# Boosted Massive Jets @ CDF & Implications

Gilad Perez

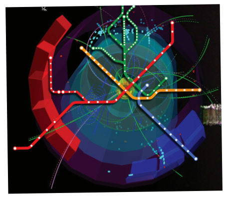
Weizmann Institute

*R, Alon, E. Duchovni, GP & P. Sinervo, for the CDF collaboration; blessed preliminary data (phase II);*

*R, Alon, E. Duchovni, GP, S. Pronko & P. Sinervo,* arXiv:1101.xxxx;

*G. Gur-Ari, M. Papucci & GP,* arXiv:1101.xxxx;

More to come ...



Boston Jet Physics Workshop

# Outline

- jet substructure, inner-jet energy flow:
  (i) jet mass => perturbative @ high mass =>
  (ii) angularity <-> 2-body (iii) planar flow <-> 3 body.

*theorist*

- First measurements: CDF preliminary (phase II).

*experimentalist*

- Data-driven method for pile up subtraction.

- Generic classification of jet shapes.

*theorist*

- Some implications of CDF's data.

# Jet Mass-Overview

✦Jet mass-sum of "massless" momenta in h-cal inside the cone: $m_J^2 = (\sum_{i \in R} P_i)^2, \ {P_i}^2 = 0$

✦Jet mass is non-trivial both for S & B for concreteness mostly focus on top-jets.

# Non trivial top-jet mass distribution

- Naively the signal is $J \propto \delta(m_J - m_t)$
- In practice $m_J^t \sim m_t + \delta m_{QCD} + \delta m_{EW}$

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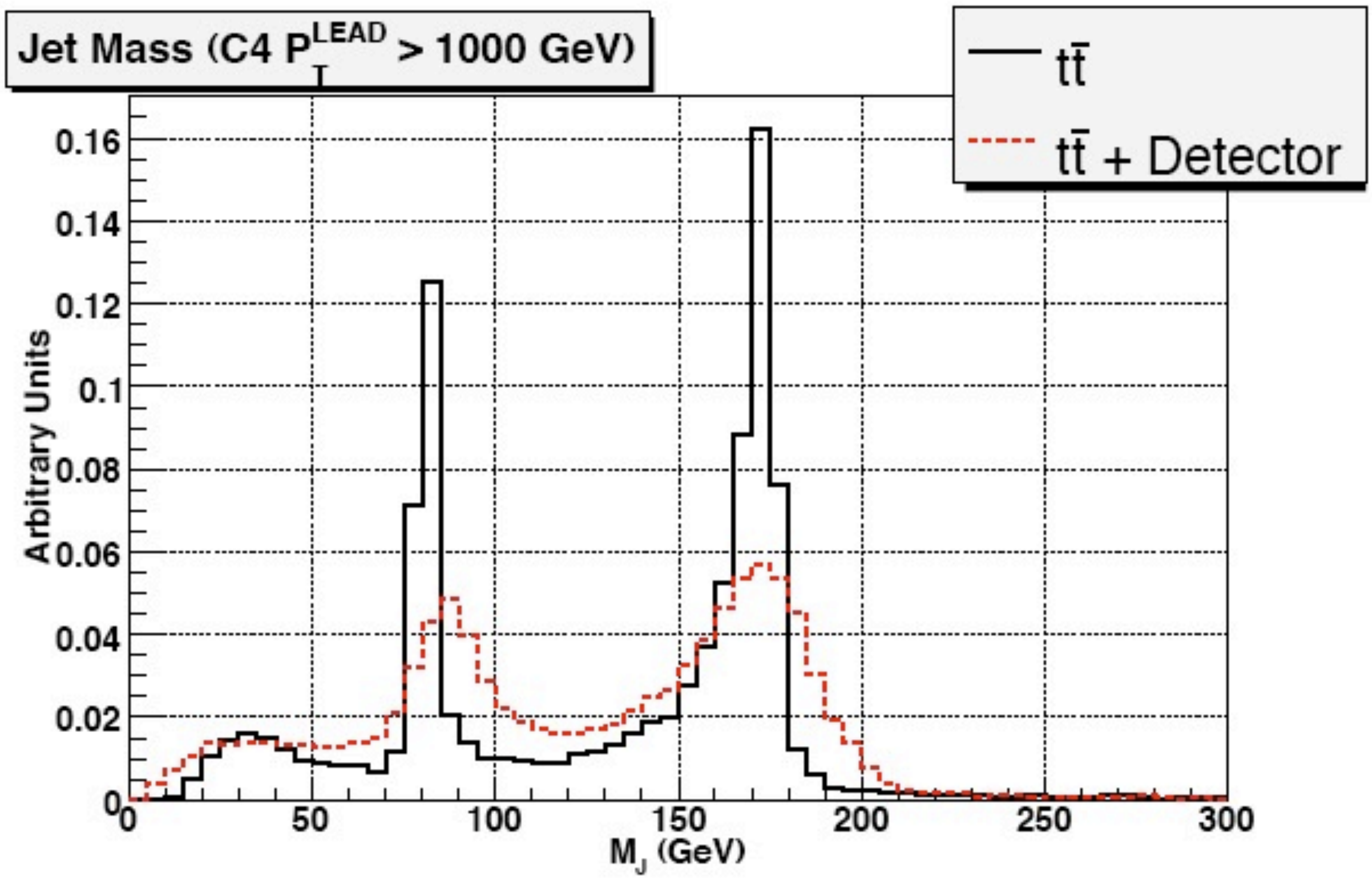
- In practice $m_J^t \sim m_t + \delta m_{QCD} + \delta m_{EW}$

+ detector smearing.

*Almeida, Lee, Perez, Sung,& Virzi (08), see also Fleming, Hoang, Mantry, Stewart (07,08).*

Sherpa => Transfer functions,
(CKKW)



# QCD jet mass distribution

Ellis, Huston, Hatakeyama, Loch and Tonnesmann, (07); Almeida, Lee, Perez, Sung, & Virzi (08).

## ✦Boosted QCD Jet via factorization:

$$\frac{d\sigma^i}{dm_J} = J^i(m_J, p_T^{min}, R^2)\, \sigma^i\,(p_T^{min})$$

$$\int dm_J\, J^i = 1 \qquad i = Q, G$$

- can interpret the jet function as a probability density functions for a jet with a given $p_T$ to acquire a mass between $m_J$ and $m_J + \delta m_J$

Full expression:

$$\frac{d\sigma_{H_A H_B \to J_1 J_2}}{dm^2_{J_1} dm^2_{J_2} d\eta} = \sum_{abcd} \int dx_a\, dx_b\, \phi_a(x_a, p_T)\, \phi_b(x_b, p_T) \frac{d\hat{\sigma}_{ab\to cd}}{dp_T d\eta}(x_a, x_b, \eta, p_T)$$
$$S\left(m^2_{J_1}, m^2_{J_2}, \eta, p_T, R^2\right)\; J_1^{(c)}(m^2_{J_1}, \eta, p_T, R^2) J_2^{(d)}(m^2_{J_2}, \eta, p_T, R^2)$$

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For large jet mass & small R,
no big corrections =>
leading log can be captured via
perturbative QCD.

- can interpret the jet fun ... en pT to acquire a mass between ...

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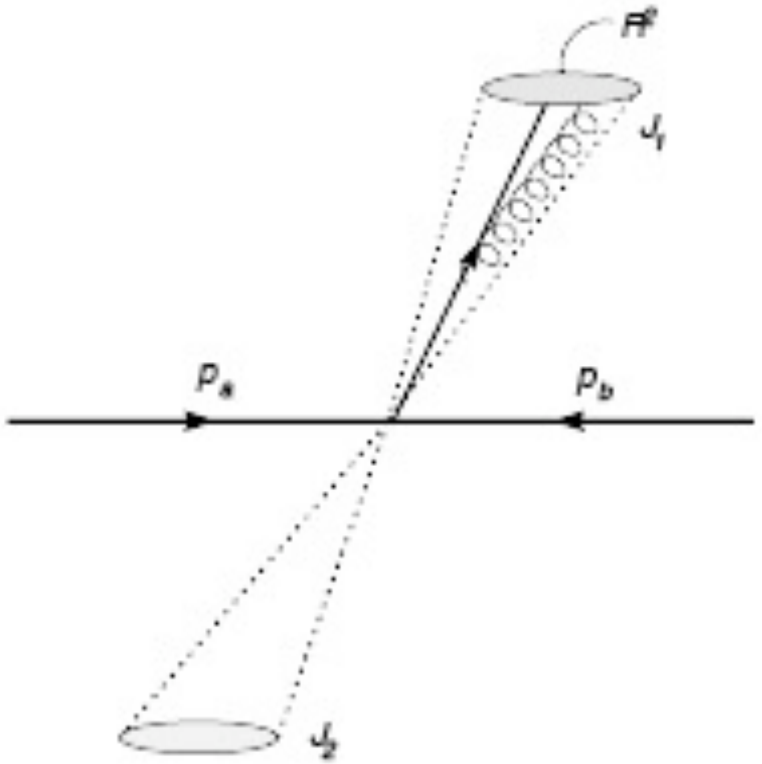
# QCD jet mass distribution, Q+G

Main idea: calculating mass due to two-body QCD bremsstrahlung:



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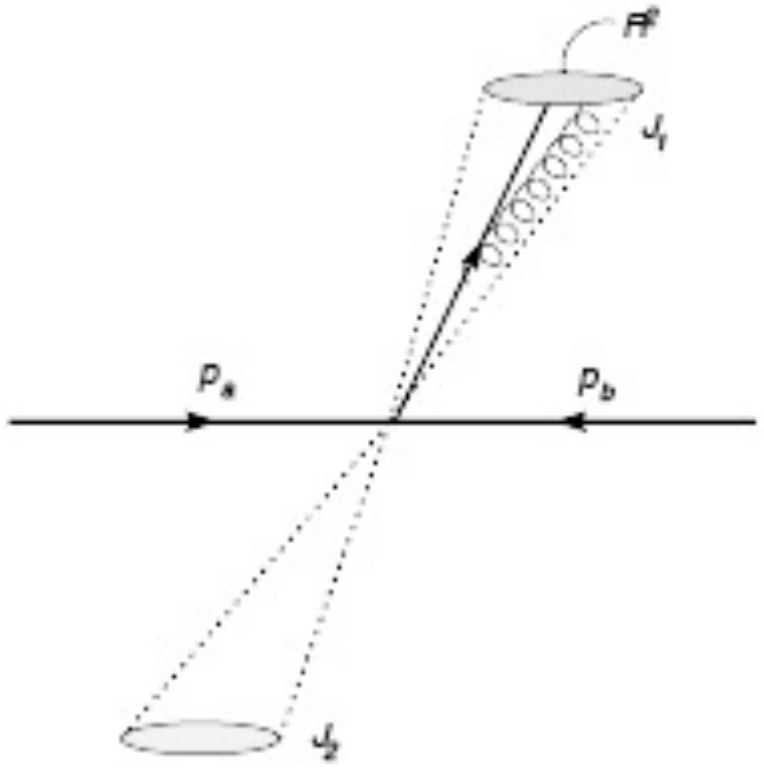

$$J^{(eik),c}(m_J, p_T, R) \simeq \alpha_S(p_T)\frac{4\,C_c}{\pi m_J}\log\left(\frac{R\,p_T}{m_J}\right)$$

$C_F = 4/3$ for quarks, $C_A = 3$ for gluons.

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$C_F = 4/3$ for quarks, $C_A = 3$ for gluons.

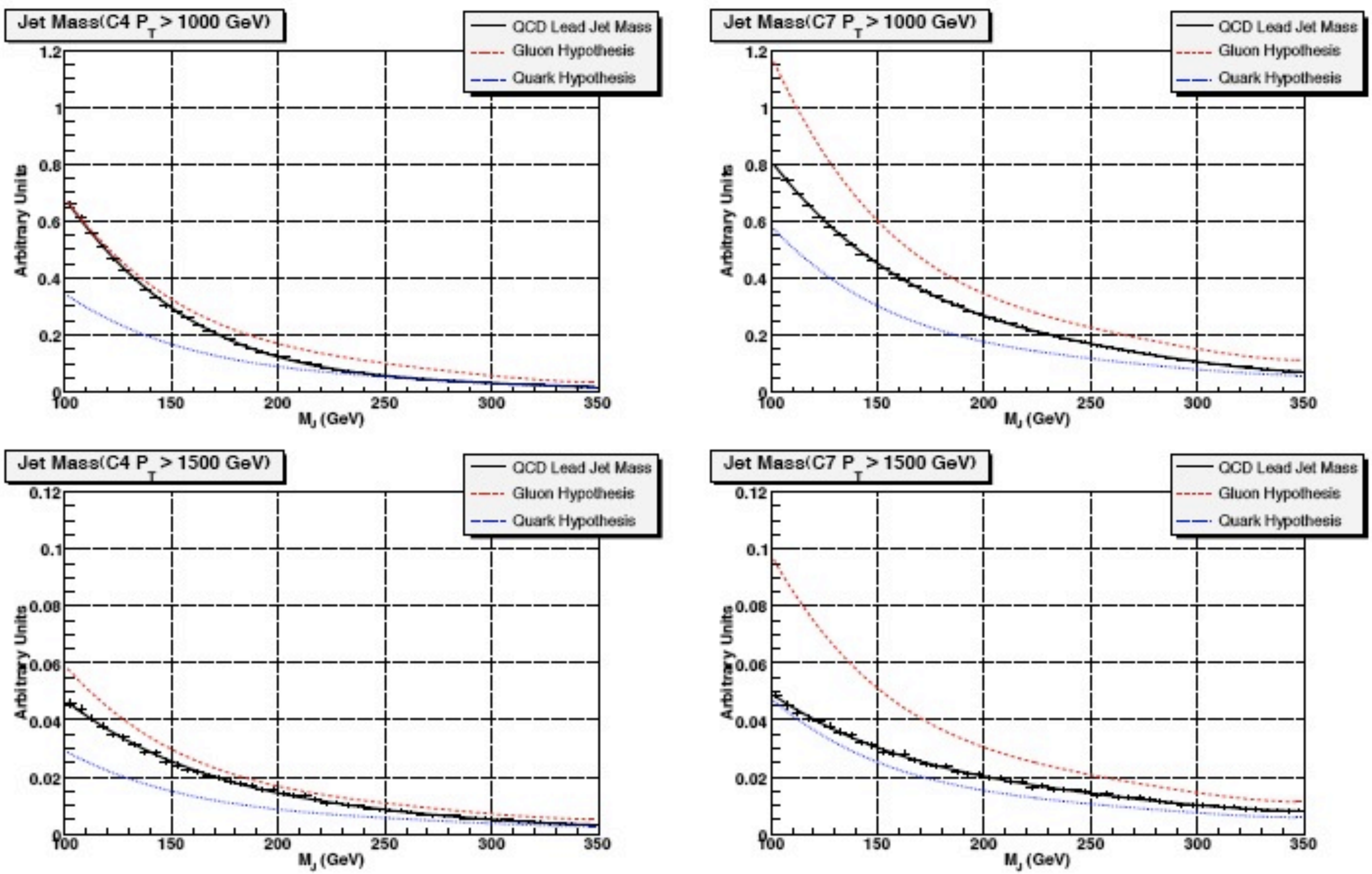
Data is admixture of the two, should be bounded by them:

$$\left.\frac{d\sigma_{pred}(R)}{dp_T dm_J}\right._{upper\ bound} = J^g(m_J, p_T, R)\sum_c \left(\frac{d\sigma^c(R)}{dp_T}\right),$$

$$\left.\frac{d\sigma_{pred}(R)}{dp_T dm_J}\right._{lower\ bound} = J^q(m_J, p_T, R)\sum_c \left(\frac{d\sigma^c(R)}{dp_T}\right),$$

# Jet mass distribution theory vs. MC

Sherpa, jet function convolved above $p_T^{\min}$



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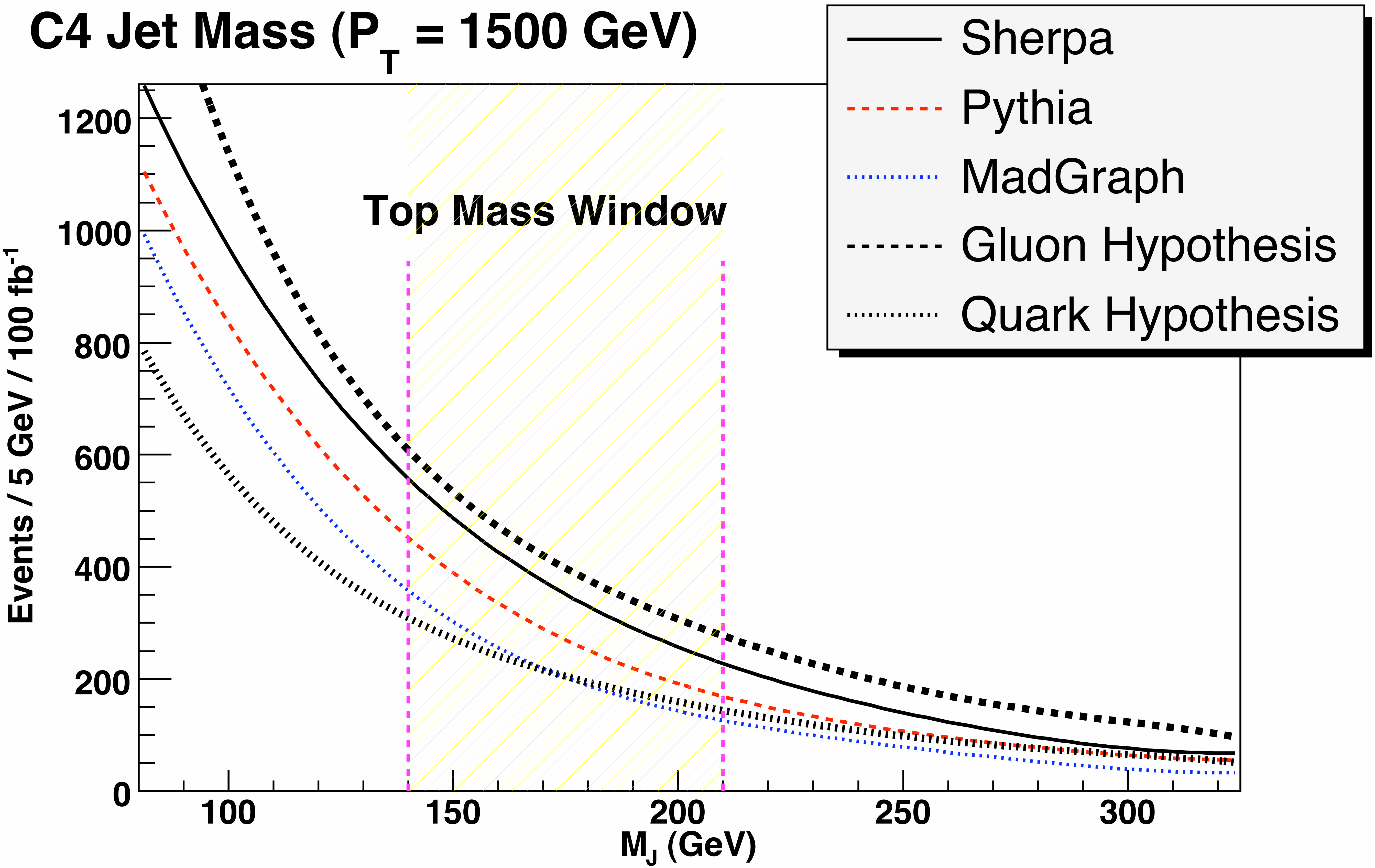

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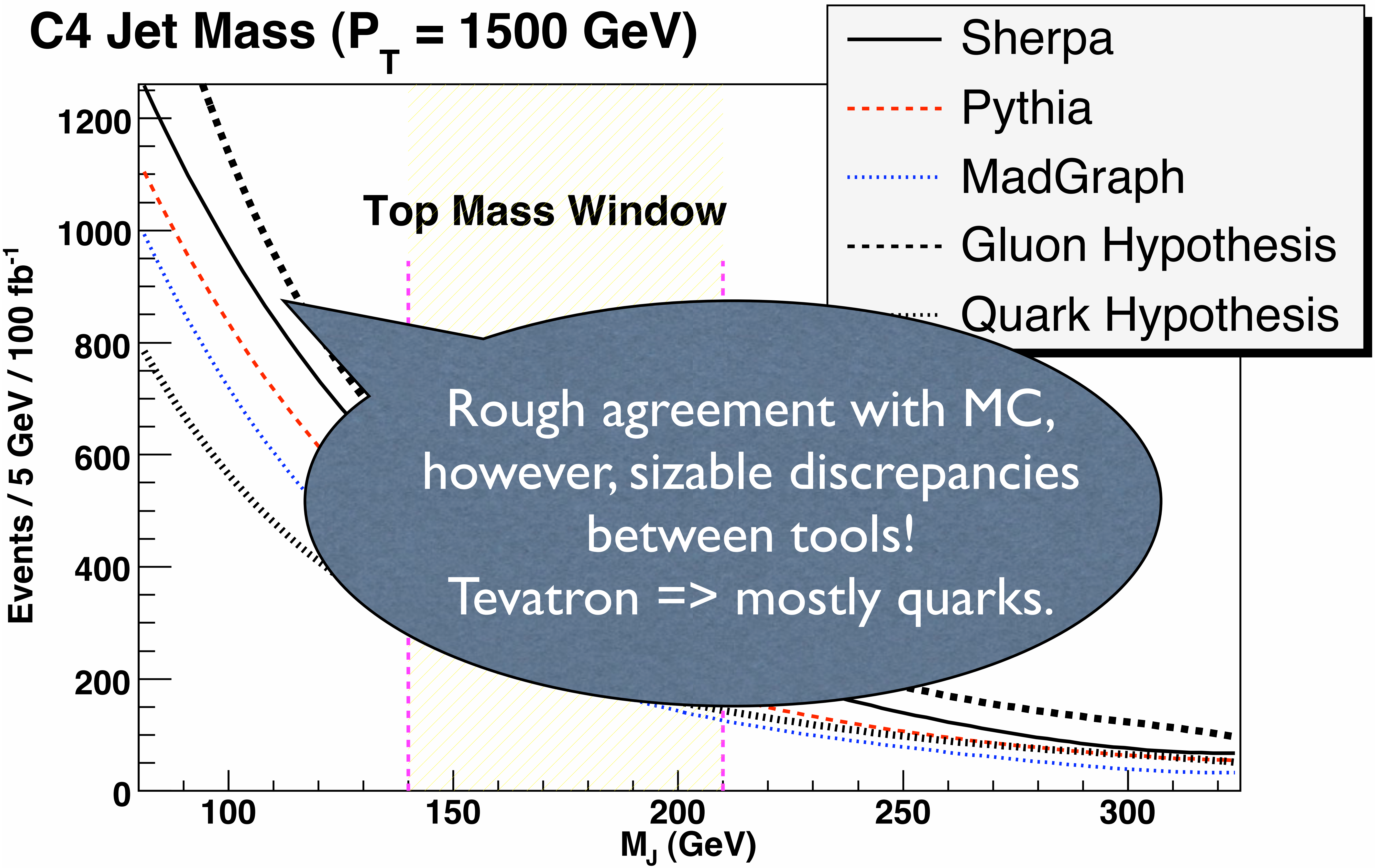
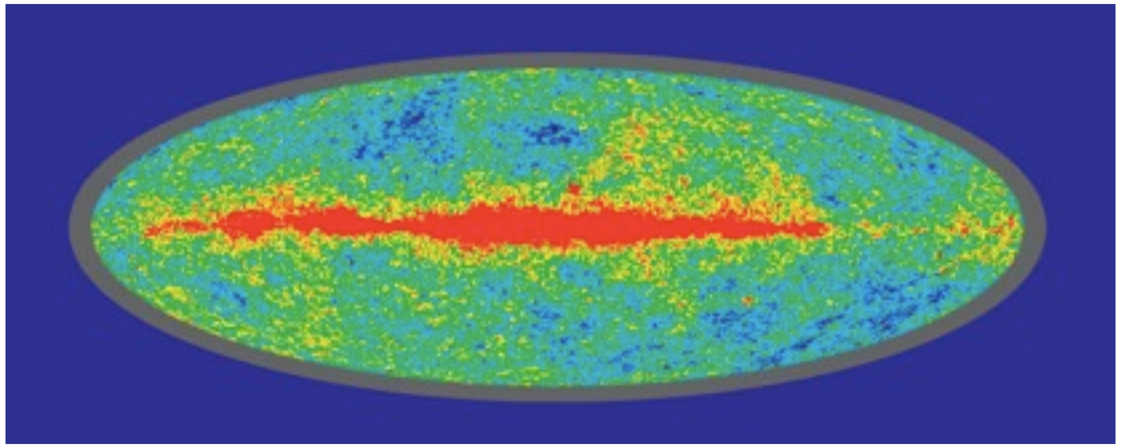
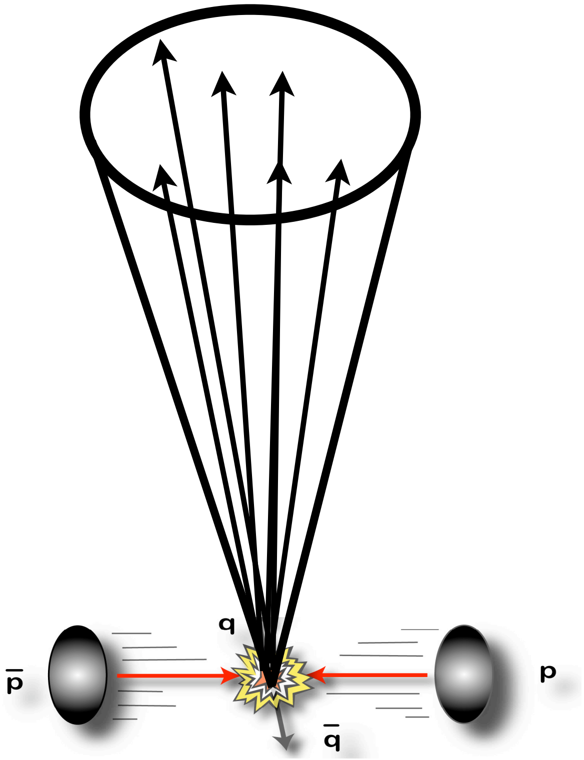


