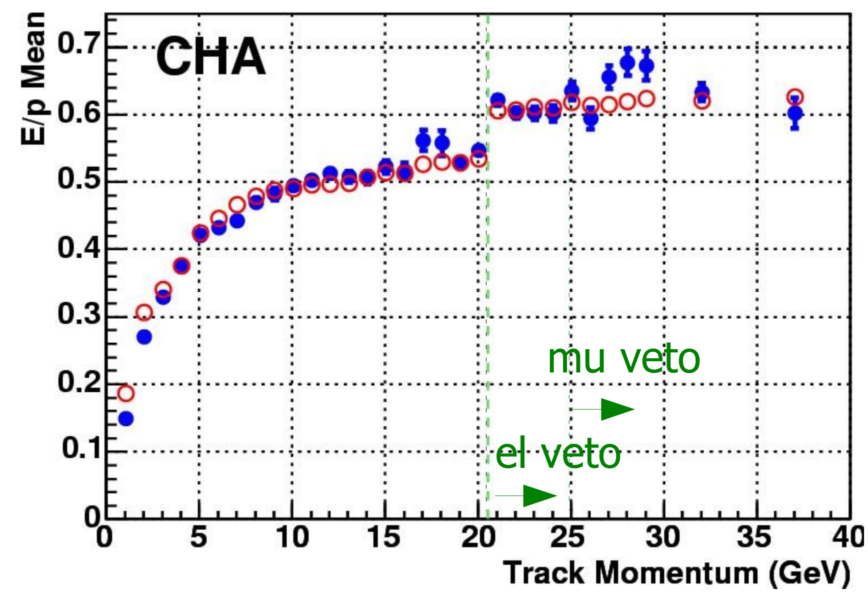
- HAD and EM probe different shower depths → can constrain R_1 and Q.
- Scan (R_1,Q) at fixed track momentum bins
- Compare simulated E/p profiles with reference data profiles (χ^2-measure)
- Extract R_2 and R_3 from energy dependence of Q using R_1 constraint.

Absolute CEM and CHA Response



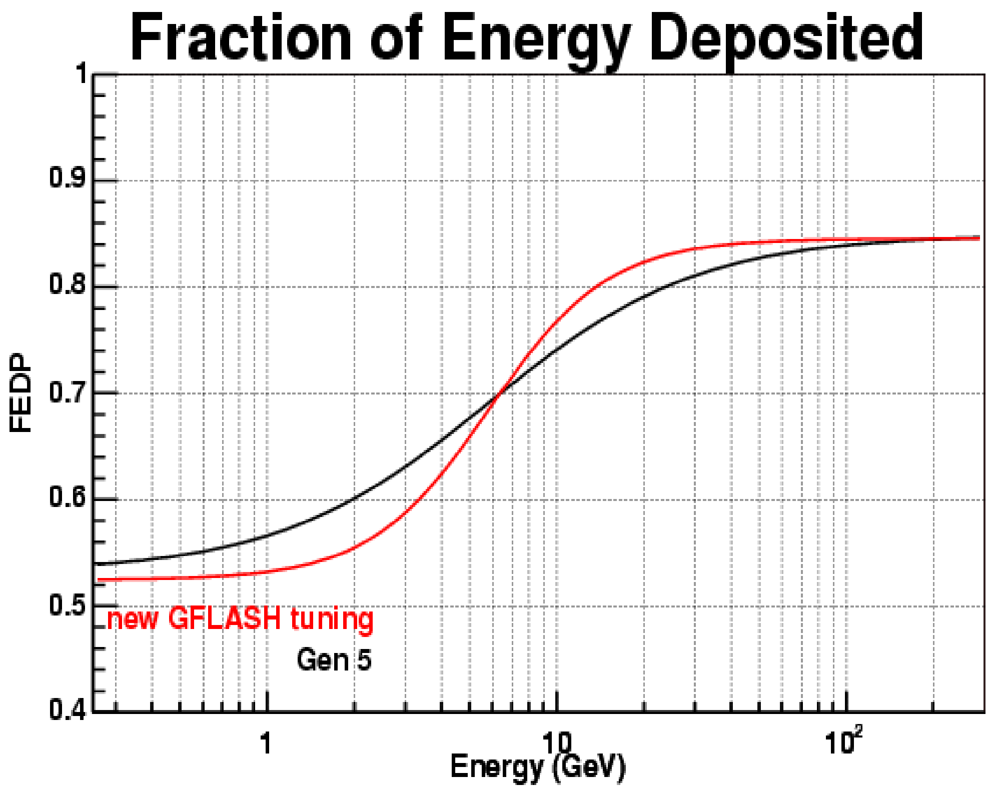
sig: EM=2x2 blocks, HAD=3x3 blocks
bck: EM=2x far strip, HAD=3xfar strip

