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

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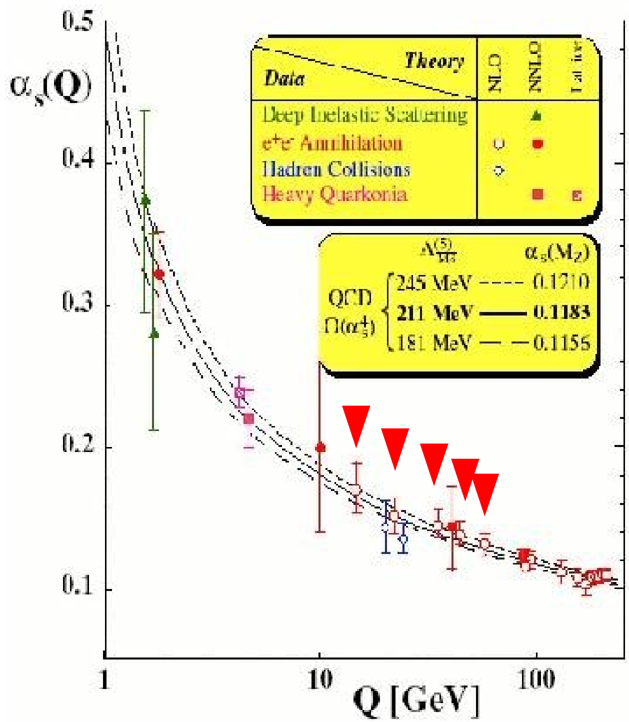
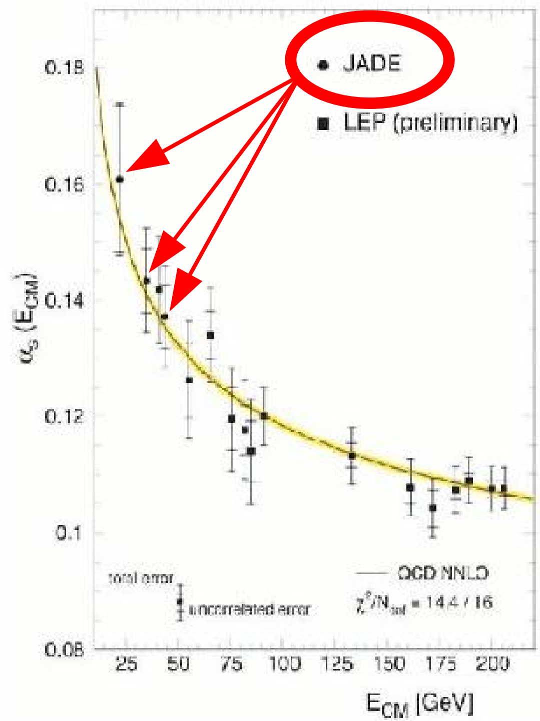
Asymptotic Freedom and Quantum ChromoDynamics: the Key to the Understanding of the Strong Nuclear Forces

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

Towards Precision Top Quark Mass Measurements

Pedro A. Movilla Fernández
Lawrence Berkeley National Laboratory

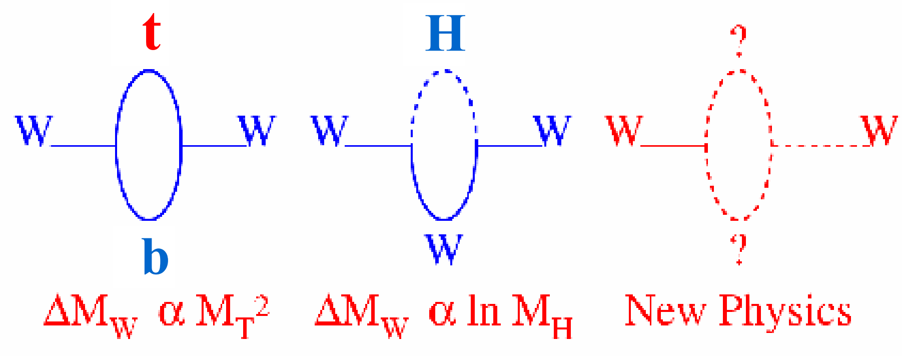
FNAL/Rockefeller U., Aug 30th 2007

Outline

- Motivation
- Improving Measurements (I)
  Multivariate Method
- Improving Measurements (II)
  Calorimeter Simulation
- Towards Precision Top Quark Mass
- Outlook

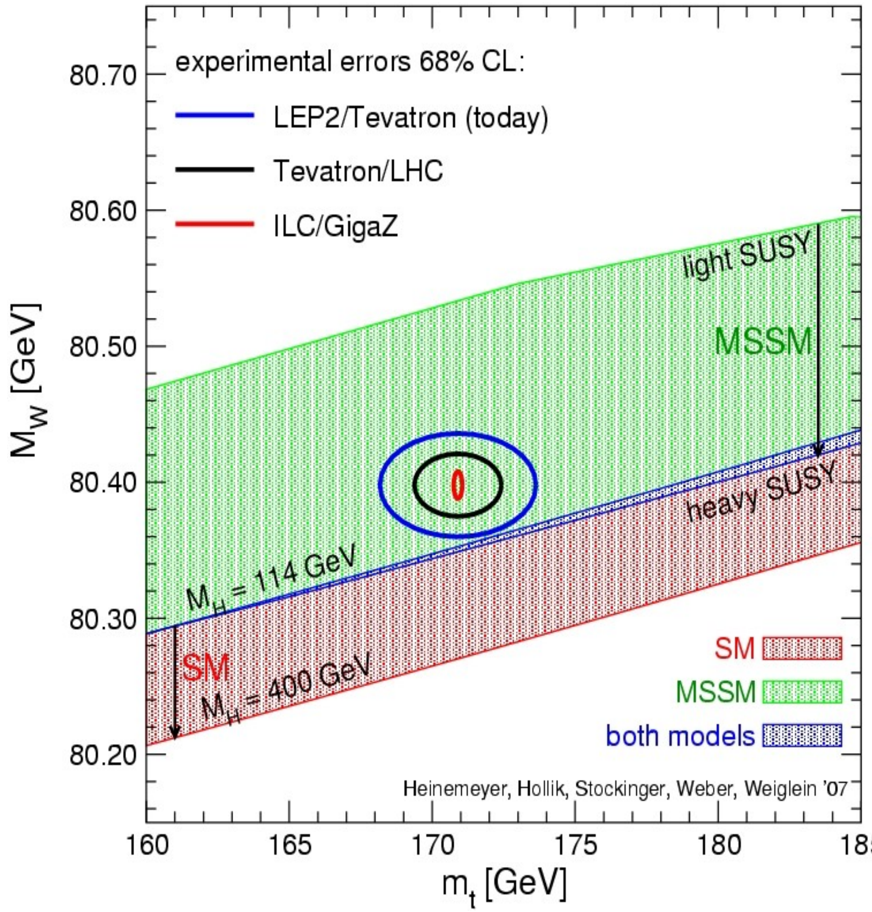
Top Quark Mass Implications

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



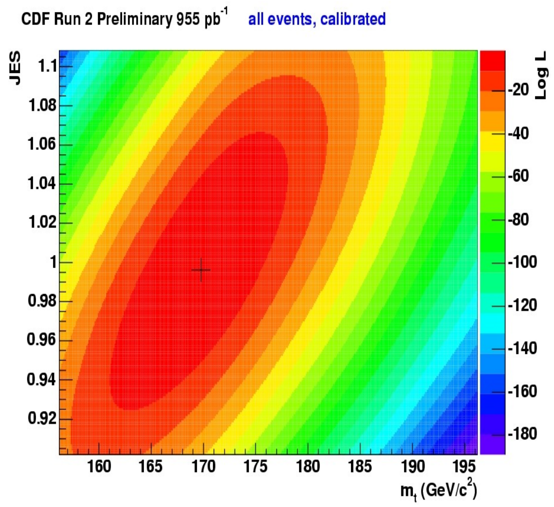
- Surprisingly large mass: A key to understand EWSB?
- Top quark and W boson mass predict the Higgs boson mass.
- Allow to impose constraints for physics beyond the SM.

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



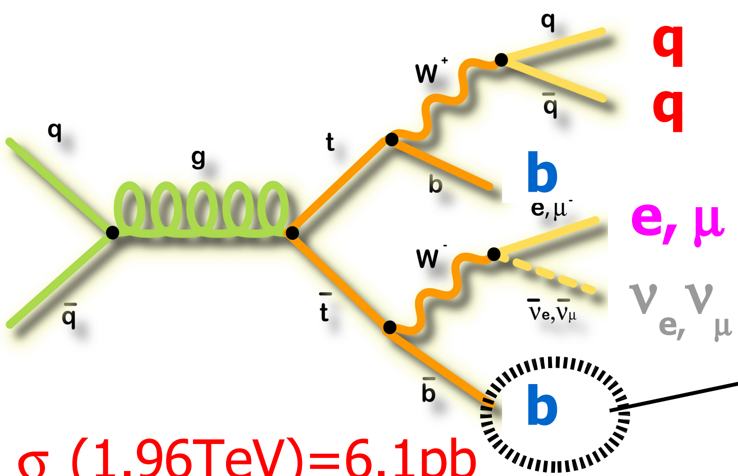
- LEP limit: m_{Higgs} > 114 GeV/c^2 @ 95% C.L.
- Electroweak fit: $m_{Higgs} = 76^{+33}_{-24}$ GeV/c^2

Improving Measurements (I)

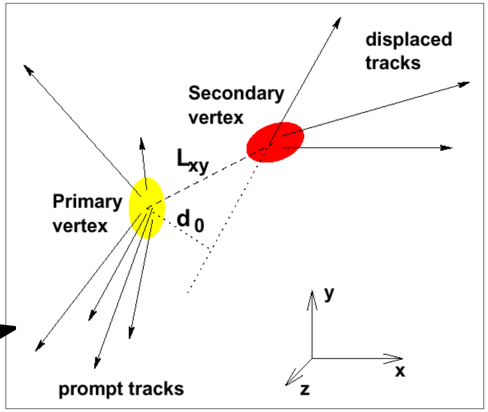


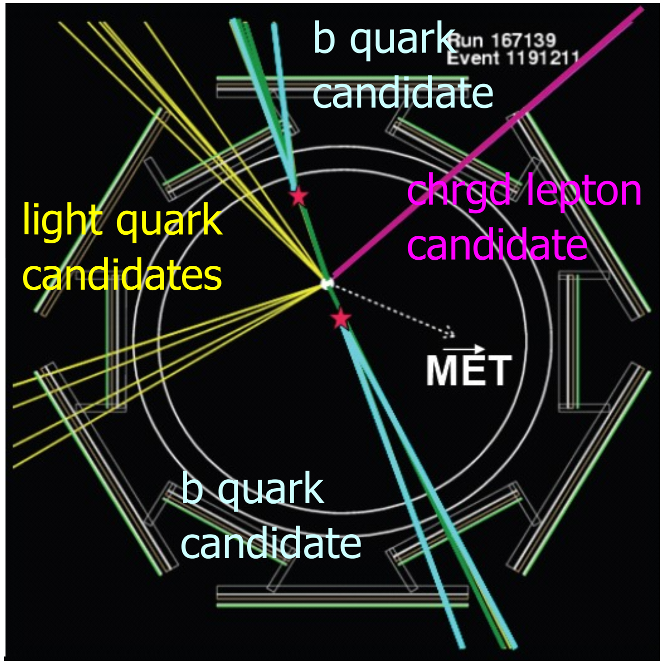
Multivariate Method

Lepton+Jets Analysis



σ_{tt}(1.96TeV)=6.1pb





- 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 to other lepton-jets analyses

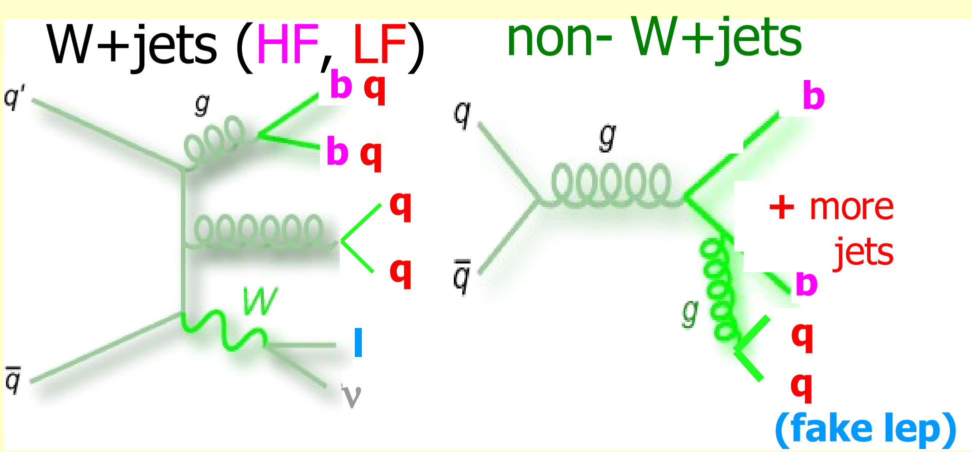
- Channel is compromise between statistics and purity:
  - BR~30%, S/B=1/4–11/1
- Moderate combinatorial quark/jet ambiguity:
  - 2-12 permutations

depending on b-tag requirement

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

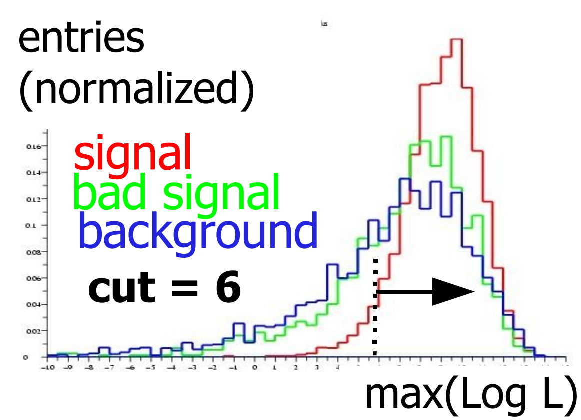
S/B in Multivariate Method

- Found **179** candidate events in **955/pb** of data.
- Background contributions:
  - non-W+jets containing fake leptons ~22%
  - W+light jets containing mistags ~ 40%
  - W+heavy flavor Wbb, Wcc, Wc ~ 33%
  - Di-Boson WW, ZZ, WZ
  - Single top



	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

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



Multivariate Method Basics (1)

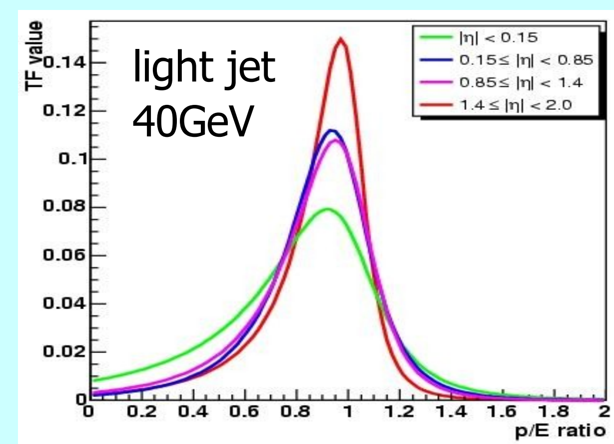
Event-by-event probability density

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

- detector level observables: $\mathcal{P}_{t\bar{t}}(\mathbf{y}|\ldots)$
- jet-quark combinations: $\sum_{i=1}^{N\mathrm{perm}}$
- b-tag weight: w_i
- phase space: $d\Phi_6(\mathbf{x})$
- proton-parton density functions: $f_{\mathrm{pdf}}(q_1)\, f_{\mathrm{pdf}}(q_2)$
- leading order signal matrix element: $|M_{\mathrm{eff}}(m_t,\mathbf{x})|^2$
- transfer functions: $W(\mathbf{y}|\mathbf{x},\mathrm{JES})$

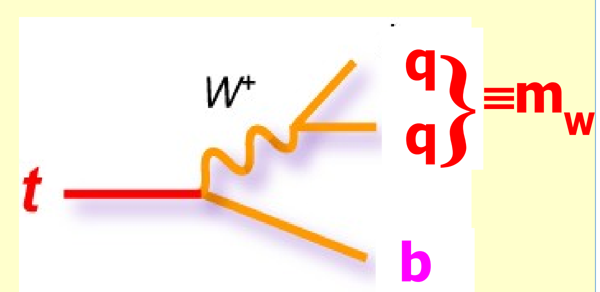
Transfer Functions

- 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 word average value/width penalizes the event probability.
  → Part of ΔJES becomes <u>statistical component</u> of Δm_t and scales down with integrated luminosity!



Multivariate Method Basics (2)

Integration

- Integration over full phase space intractable, make simplifying assumptions:
  - quark angles | charged lepton momentum | quark & lepton masses
- 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), $p_x(t\bar{t})$, $p_y(t\bar{t})$
- Use of modified ("effective") propagators:
  - corrects mismatch between ME, MC and integration assumptions

Matrix Element

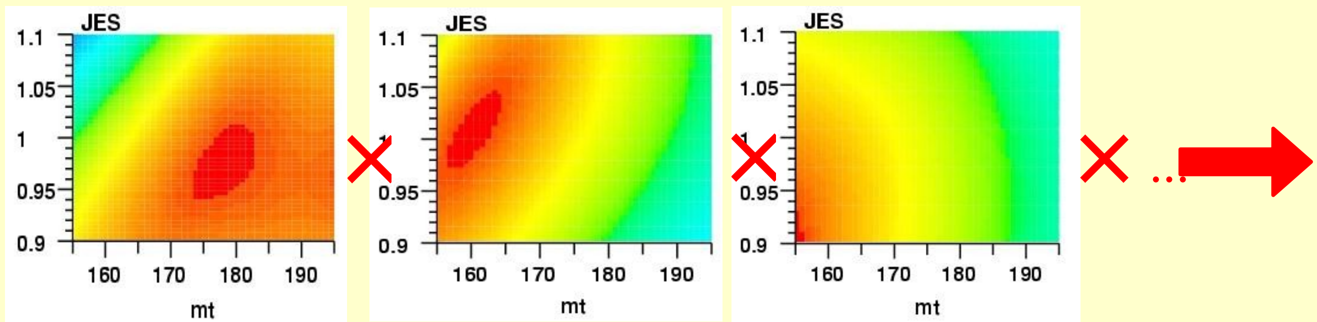
- Use complete signal matrix elements (R. Kleiss and W.J. Stirling, Z.Phys. C40 (1988) 419) for a more consistent approach:
  - $qq \rightarrow tt$ + $gg \rightarrow tt$ tree level amplitudes | finite width of W, top quark | non-zero b-quark masses | complete spin correlations between top production and decay

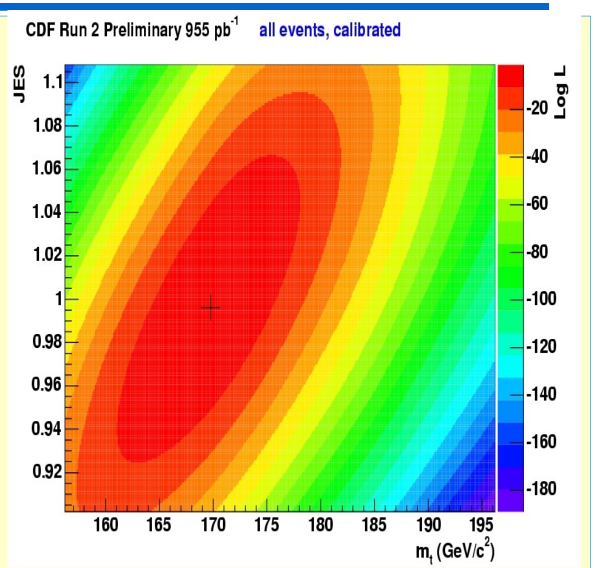
Multivariate aspect

- Signal probability is weighted using a specially designed S/B discriminant.
- Requirements for the second variable
  - minimum top quark mass dependence
  - minimum JES dependence

  } essential to allow multiplication of per-event likelihoods
  - maximum S/B discrimination

Extracting the Top Quark Mass





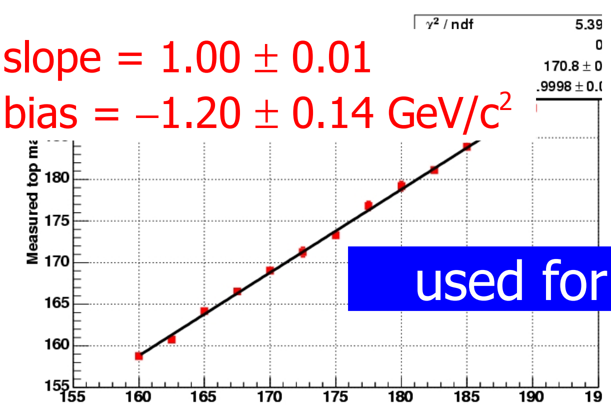
- Build the total 2-dim. likelihood and extract peak of profile likelihood:
- Correct mass and uncertainty value using calibration obtained from pseudo-experiments

$$M_{top} = 169.8 \pm 2.3\,(\text{stat.} + \text{JES}) \pm 1.4\,(\text{syst.})\ \text{GeV/c}^2$$
$$M_{top} = 169.8 \pm 2.7\,(\text{tot.})\ \text{GeV/c}^2$$
$$\text{JES} = 0.996 \pm 0.018\,(\text{stat.})$$