# Jet sub-structure





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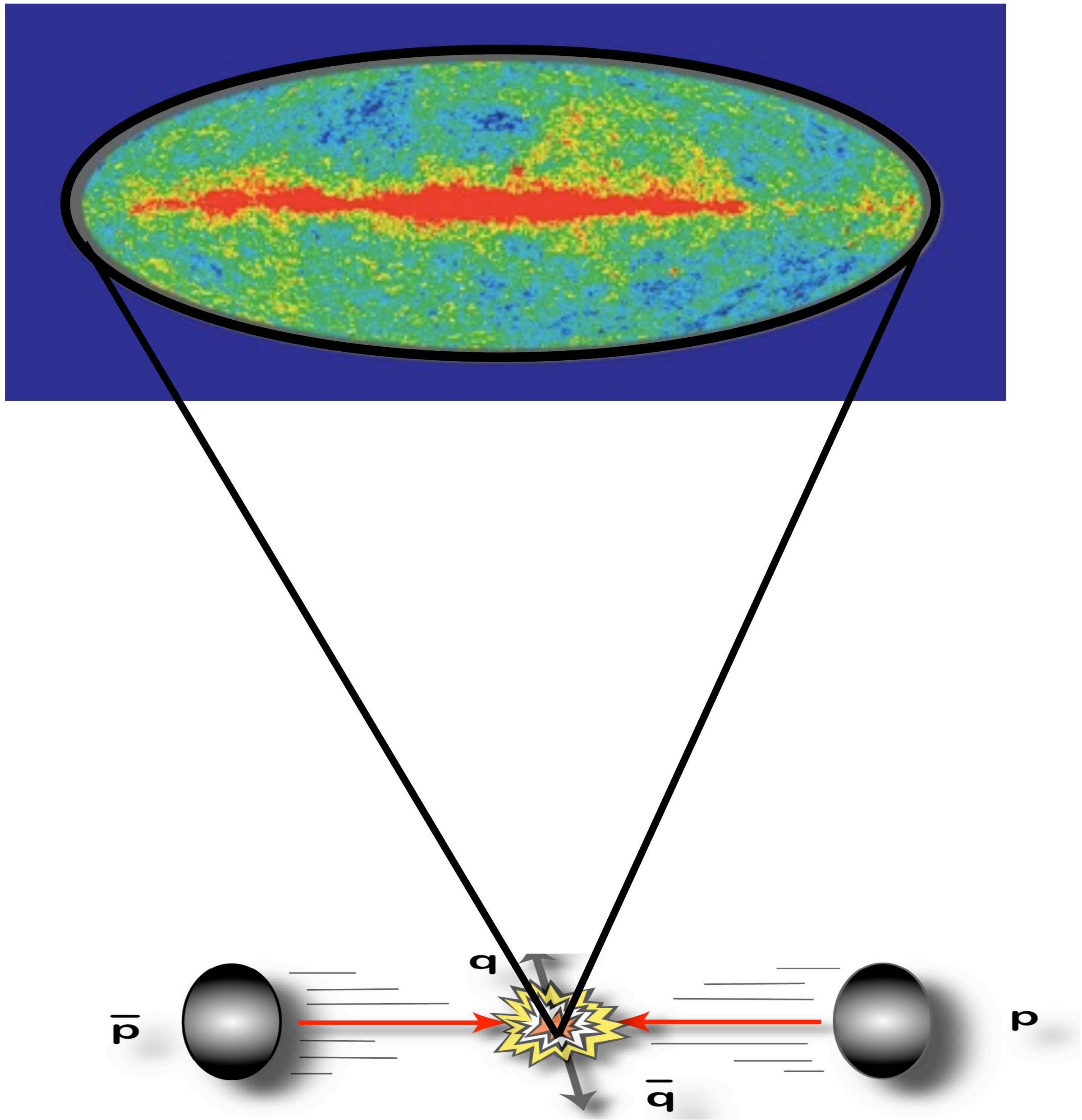


Fixing mass => more control (looking @ set of moments):

(i) Angularity.
(ii) Planar flow.

(no manipulation of jet energy deposition)

# IR-safe jet-shapes which distinguish between massive & QCD jets?

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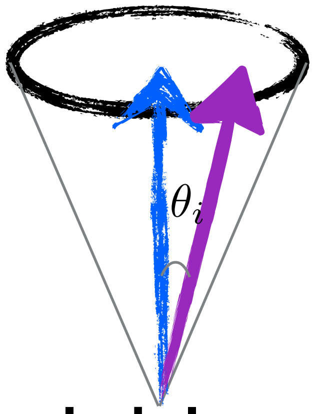


- Once jet mass fixed @ high scale
  - ➡ Large class of jet-shapes become perturbatively calculable

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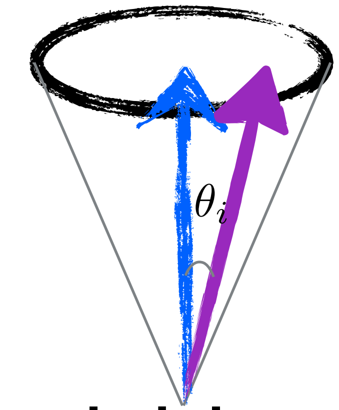


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- Angularity (2-body final state): Berger, K´ucs and Sterman (03)

$$\tau_a(R,p_T)=\frac{1}{m_J}\sum_{i\in jet}\omega_i\sin^a\theta_i\,[1-\cos\theta_i]^{1-a}\sim\frac{2^{a-1}}{m_J}\sum_{i\in jet}\omega_i\,\theta_i^{2-a}\quad\propto_{a=-2}\sum_i\omega_i\theta_i^4$$

emphasize cone-edge radiation

*Almeida, Lee, GP, Sterman, Sung, & Virzi (08)*

# Higher moments, angularity (2 body)

- Given jet mass & momenta, only one additional independent, variable to describe energy flow:

$$\tau_{-2} \sim \frac{1}{m} \sum_{i \in J} E_i \theta_i^4$$

- If mass is due to 2-body => sharp prediction (kinematics):

$$\theta_{\min} \sim \frac{m_J}{p_J} \Rightarrow \tau_{-2}^{\min} \approx \left(\frac{m_J}{p_J}\right)^3$$

$$\theta_{\max} \sim R \Rightarrow \tau_{-2}^{\max} \approx R^2 \frac{m_J}{p_J}$$

Almeida, Lee, GP, Stermam & Sung, PRD (10).

# 2-body jet's kinematics, *Z/W/h*

✦Angularities "distinguish" between Higgs & QCD jets (2-body only one variable<=>asymmetry):

$$\frac{dJ^h}{d\tilde{\tau}_a} \propto \frac{1}{|a|\left(\tau_a\right)^{1-\frac{2}{a}}} \qquad \text{vs.} \qquad \frac{dJ^{\mathrm{QCD}}}{d\tilde{\tau}_a} \propto \frac{1}{|a|\,\tilde{\tau}_a}$$

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$$\tau_{-2} \propto \frac{1}{z} \qquad\qquad z = \min(p_{T^1}, p_{T^2})/p_T$$

$$\frac{dJ^h}{dz} \propto z^4 \qquad \text{vs.} \qquad \frac{dJ^{\rm QCD}}{dz} \propto z^3$$

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VS.

$$\frac{dJ^{\rm QCD}}{d\tau_a} \propto \frac{1}{|a|\,\tau_a}$$

Difference is not so big!!

$\tau_{-2}$ … $= \min(p_{T^1}, p_{T^2})/p_T$

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# 2-body jet's kinematics, *Z/W/h*

$P^x(\theta_s) = (dJ^x/d\theta_s)/J^x$ => $P^x(\tilde{\tau}_a)$ ; $R(\tilde{\tau}_a) = \frac{P^{\rm sig}(\tilde{\tau}_a)}{P^{\rm QCD}(\tilde{\tau}_a)}$

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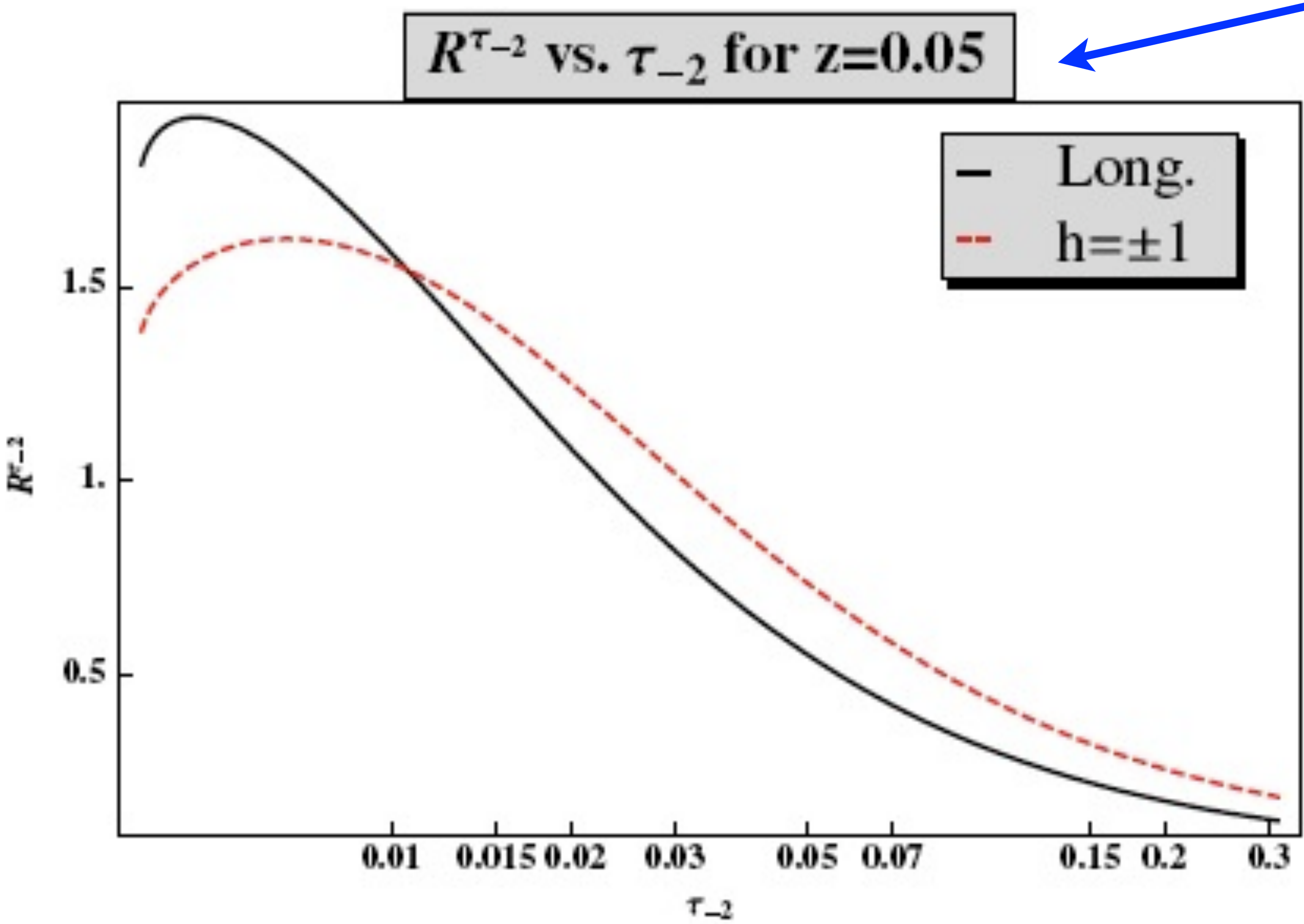


FIG. 3 (color online). The ratio between the signal and background probabilities to have jet angularity $\tilde{\tau}_{-2}$, $R^{\tilde{\tau}_{-2}}$.

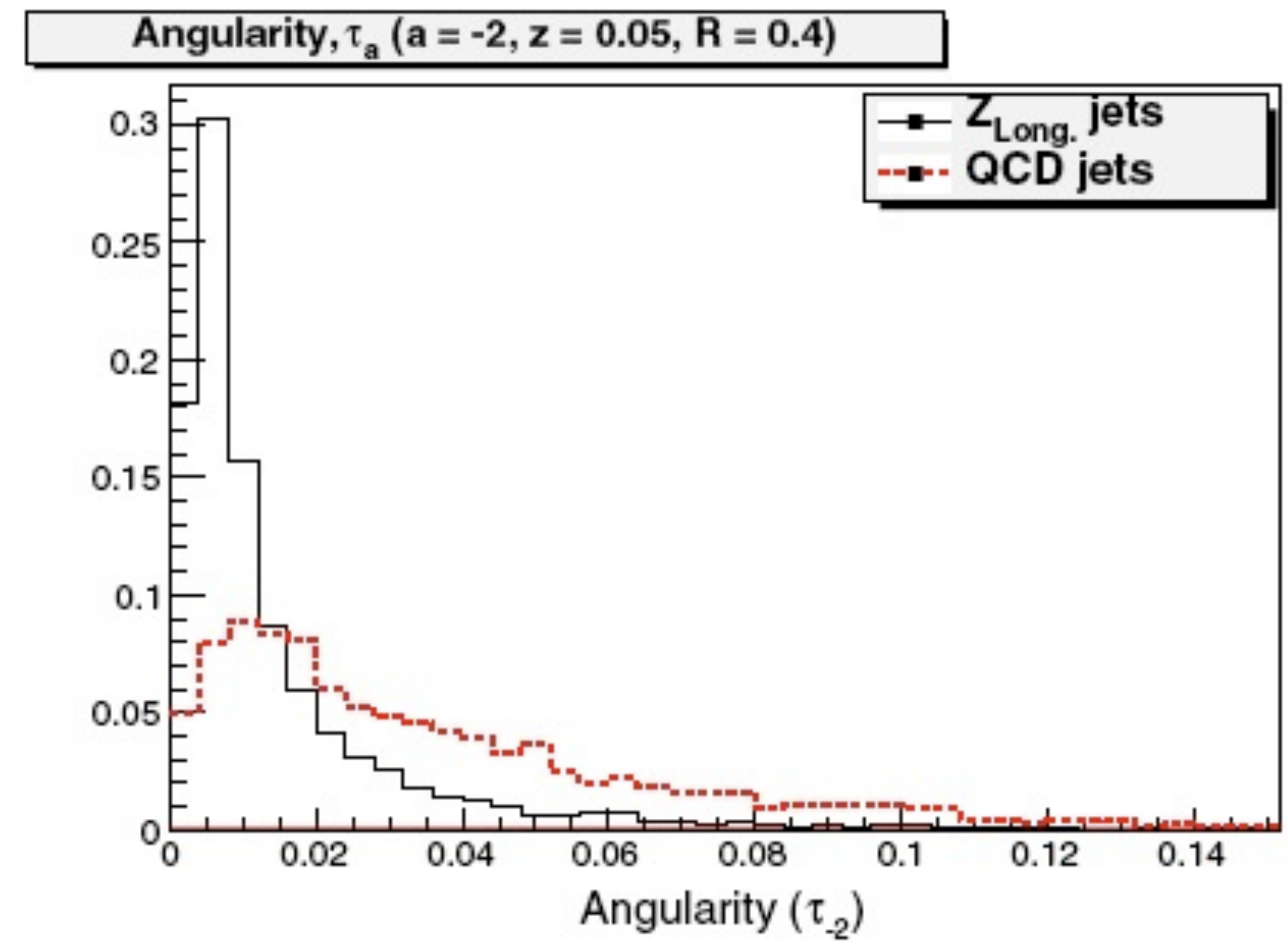


FIG. 4 (color online). The angularity distribution for QCD (red-dashed curve) and longitudinal $Z$ (black-solid curve) jets obtained from MADGRAPH. Both distributions are normalized to the same area.

$$(z = m_J/p_T)$$

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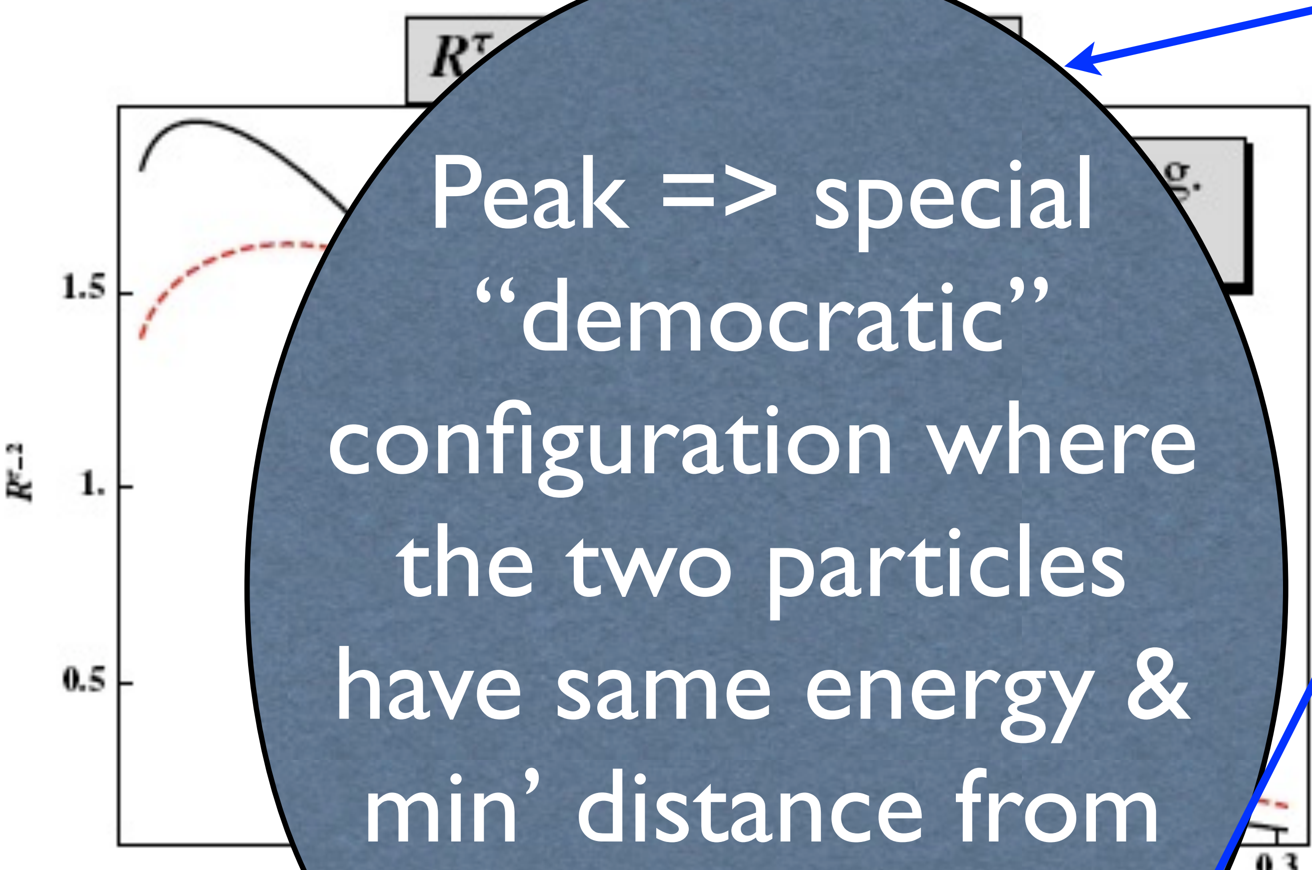
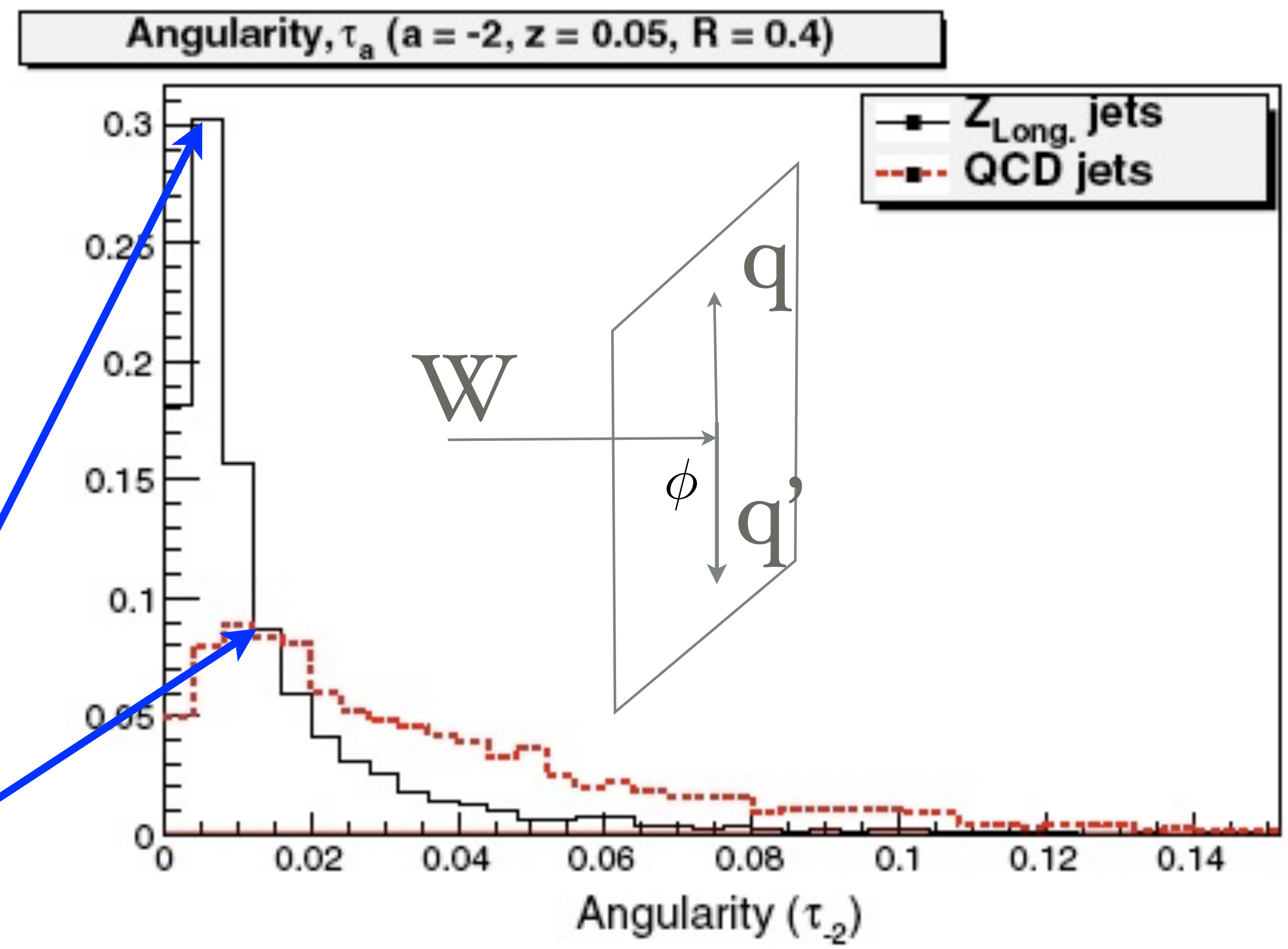



Peak => special "democratic" configuration where the two particles have same energy & min' distance from jet axis $\theta_m \approx z$ .