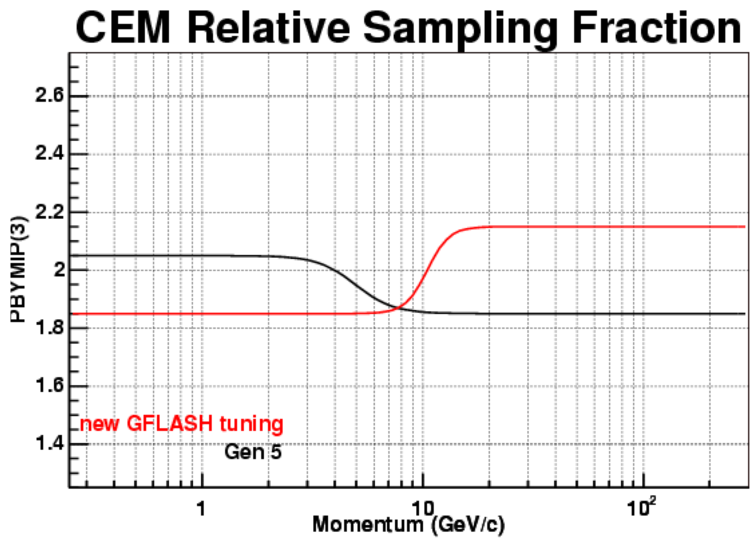


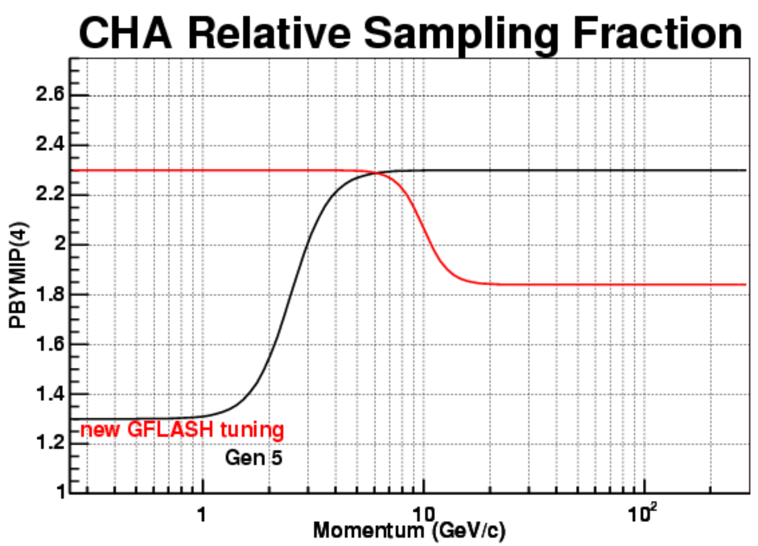


- These are <u>not primary tune</u> observables but serve as cross checks
- Responses dependent on shower start, shapes are more complicated than TOT and MIP
- Reasonable agreement

Parametrization (Central)



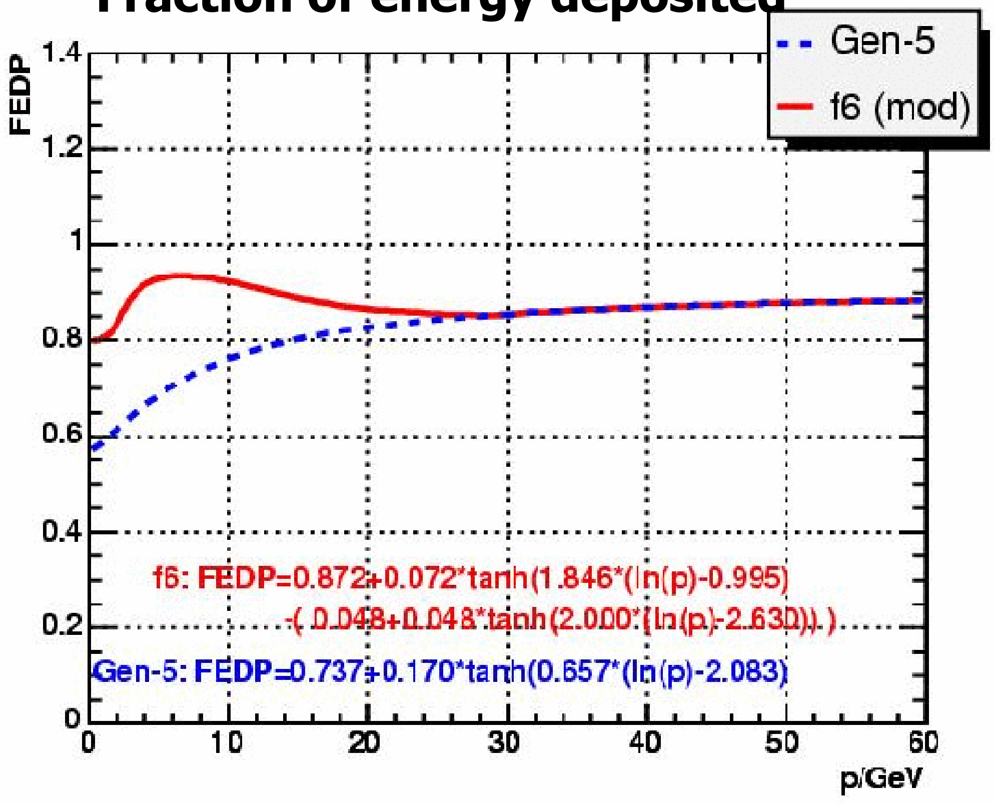




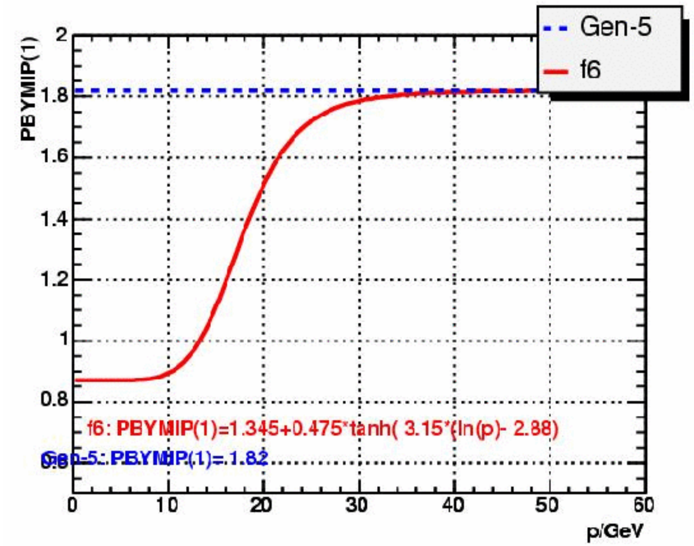
- Smooth parametrization connecting in-situ tuning and test beam tuning result.