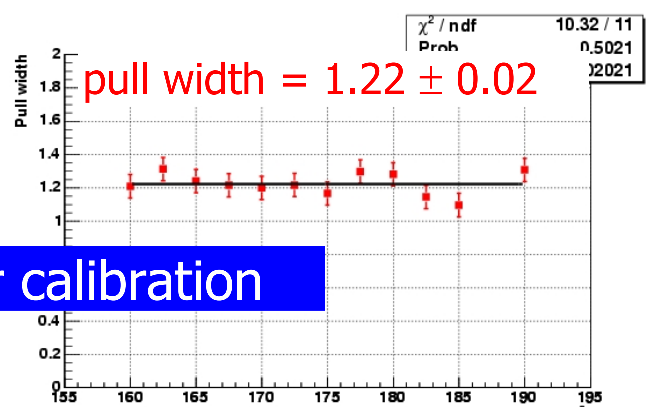
Only 0.1 GeV/c^2 less precise than world's single best 1fb^{-1} result!

slope = 1.00 ± 0.01

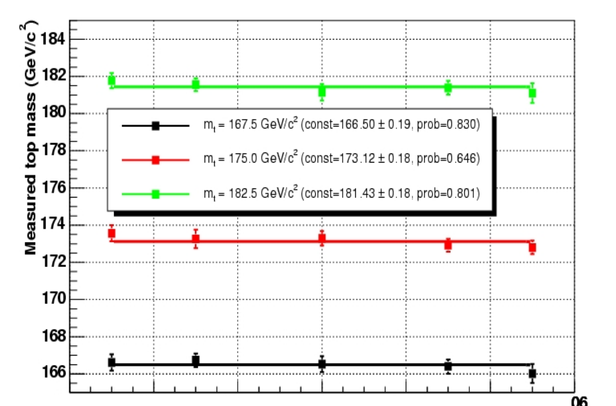
bias = –1.20 ± 0.14 GeV/c^2



pull width = 1.22 ± 0.02



used for calibration



Measured vs. input mass

Pull Widths

Input JES Variation

Future Plans

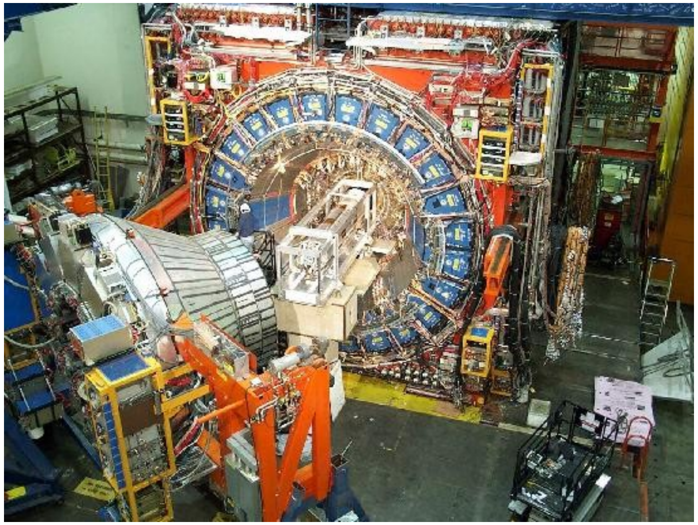
- Major problem is the presence bad signal:
  - wrong jet-to-parton assignment
  - ISR/FSR jets among the four leading jets: contamination is highest in least energetic jet

hurts resolution, causes bias, causes pull widths ≠ 1

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

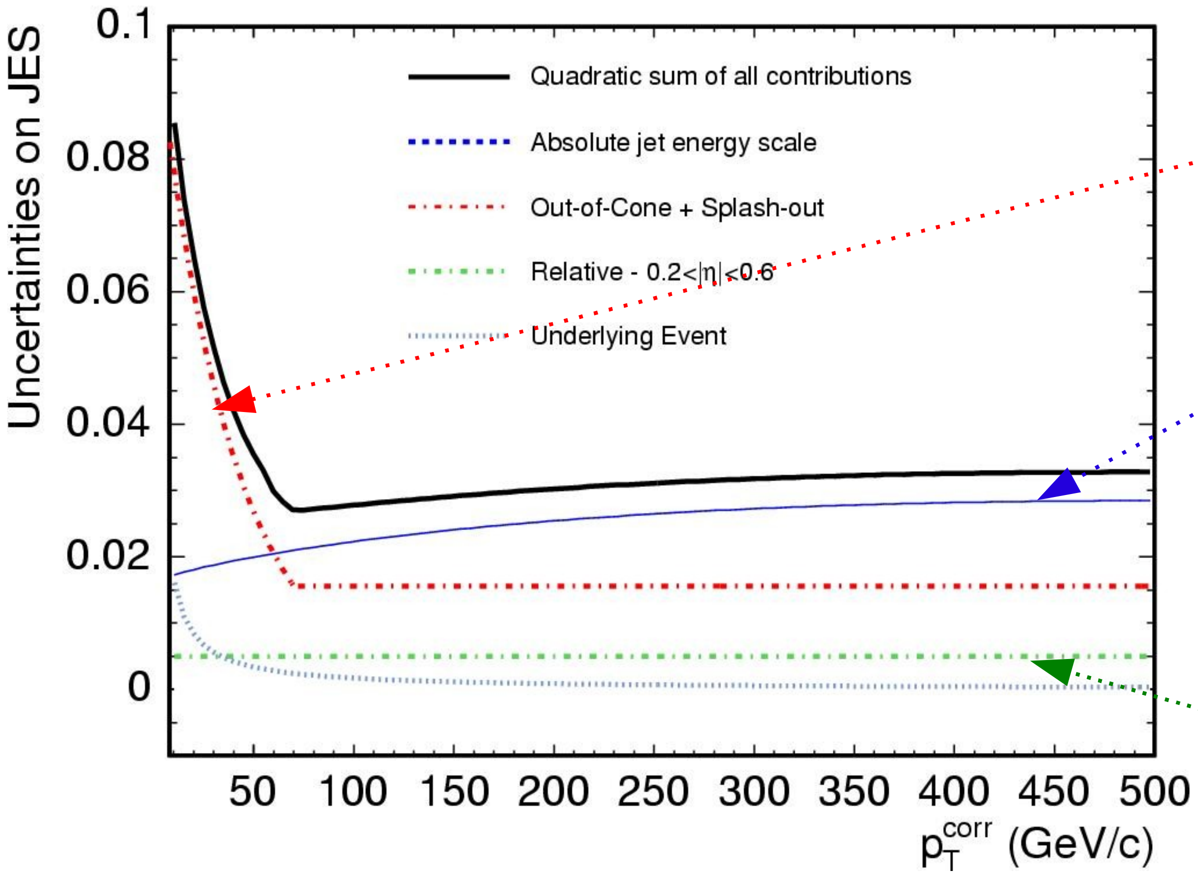
- Get rid of simplifying integration assumptions and effective propagators:
  - Requires expansion of integration phase space (up to 19 dimensions)
- Improve background discrimination:
  - ANN discriminant with no top quark mass and JES dependence?
- Introduce a-priori JES constraint

Improving Measurements (II)



Calorimeter Simulation

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).

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:

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

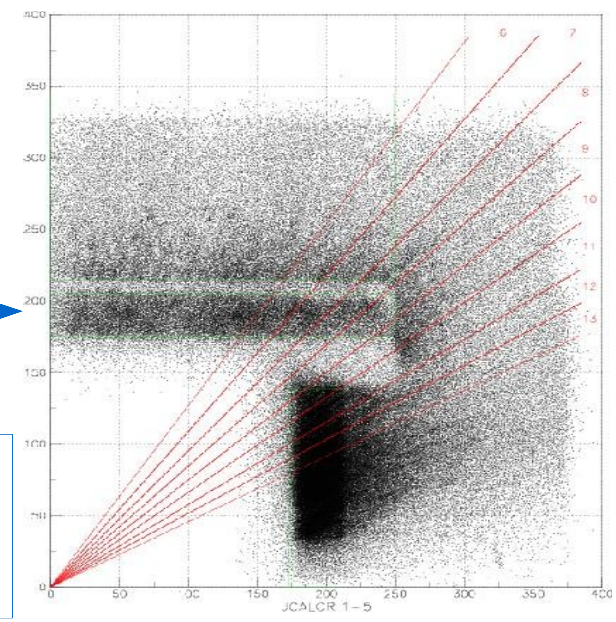
$$\hat{k} = EM\,,\, HAD$$

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

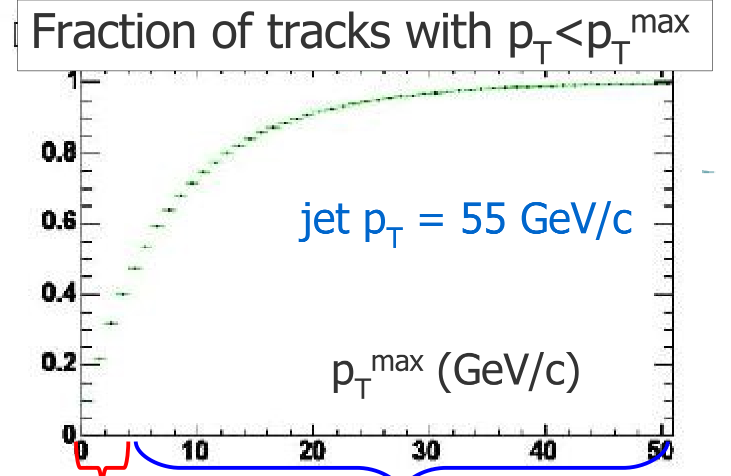
incident energy → sampling fluctuations resolution effects → deposited energy → **visible energy**

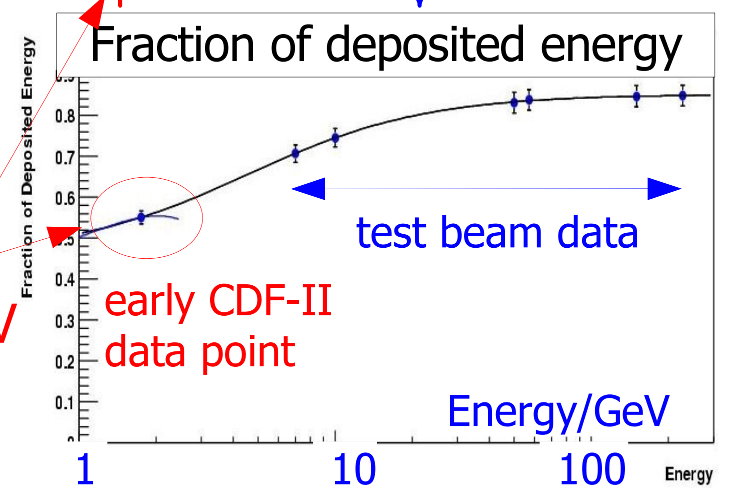
In Situ Tuning Approach

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

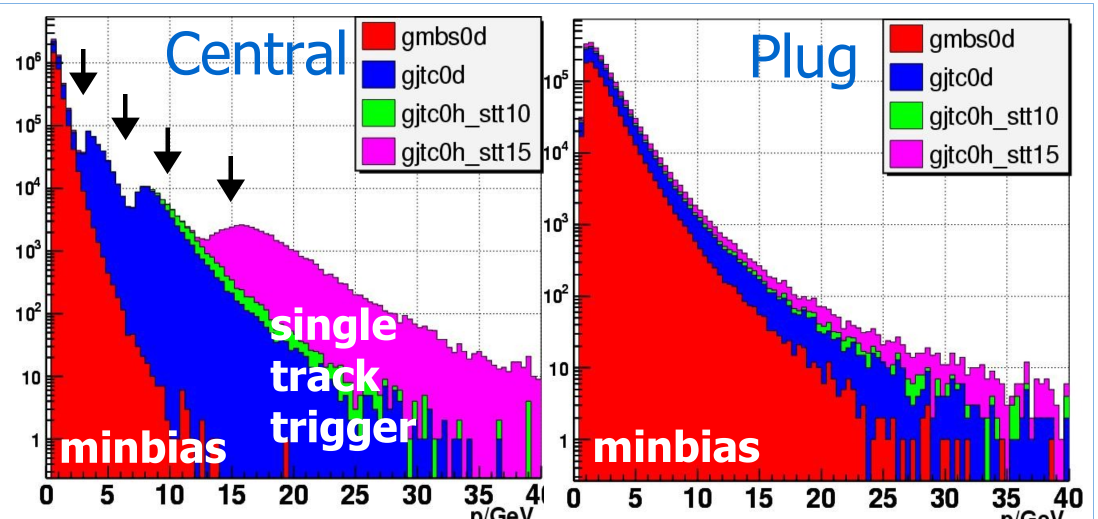
- Early Run-II: Poor in-situ control up to 2.5 (5) GeV





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

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

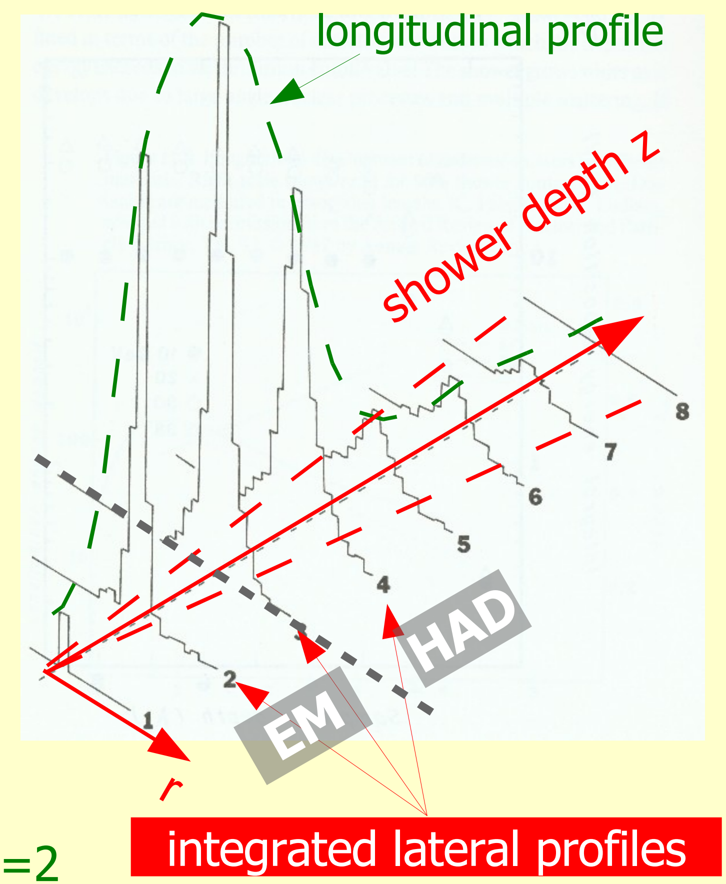
- r: radial distance from shower center
- z = shower depth

- 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

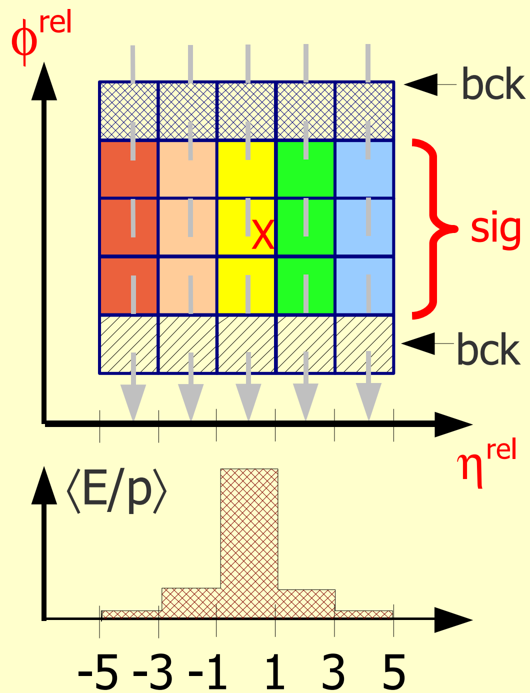


- Hadronic showers: linear dependence on shower depth
- Logarithmic dependence on incident particle energy

7 parameters

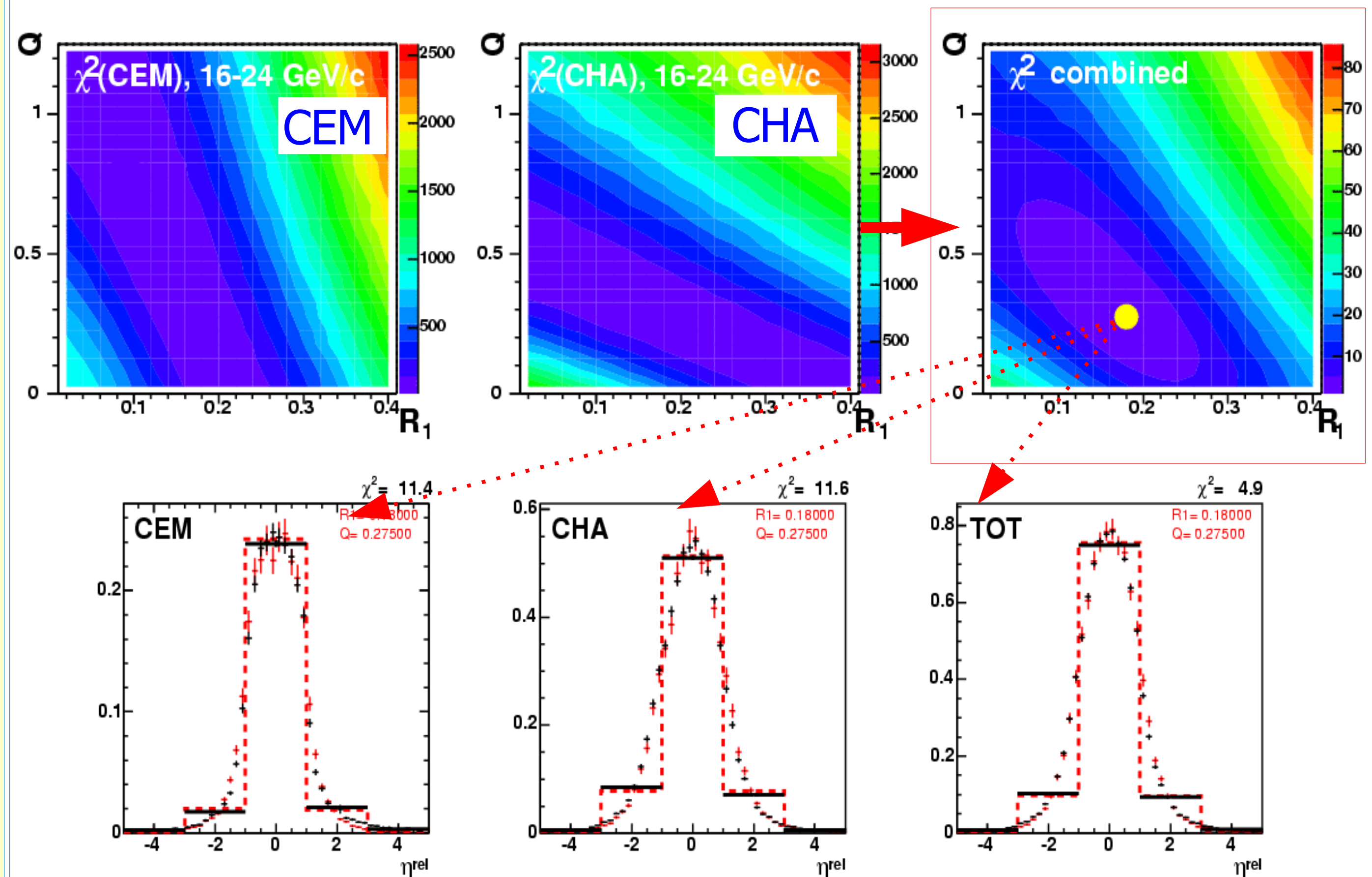
Lateral Profile Tuning

X extrapol. track impact point



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

Example: 20 GeV profile (Central)



Tuning

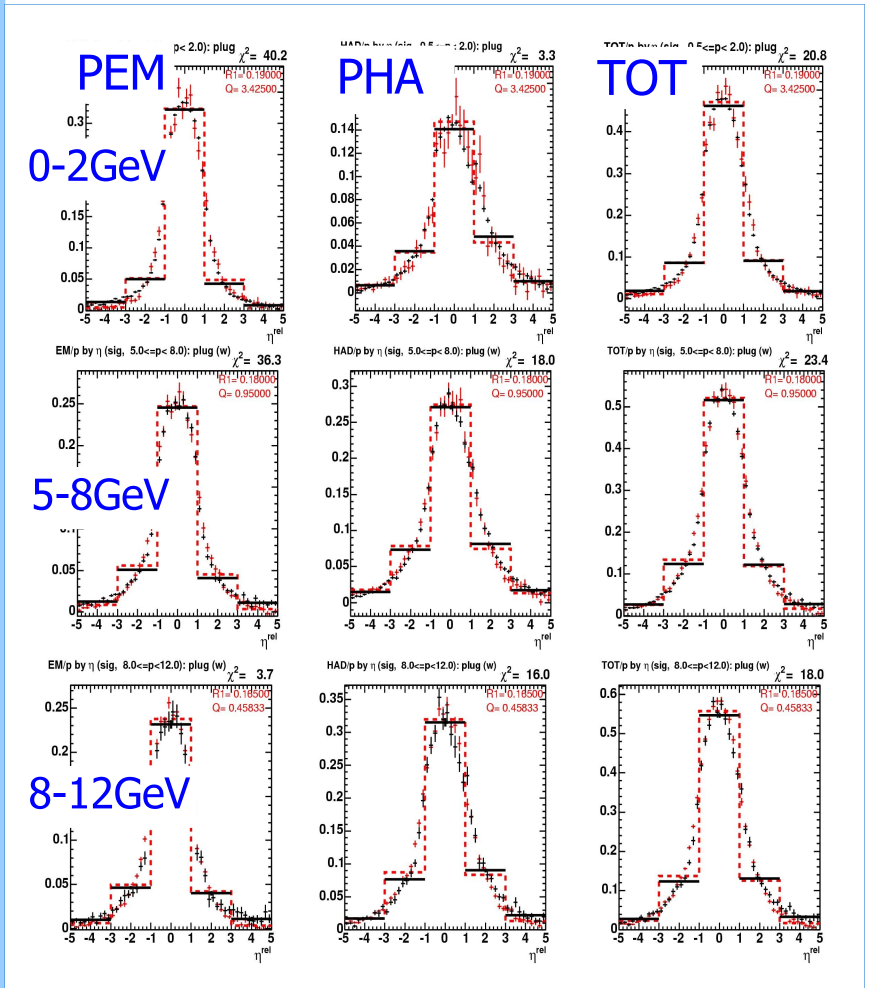
$$\langle R_0(E_{inc}, z) \rangle = [R_1 + (R_2 - R_3 \ln E_{inc}) z]^n$$