$(z = m_J/p_T)$

FIG. 3 (color ... nd back-
ground proba... .

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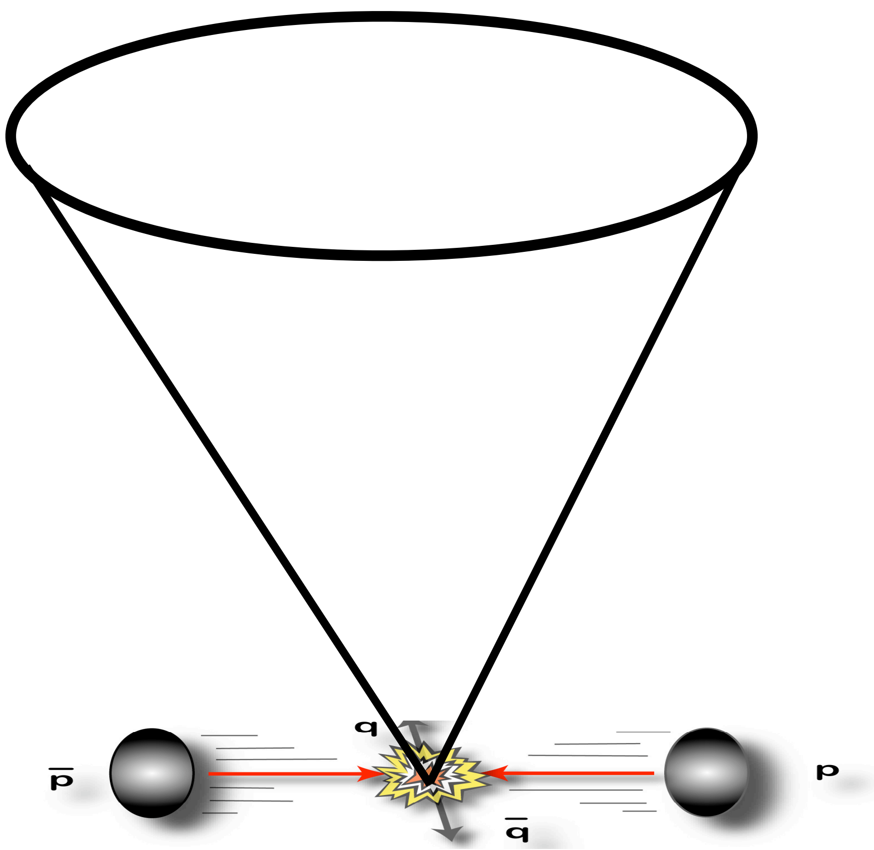
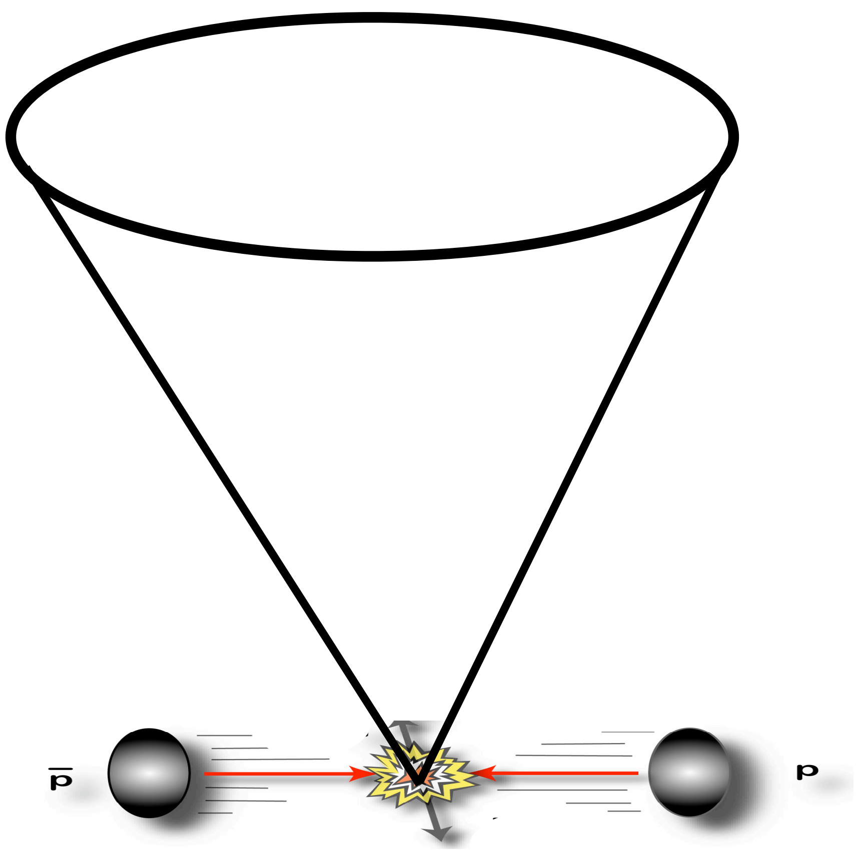
# Planar flow

- Top-jet is 3 body vs. massive QCD jet <=> 2-body (previous result)

Thaler & Wang, JHEP (08);
Almeida, Lee, GP, Stermam, Sung & Virzi, PRD (09).




QCD massive jet




top jet

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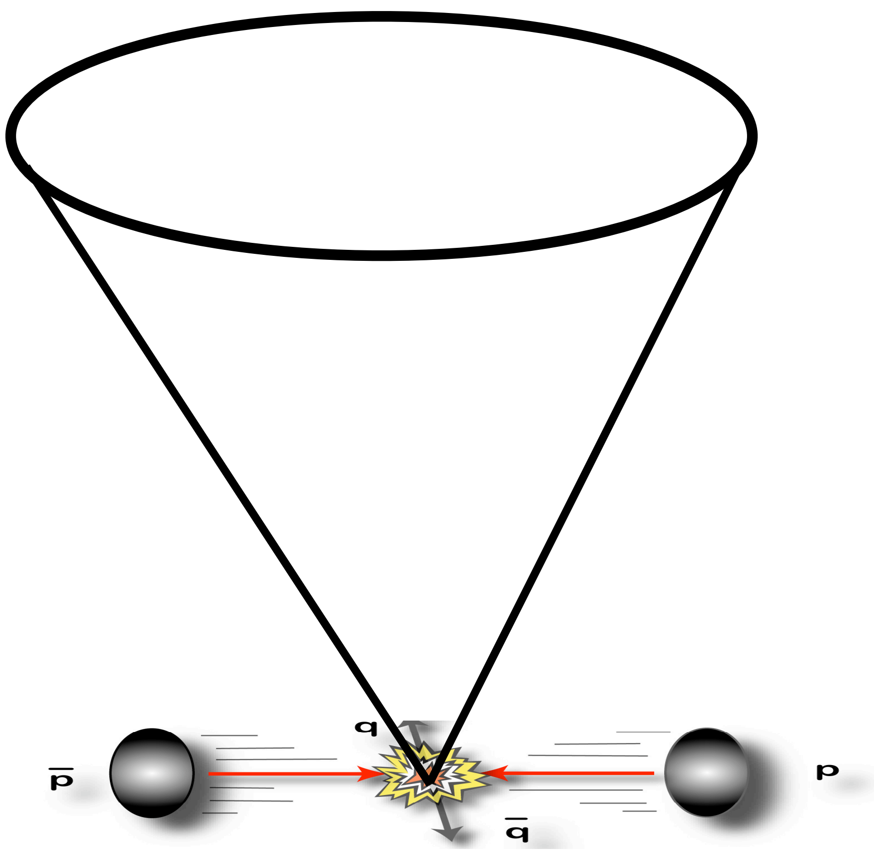

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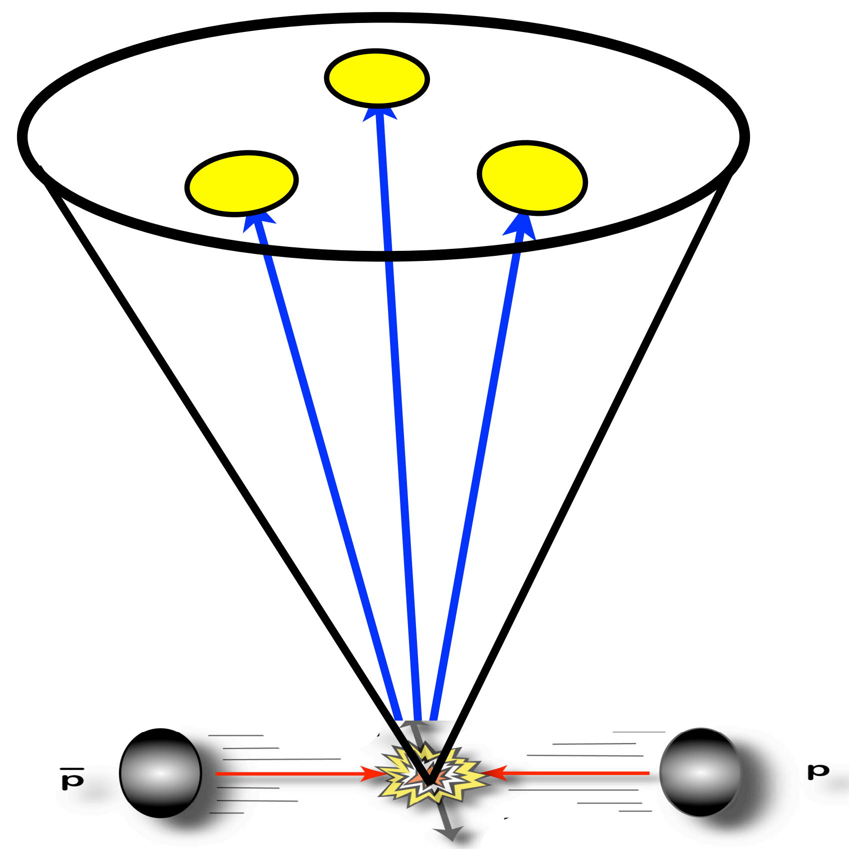

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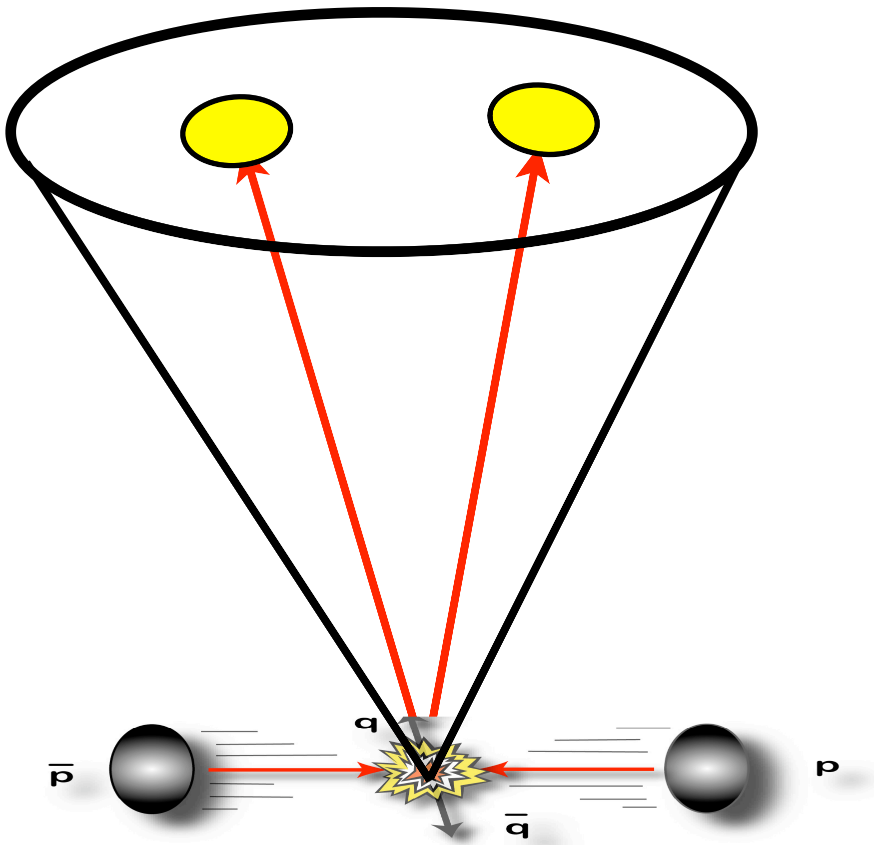


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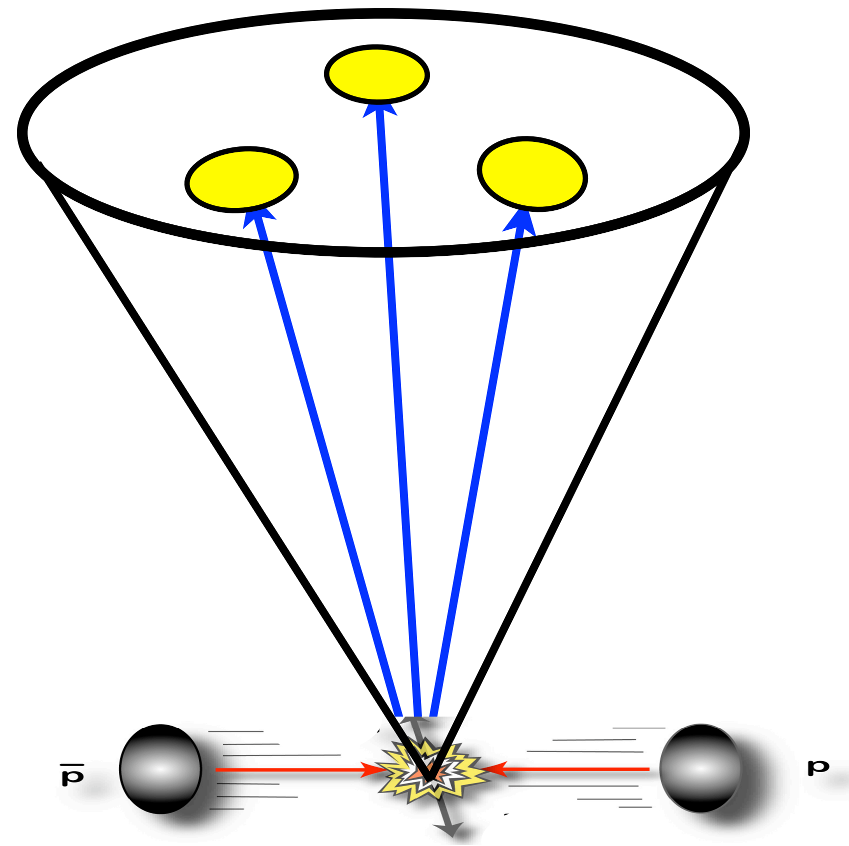


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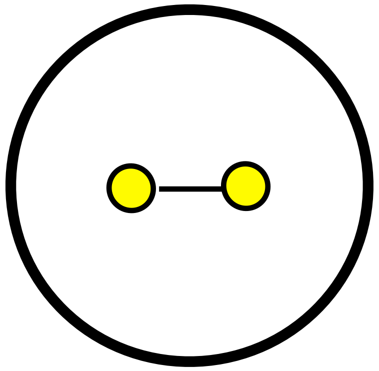
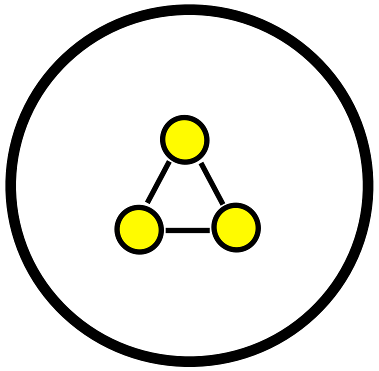
- Planar flow, *Pf*, measures the energy ratio between two primary axes of cone surface:

(i) "moment of inertia ":
$$I_E^{kl} = \frac{1}{m_J} \sum_{i \in R} E_i \frac{p_{i,k}}{E_i} \frac{p_{i,l}}{E_i} \,,$$

(ii) Planar flow:
$$Pf = 4\, \frac{\det(\mathrm{I_E})}{\mathrm{tr}(\mathrm{I_E})^2} = \frac{4\lambda_1\lambda_2}{(\lambda_1+\lambda_2)^2}$$

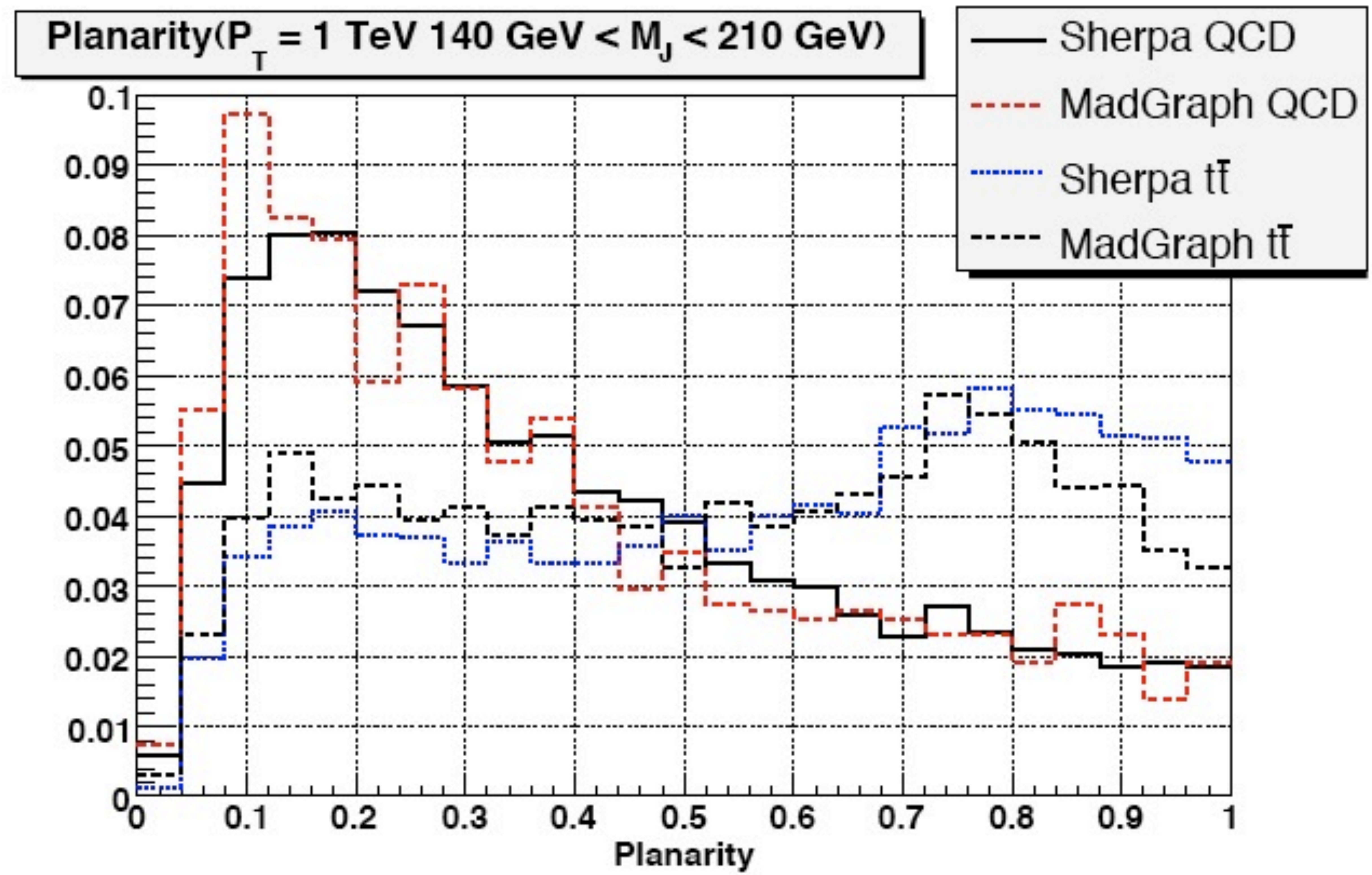


leading order QCD, *Pf=0*



top jet, *Pf=1*

# Planar flow, QCD vs top jets



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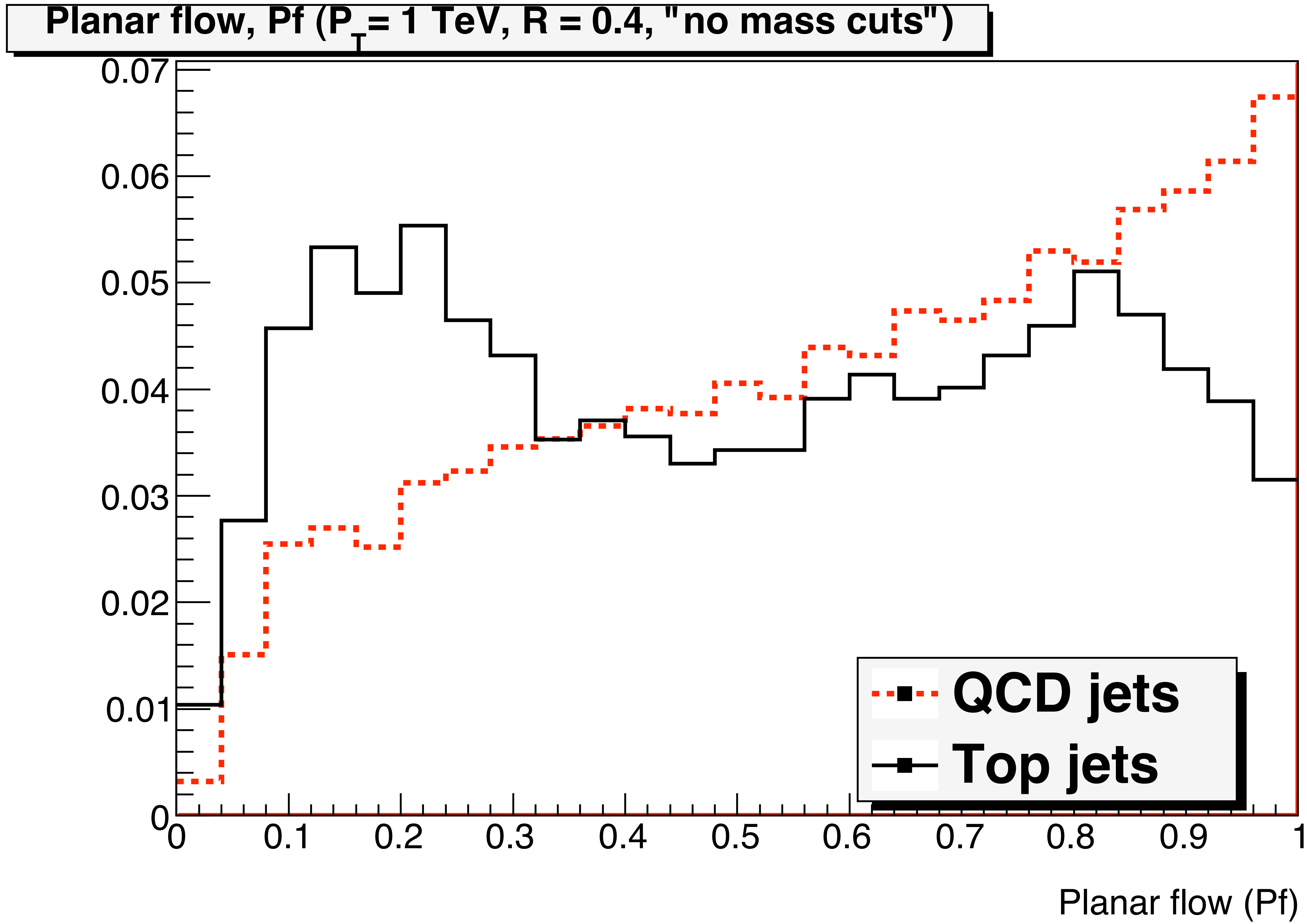