Parametrization (Plug)

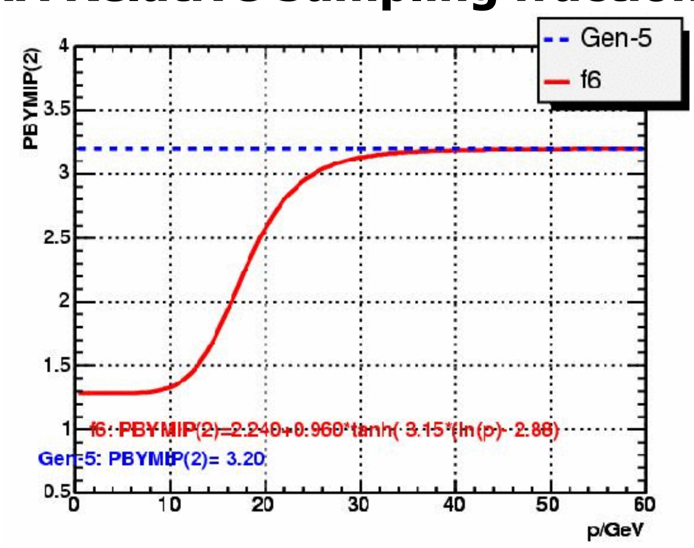
Fraction of energy deposited



PEM Relative Sampling fraction



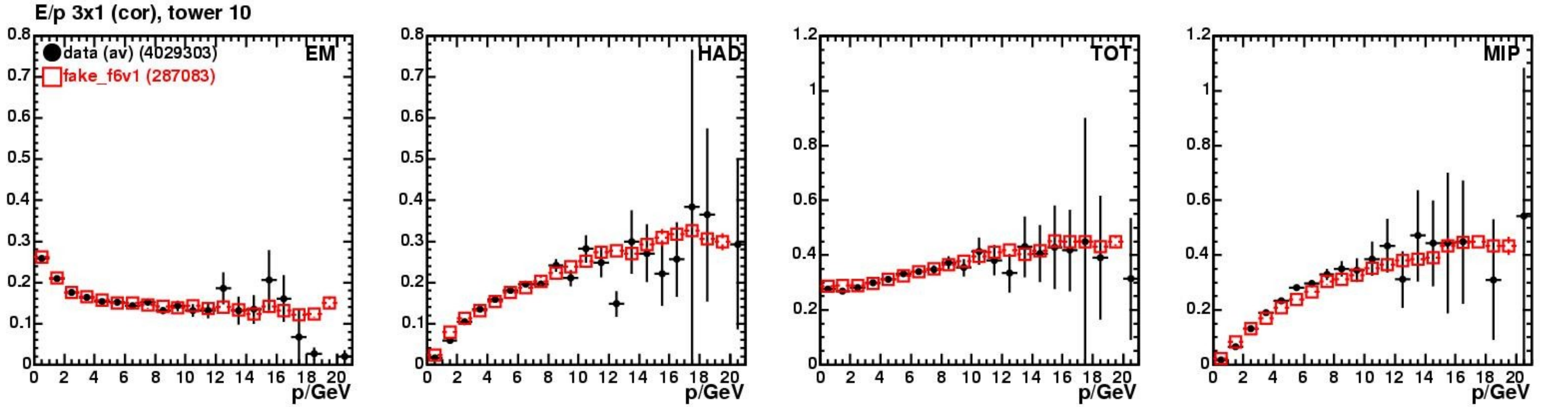
PHA Relative Sampling fraction



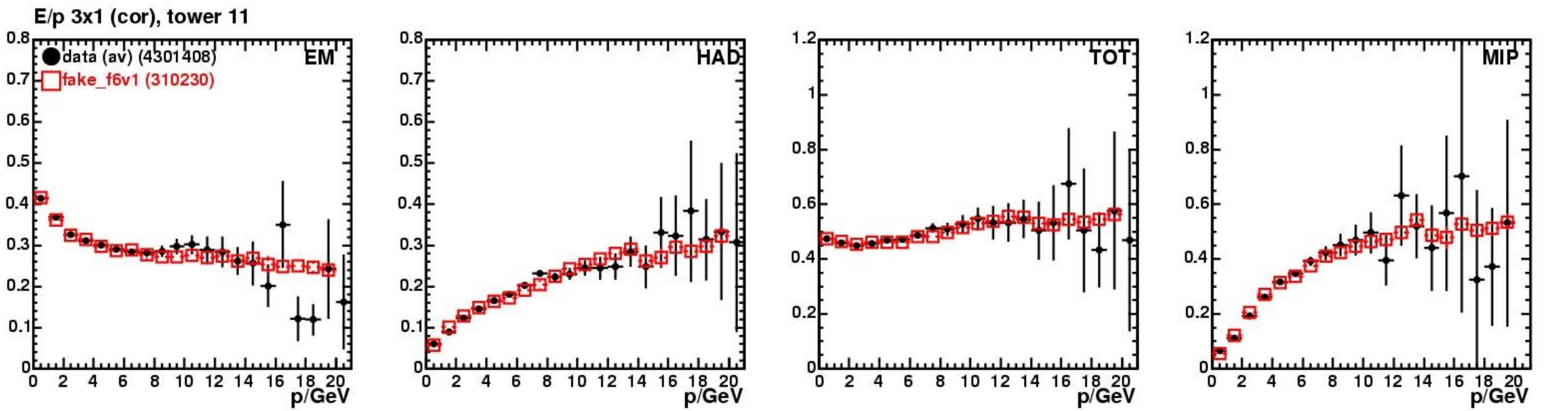
- Smooth parametrization connecting in-situ tuning and test beam tuning result.