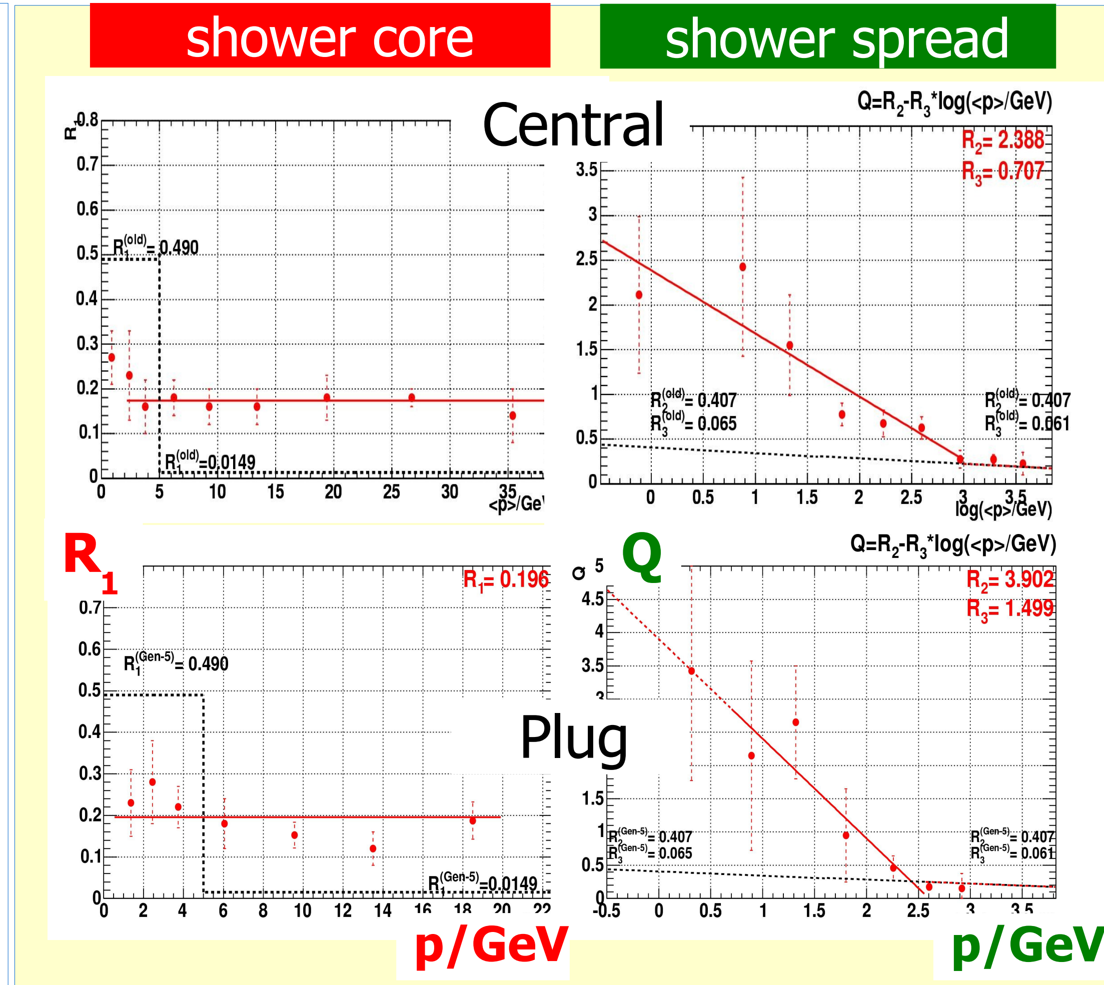
core term R_1

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.

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

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

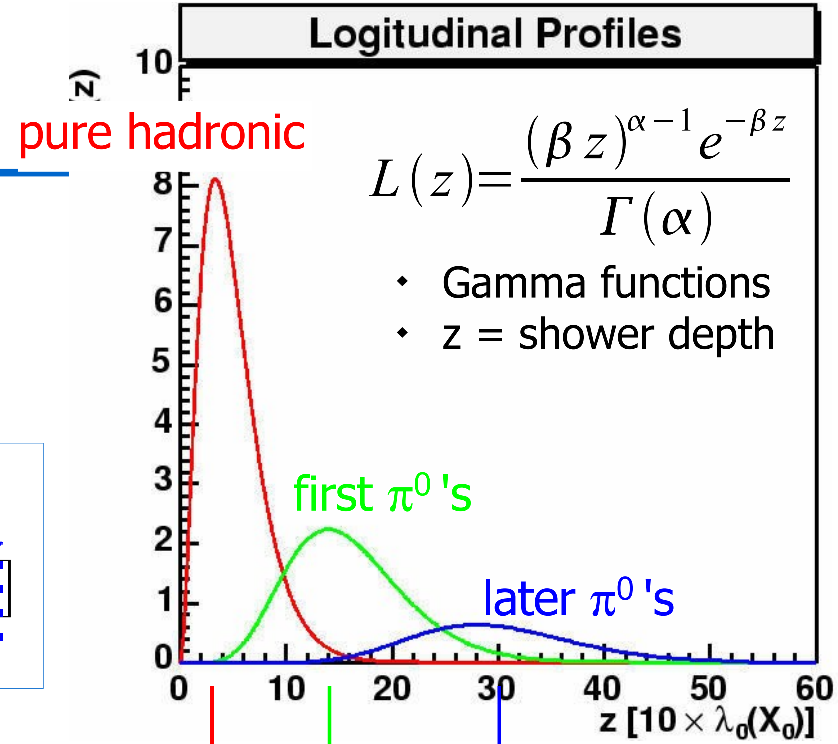
- Hadrons: superposition of 3 shower classes:

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

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

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

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



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

- Gamma functions
- z = shower depth

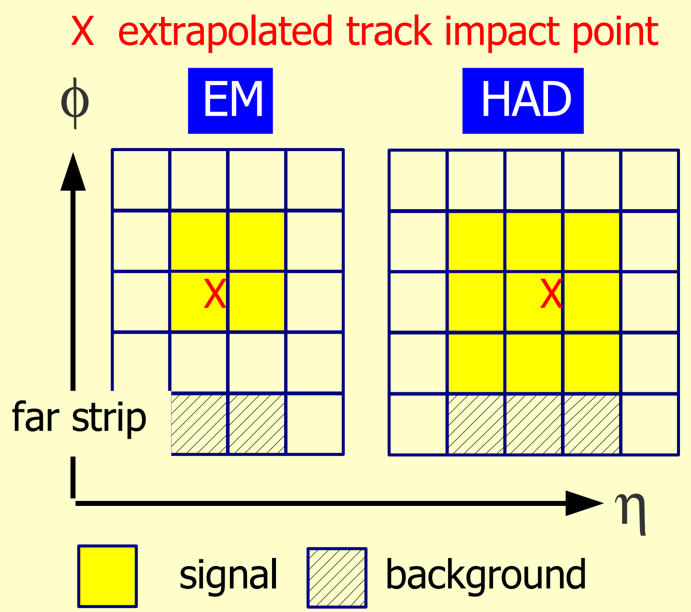
- Incident particle energy dependence of fractions

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

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

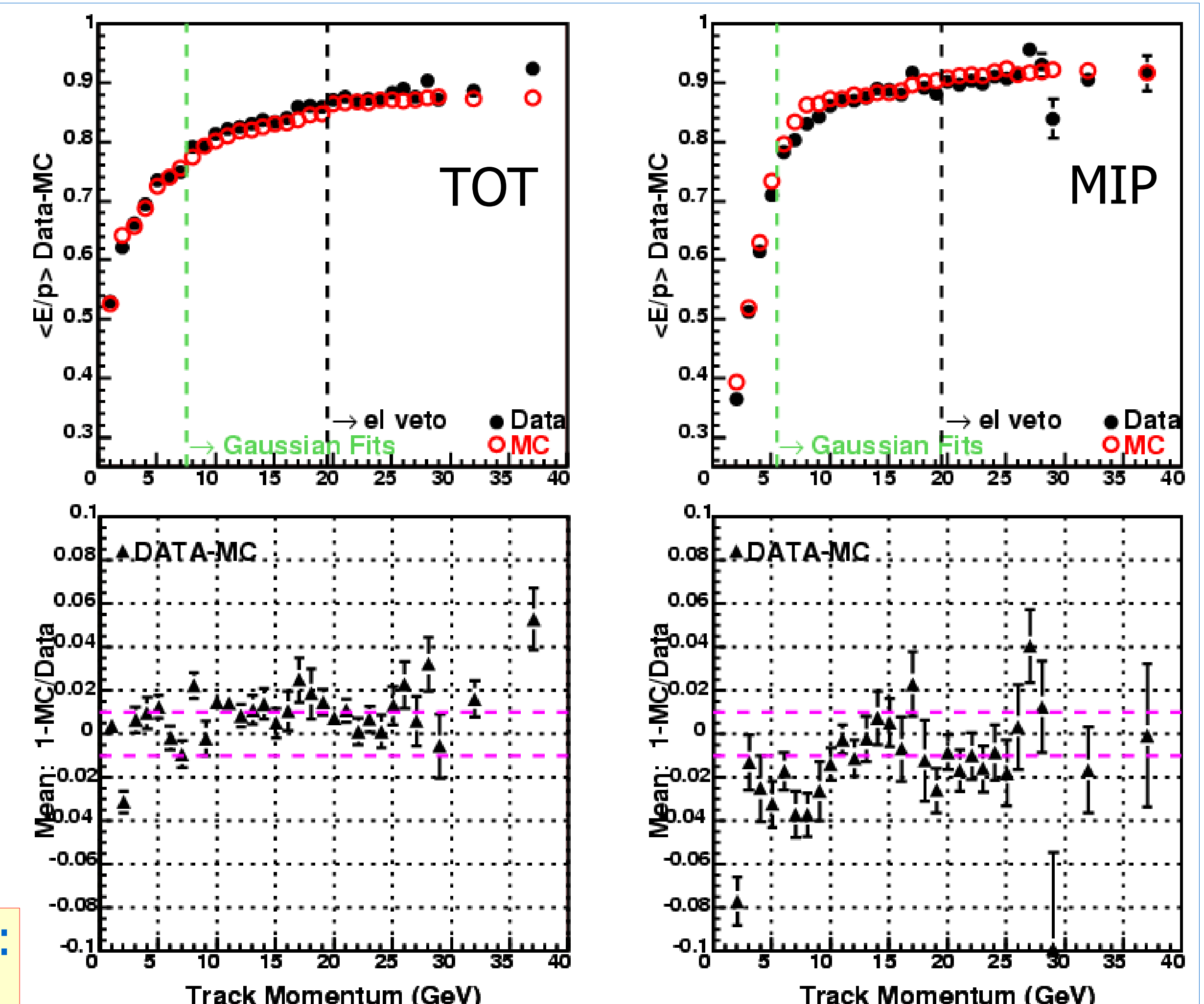
Total of 20 parameters:
means & widths of
- the class fractions f's,
- the α's and β's

Absolute Response Tuning (Central)



sig: EM=2 x2 blocks
HAD=3 x3 blocks

bck: EM=2 x far strip
HAD=3 x far strip

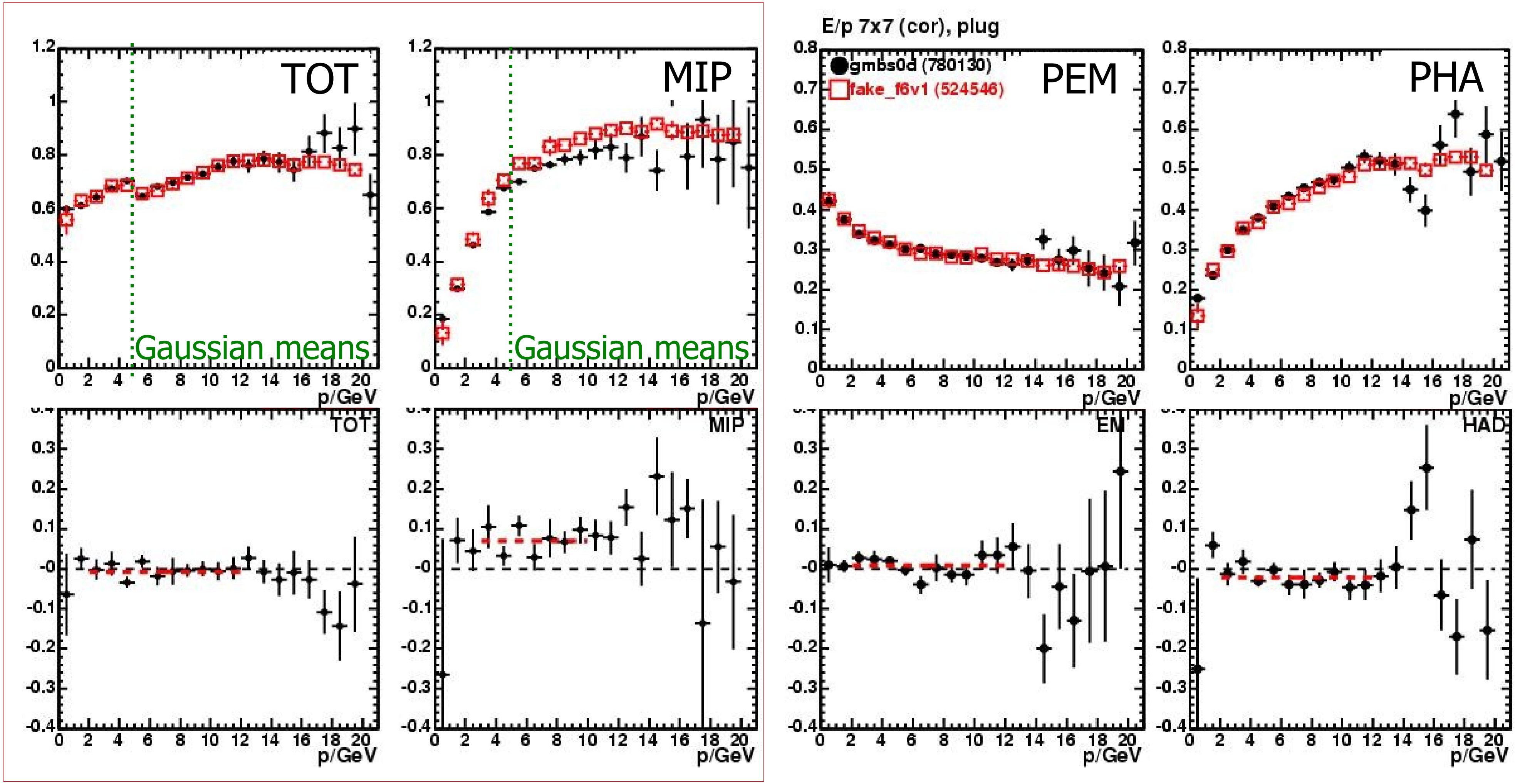


Tuning

- FEDP and relative sampling fractions:

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

- 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

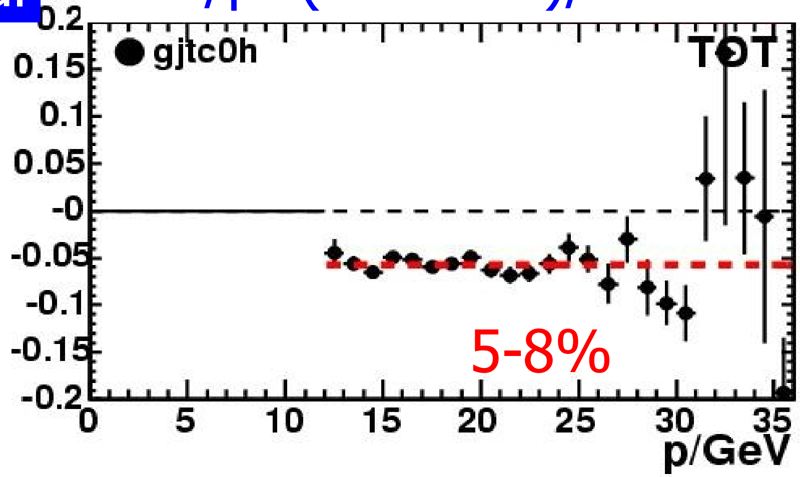


- Priority to get TOT right
- Moderate discrepancy in MIP

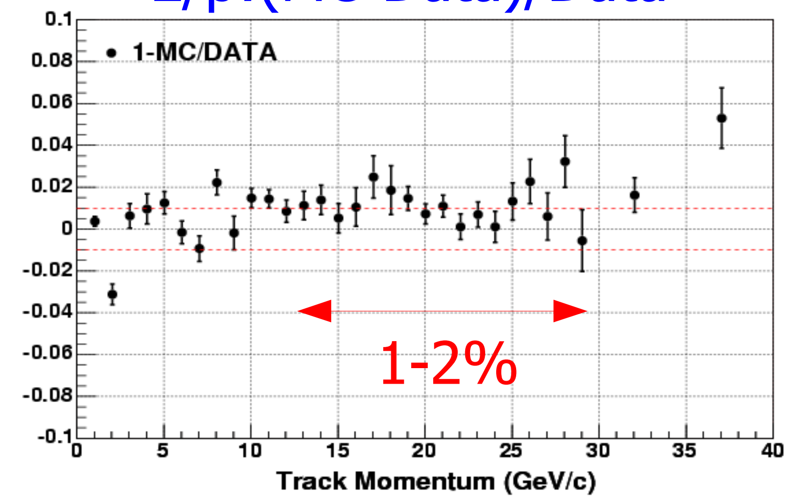
Changes

Central

E/p: (Data-MC)/Data



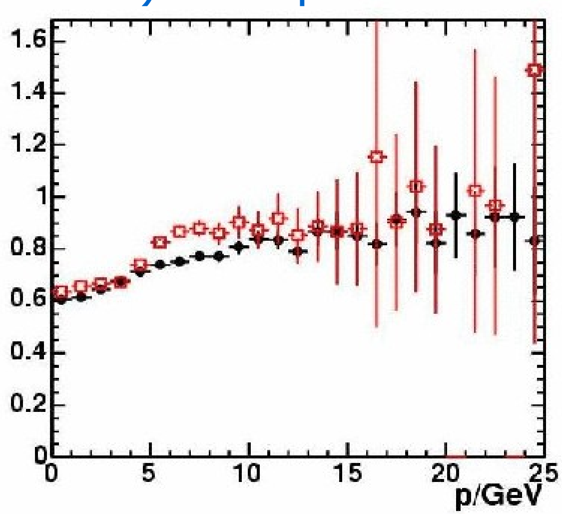
E/p:(MC-Data)/Data



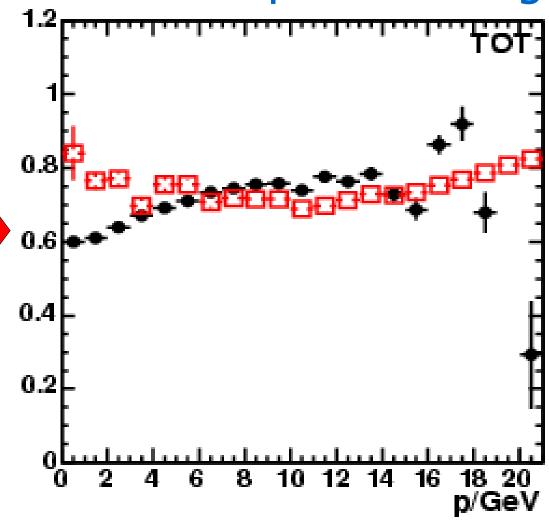
Plug

E/p (total response)