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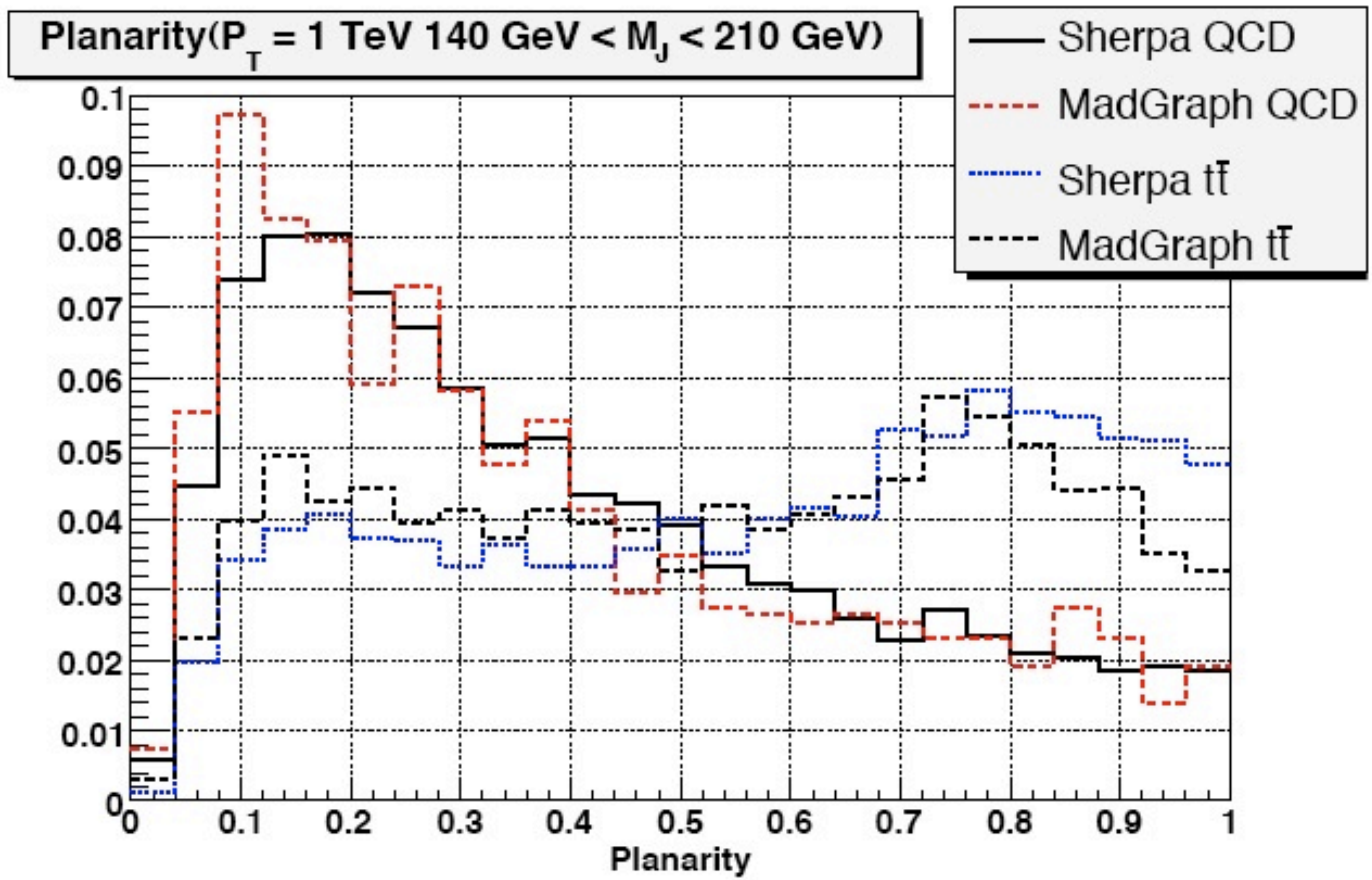
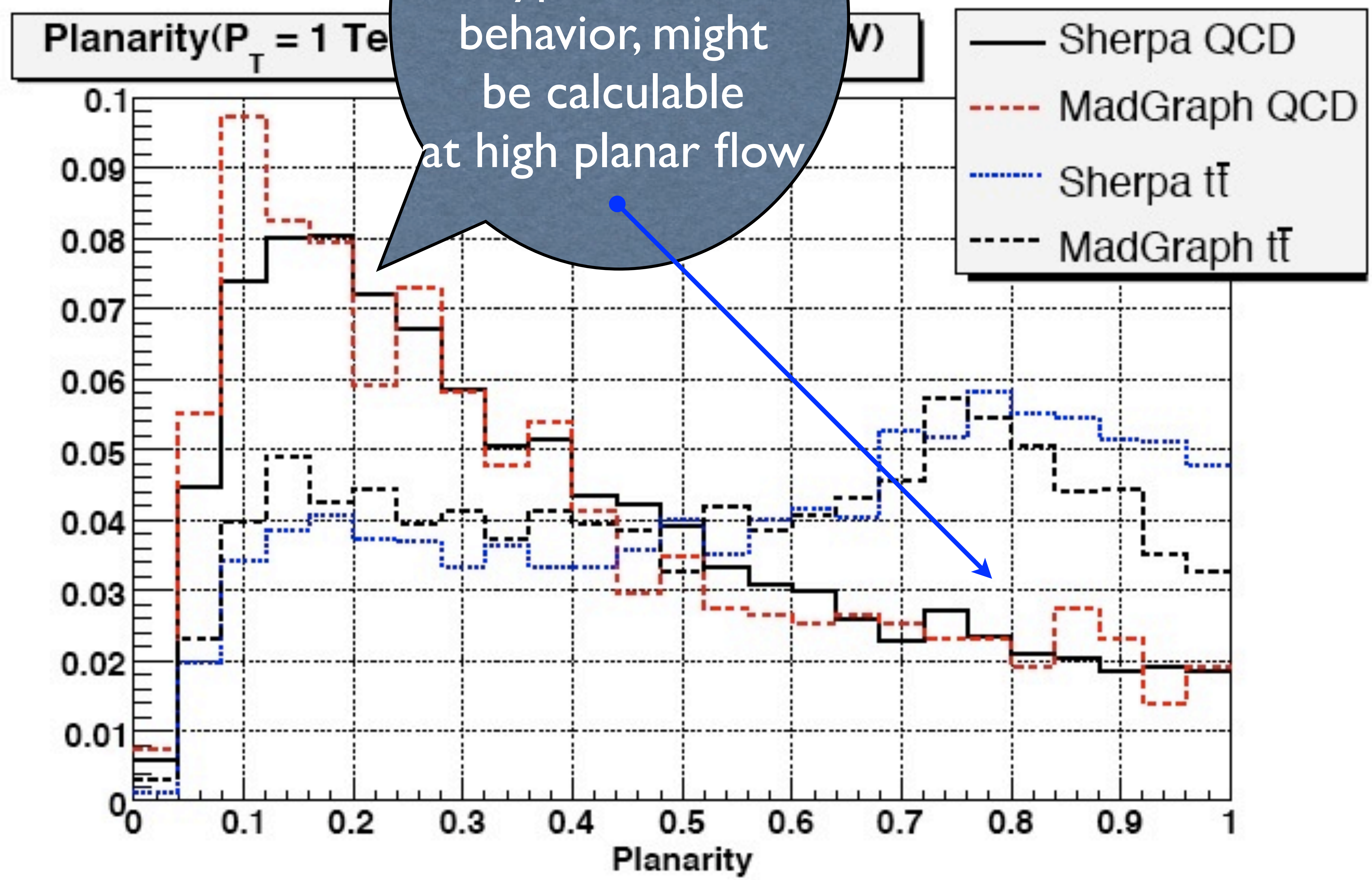


# Planar flo CD vs top jets

Guess: QCD
Planar flow shows
a “typical” QCD
behavior, might
be calculable
at high planar flow



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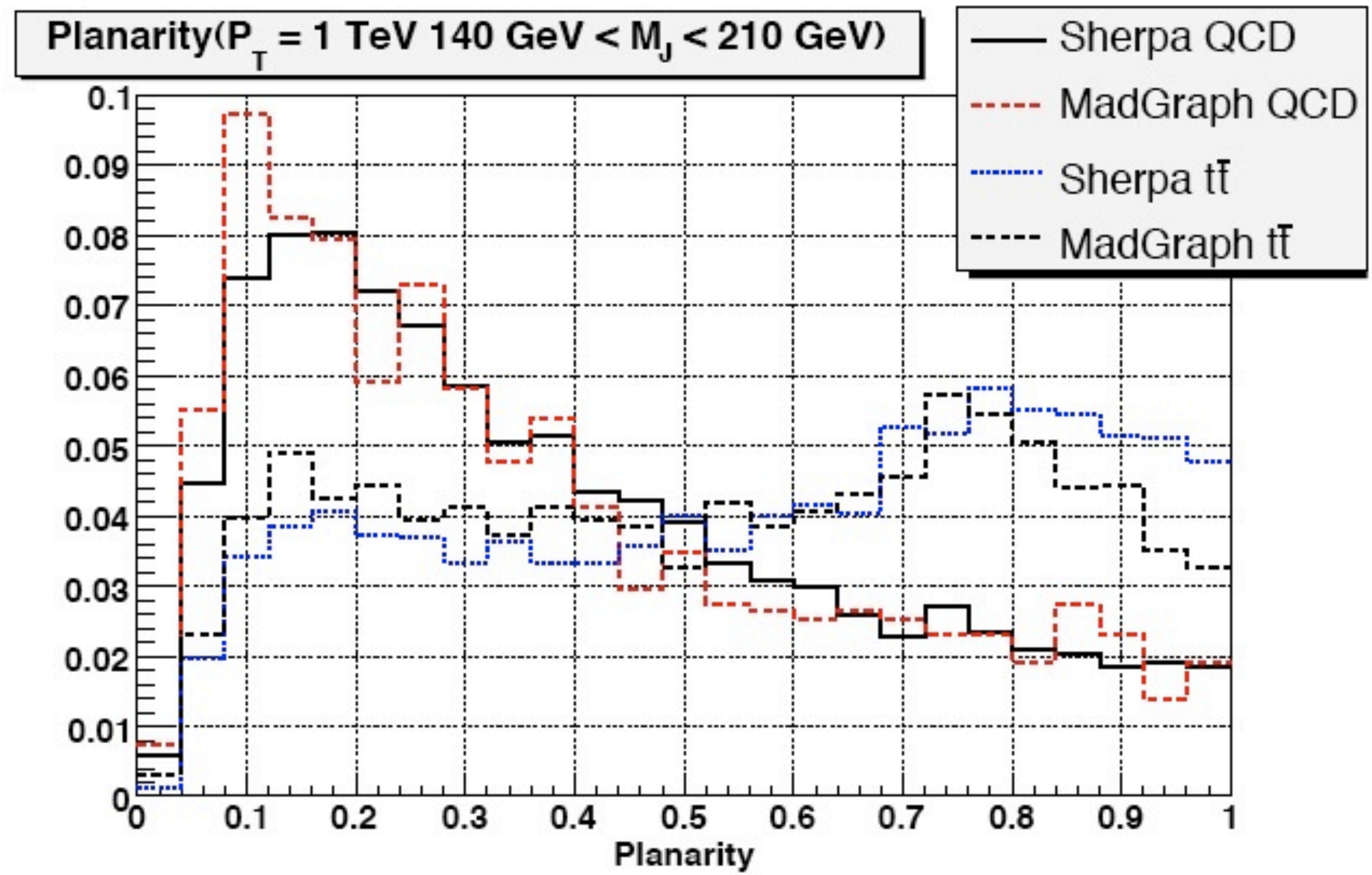

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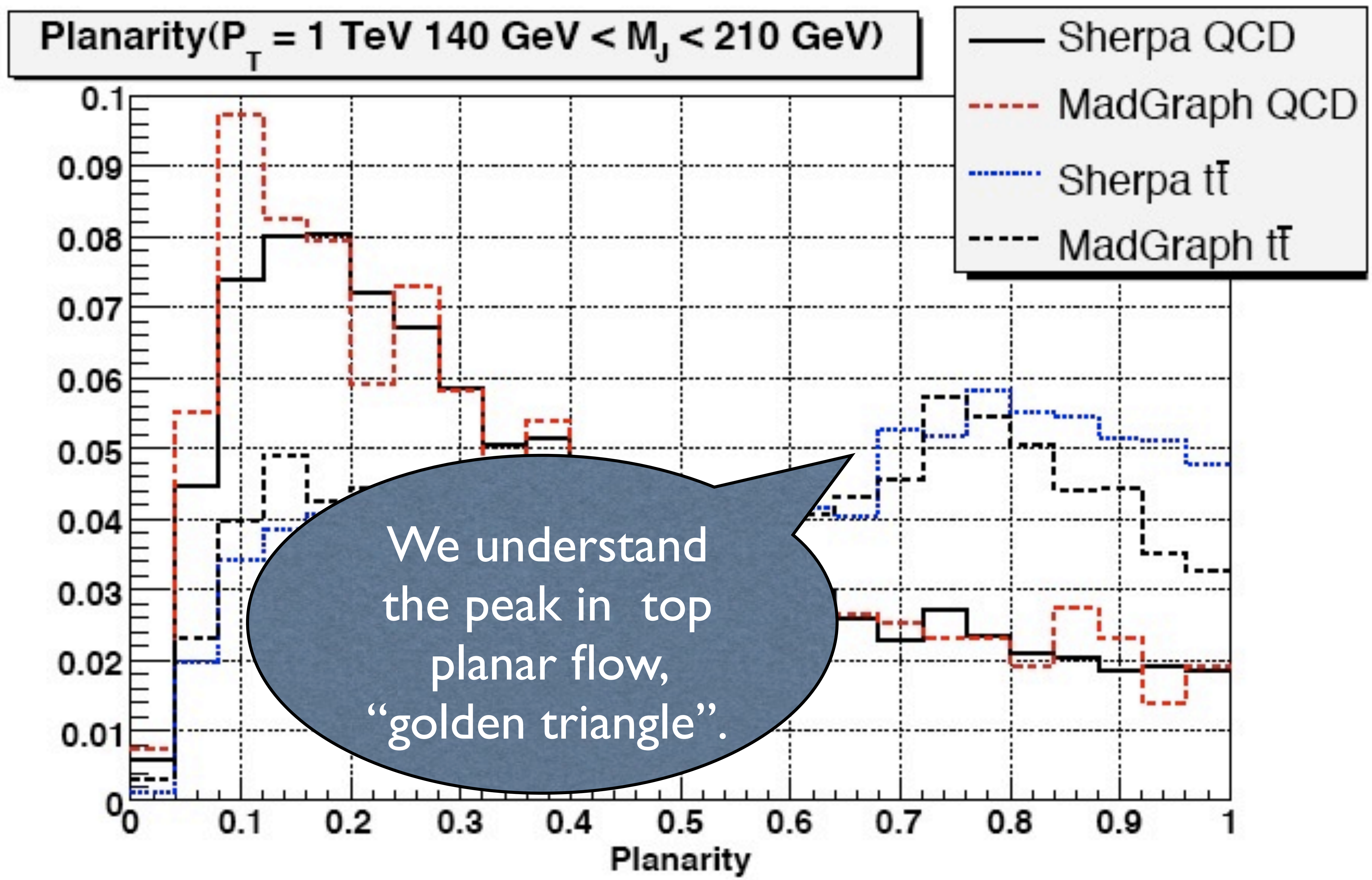


# Boosted massive jets @ CDF (phase II)

*R, Alon, E. Duchovni, GP & P. Sinervo, for the CDF; blessed* ***preliminary*** *data;*

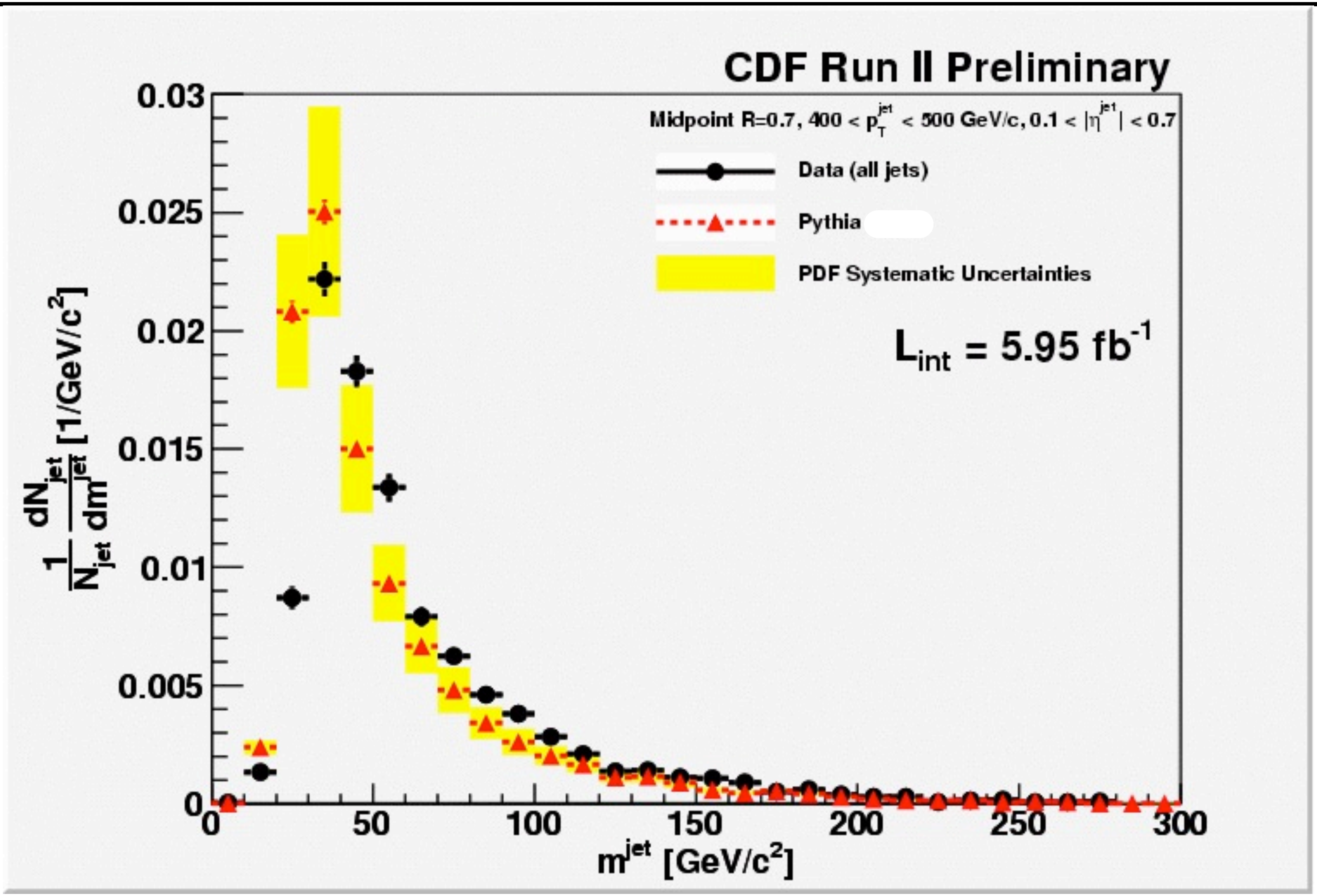
*experimentalist*

# The preliminary data to be looked at

| Cut Flow | | |
|---|---|---|
| | R = 0.4 | R = 0.7 |
| All Data, 5.95 $fb^{-1}$ | 75,764,270 events | |
| At least one jet with $p_T > 400$ GeV/c, $0.1 < \|\eta\| < 0.7$, and event quality cuts | 2,153 | 2,700 |
| $m^{jet2} < 100$ GeV/$c^2$ and $S_{MET} < 4$ (with $p_T^{jet2} > 100$ GeV/c and MI corrections) | 1,837 | 2,108 |

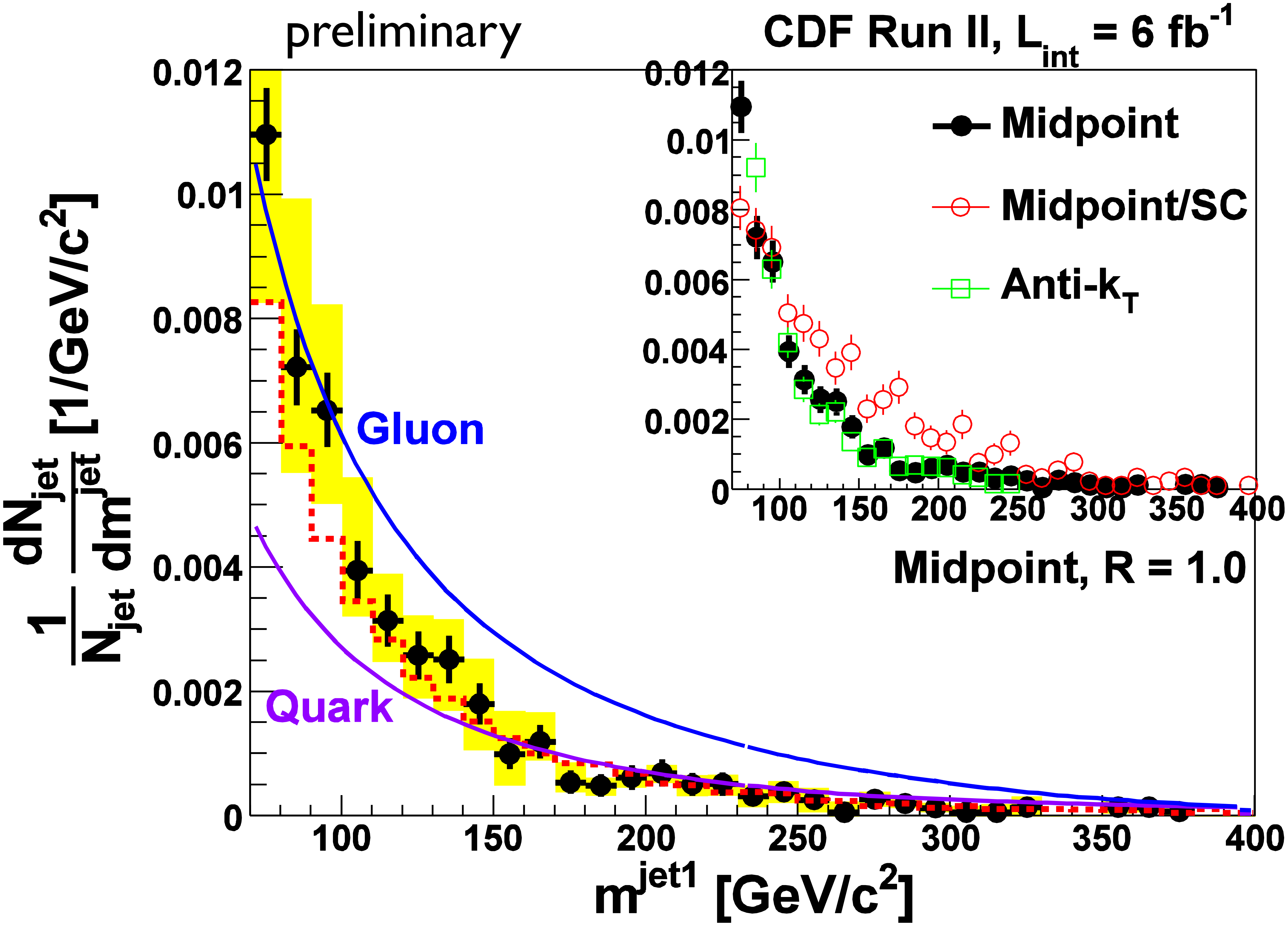
Top rejection cut.