Absolute Response Tuning (Crack)

- Tower 10



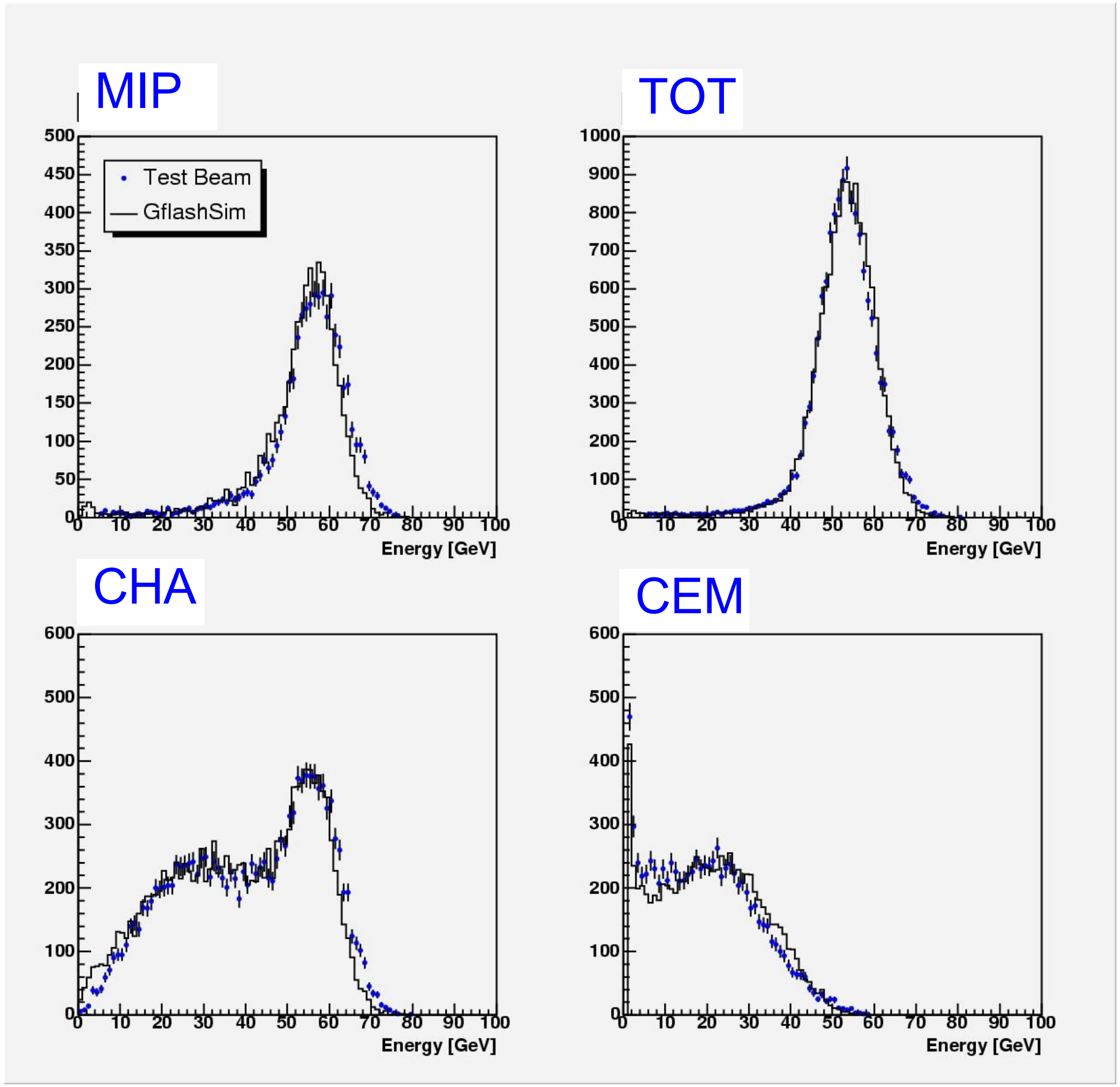
- Tower 11



sig: EM=3x1 strip, HAD=3x1 strip

bck: 1.5 x both side towers

Comparison with 57 GeV Test Beam Data



Gaussian Fits of the MIP and Total

MIP

57 GeV testbeam	57.2668 ± 6.3638
f4 tune MC	56.1179 ± 5.6968
percent difference	-2.0%

TOT

57 GeV testbeam	53.4797 ± 6.2428
f4 tune MC	53.6959 ± 6.3393
percent difference	+0.4%

- Reassure latest tuning using pure pion response from 57 GeV test beam.
- Reasonable agreement of E/p shapes between MC and data.