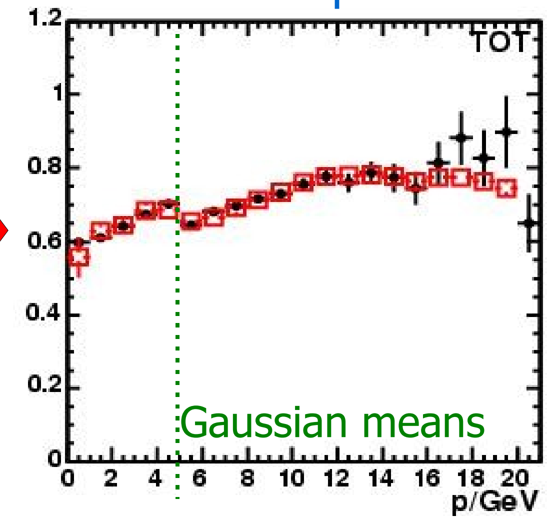
a) initial picture



b) after lateral profile tuning



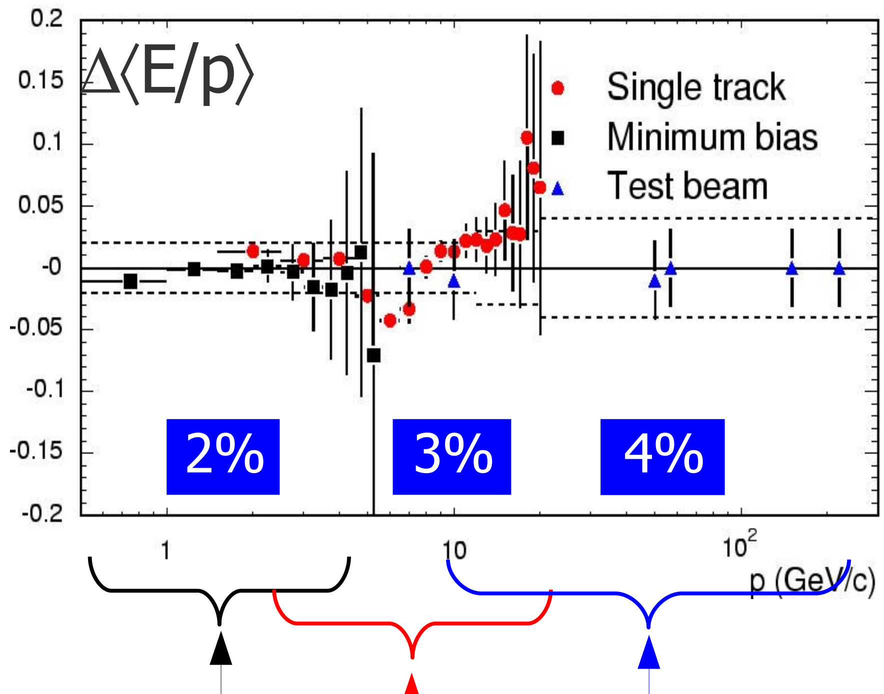
c) after absolute response tuning



- 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:

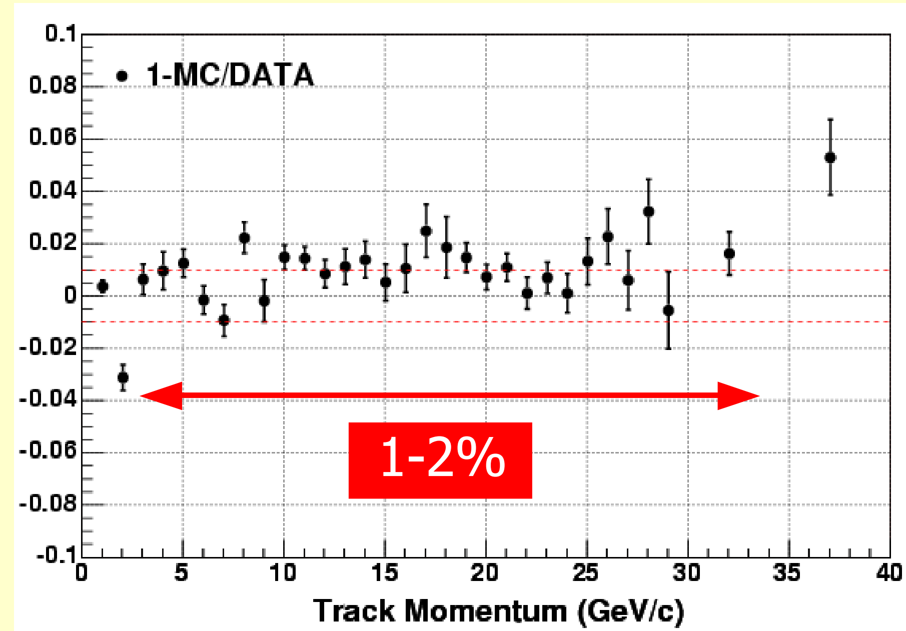


in-situ tuning
p<2.5(5) GeV/c

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

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

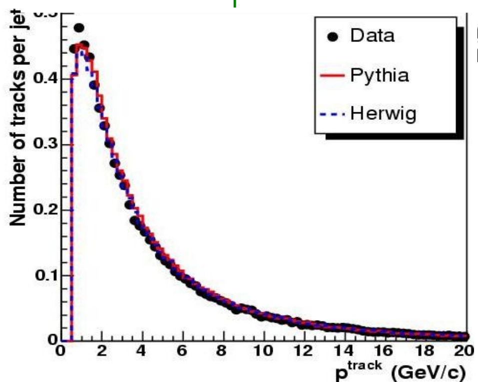
now



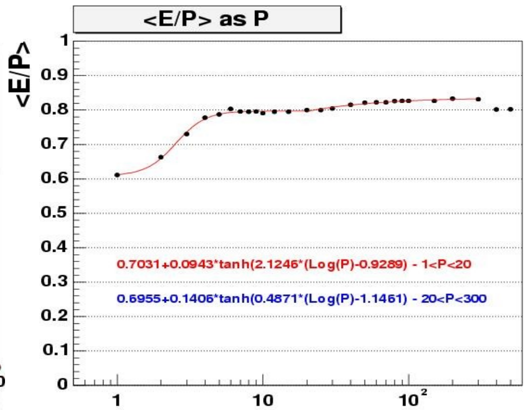
- Better and consistent tuning.
- Percentages directly translate into JES uncertainties (next page)

Jet Energy Scale Uncertainties

e.g. jet p_T=50-60GeV

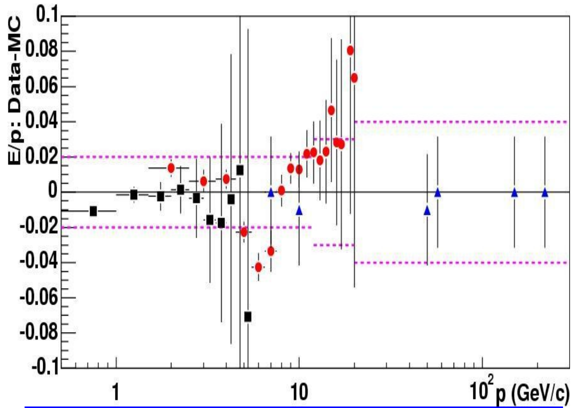


particle spectrum



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

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

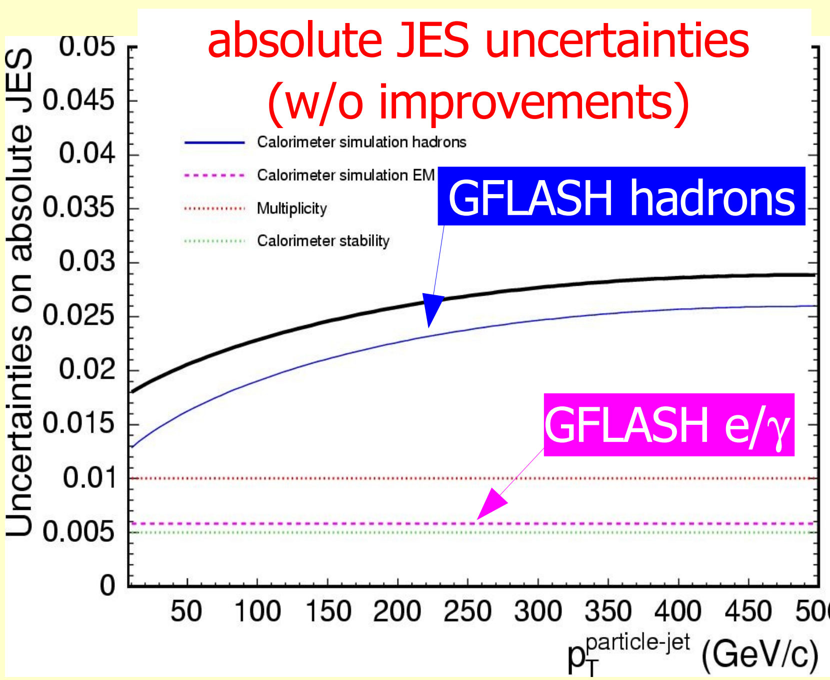


$\Delta \langle E/p\rangle$

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

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

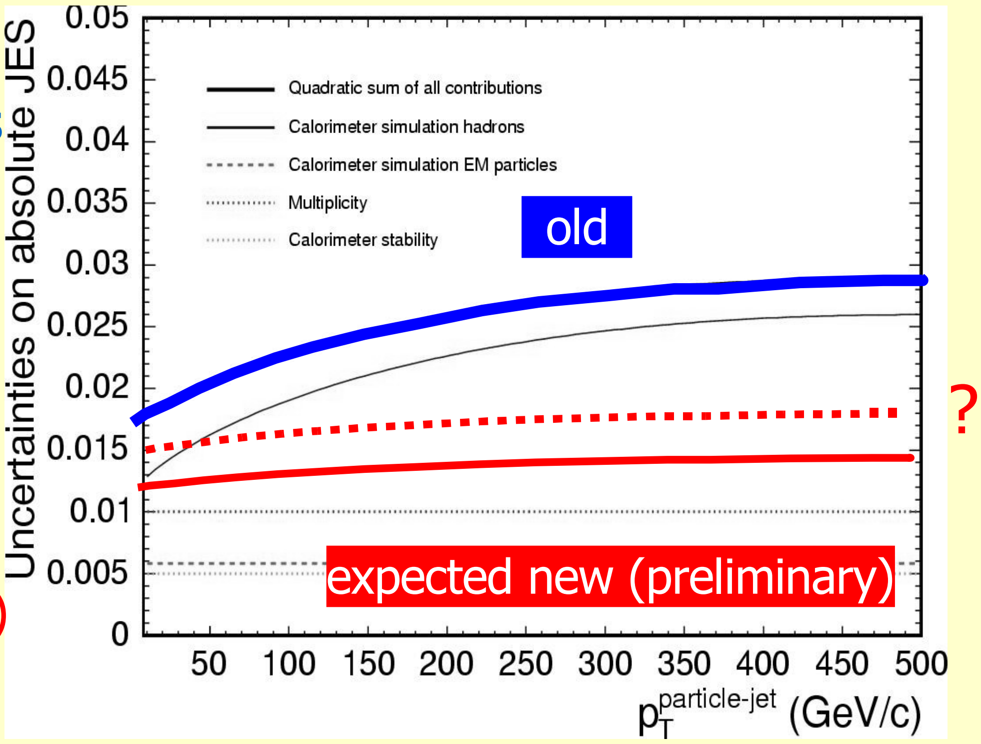
$\rightarrow$ absolute JES uncertainty



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:

  expected JES uncertainty:
  1.8-2.8% → 1.4-2.0% (preliminary)



Impact to performance top quark mass measurements:

- w/o in situ JES: di-lepton channel
- w/ in situ JES but a-priory JES constraint: all-jets channel
- reduction of residual JES uncertainties: all analyses

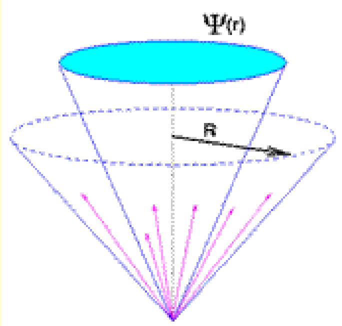
→ Reduction of ΔM_{top}(Absolute), ΔM_{top}(JES_{stat})?

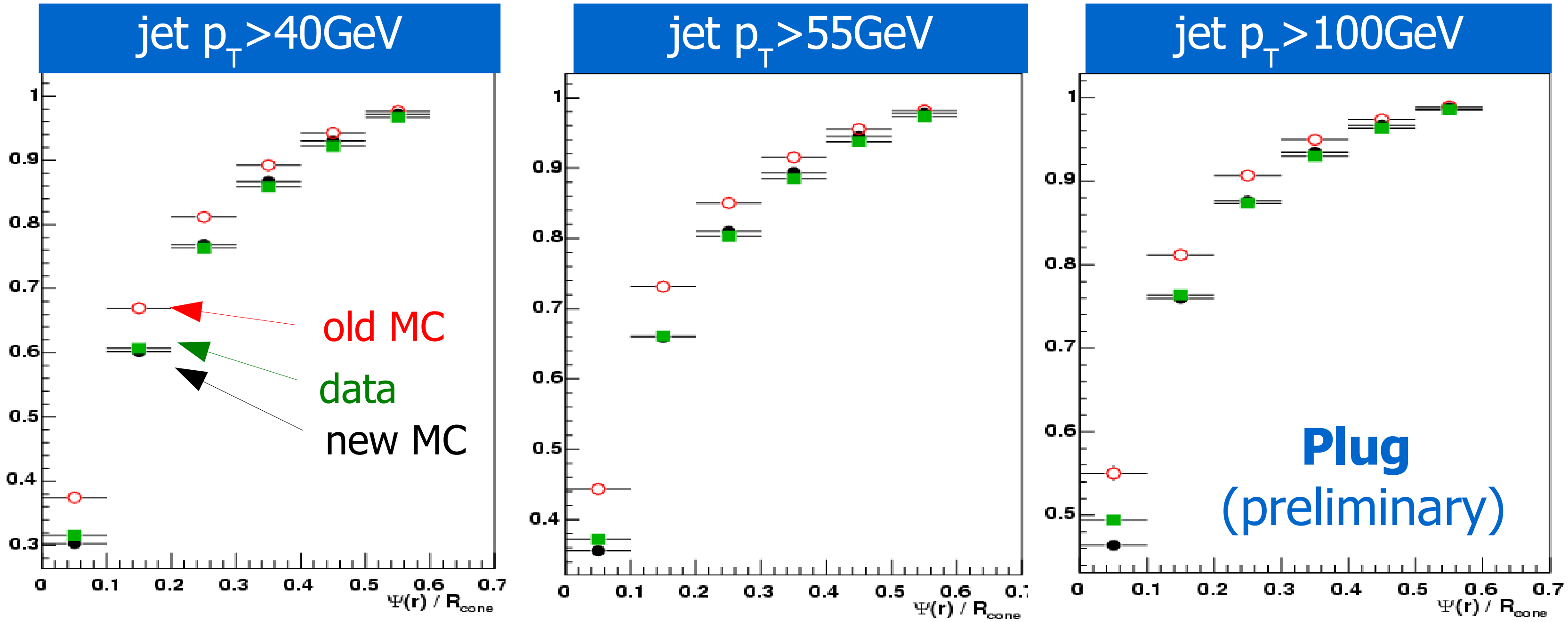
... more comments later!

Jet Shapes

- For example: Integrated jet energy flow

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

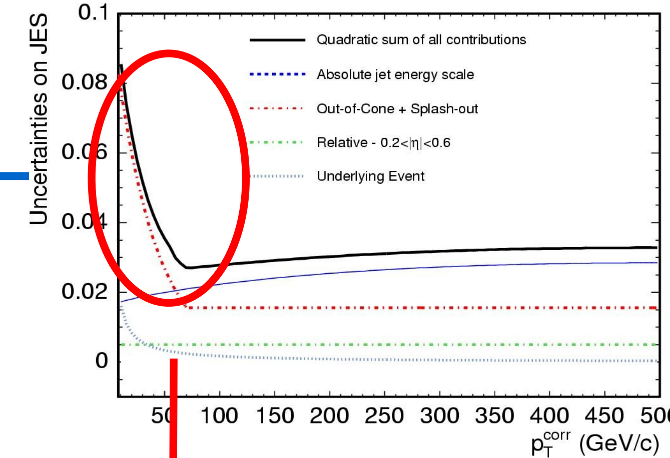




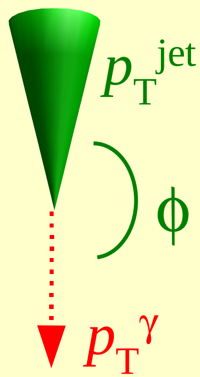
- Much better agreement
  - → reduces bias in relative correction Plug to Central
  - → impact to OOC uncertainties

  (next slides)

OOC Uncertainties

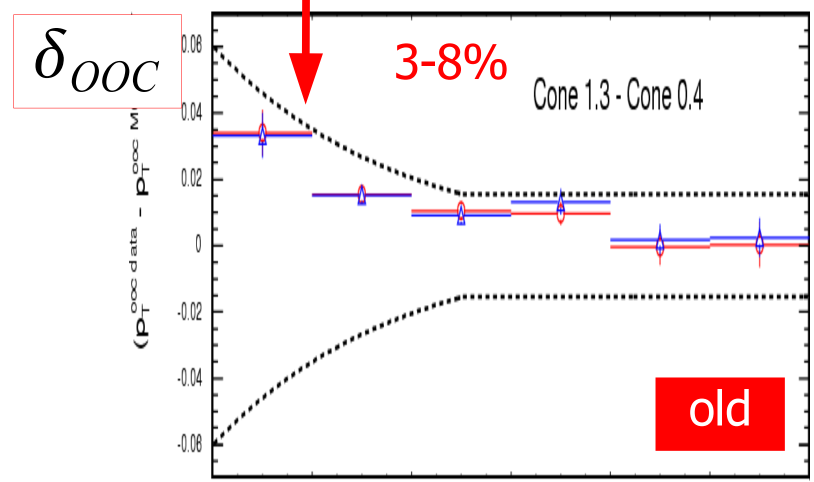


- Photon-jet balance technique: validate the probe jet using well measured photon energy

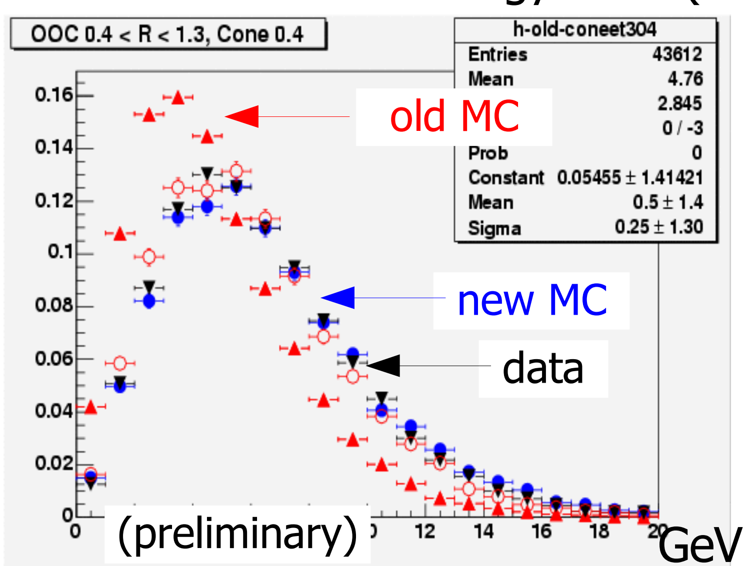


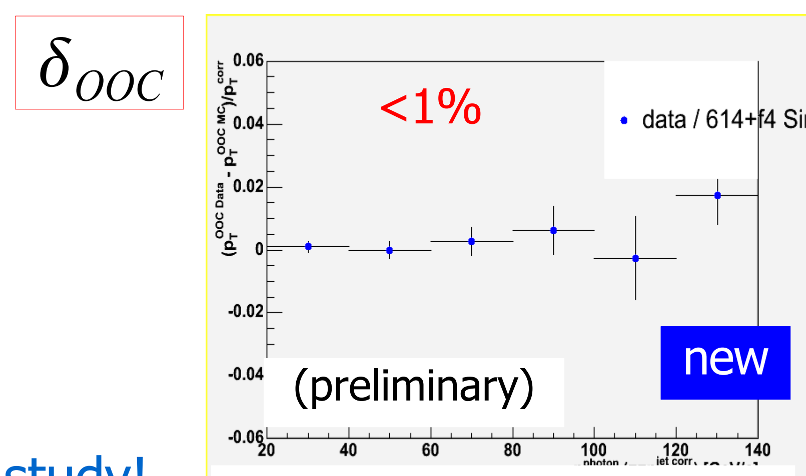
$$f_\gamma = 1 - \frac{p_T^{jet}}{p_T^{\gamma}}$$

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



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





corrected jet p_T(GeV/c)

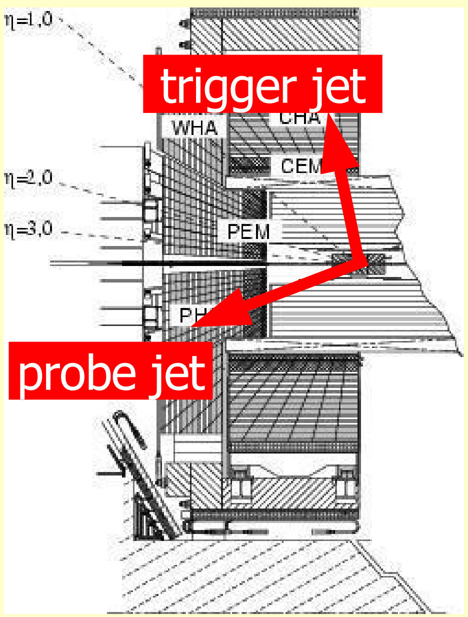
→ Reduction of ΔM_{top}(OOC)?

... still under study!