# Jet mass distribution




**Distribution of jet mass after MI correction for jets with 400 < $p_T$ < 500 GeV/c, cone R=0.7, data and QCD MC**

# Jet mass distribution, high mass region



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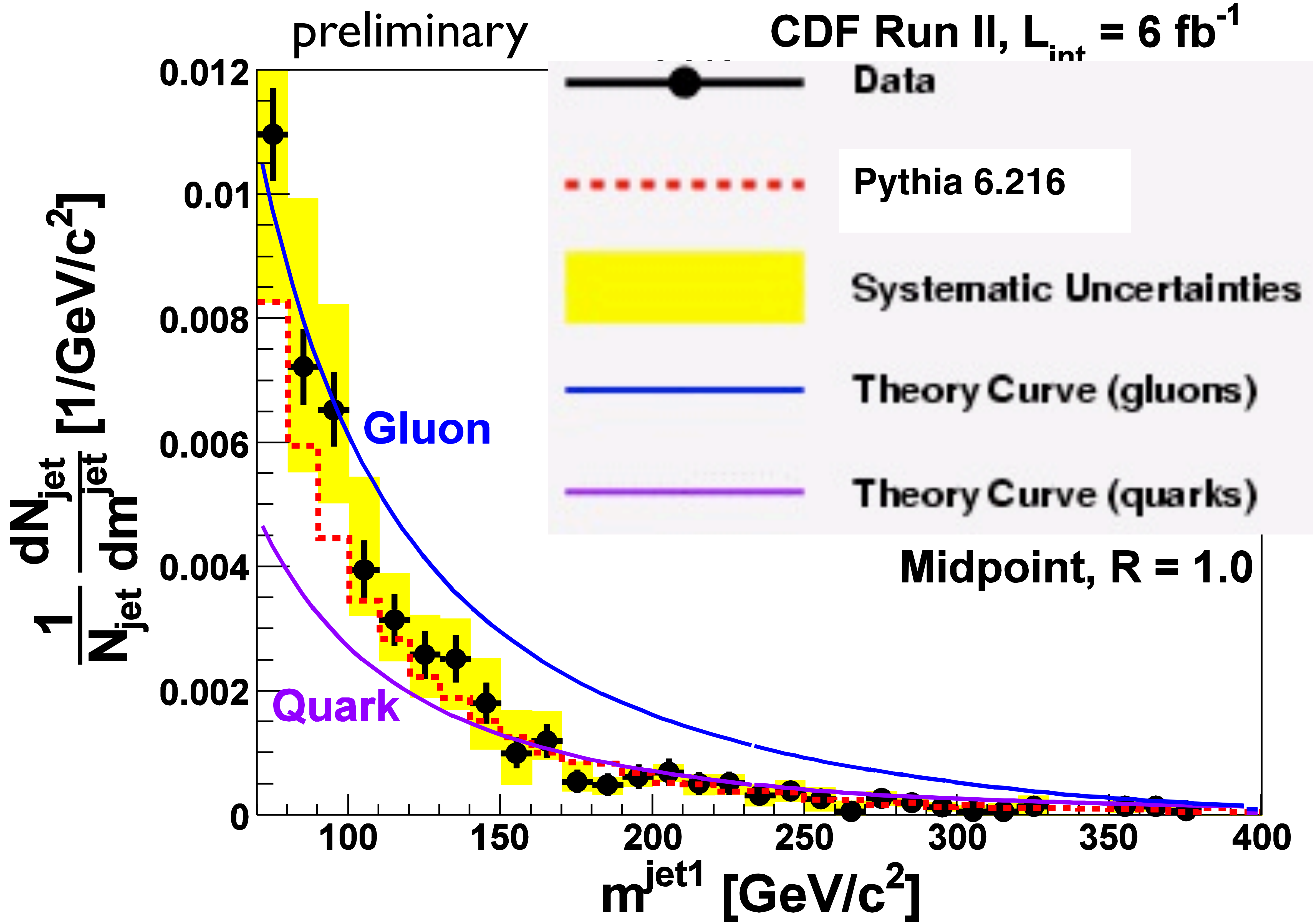

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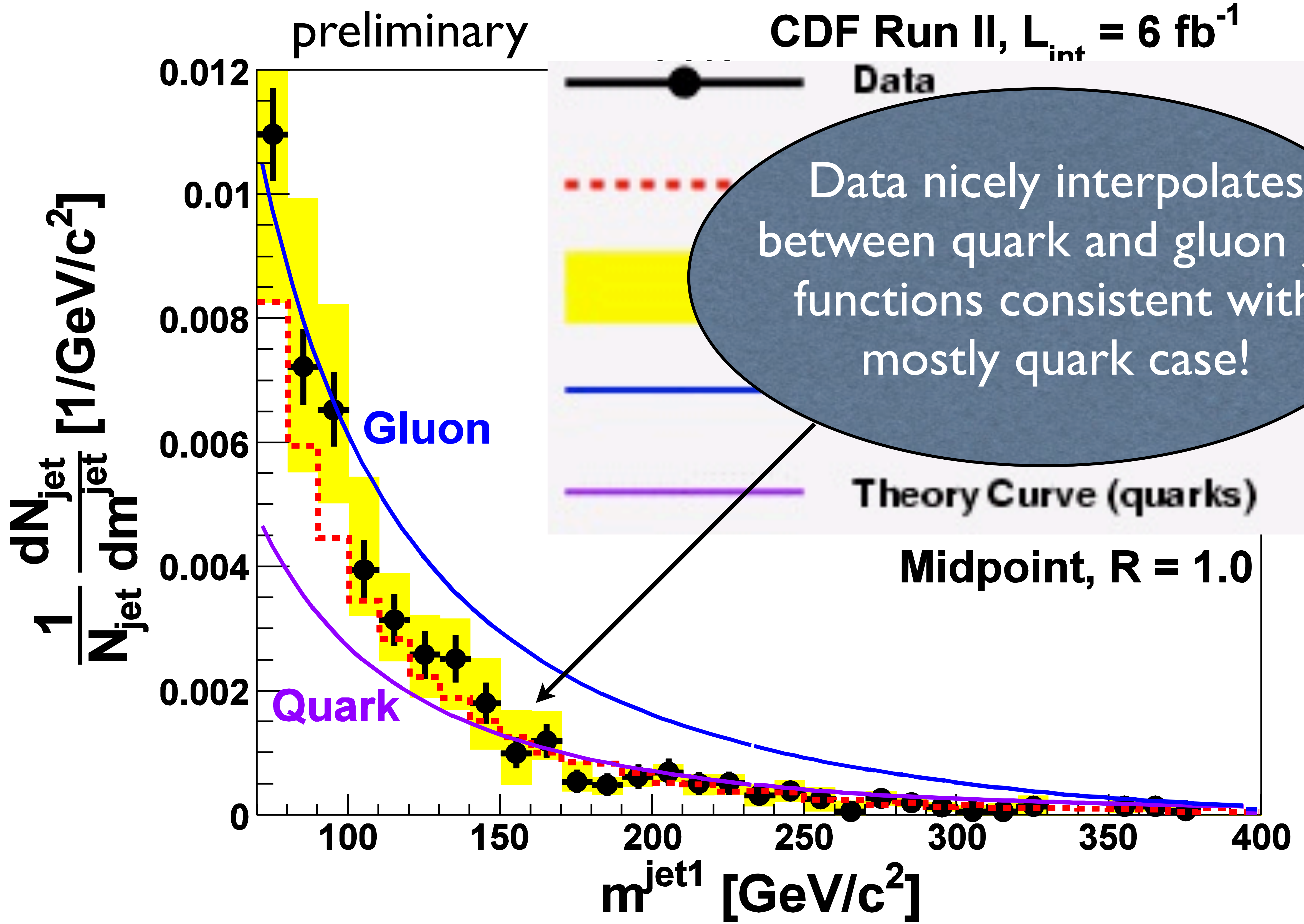

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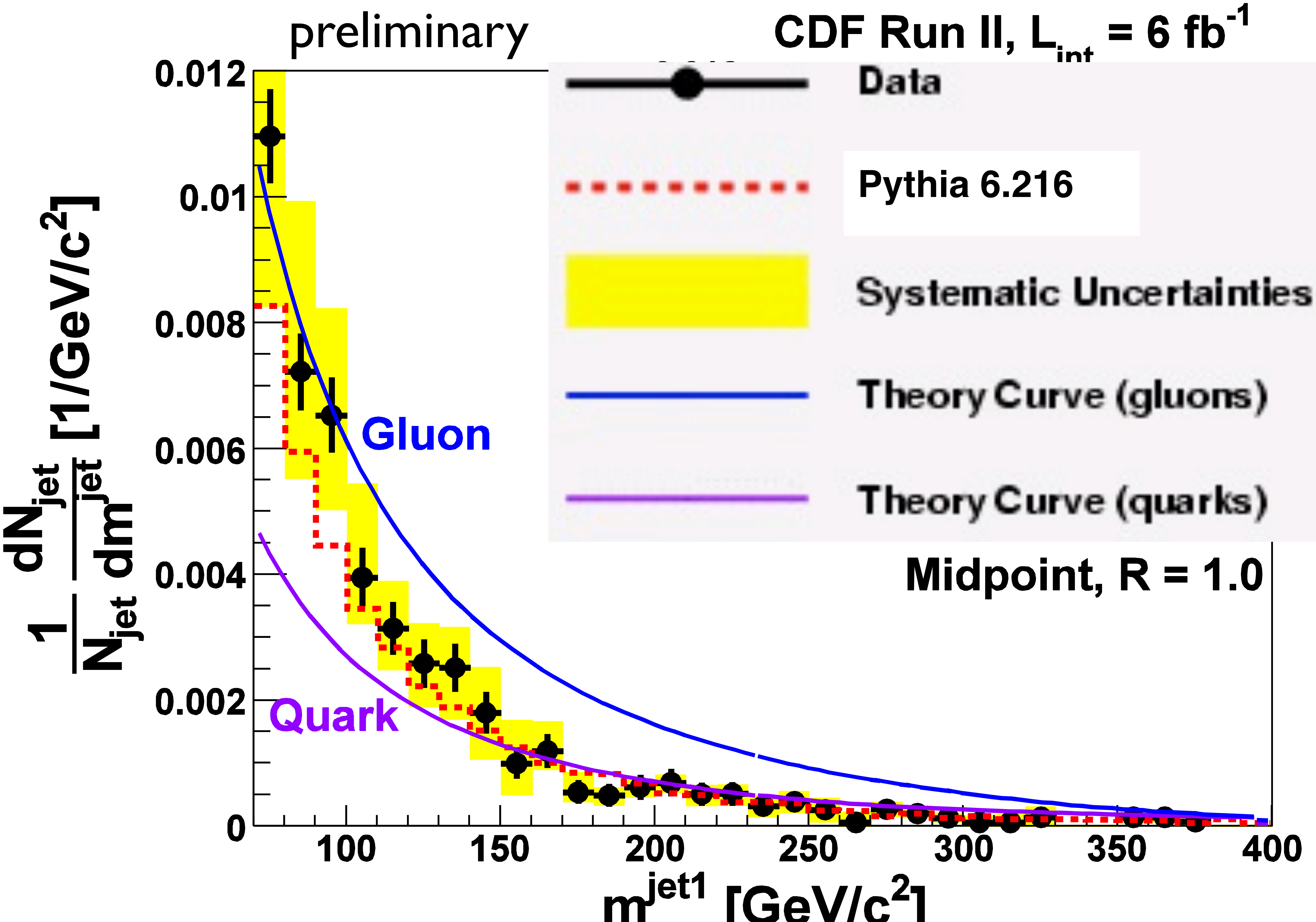

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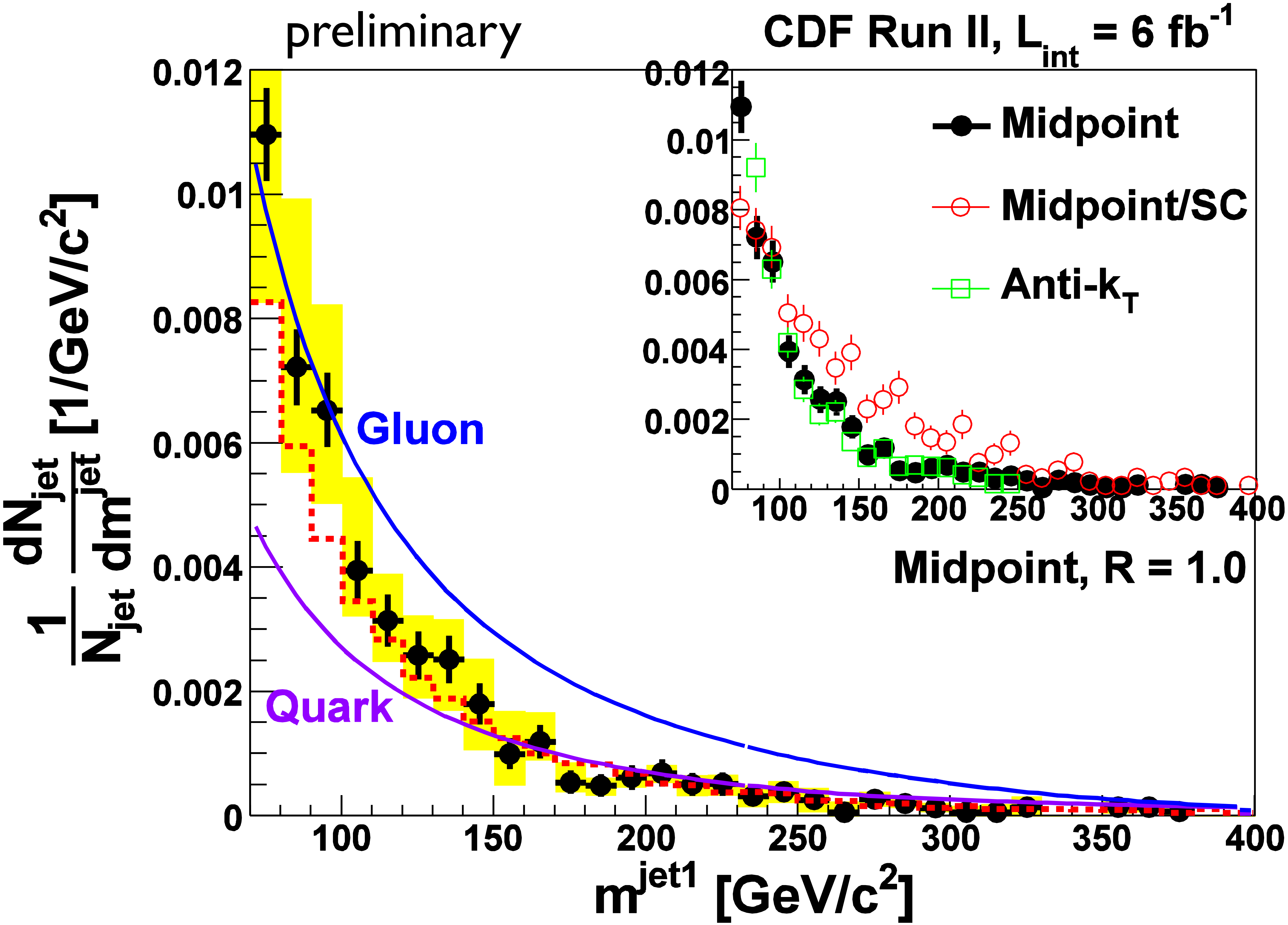
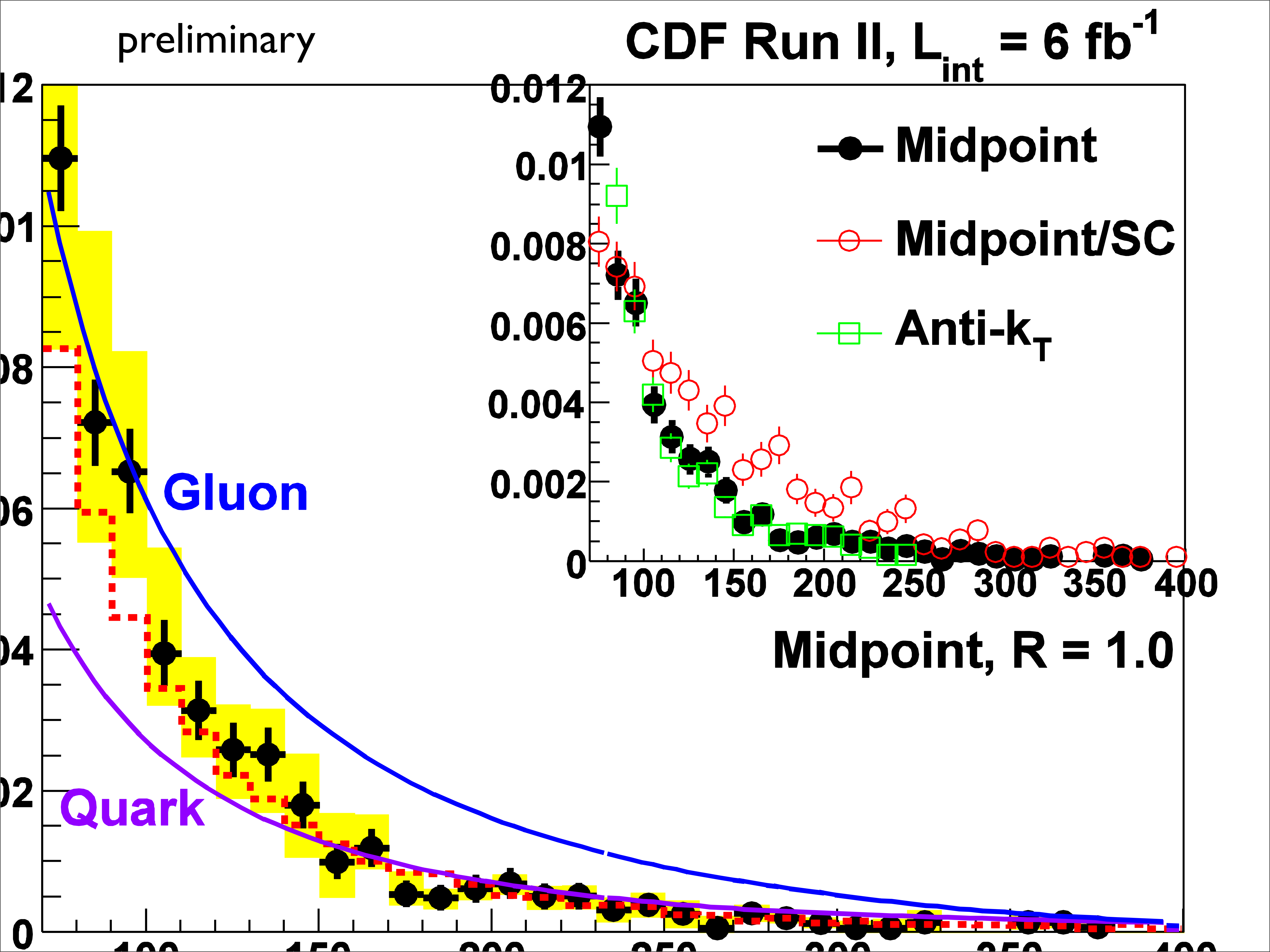
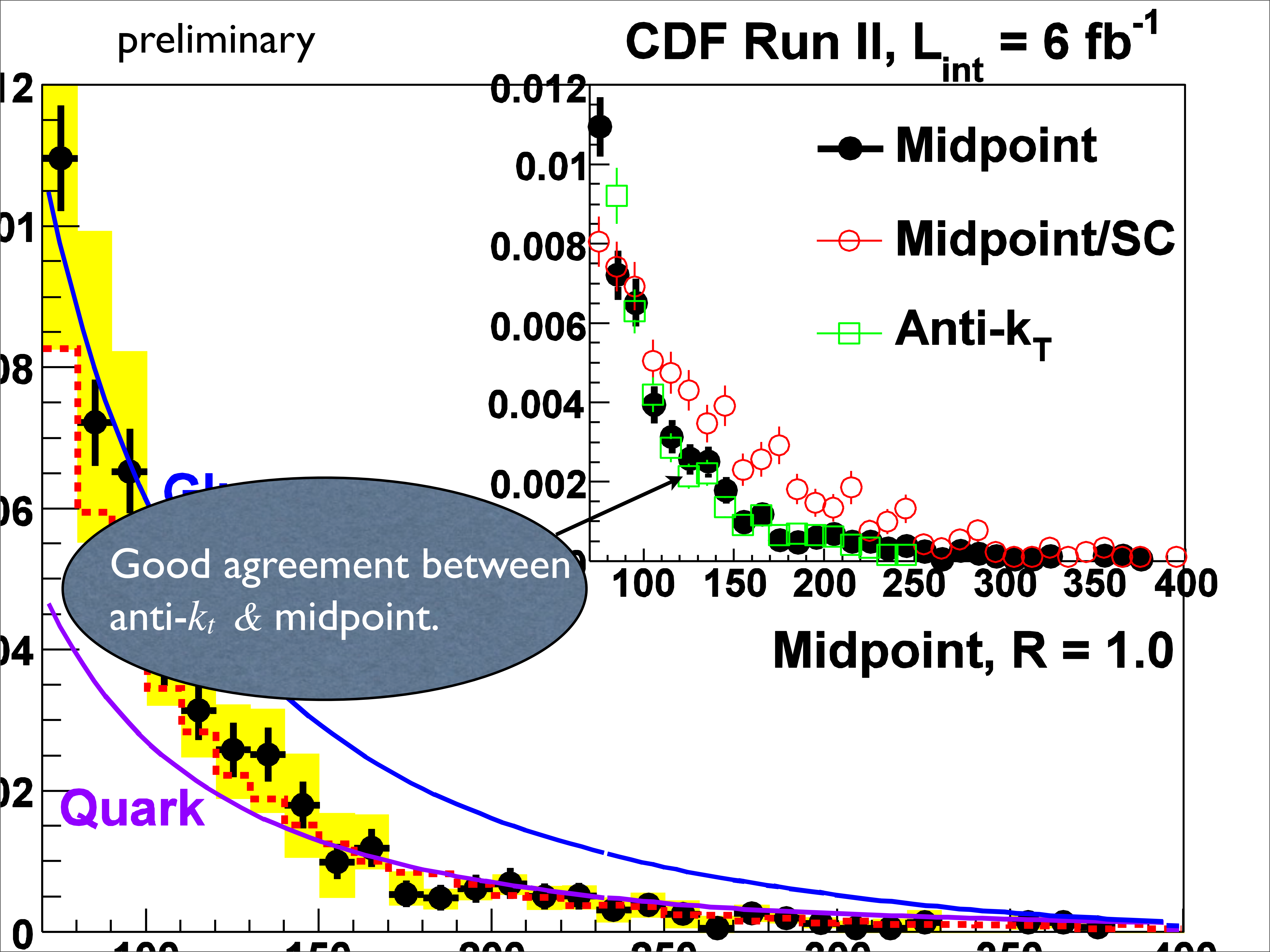
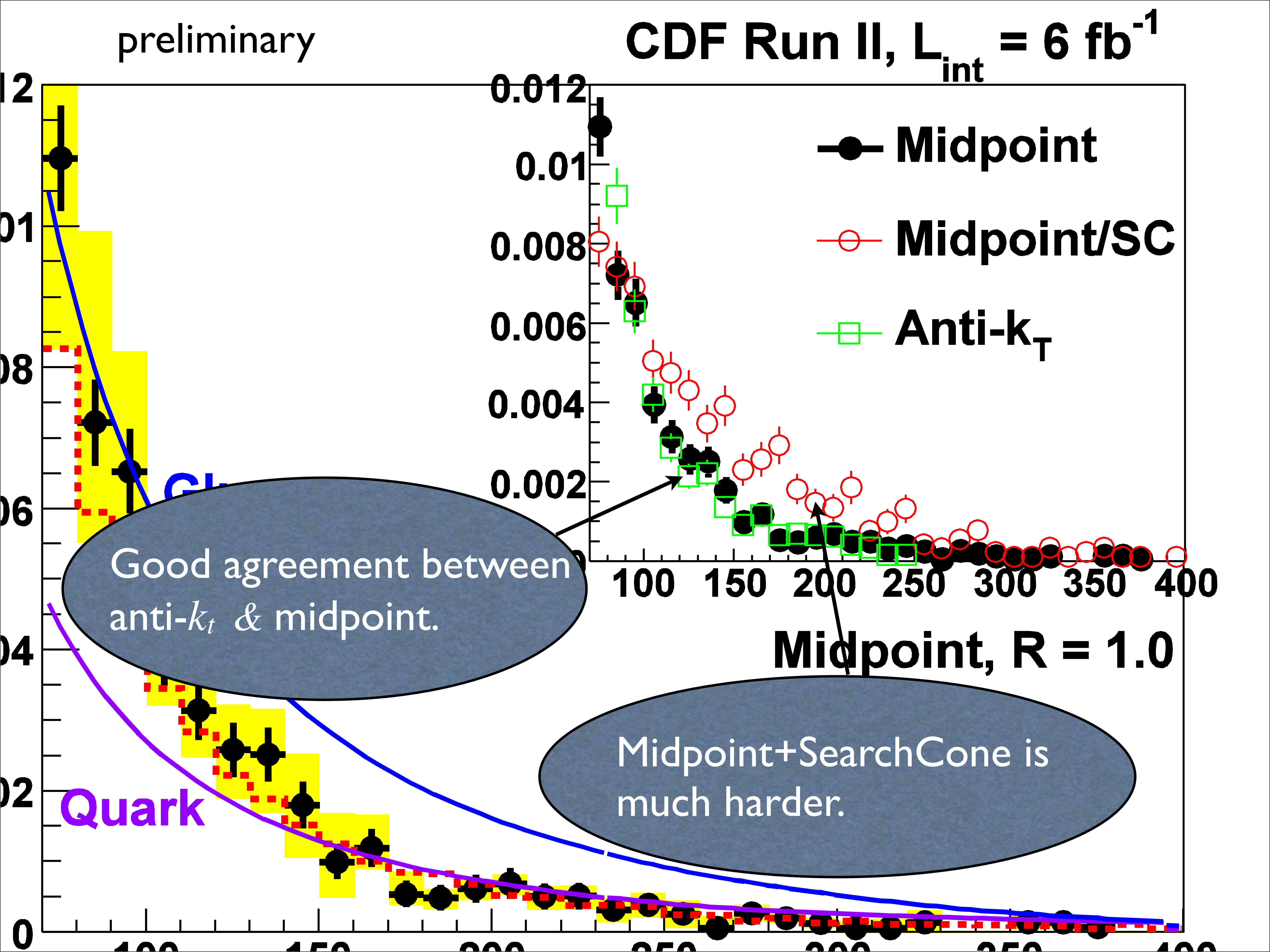