Tuning Uncertainties

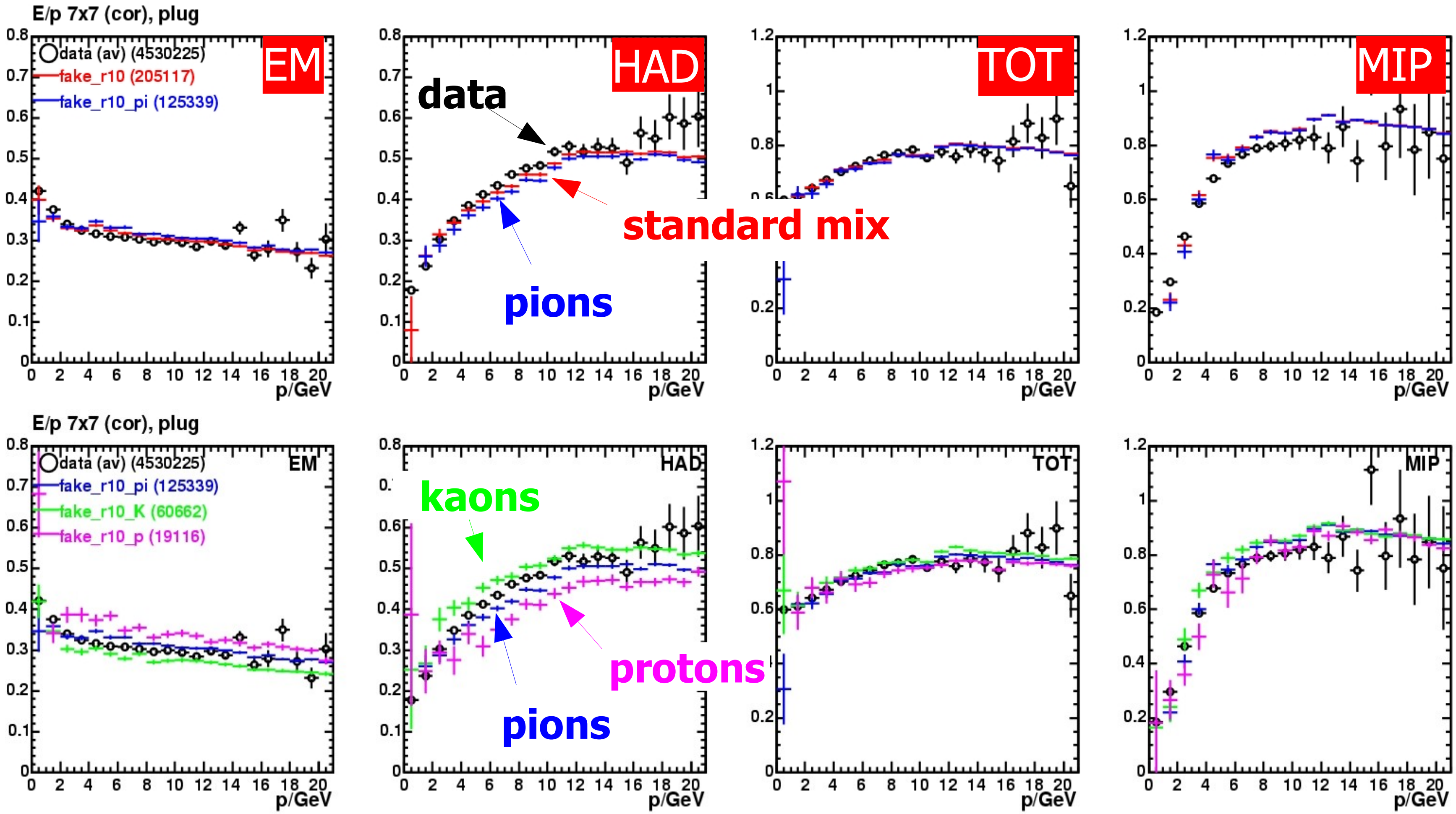
- E/p analysis
  - For TOT and MIP we consider Gaussians so we are insensitive to background contamination (e.g.: high p muons or electrons).
  - Treatment of uncorrelated background ensures that we can compare E/p from different event activity.
  - CES partially suppresses correlated background in Central.
  - Not sure about correlated background sources in the Plug (we don't use PES) – at least we are using a reasonable MC tool (Pythia) to model background.
  - Differences due to momentum spectrum has proven to be negligible.

- Lateral profile dependence
  - Profile mismatch can cause leakage effects .
  - After tuning this effect should be under control.

- Flavor dependence
  - MC mixture used at low p: minimum bias composition
    at high p: pions/kaons/protons = .6/.3/.1
  - very weak flavor dependence for primary variable TOT
  - moderate effect for MIP response (CHA, PHA sampling fractions)
  - larger effect for EM (CEM, PEM sampling fractions)
  - negligible effect for hadronic E/p profiles due to normalization