Di-Jet Balance

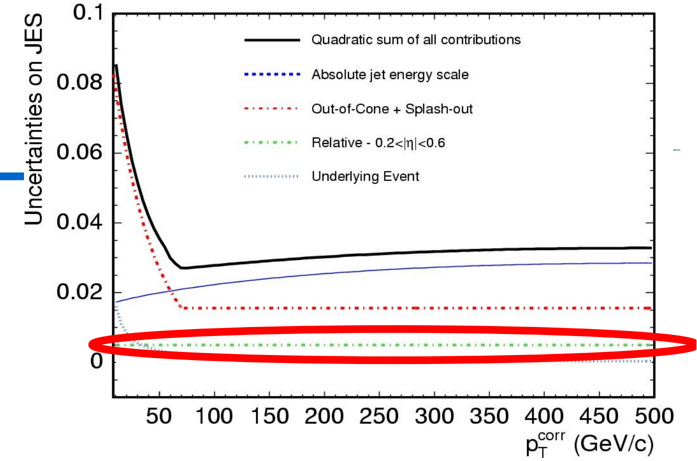
Di-jet balancing technique

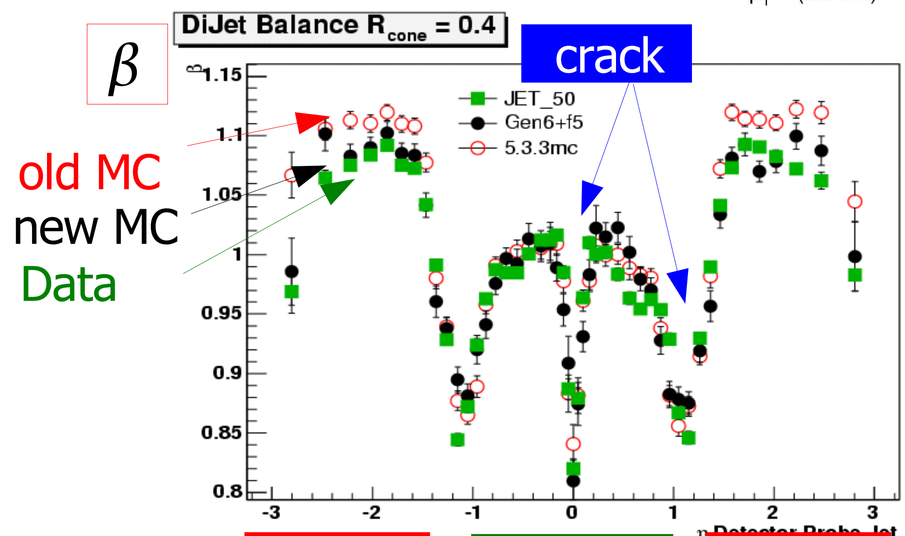
- Monitoring and correction of the inhomogeneous calorimeter response using reference jet p_T in Central part.

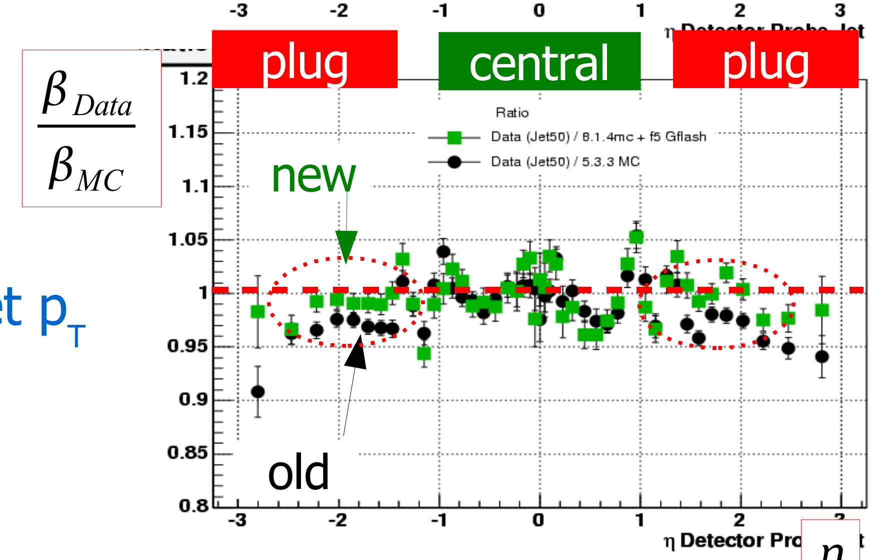


$$f = \frac{p_T^{probe} - p_T^{trigger}}{(p_T^{probe} + p_T^{trigger})/2}$$

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



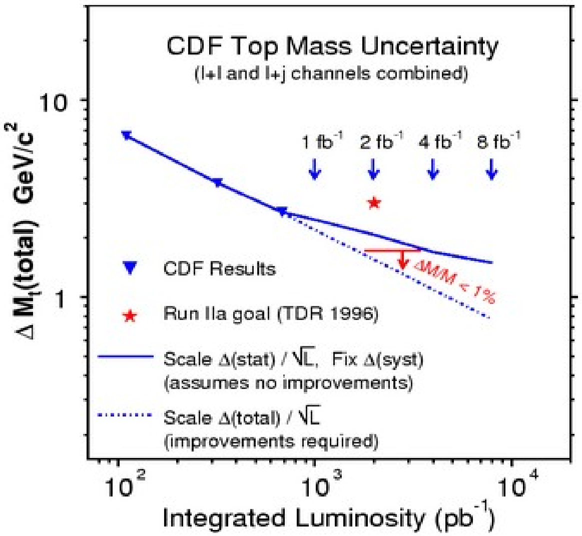




- Improvements for certain cone sizes and jet p_T

→ Reduction of ΔM_{top}(Relative)?

Towards Precision Top Quark Mass



Di-Lepton Channel

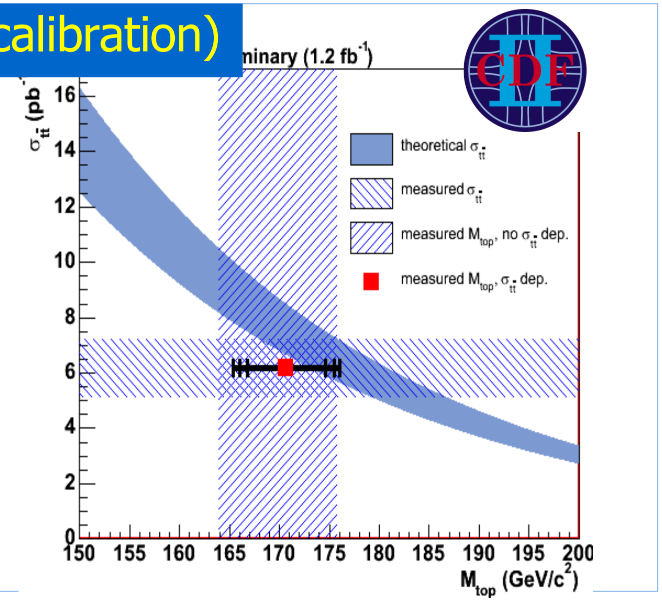
Template Method, $p_z(tt)$ assumption, 1.2fb^{-1} (no in situ JES calibration)

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



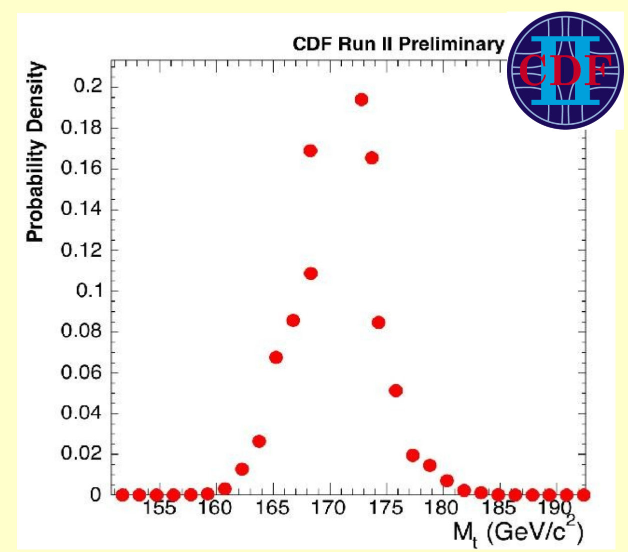
Matrix Element Method, 1.8fb^{-1} (no in situ JES calibration)

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

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)

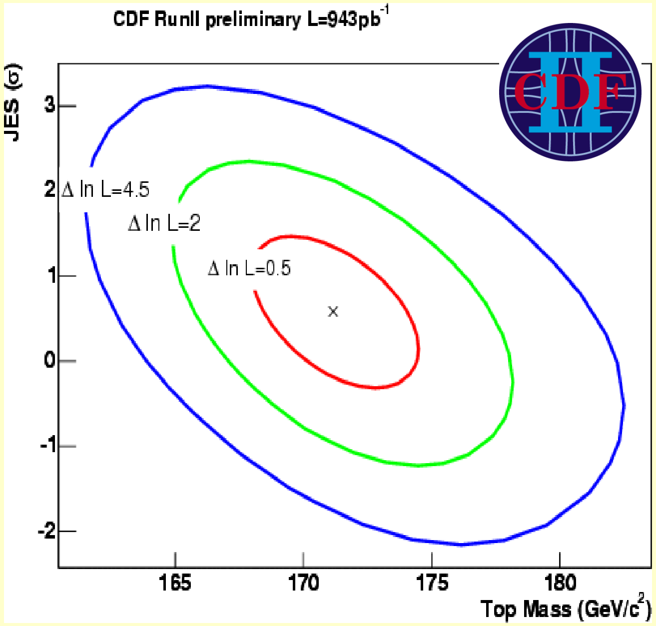
a priori JES constraint

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

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

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.

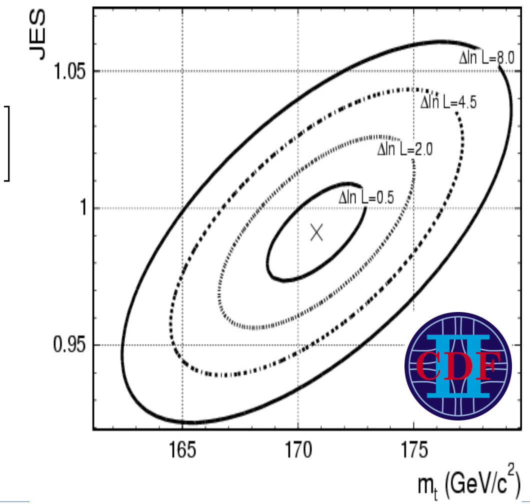
JES Uncertainties (Lepton-Jets)

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

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

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

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

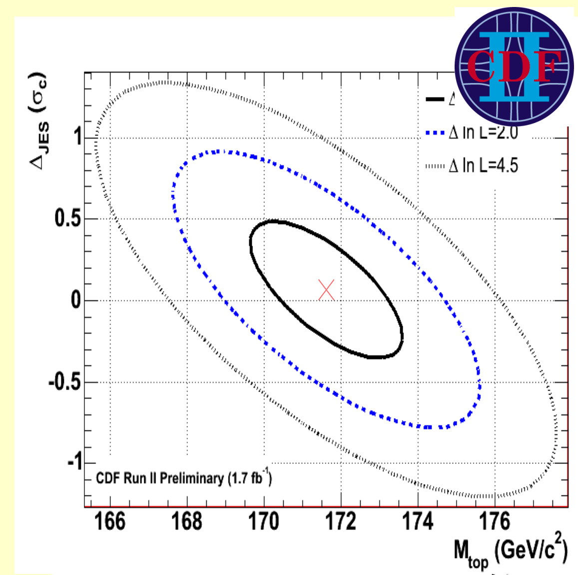
$$L = L_{1\,tag}(m_t, \Delta_{\mathrm{JES}}) \times L_{2\,tag}(m_t, \Delta_{\mathrm{JES}}) \times \exp\left(\frac{-\Delta^2_{\mathrm{JES}}}{2\sigma^2_c} \right)$$

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

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

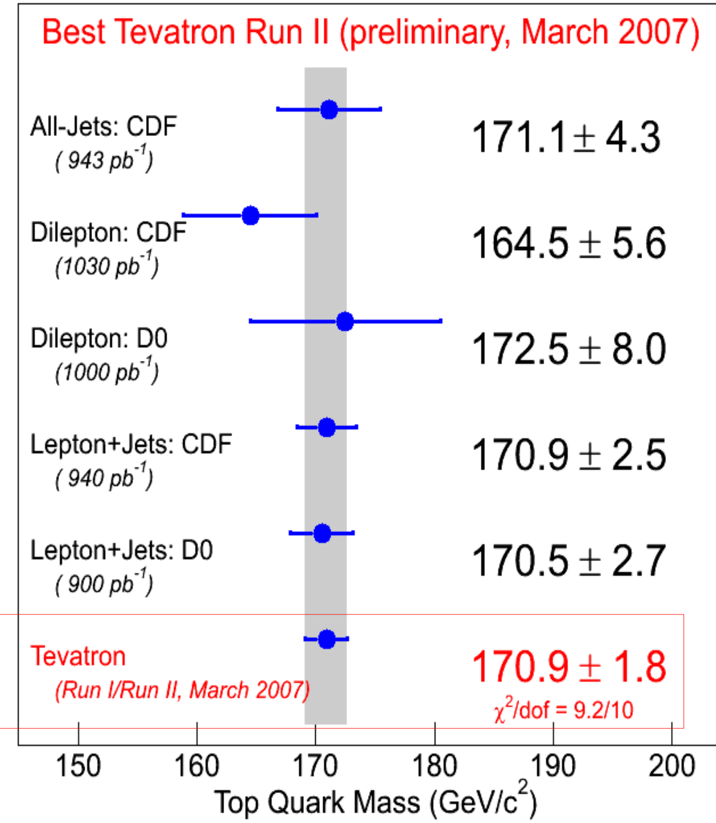
Tevatron combination (March '07)

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%

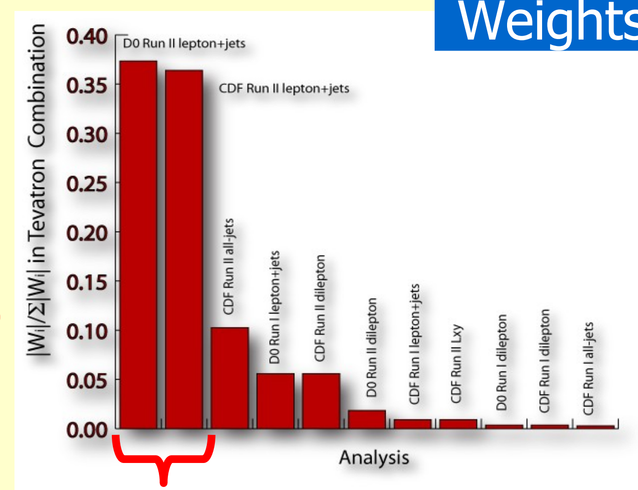
p (di-lep/all-jets) = 7%
p (lep-jets/all-jets) = 75%
p (di-lep/lep-jets) = 12%

1.1%



- 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



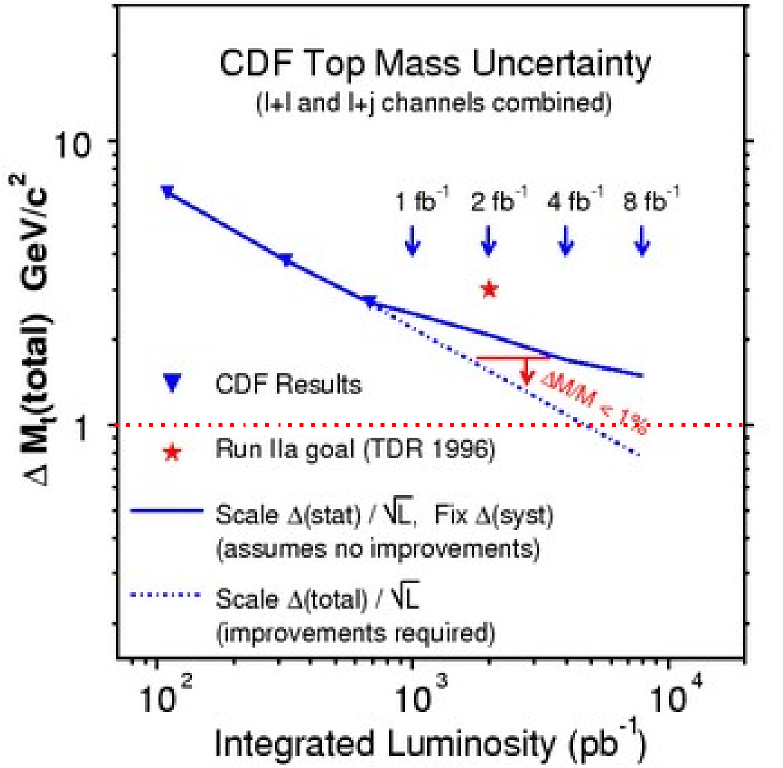
Lepton+Jets

Outlook

- Confidence through a consistent picture of many top mass measurements at Tevatron

Combined CDF&D0 result (March '07): **1.1%**

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

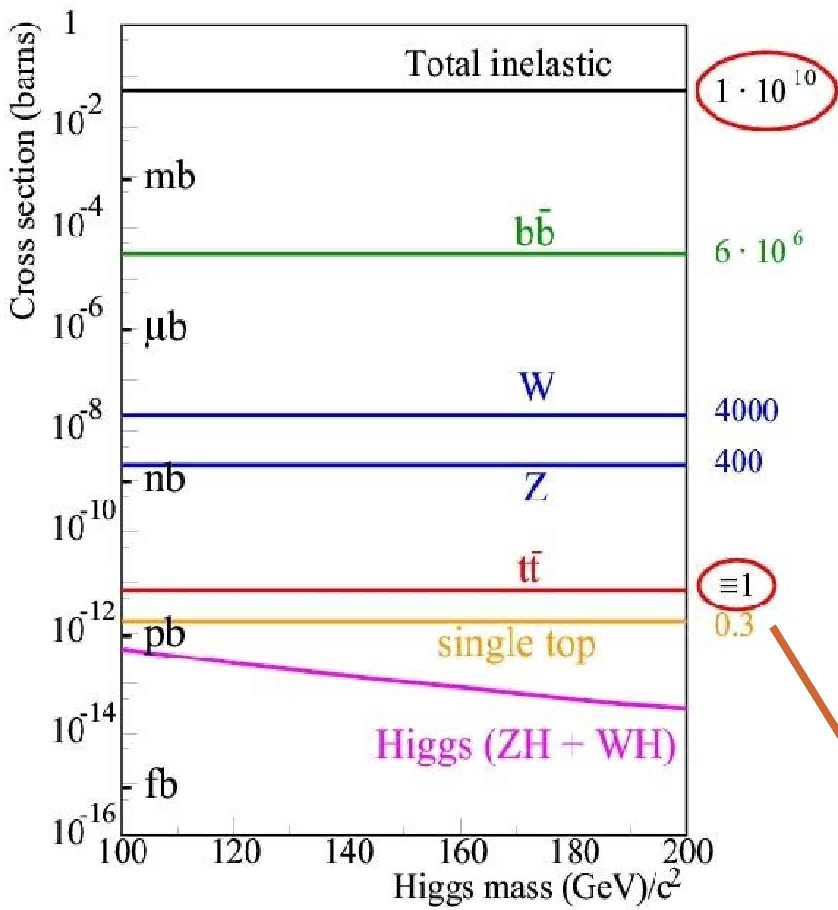


- Lessons from Run-II: Improvements are based on
  - High b-tagging efficiency
  - Improved analysis techniques
  - In-situ W-jj calibration of the JES
- Claiming high precision requires mutual verification in all channels.
- We are therefore awaiting how future measurements will benefit from reduced JES uncertainties through better calorimeter simulation.
- Limiting factor at the end of Run-II expected to be ISR/FSR (=theoretical).
- Goal: $\Delta M_{top} < 1$ GeV/c^2 at the end of Run-II (=5-10 years LHC!!!)

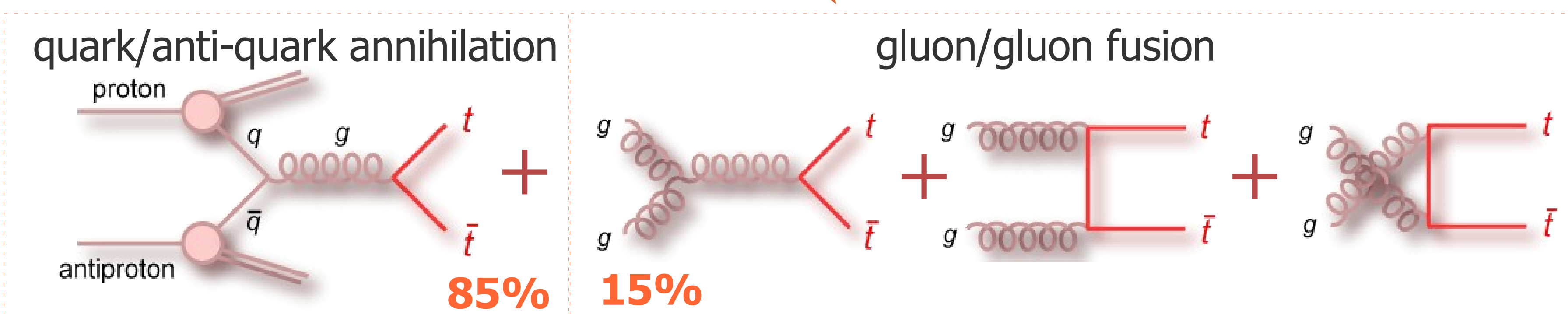
Tevatron might be the lasting legacy for the top quark mass!