preliminary
CDF Run II, $L_{int}$ = 6 $fb^{-1}$
Gluon
Quark
Midpoint
Midpoint/SC
Anti-$k_T$
Midpoint, R = 1.0
0.012
0.01
0.008
0.006
0.004
0.002
0
100
150
200
250
300
350
400

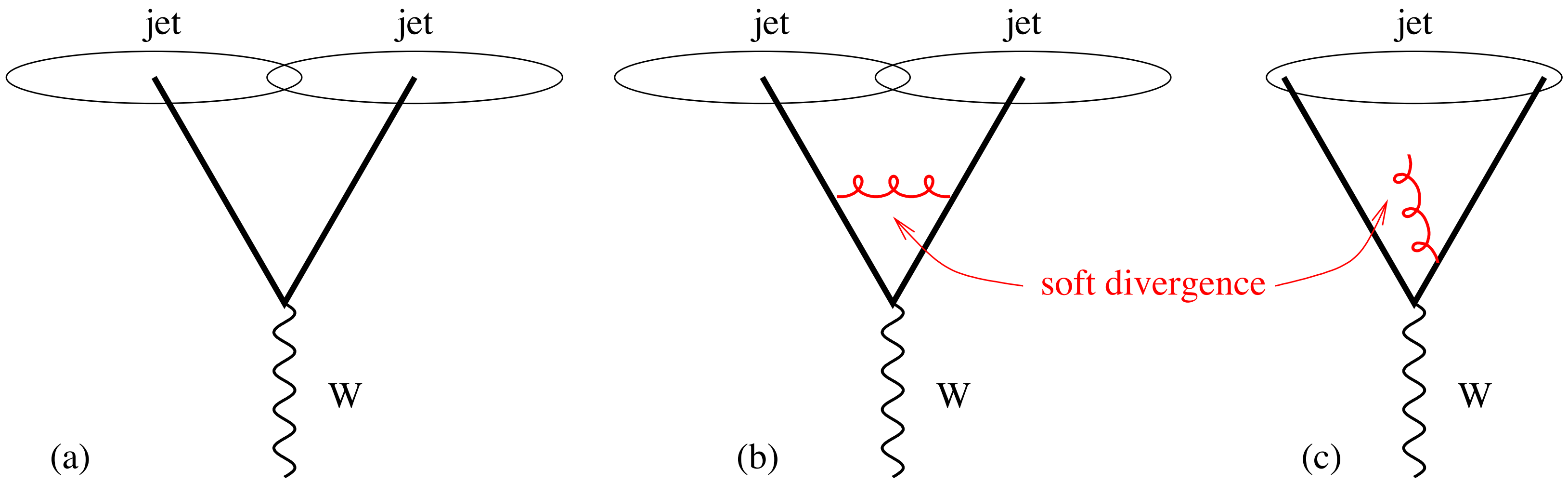

preliminary
CDF Run II, $L_{int}$ = 6 $fb^{-1}$
0.012
0.01
0.008
0.006
0.004
0.002
0
100
150
200
250
300
350
400
Midpoint
Midpoint/SC
Anti-$k_T$
Midpoint, R = 1.0
Quark
Good agreement between anti-$k_t$ & midpoint.
0


preliminary
CDF Run II, $L_{int}$ = 6 $fb^{-1}$
Midpoint
Midpoint/SC
Anti-$k_T$
Quark
Midpoint, R = 1.0
Good agreement between anti-$k_t$ & midpoint.
Midpoint+SearchCone is much harder.

# IR-collinear sensitivity & jet mass

MidPoint searchcone $IR_{2+1}$ => harder jets.

Salam, Eur. Phys. J. (2010)




2 perturbative massless jets

massive jet

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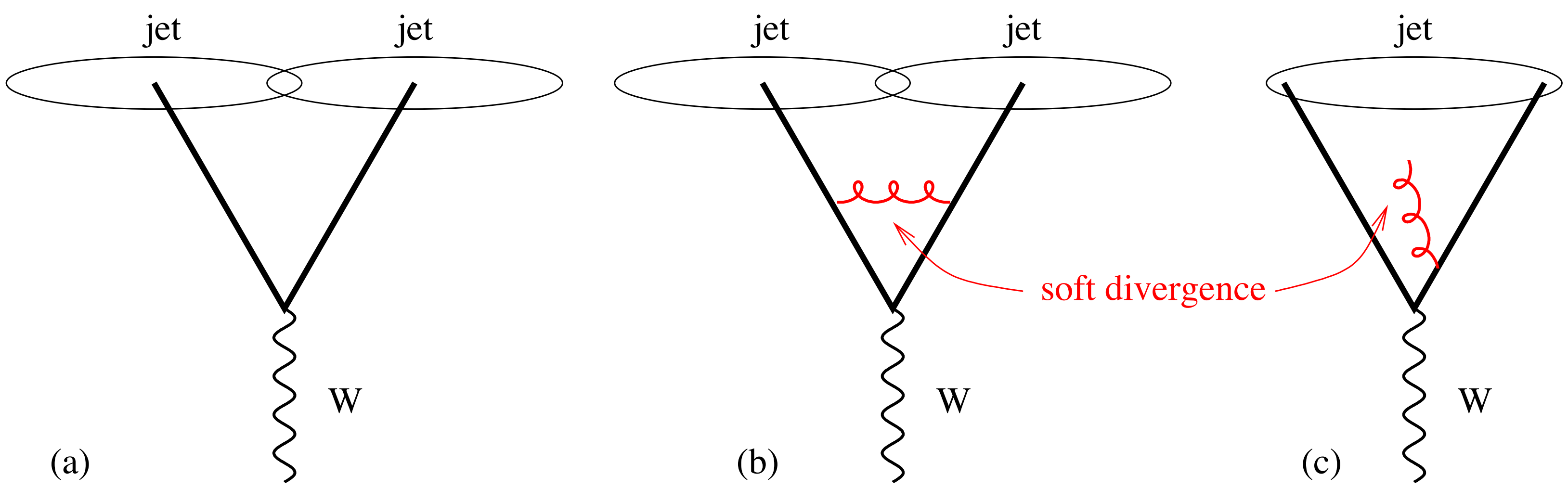
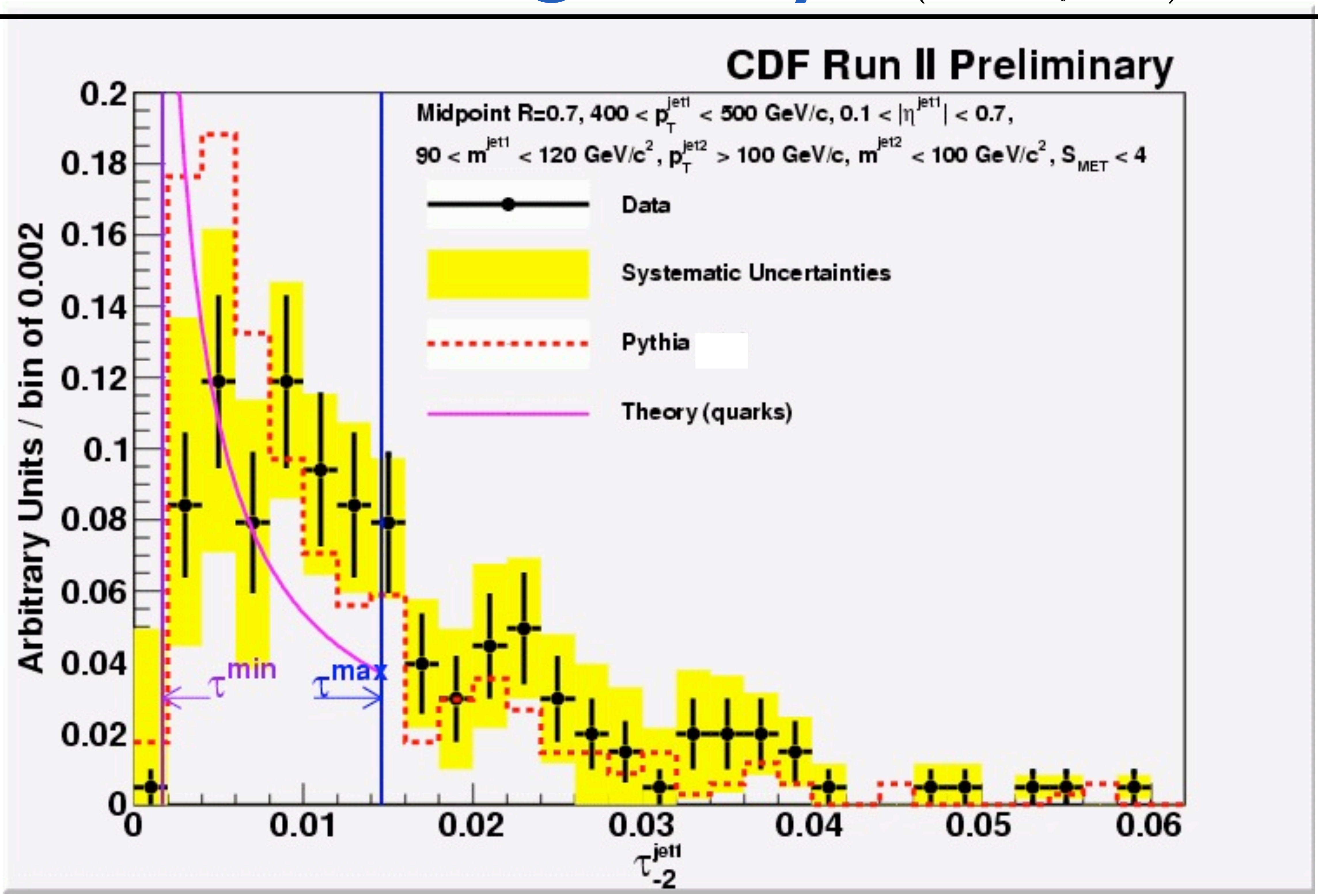



2 perturbative massless jets

massive jet

MidPoint $IR_{3+1}$ => problem postponed to NLO.

# Angularity $\left(\propto_{a=-2} \sum_i \omega_i \theta_i^4\right)$

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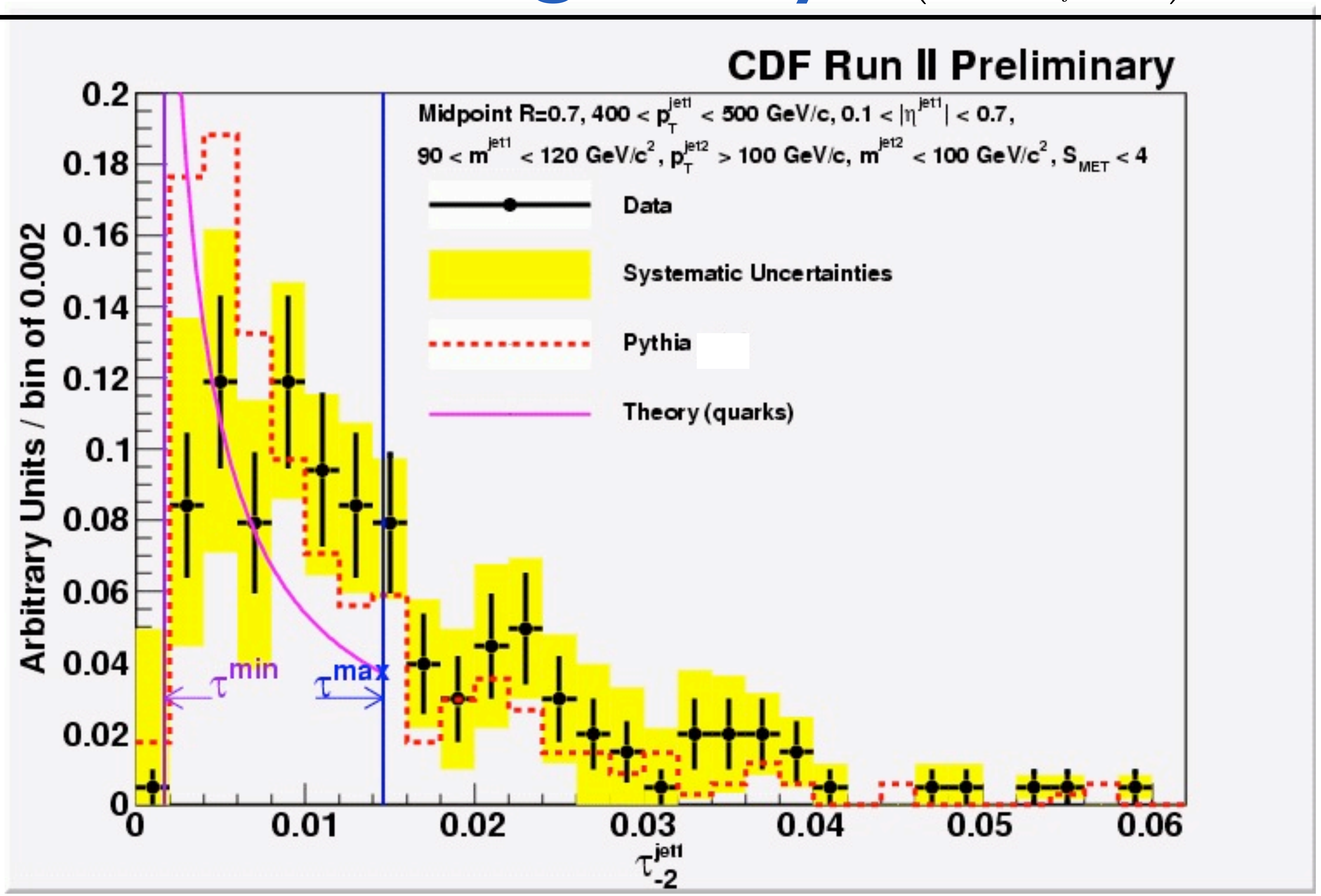


$$\tau_a^{\min}(z) \sim \left(\frac{z}{2}\right)^{1-a}, \quad \tau_a^{\max}(R, p_T) \sim 2^{a-1} R^{-a} z$$

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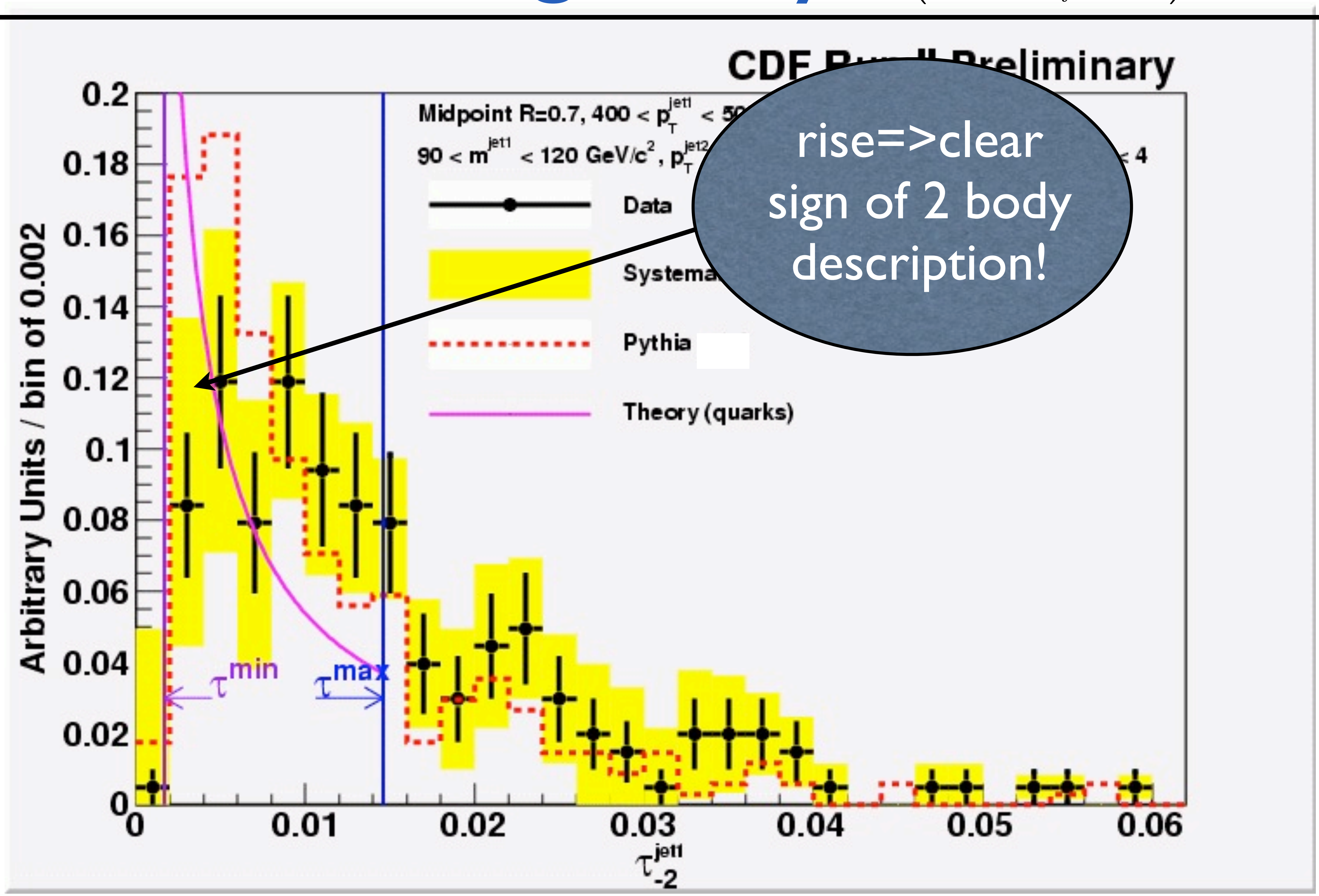


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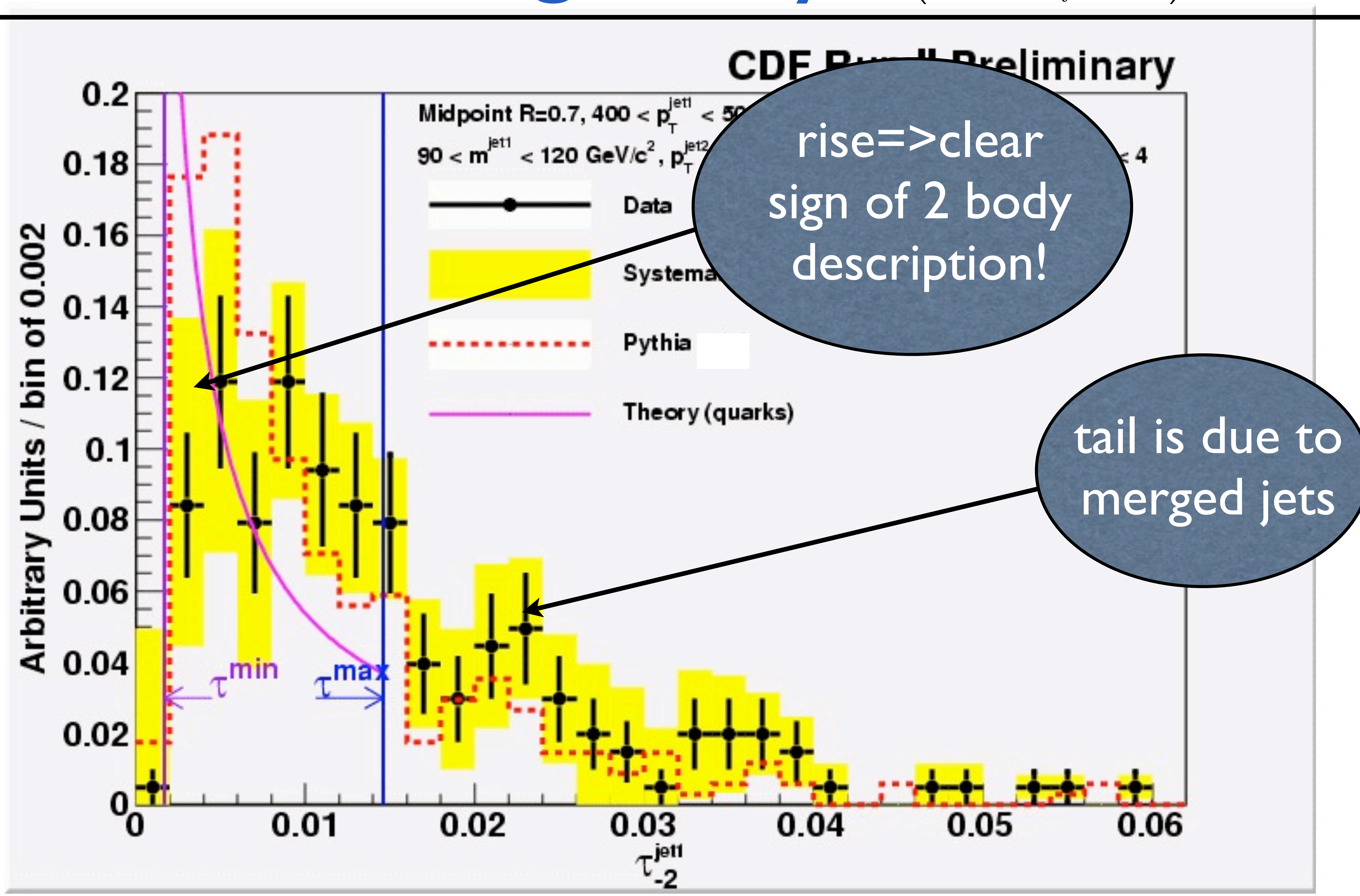