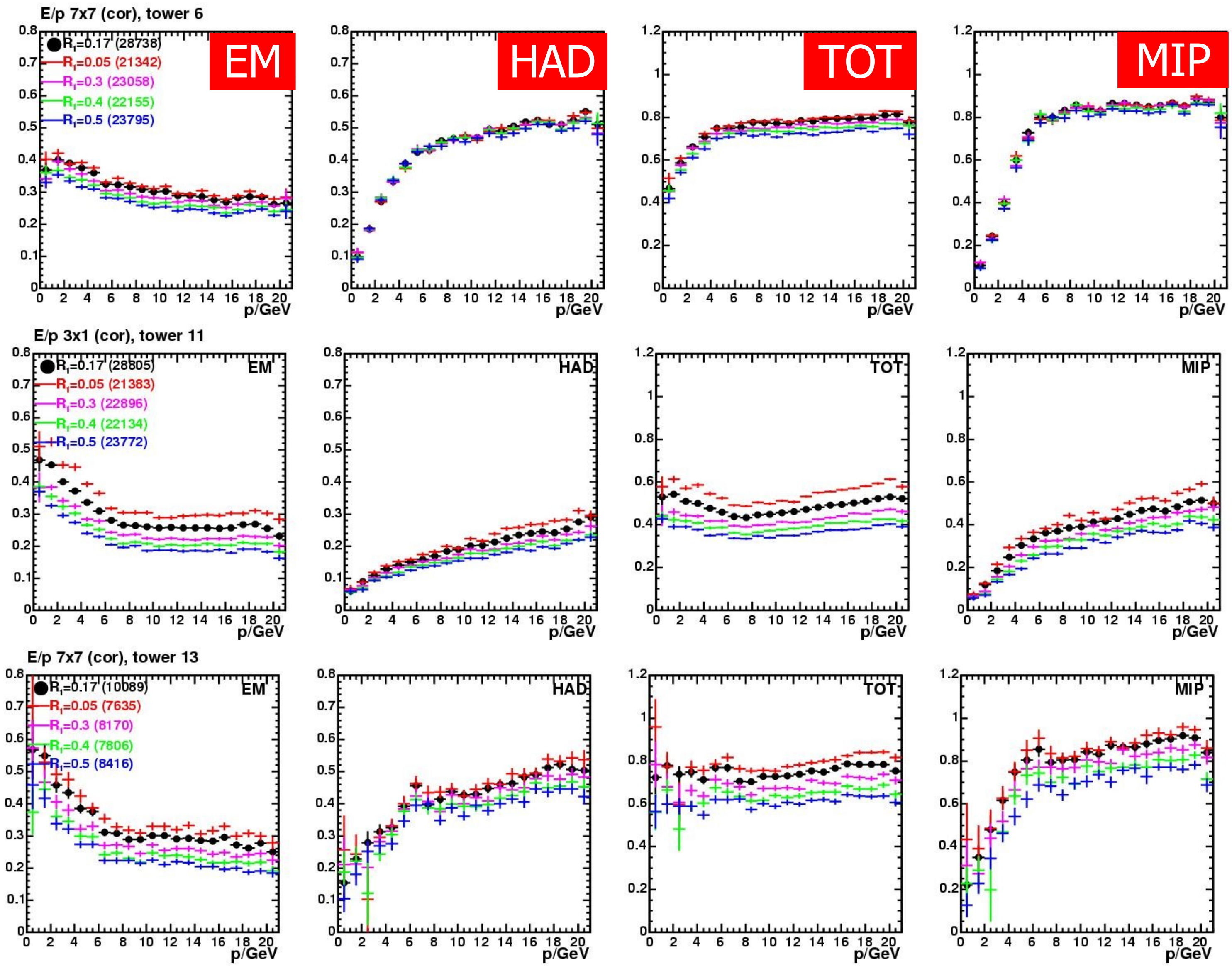
Flavor Dependence

- Extreme scenario: consider individual flavors (FAKEEV flavor/anti-flavor = 50%/50%) NB: Minbias spectrum dominates low p.



- GFLASH treats pion/kaon/proton showers equally! Flavor dependence is pure effect of different typical shower starts given by GEANT cross sections!
- Little /moderate effect in TOT/ MIP due to almost complete coverage of shower shapes.