Backup Slides

Top Quark Production



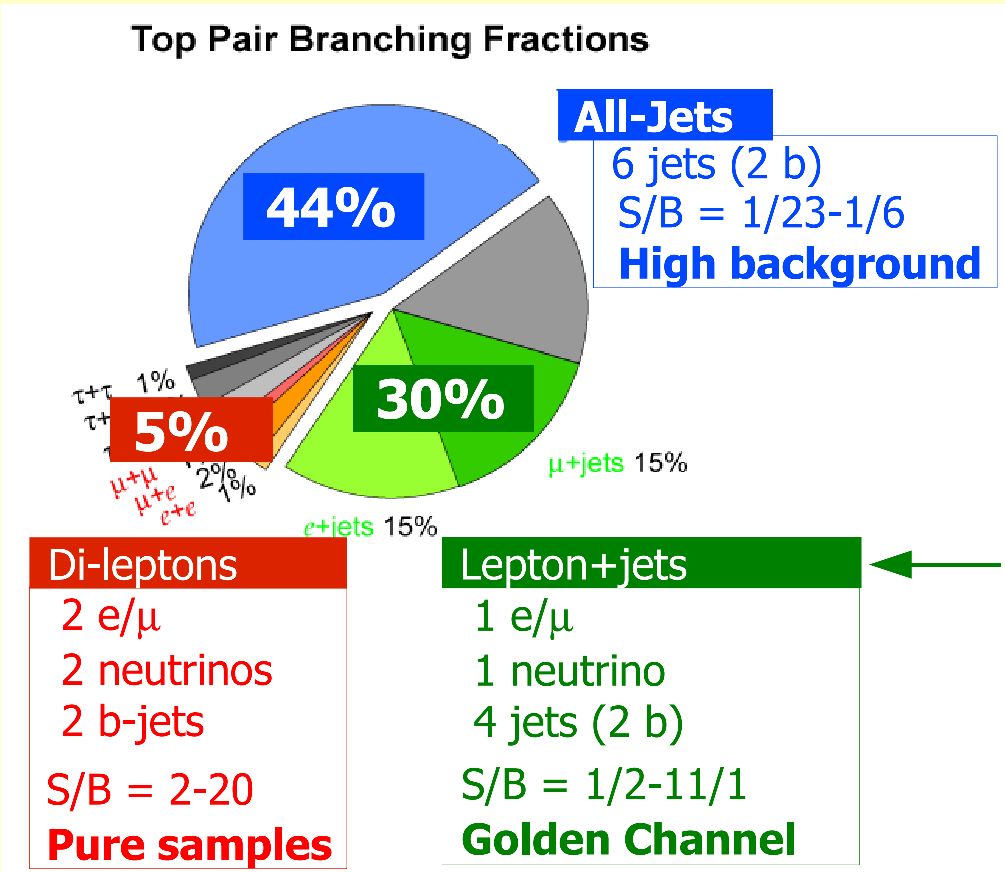
- Top quarks are mainly produced in pairs via quark/antiquark annihilation, and gluon/gluon fusion:
  $\sigma_{tt}(1.96\text{TeV})=6.1\text{pb}$
- Single top production:
  $\sigma_{t\text{-channel}}(1.96\text{TeV})=1.98\text{ pb}$
  $\sigma_{s\text{-channel}}(1.96\text{TeV})=0.88\text{ pb}$
  ...ignored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

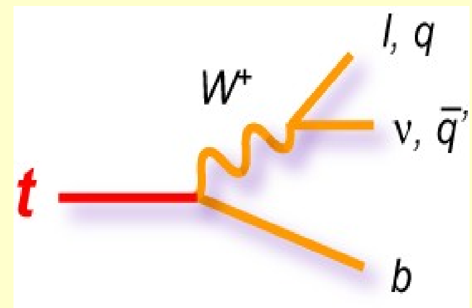


Top Quark Signatures

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

- W decay determines experimental signature:





most precise results obtained in this channel

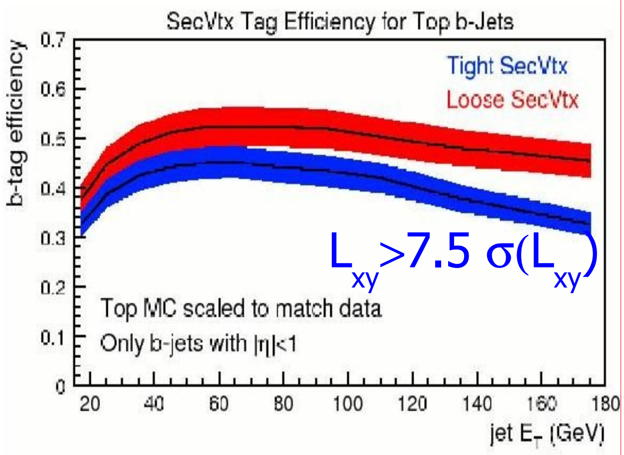
Challenges of Top Quark Physics

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 2nd part of talk

Measurement Strategies (1)

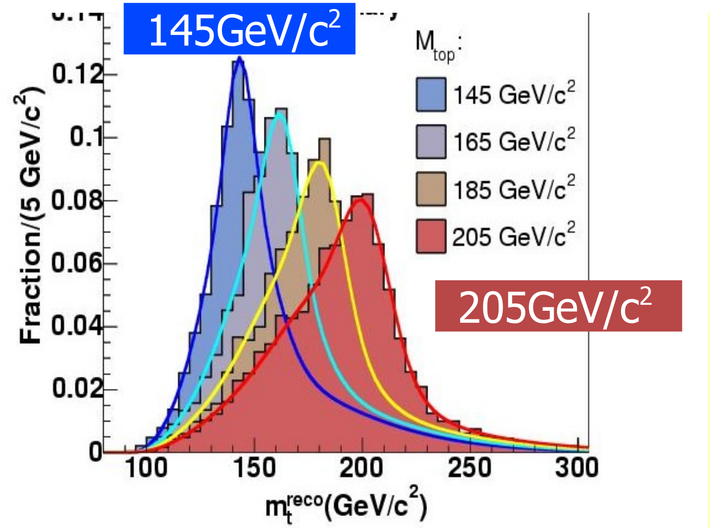
Template Method (TM):

- 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

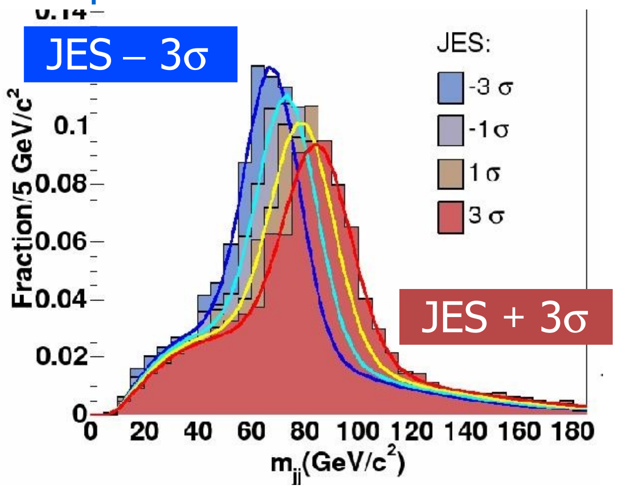
– limited kinematic information, just <u>one number</u> per event

Example: "reconstructed" top mass



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

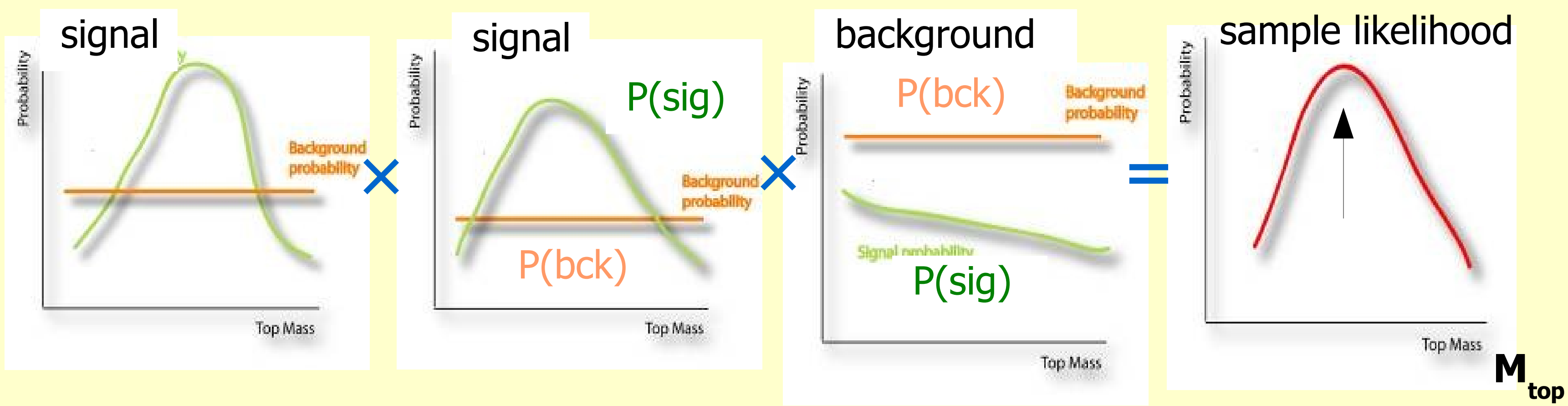
Example: "reconstructed" W mass



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

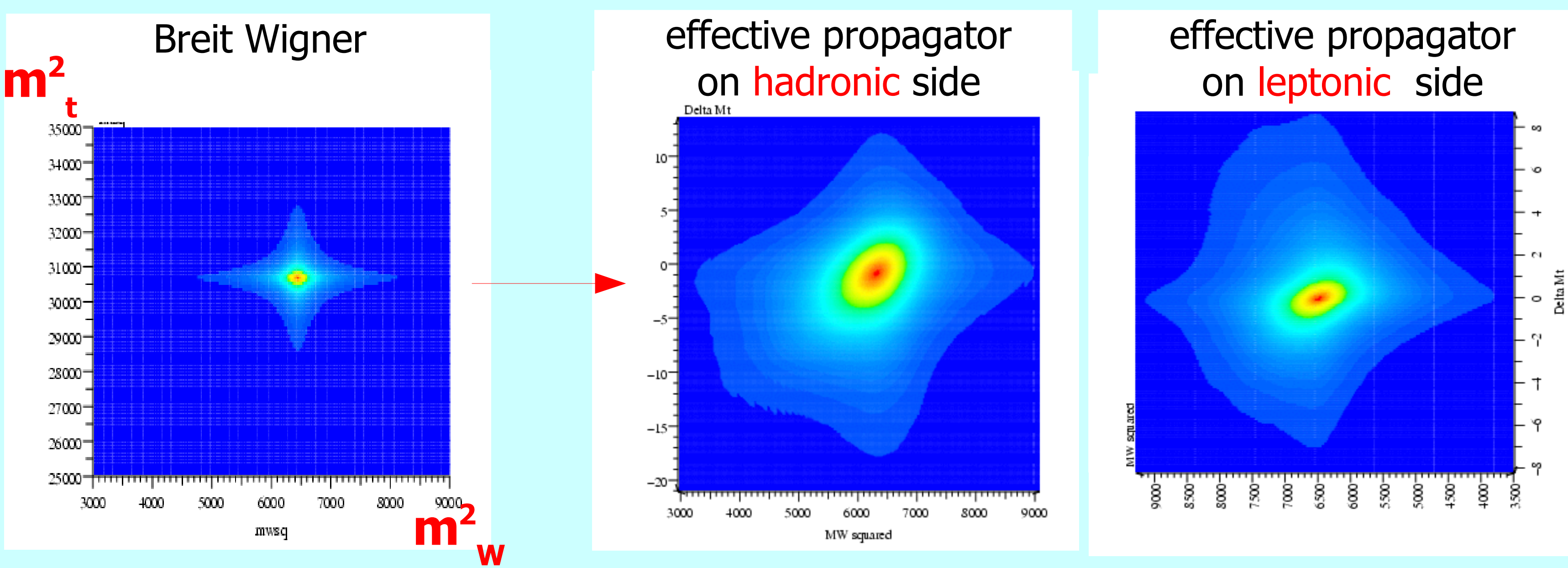
– extremely CPU intensive numerical integrations

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

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), $p_x(t\bar{t})$, $p_y(t\bar{t})$

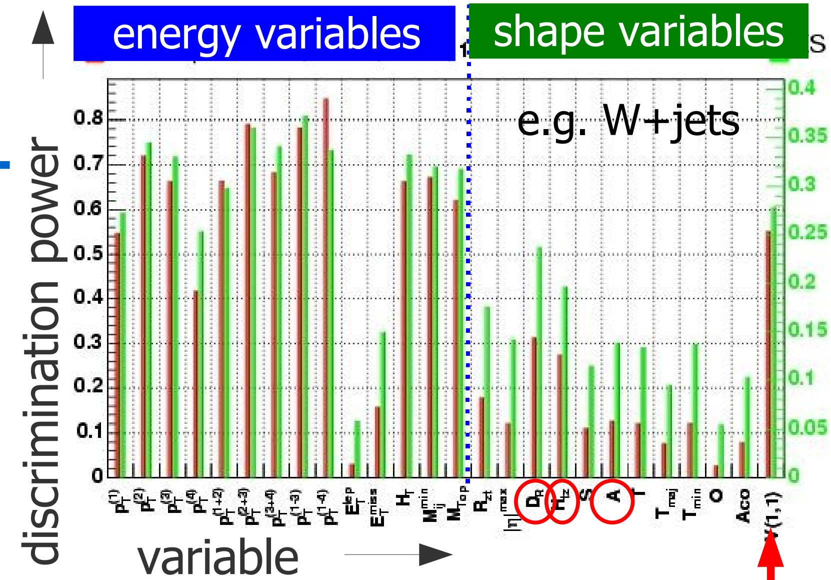
- Effective propagators are used when integrating over mass variables
  $\rightarrow$ corrects for mismatch between ME, MC and integration assumptions



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
  → m_t / JES systematics mutually cancel

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

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

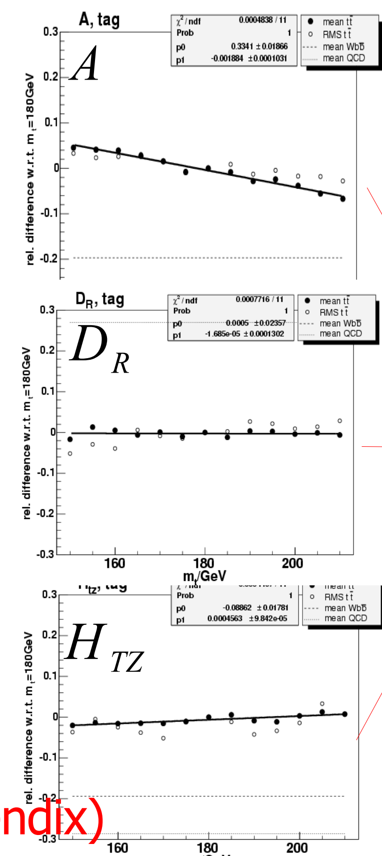
$$D_R = \min(\Delta R_{ij}) \times p_T^{(\min)} / E_T^{\text{lep}}$$

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

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

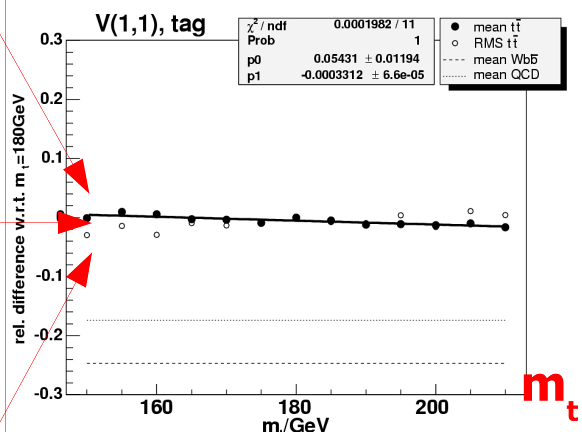
p_z^{ν}: smallest of neutrino p_z solutions

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



Hybrid variable

rel. change mean&r.m.s.

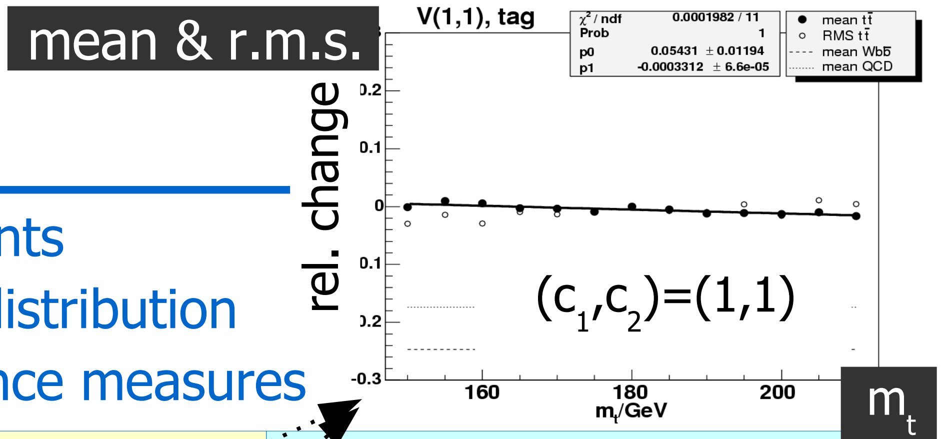


default $(c_1,c_2)=(1,1)$

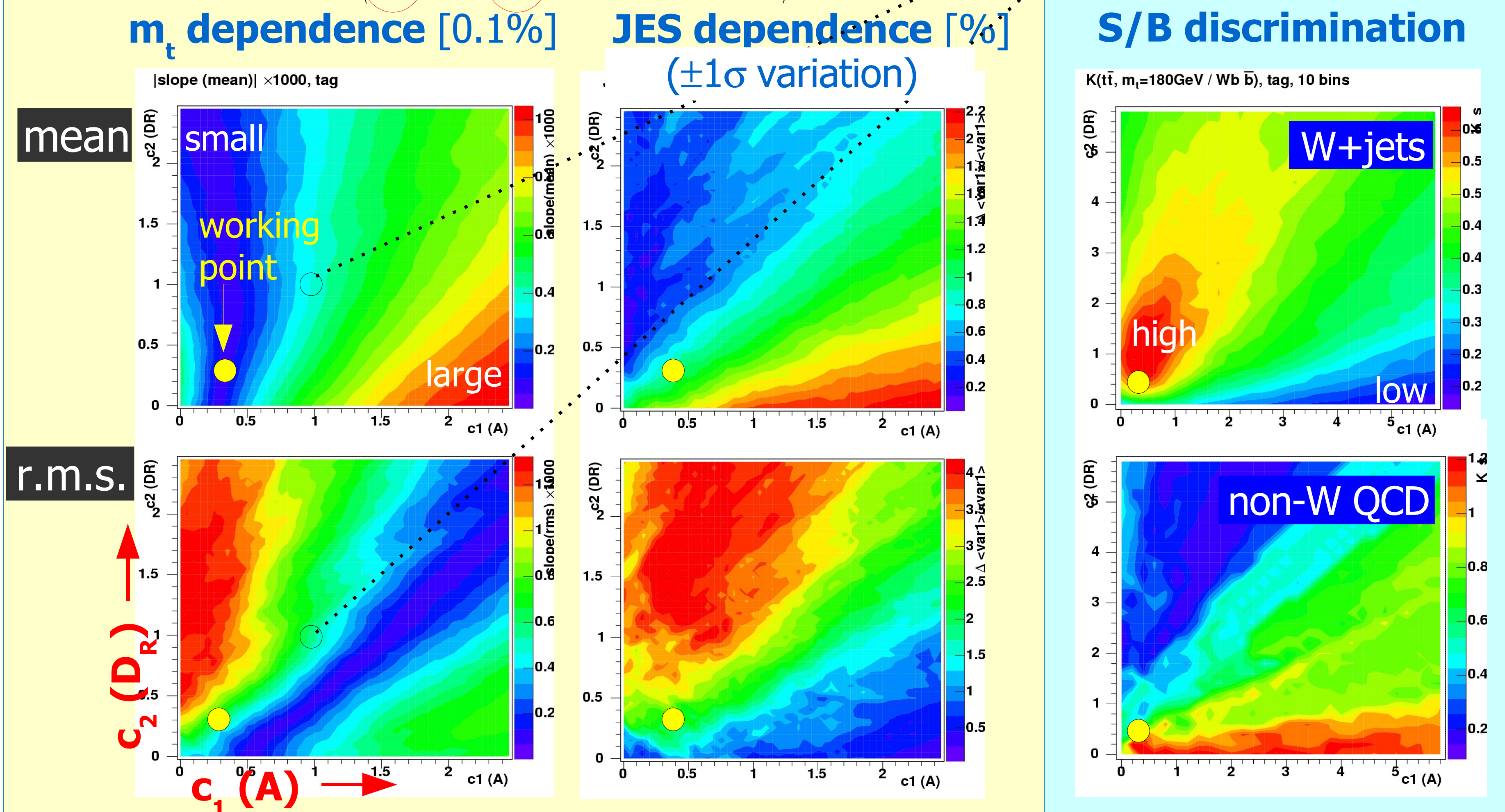
...systematic fine tuning of coefficients (appendix)