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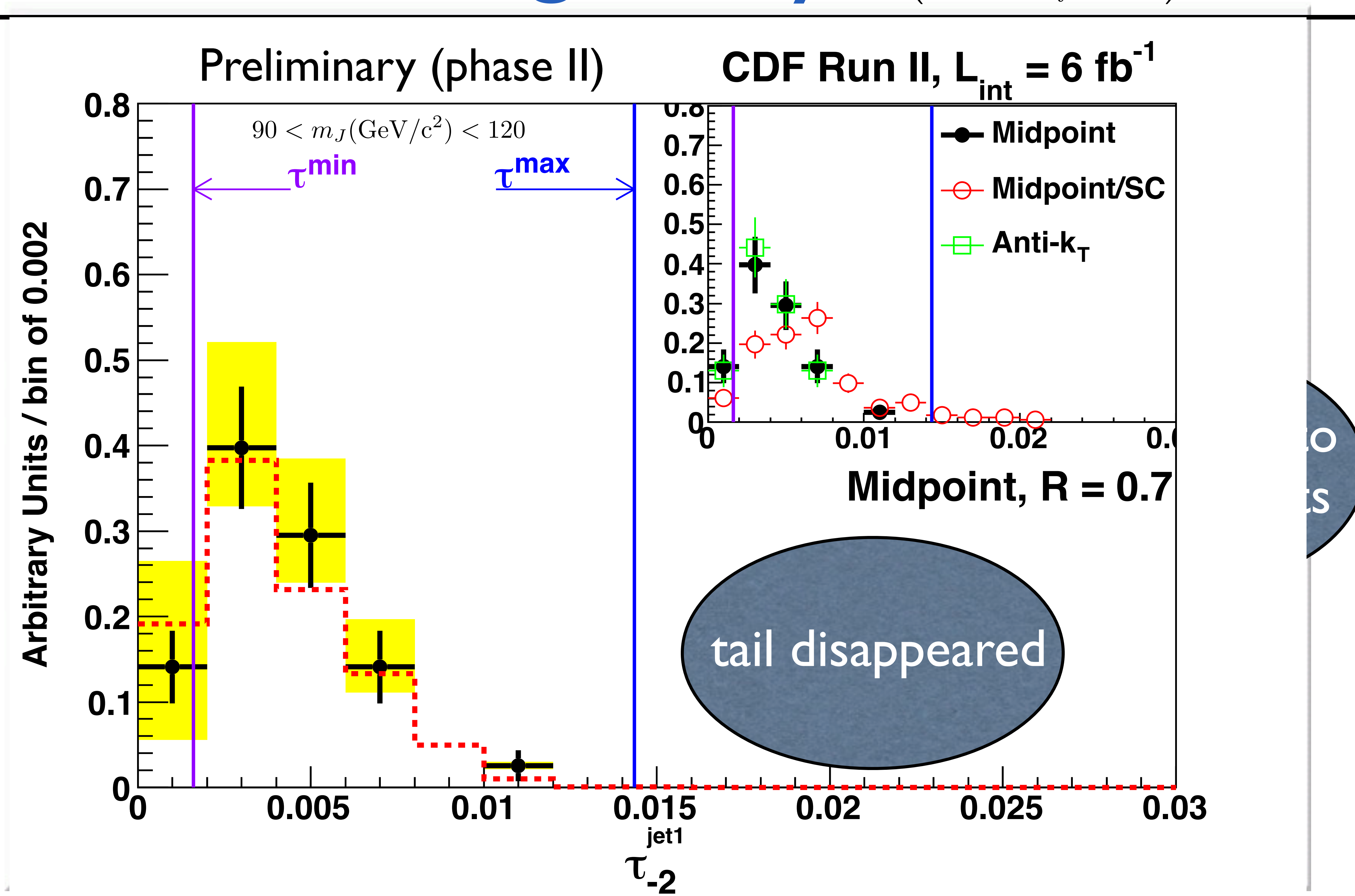
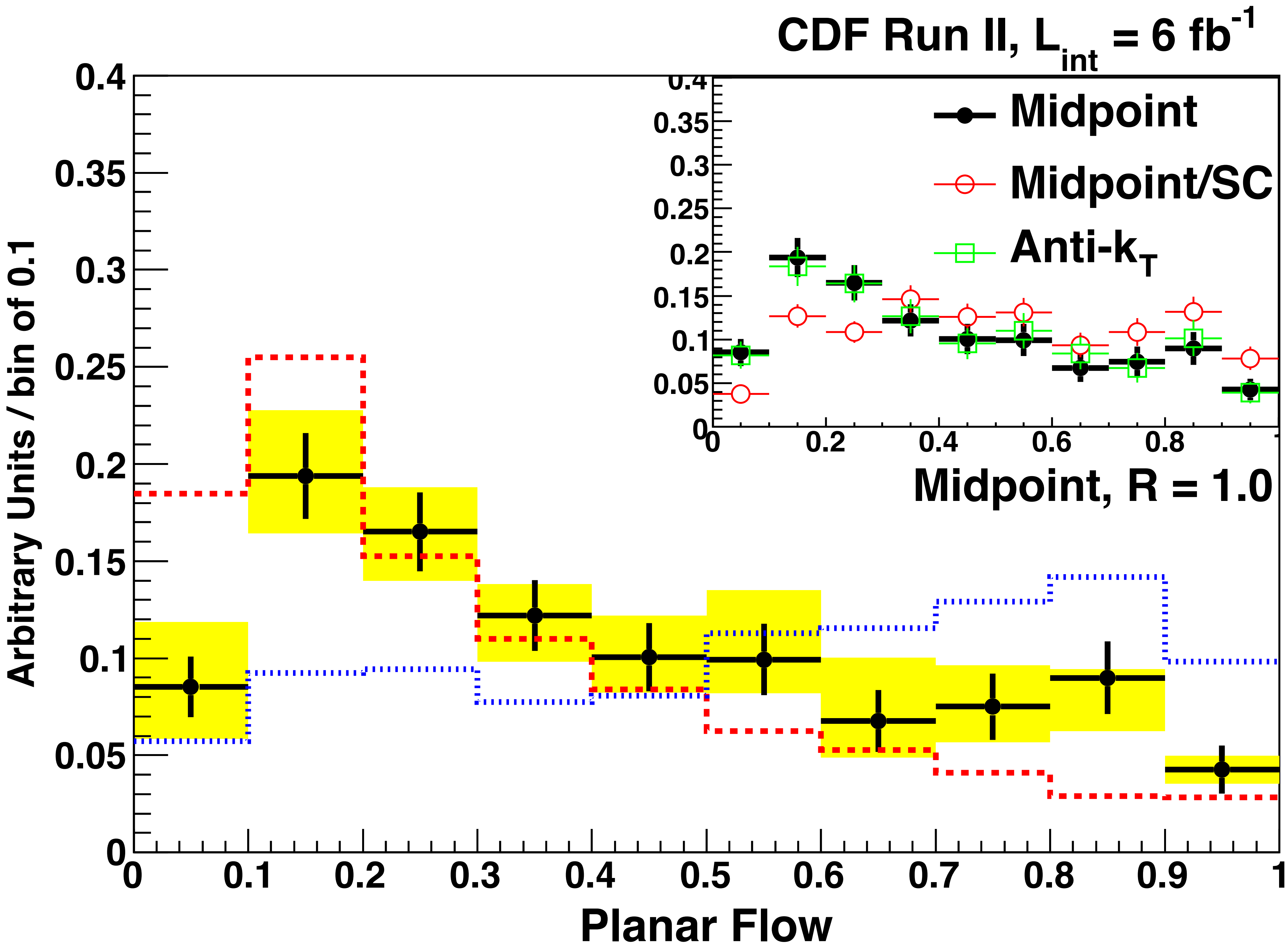



$$\tau_a^{\min}(z) \sim \left(\frac{z}{2}\right)^{1-a}, \quad \tau_a^{\max}(R, p_T) \sim 2^{a-1} R^{-a} z$$

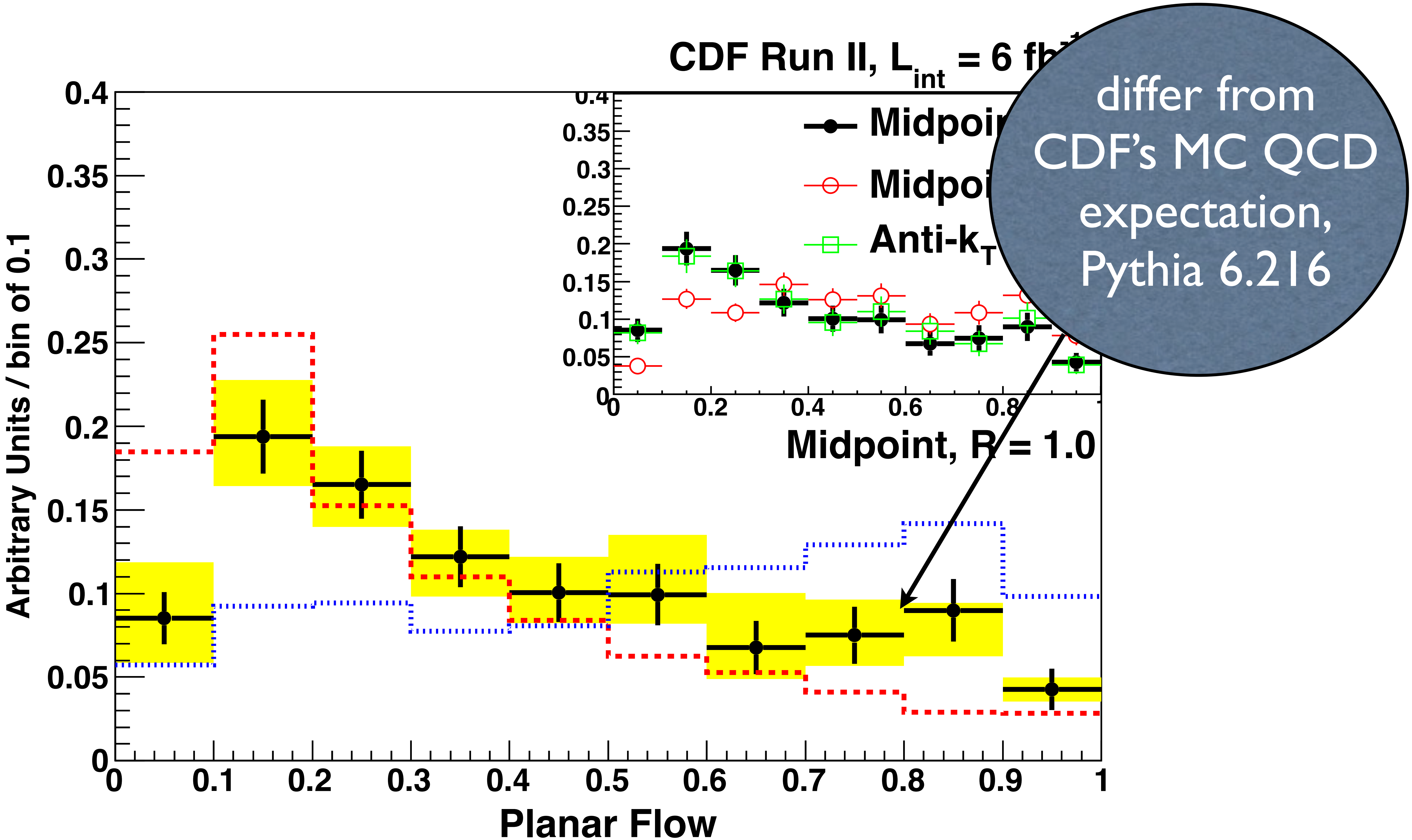
# Planar flow



CDF Run II, $L_{int}$ = 6 $fb^{-1}$
Midpoint
Midpoint/SC
Anti-$k_T$
Midpoint, R = 1.0
Arbitrary Units / bin of 0.1
Planar Flow

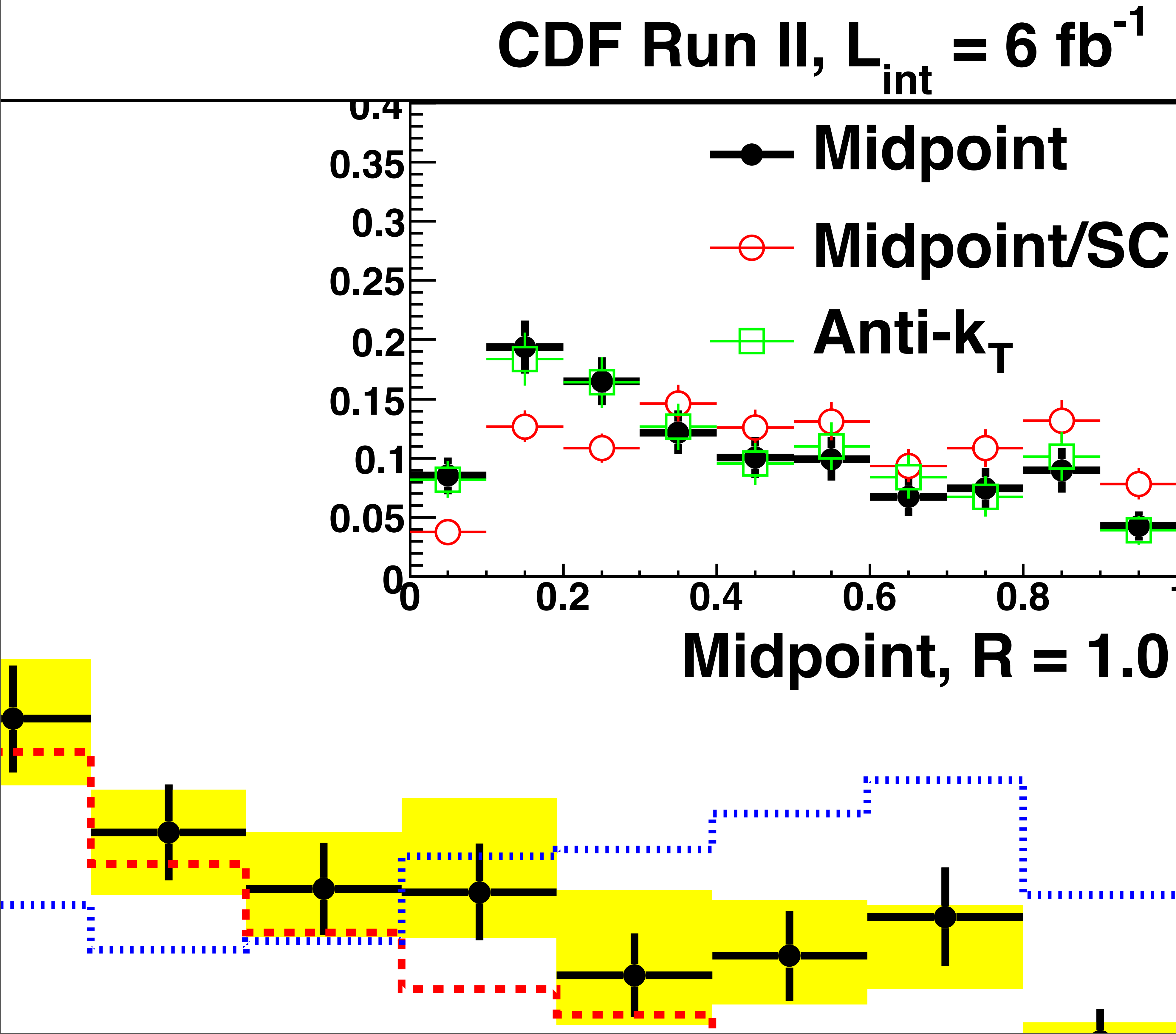

,

# Planar flow

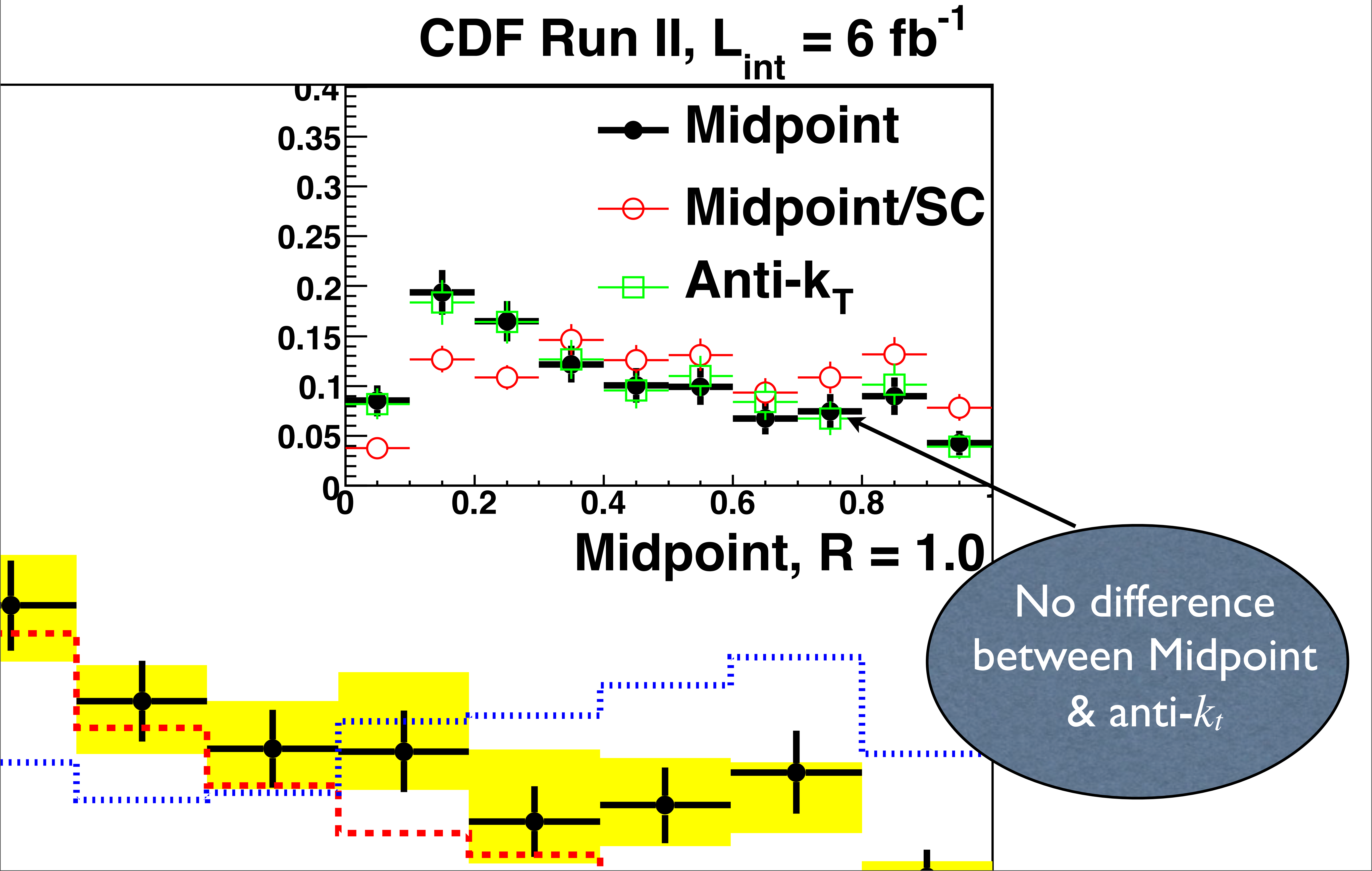

CDF Run II, $L_{int}$ = 6 fb
Midpoi
Midpoi
Anti-$k_T$
Midpoint, R = 1.0
Arbitrary Units / bin of 0.1
Planar Flow
differ from
CDF's MC QCD
expectation,
Pythia 6.216

,

# Planar flow

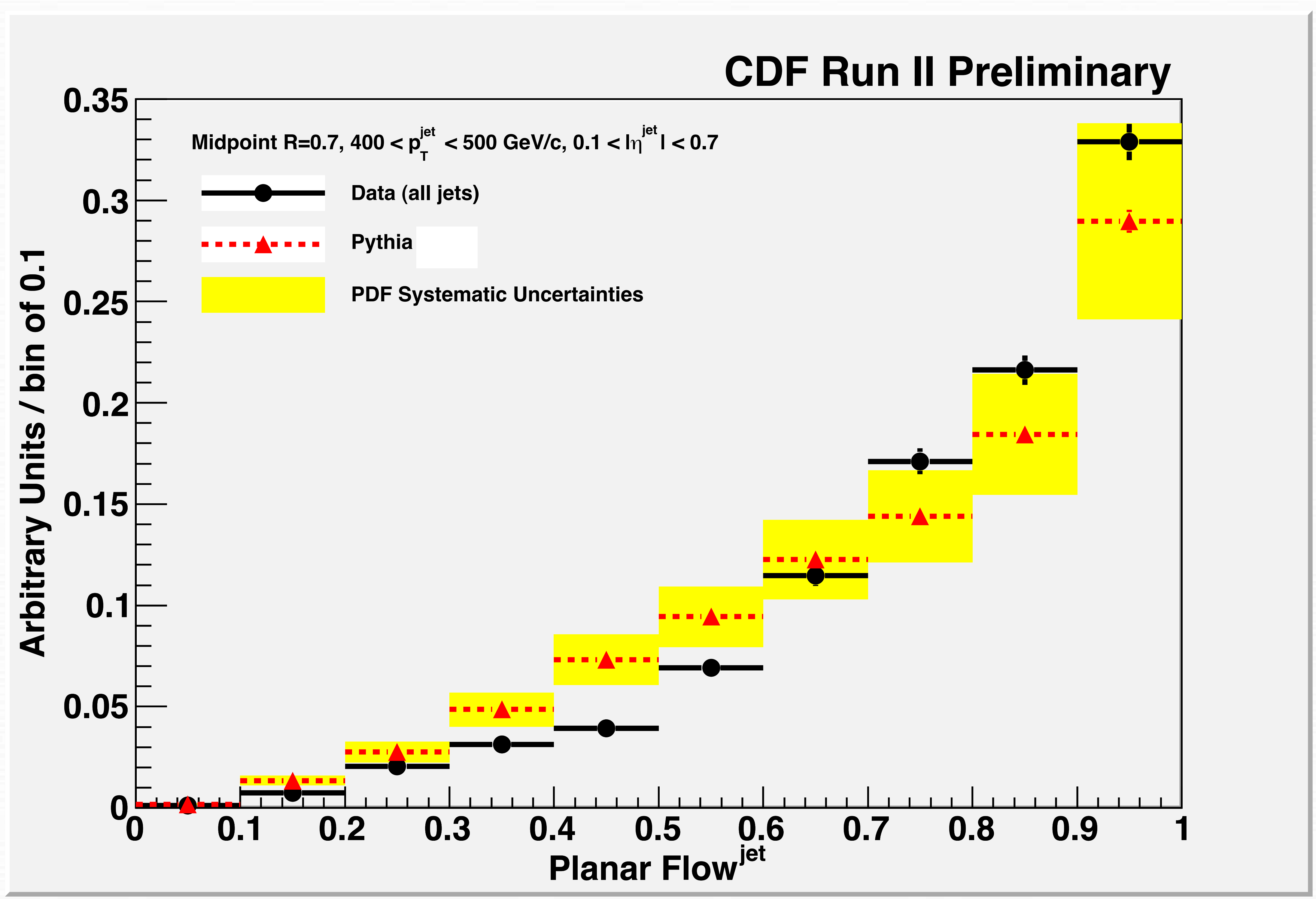

CDF Run II, $L_{int}$ = 6 $fb^{-1}$
Midpoint
Midpoint/SC
Anti-$k_T$
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.2
0.4
0.6
0.8
Midpoint, R = 1.0