Lateral Profile Dependence



tower 6

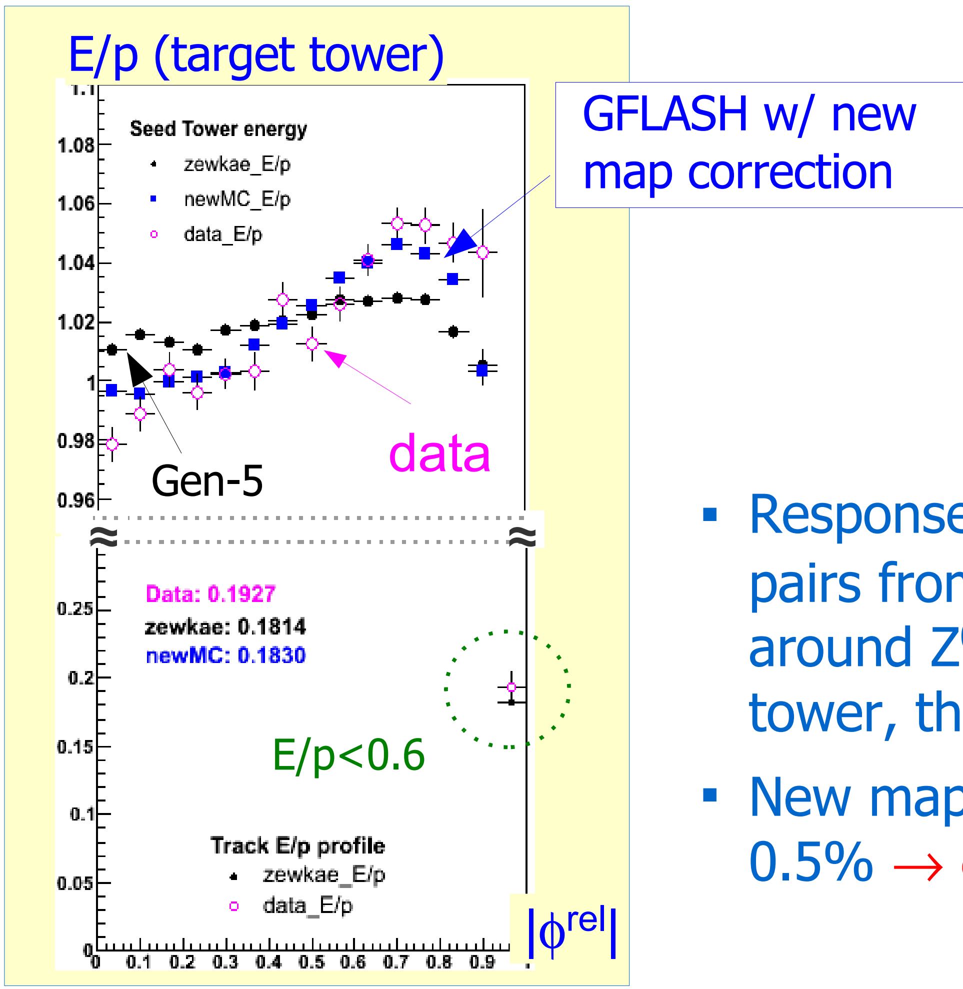
tower 11

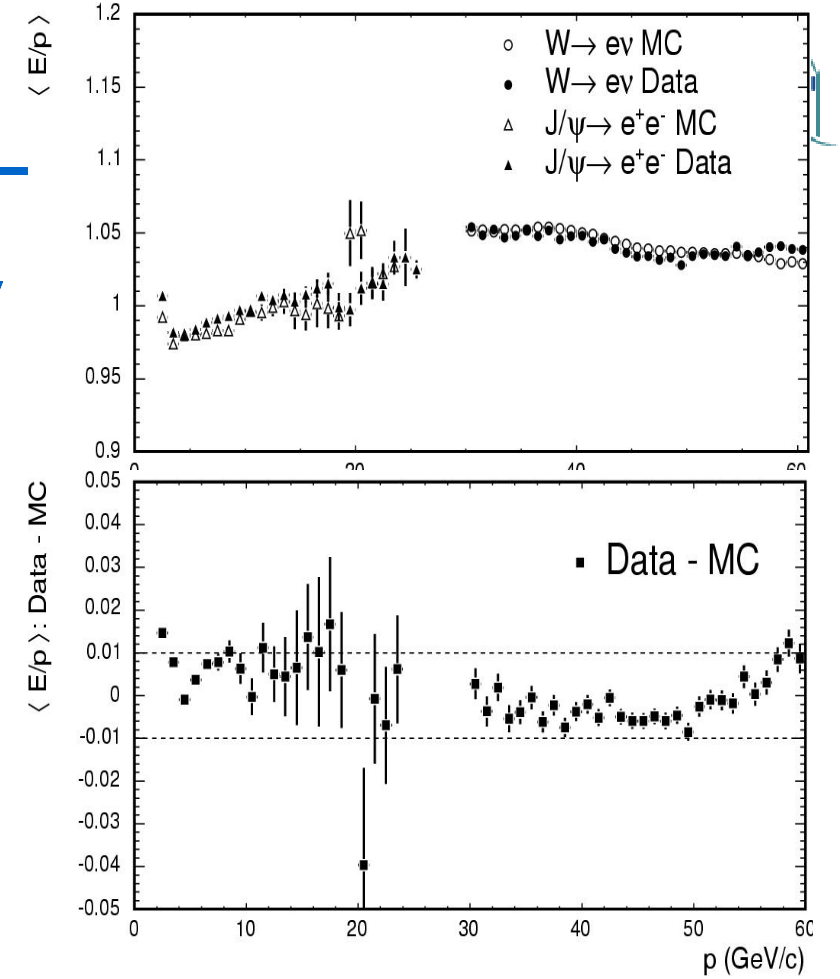
tower 13

- Effect of varying the lateral profile core parameter R_1 from 0.05 to 0.50.
  R_1 values used in Gen-5: 0.490 (p<5GeV), 0.015 (p>5GeV)

Electron Response

- Electromagnetic scale is tuned in-situ using electrons from J/ψ (low p)or W (high p) decay
- MC – data discrepancy ...
  - e pointing to inner 0.9x0.9 of target tower: 0.5%
  - e pointing to ϕ cracks (WLS, steel bar): **1.6%**

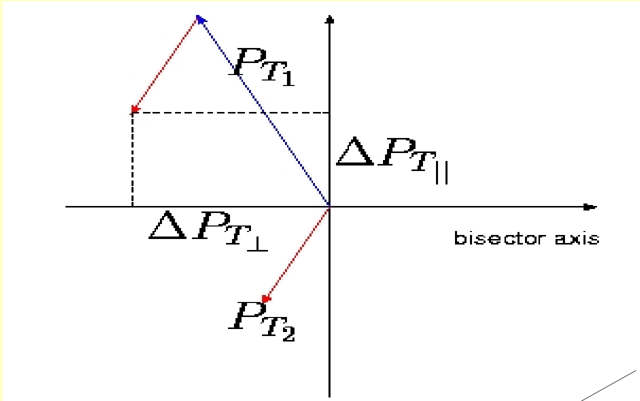




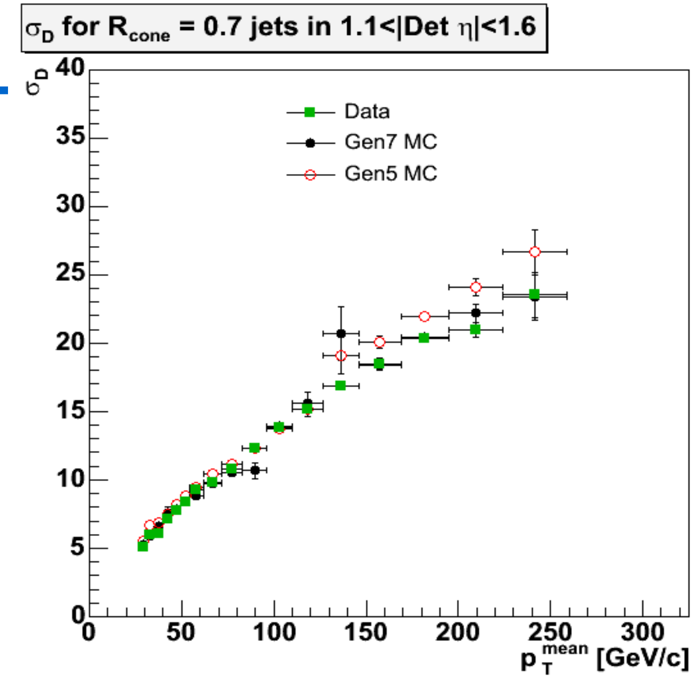
- Response along ϕ is monitored using electron pairs from Z^0 decays in a mass window around Z^0 mass. One keg in Central target tower, the other leg probes ϕ profile.
- New map correction in phi plus MC scaling by 0.5% $\rightarrow$ ϕ profile has significantly improved.