Hybrid Variable

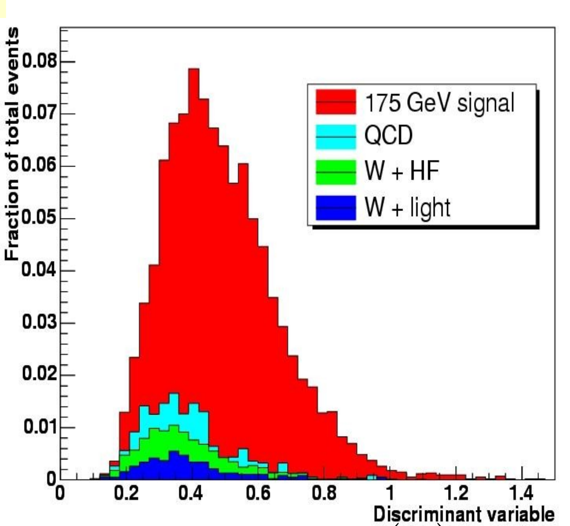
- Fine tuning of two independent coefficients
- Study relative changes w.r.t. reference distribution
- S/B discrimination quantified by divergence measures



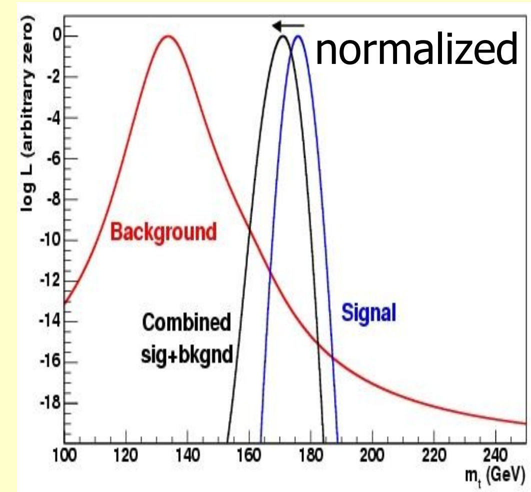
$$V=\left(\hat{c}_1 A+\hat{c}_2 D_R+\hat{c}_3 H_{TZ}\right)\times N$$



Background Treatment



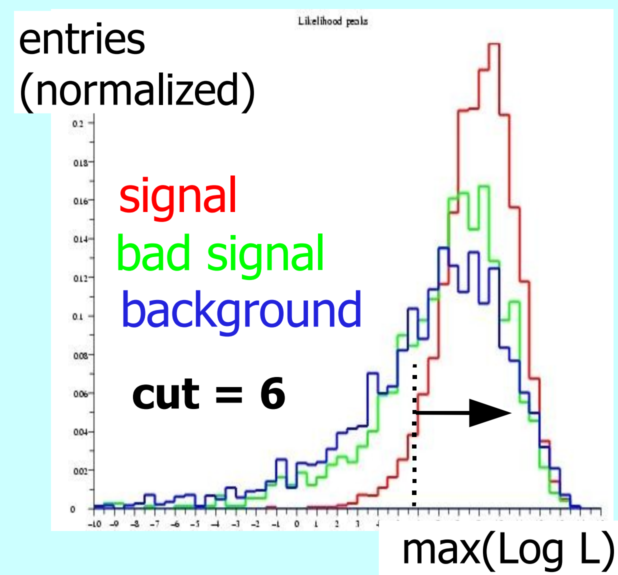
- Adding background shifts signal likelihood curve
- Subtract average log background weighted by background probability



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

- 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%



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)

Systematics

(status 03/07/2007)

physics model

Uncertainties [GeV/c^2]	Di-Lept (ME 1030 pb^{-1})	(ME 955 pb^{-1})	ll-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

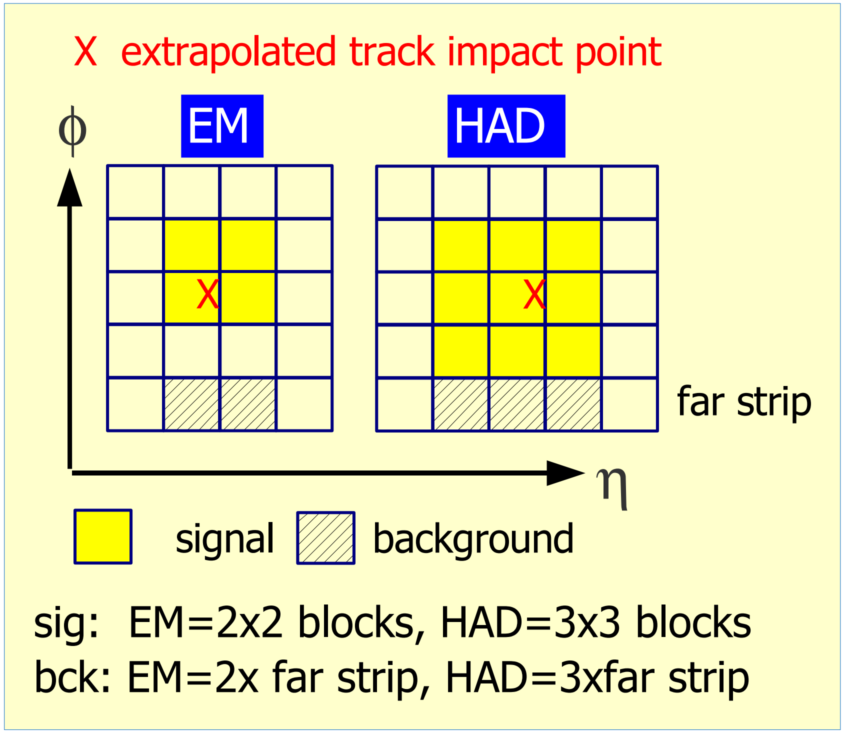
Lepton+Jets (ME 370 pb^{-1})

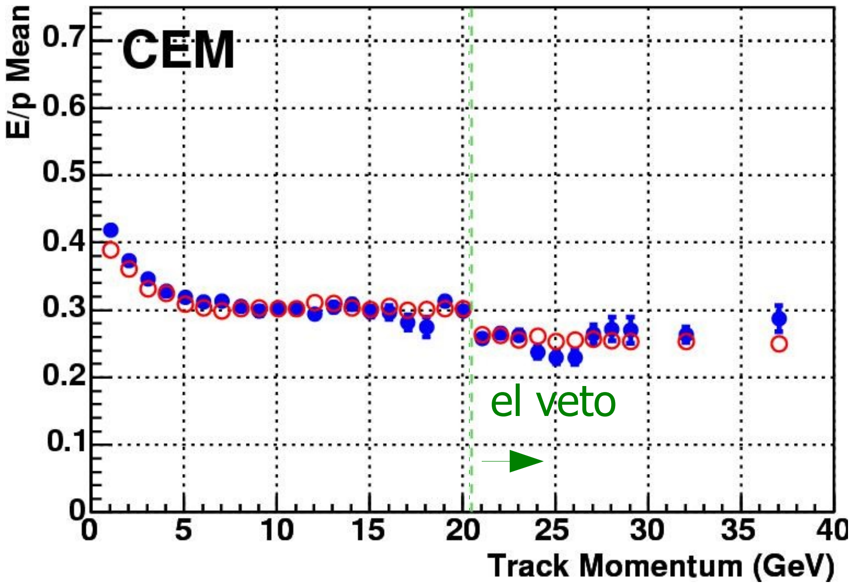
Source of Uncertainty	b-Tagging Analysis
Statistical uncertainty and jet energy scale	$+4.1$ -4.5
JES only	3.5
Physics modeling:	
Signal modeling	±0.46
Background modeling	±0.40
PDF uncertainty	$+0.16$ -0.39
b fragmentation	±0.56
b/c semileptonic decays	±0.05
Detector modeling:	
JES p_T dependence	±0.19
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

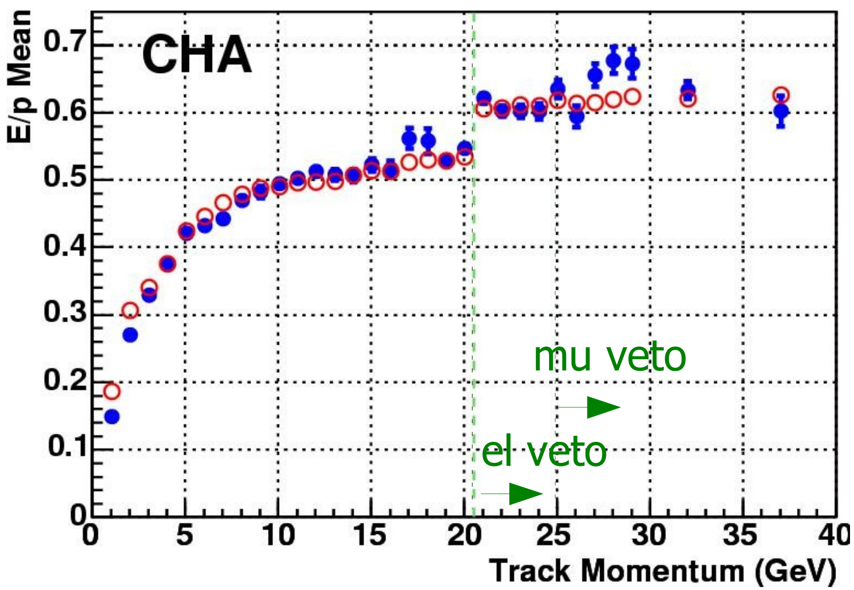
- Non-JES systematics mainly dominated by physics model:
  - amount of FSR gluon radiation, hadronization model,...

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

Absolute CEM and CHA Response

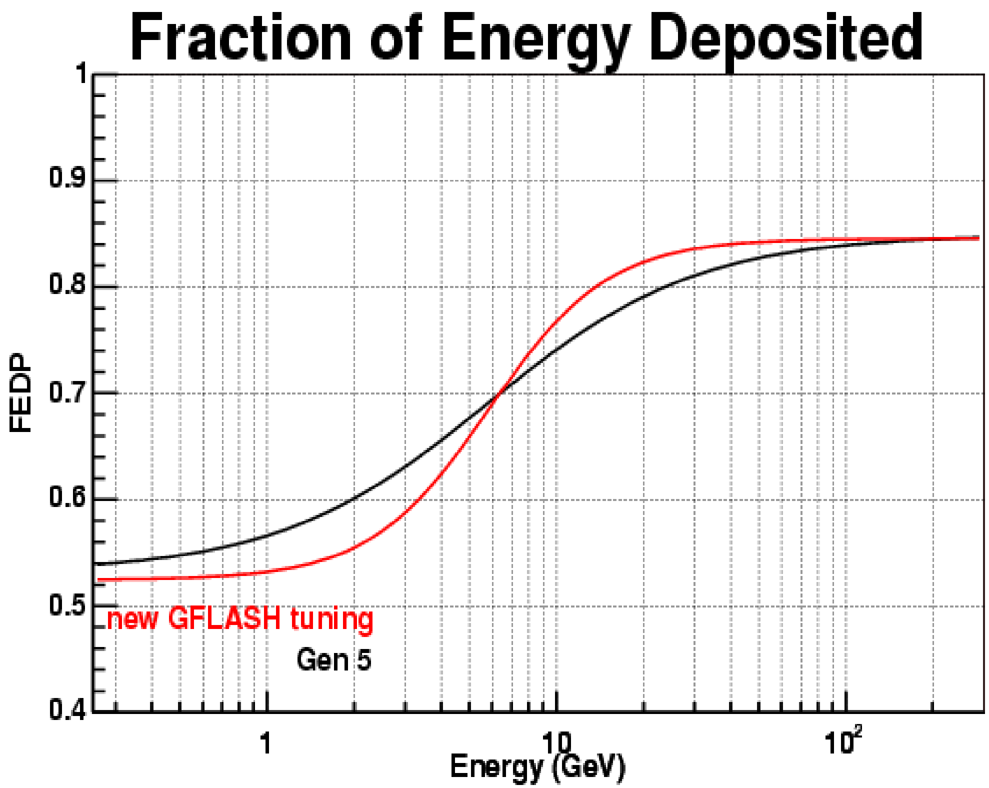


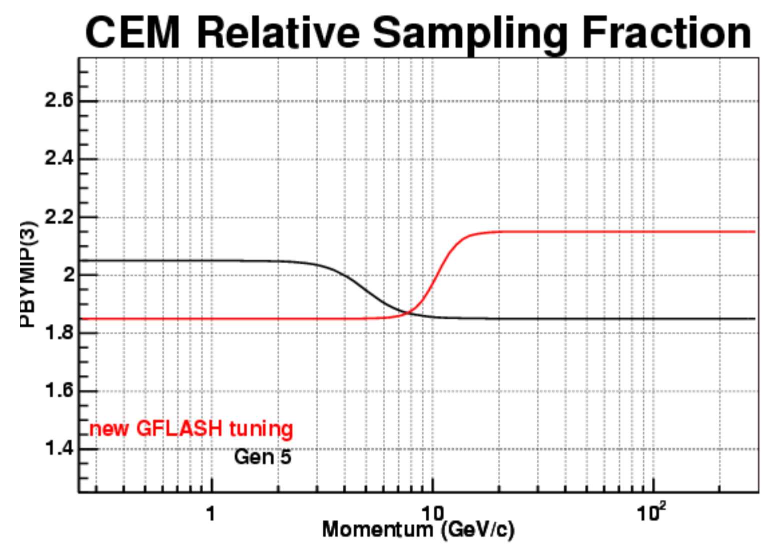


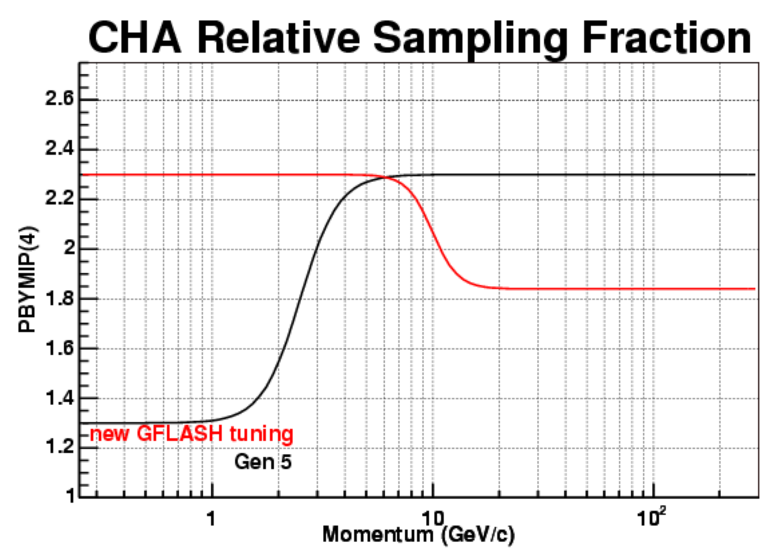


- These are not primary tune observables but serve as cross checks
- Responses dependent on shower start, shapes are more complicated than TOT and MIP
- Reasonable agreement

Parametrization (Central)



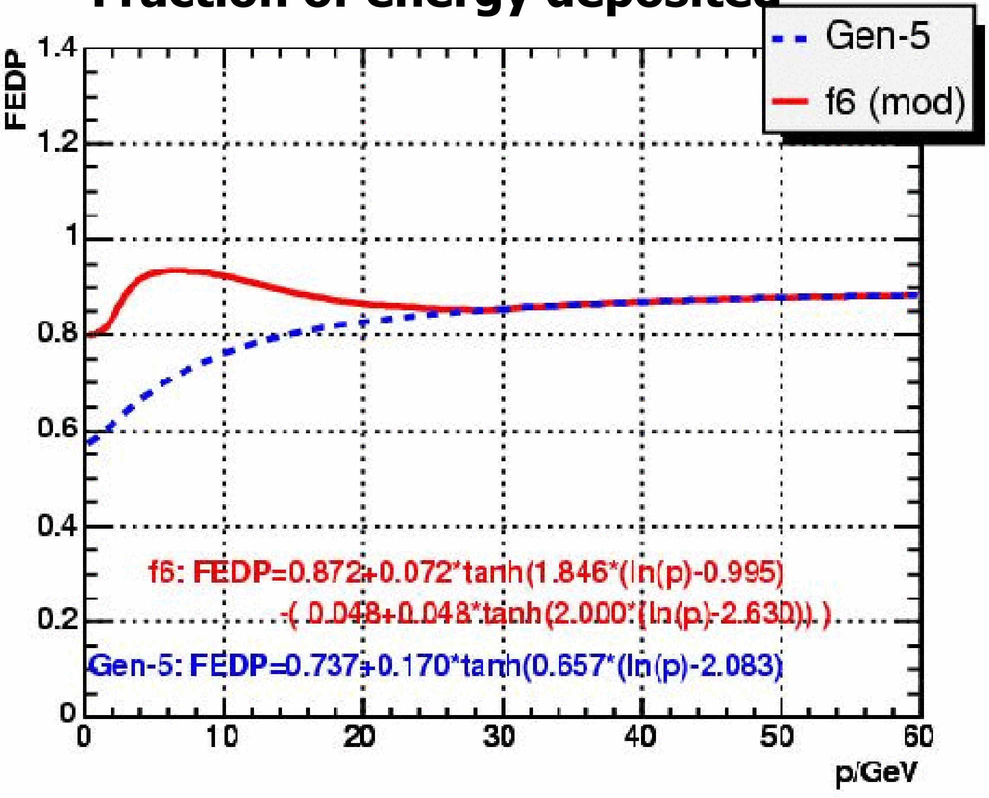




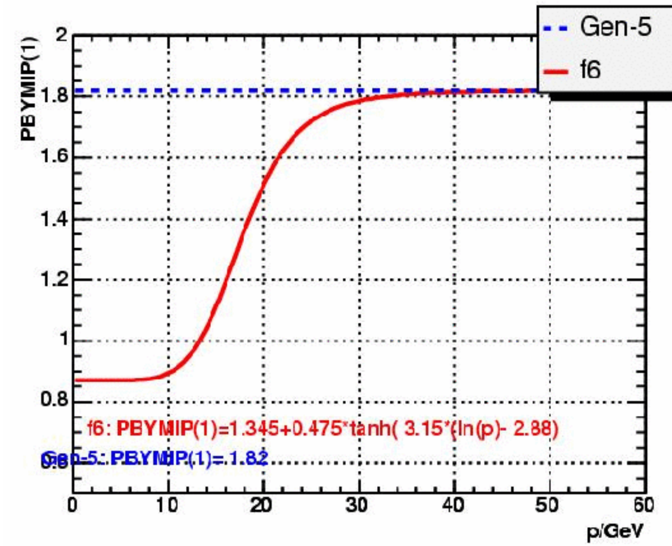
- Smooth parametrization connecting in-situ tuning and test beam tuning result.

Parametrization (Plug)

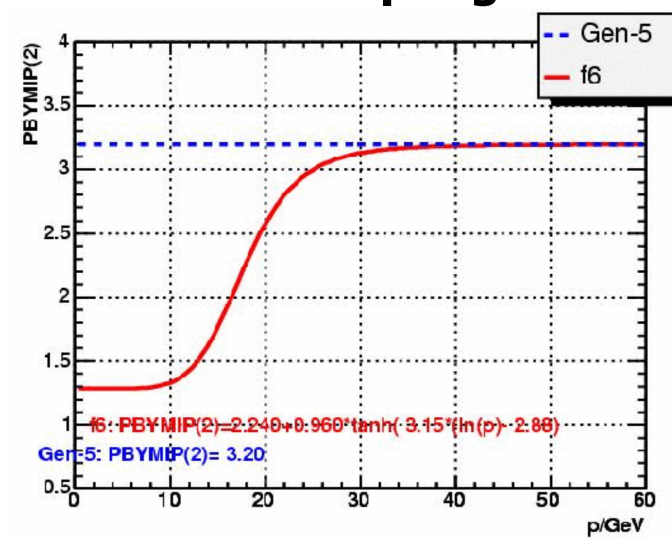
Fraction of energy deposited



PEM Relative Sampling fraction



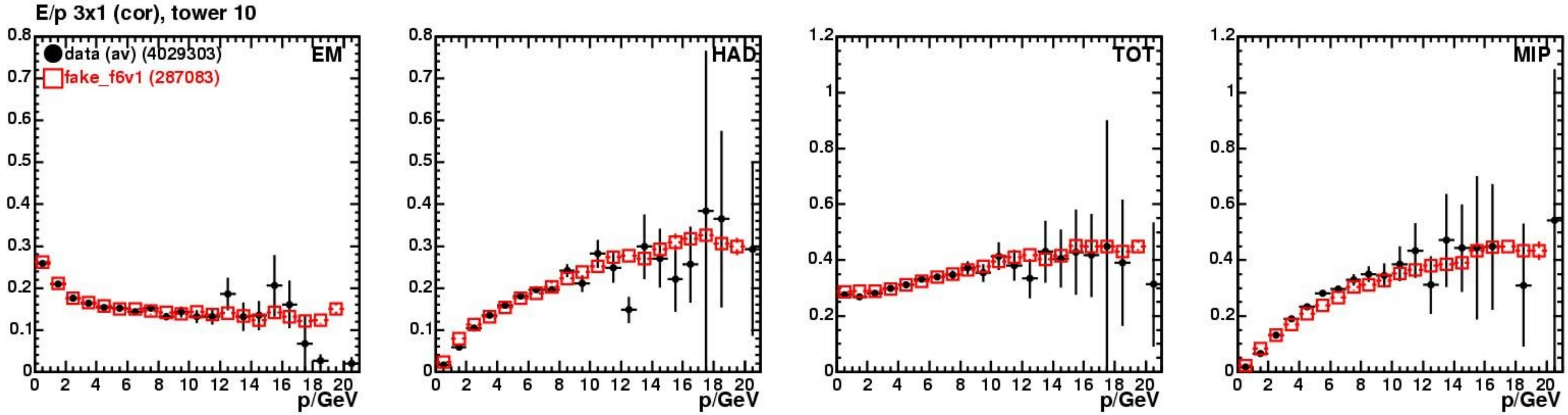
PHA Relative Sampling fraction



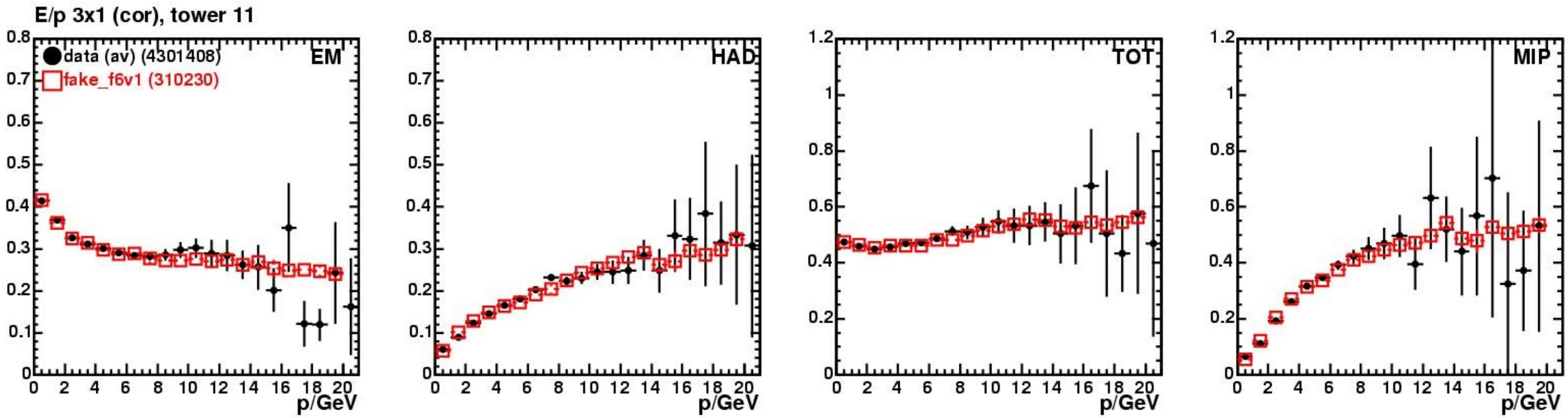
- Smooth parametrization connecting in-situ tuning and test beam tuning result.

Absolute Response Tuning (Crack)

- Tower 10

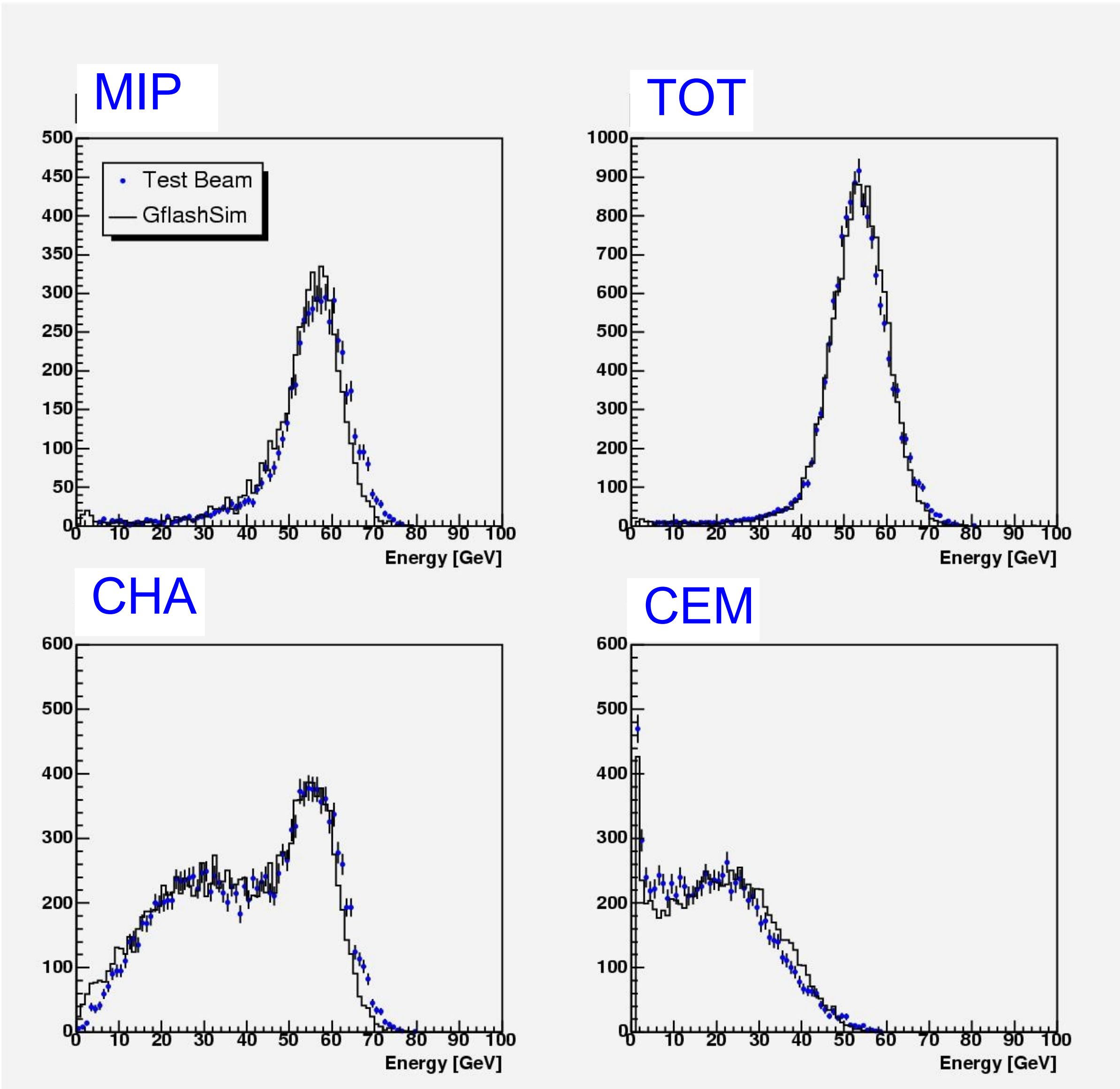


- Tower 11



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

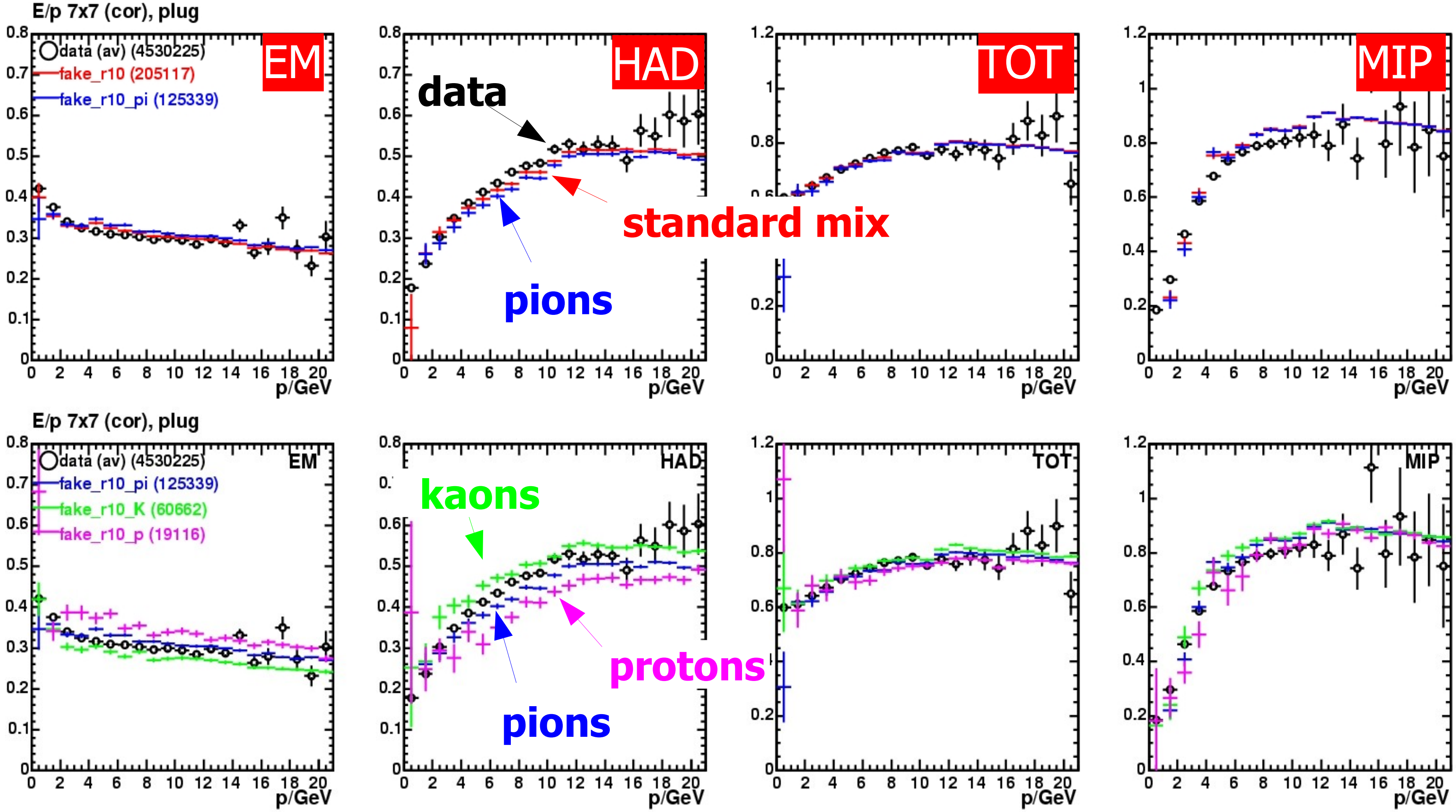
- E/p analysis
  - For TOT and MIP we consider Gaussians so we are insensitive to background contamination (e.g.: high p muons or electrons).
  - Treatment of uncorrelated background ensures that we can compare E/p from different event activity.
  - CES partially suppresses correlated background in Central.
  - 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

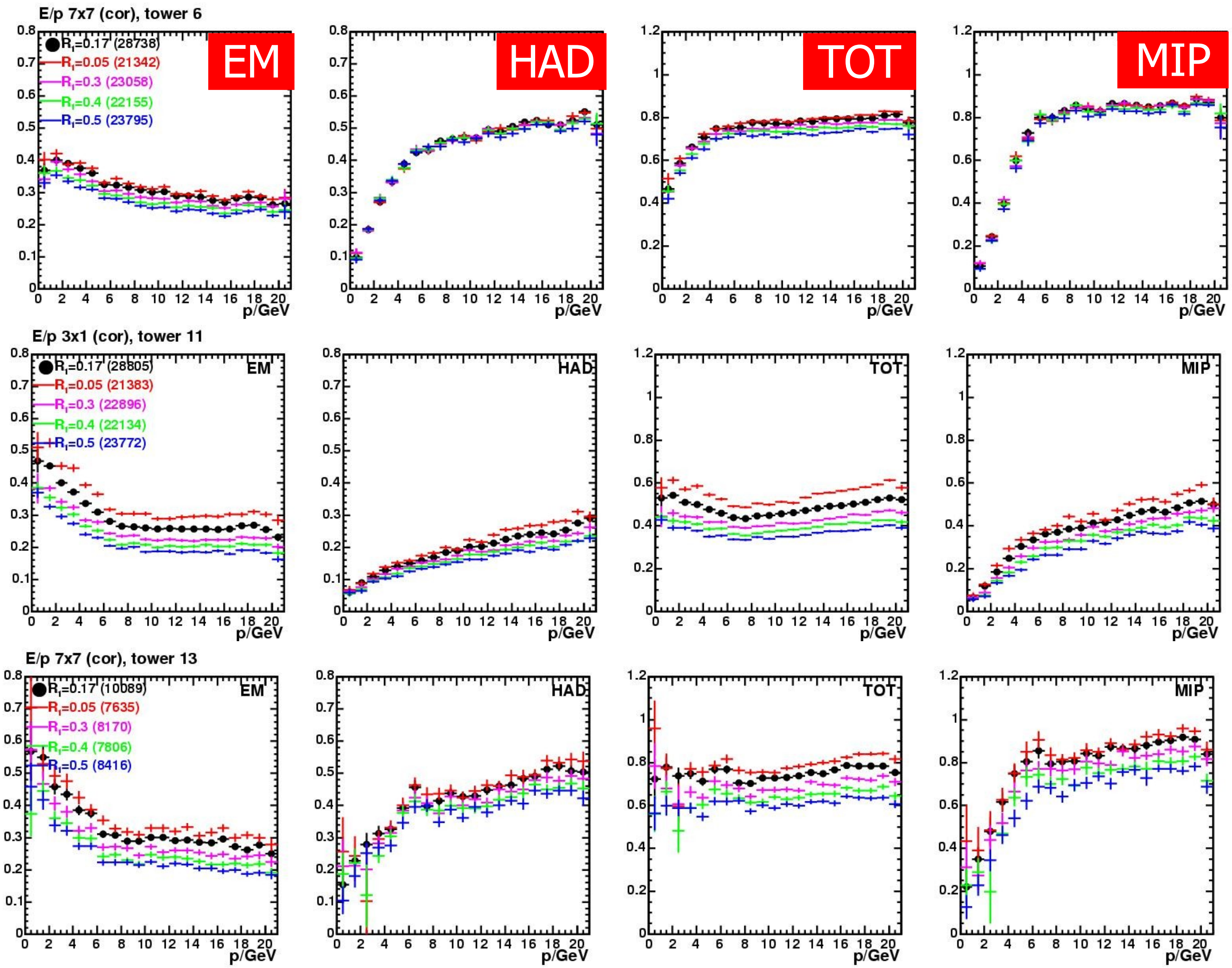
Flavor Dependence

- 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

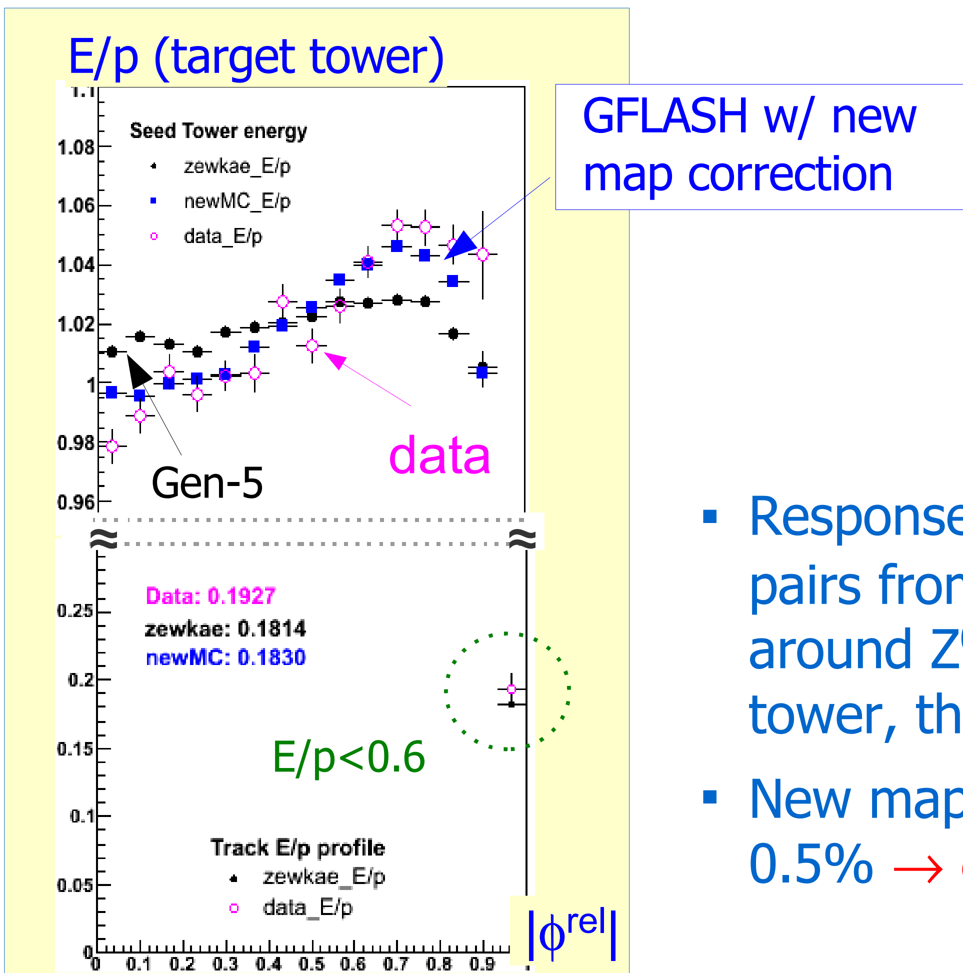
tower 11

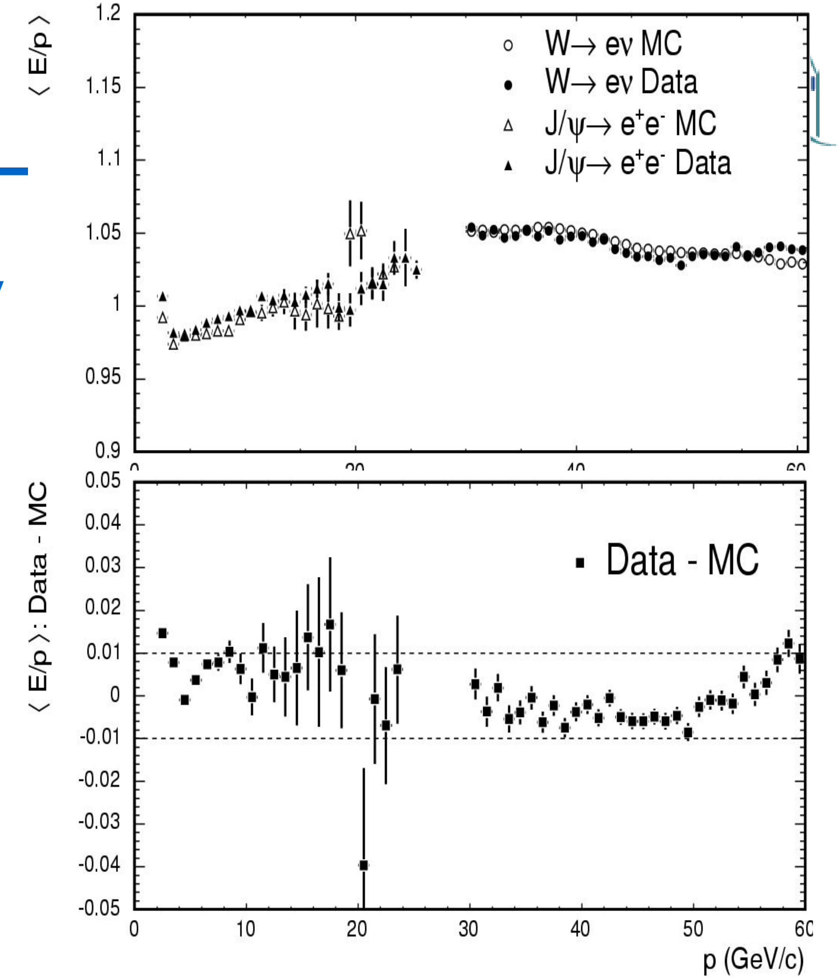
tower 13

- 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%**

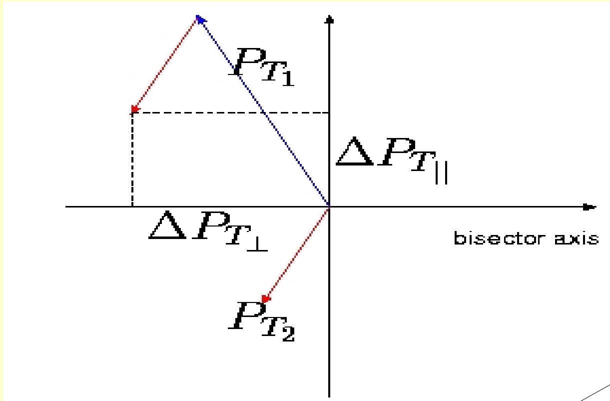




- Response along φ is monitored using electron pairs from Z^0 decays in a mass window around Z^0 mass. One keg in Central target tower, the other leg probes φ profile.
- New map correction in phi plus MC scaling by 0.5% → φ profile has significantly improved.

Jet Energy Resolution

Bi-Sector Method



- $\sigma_{||}$ = RMS of the $\Delta p_T^{||}$
- σ_{PERP} = RMS of the Δp_T^{PERP}
- $\sigma_D = \sqrt{\sigma_{||}^2 - \sigma_{PERP}^2}$

dominated by physics effects (ISR recoil) and detector resolution

dominated by physics effects

dominated by calorimeter resolution

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