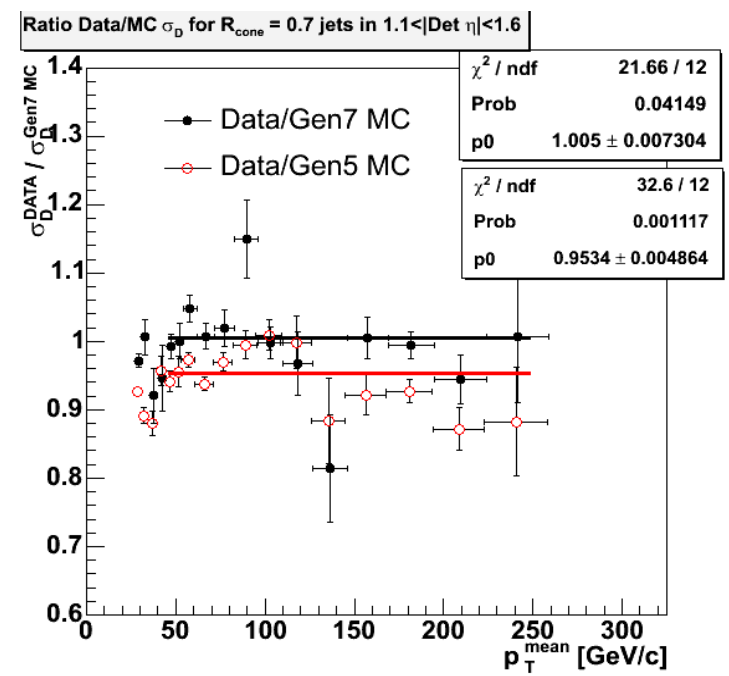
Jet Energy Resolution

Bi-Sector Method



- $\sigma_{||}$ = RMS of the $\Delta p_T^{||}$ ← dominated by physics effects (ISR recoil) and detector resolution
- σ_{PERP} = RMS of the $\Delta p_T^{\mathrm{PERP}}$ ← dominated by physics effects
- $\sigma_D = \sqrt{\sigma_{||}^2 - \sigma_{\mathrm{PERP}}^2}$ ← dominated by calorimeter resolution





- Simulated and measured resolution agree better in certain detector regions.

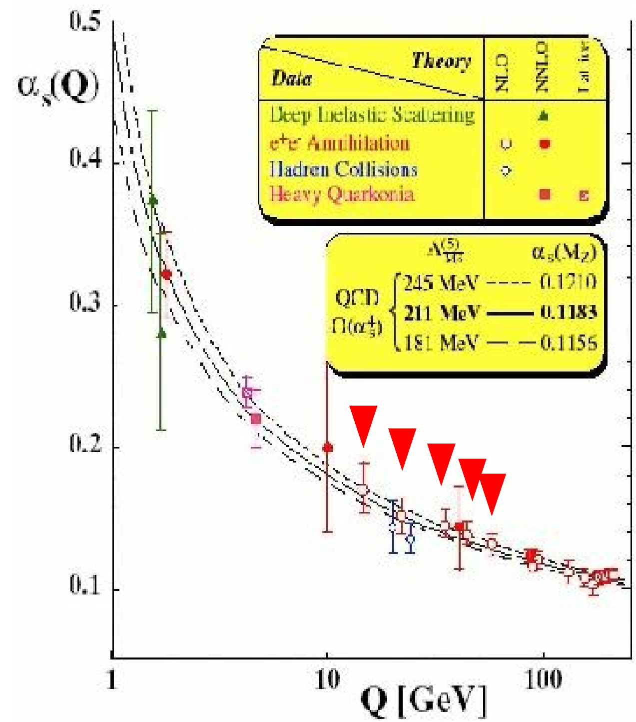
Advanced information on the Nobel Prize in Physics, 5 October 2004

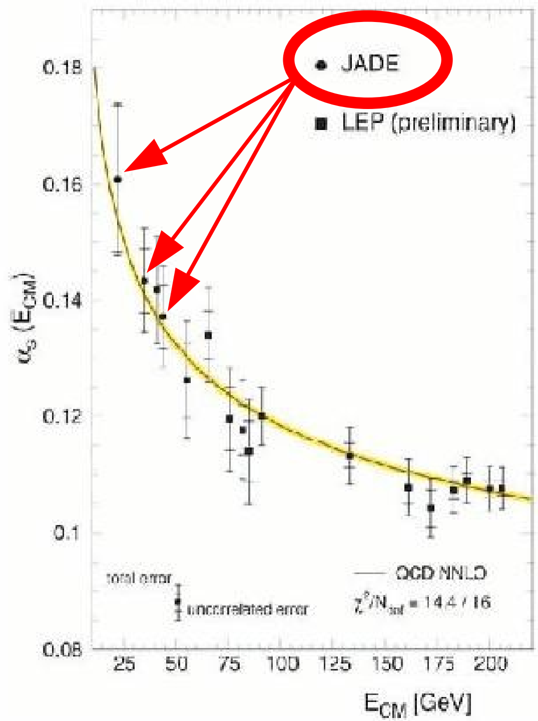
KUNGL. VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Information Department, P.O. Box 50005, SE-104 05 Stockholm, Sweden
Phone: +46 8 673 95 00, Fax: +46 8 15 56 70, E-mail: info@kva.se, Website: www.kva.se

Asymptotic Freedom and Quantum ChromoDynamics: the Key to the Understanding of the Strong Nuclear Forces

David J. Gross H. David Politzer Frank Wilczek





...taken from the Physics Nobel Prize press release (Oct 5, 2004)

The left-hand panel shows a collection of different measurements by S. Bethke from High-Energy International Conference in Quantum Chromodynamics, Montpellier 2002 (hep-ex/0211012). The right-hand panel shows a collection by P. Zerwas, Eur. Phys. J. C34(2004)41. JADE was one of the experiments at PETRA at DESY. NNLO means Next-to-Next-to-Leading Order computation in QCD.

http://nobelprize.org/physics/laureates/2004/press.html