# Planar flow



CDF Run II, $L_{int}$ = 6 $fb^{-1}$
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.2
0.4
0.6
0.8
Midpoint
Midpoint/SC
Anti-$k_T$
Midpoint, R = 1.0
No difference between Midpoint & anti-$k_t$

# Planar flow, no mass cut

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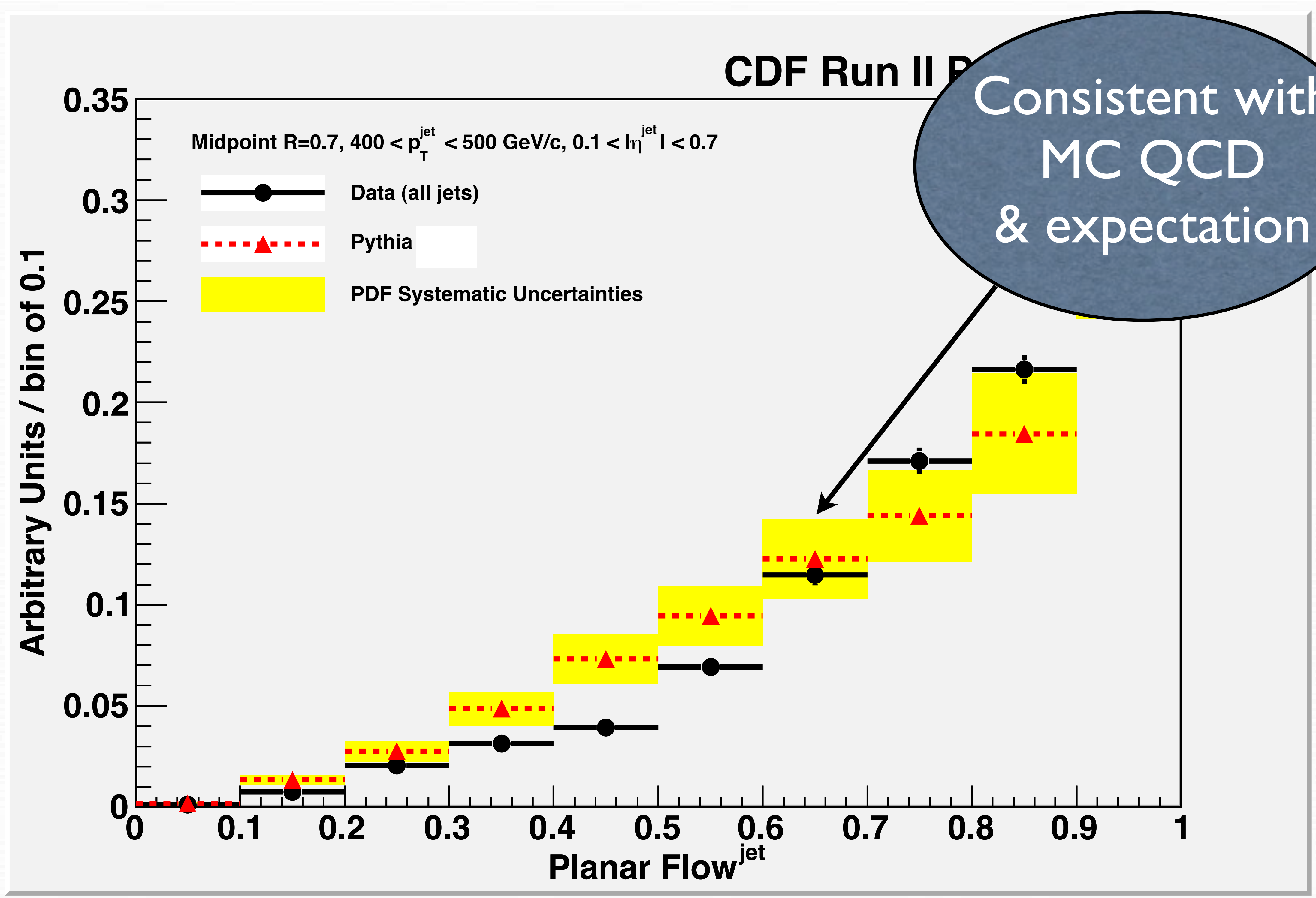
# Planar flow, no mass cut

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# Excess in di-massive jets

Let us look at the "SL" & 'hadronic" data samples separately

(including 30% sys' uncertainties from JES & mass measurements):

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[$130<m_j<210$ (GeV), $4<s_{MET}<10$]

$$\mathrm{QCD}_{\mathrm{data\,driven}} : \quad 31 \pm 8.1\,(\mathrm{stat.}) \pm 9.3\,(\mathrm{syst.})\,,$$
$$t\bar{t} : \quad 1.9 \pm 0.5\,.$$

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32 observed events => ~ 3.4 standard deviations

# Back to Theory

*theorist*

(i) Meothod for pile up subtraction for massive jets.

*R, Alon, E. Duchovni, GP, S. Pronko & P. Sinervo*, arXiv:1101.xxxx.

(ii) Characterization of massive jets.

*G. Gur-Ari, M. Papucci & GP*, arXiv:1101.xxxx;

(iii) Some trivial implications of the recent data.

# Data-driven method of pile-up correction for substructure of massive jets (brief)

- Soft semi-coherent contributions smear E-flow distributions.

Dokshitzer, Lucenti, Marchesini and Salam, JHEP (98); Webber, PLB (94).

- Global corrections elegantly dealt with the concept of jet area.

Cacciari and Salam, PLB (08); Cacciari, Salam and Soyez, JHEP (08).

- What about jet shape specific correction (differential correction)?

- Can be addressed by generalization of the jet area concept.

Cacciari and Salam, PLB (08); Cacciari, Salam and Soyez, JHEP (08); Sapeta and Q. C. Zhang, 1009.1143.

A_X = [ X({p_i, g_i}) - X({p_i}) ]/(nu_g <g_t>)

X_{pileup subtracted} = X - A_X * rho

(where X({p_i,g_i}) is the value of X in the presence of ghosts and genuine jet particles p_i and X({p_i}) is its value given just the particles p_i, nu_g is the ghost density and <g_t> average ghost momentum.)

# Data-driven method of pile-up correction for massive jets

- An analytical close form can be obtained for narrow massive jets, mass, angularity & Pf (qualitatively verified by recent data).

*R, Alon, E. Duchovni, GP, S. Pronko & P. Sinervo*, arXiv:1101.xxxx.

$$\Delta X\big|_{p_J,m_J} = \frac{\partial X}{\partial m_J}\Big|_{p_J,m_J}\delta m_J + \sum_{i\in R^{90^o}} \frac{\partial X}{\partial E_i}\Big|_{p_J,m_J}\delta E_i\,,$$

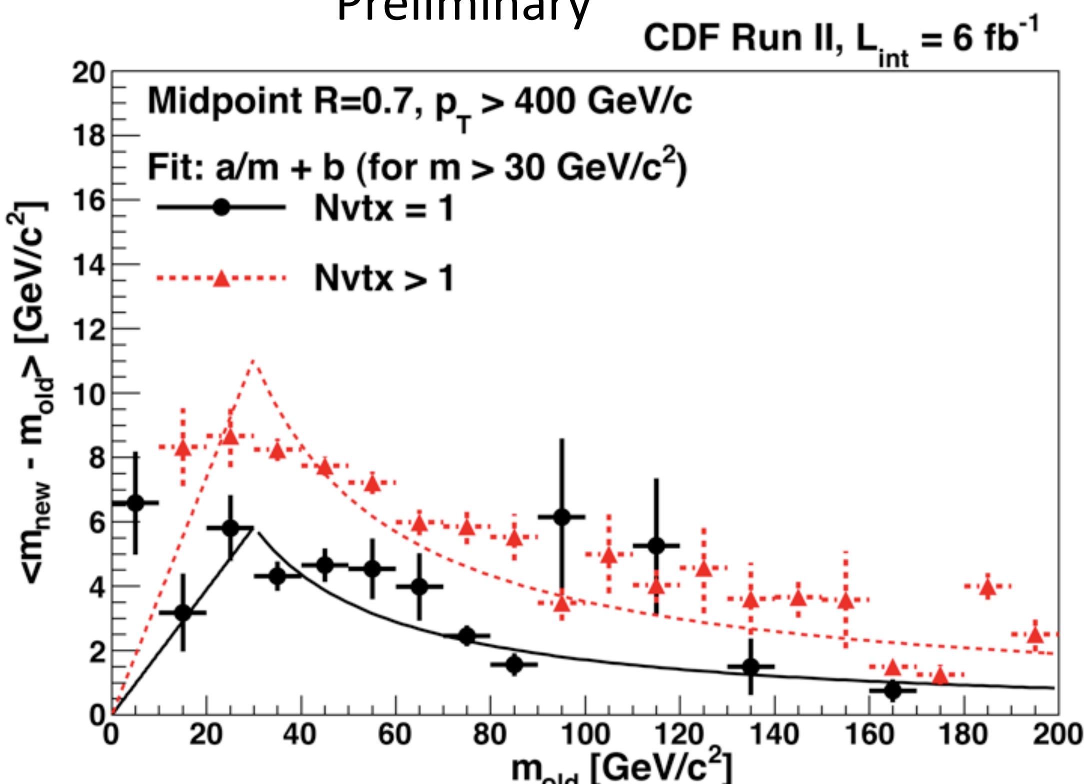
$$\Delta X(p_J,m_J) = f(X,p_J,m_J)\delta m_J^2 \oplus g(X,p_J,m_J)\delta E\,,$$

- Trivial ex., jet mass: $\Delta m_J\big|_{p_J,m_J} = \sum_{i\in R^{90^o}} \frac{\partial m}{\partial E_i}\Big|_{p_T,m_J}\delta E_i\,.\quad \Delta m_J^2 \sim p_J \sum_{i\in R^{90^o}} \delta E_i\theta_i^2 \equiv \sum_{i\in R^{90^o}} \delta m_i^2\,.$

$$\Delta m_J^2 = 2m_J\delta m_J \quad \Longrightarrow \quad \delta m_J \sim \sum_{i\in R^{90^o}} \frac{\delta m_i^2}{2m_J}\,.$$

# Data-driven method of pile-up correction for massive jets

Preliminary



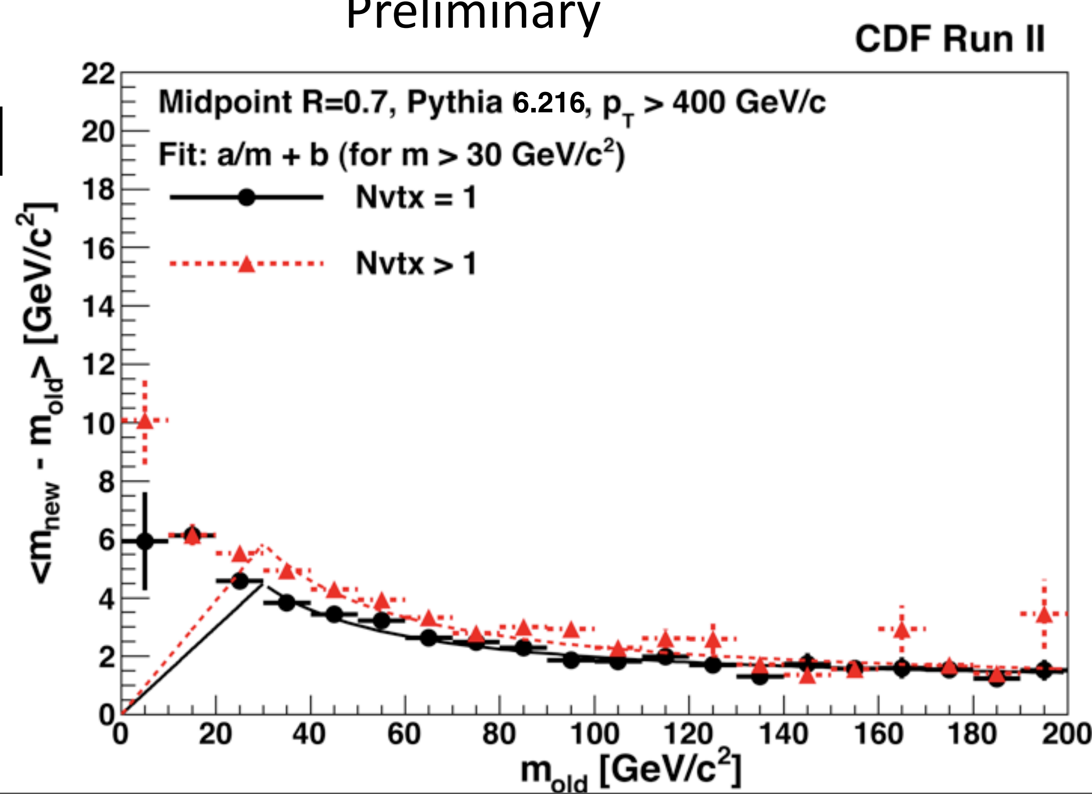

- A be obtained for narrow massive j ualitatively verified by recent data).

R, Alon, E. Duchovni, GP, S. Pronko & P. Sinervo, arXiv:1101.xxxx.

$$\delta m_J + \sum_{i\in R^{90^o}} \frac{\partial X}{\partial E_i}\Big|_{p_J,m_J} \delta E_i \,,$$

$$, m_J)\delta m_J^2 \oplus g(X,p_J,m_J)\delta E \,,$$

Preliminary




- T

$$= \sum_{i\in R^{90^o}} \frac{\partial m}{\partial E_i}\Big|_{p_T,m_J} \delta E_i \,. \quad \Delta m_J^2 \sim p_J \sum_{i\in R^{90^o}} \delta E_i \theta_i^2 \equiv \sum_{i\in R^{90^o}} \delta m_i^2 \,.$$

$$\delta m_J \sim \sum_{i\in R^{90^o}} \frac{\delta m_i^2}{2m_J} \,.$$

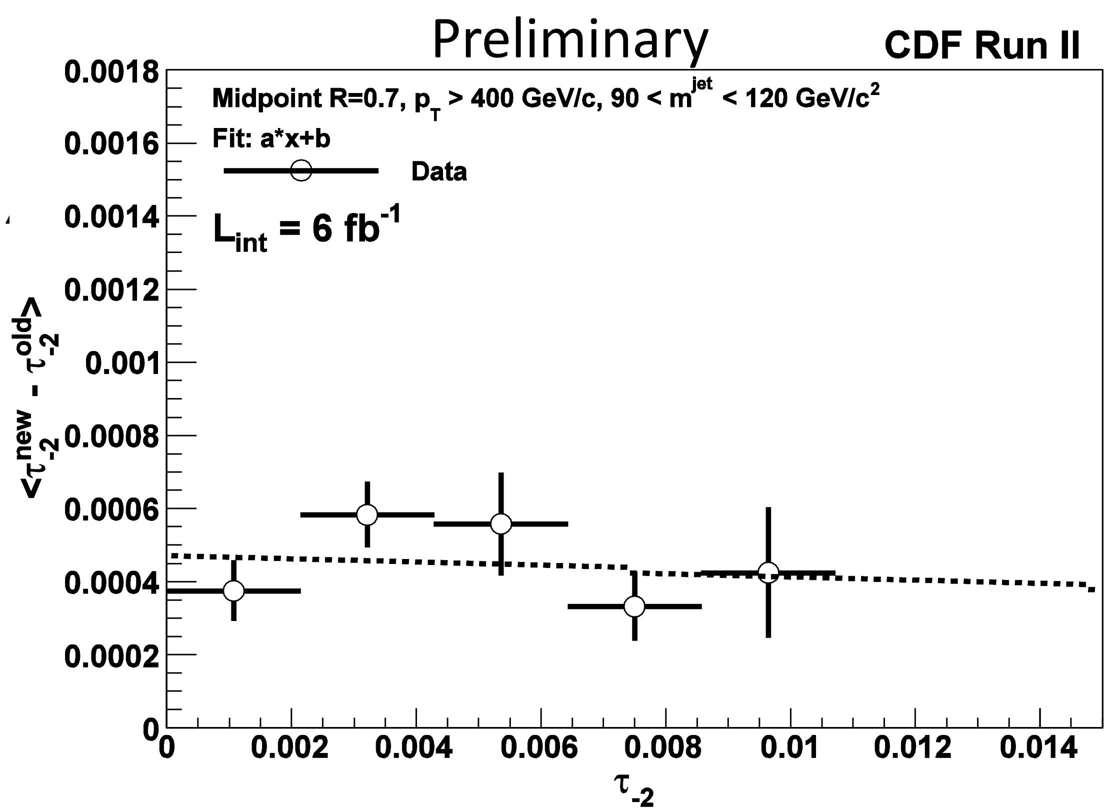
# Data-driven method of pile-up correction for angularity

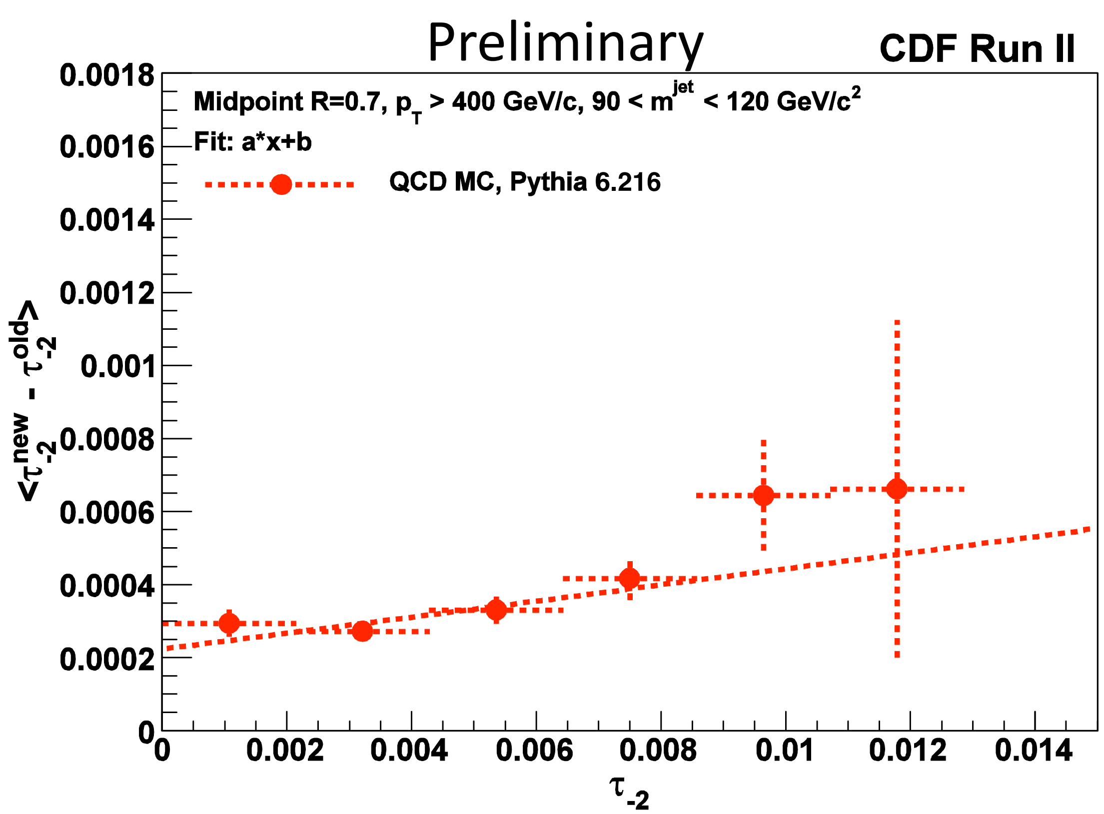
- Angularity: $\Delta\tau_a = \frac{\partial \tau_a}{\partial m_J}\delta m_J + \sum_{i\in R^{90^o}} \frac{\partial \tau_a}{\partial E_i}\delta E_i$ ⟹ $\sum_{i\in R^{90^o}} \frac{\delta m_i^2}{2m_J^2}\left(\frac{2^a m_J}{p_J}\theta_i^{-a} \oplus \tau_a^J\right)$

# Data-driven method of pile-up correction for angularity

- Angularity:

$$\sum_{i\in R^{90^o}} \frac{\delta m_i^2}{2m_J^2}\left(\frac{2^a m_J}{p_J}\theta_i^{-a}\oplus \tau_a^J\right)$$



# Data-driven method of pile-up correction for planar flow

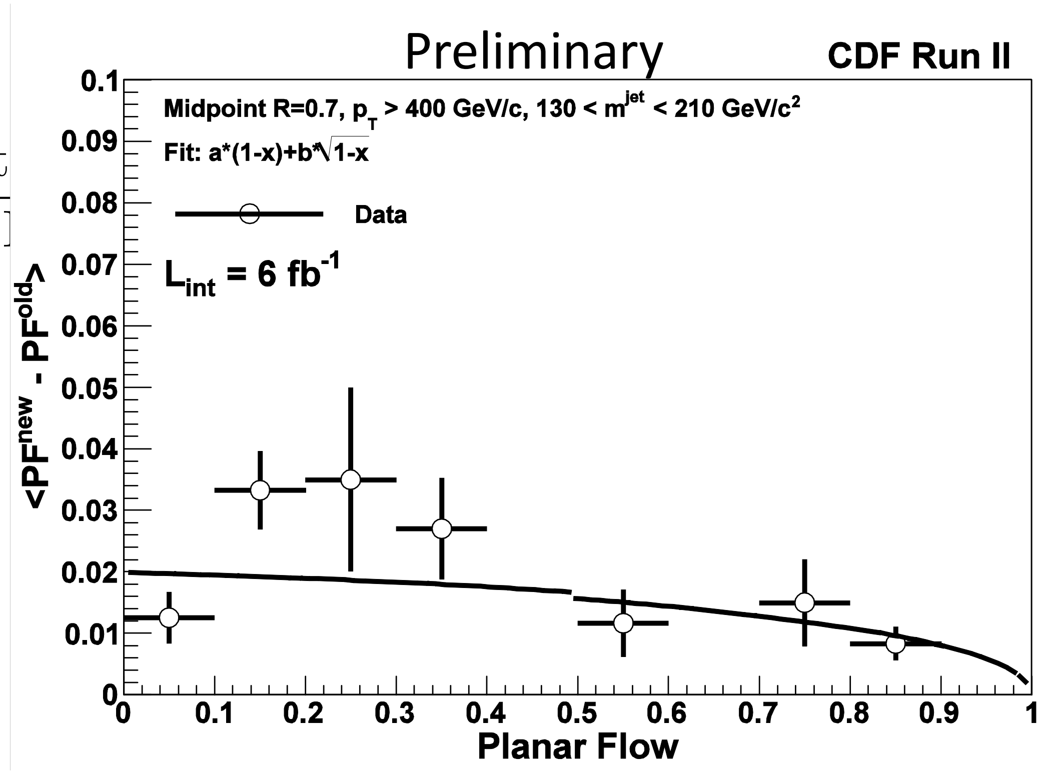
- **PF:** $Pf = 4\,\frac{\det(\mathrm{I_E})}{\mathrm{tr}(\mathrm{I_E})^2} = \frac{4\lambda_1\lambda_2}{(\lambda_1+\lambda_2)^2}, \qquad I_E = p_0\,\sigma_0 + p_x\,\sigma_x + p_z\,\sigma_z\,, \qquad p_0 \simeq \frac{m_J}{\sqrt{2}\,P_J}$

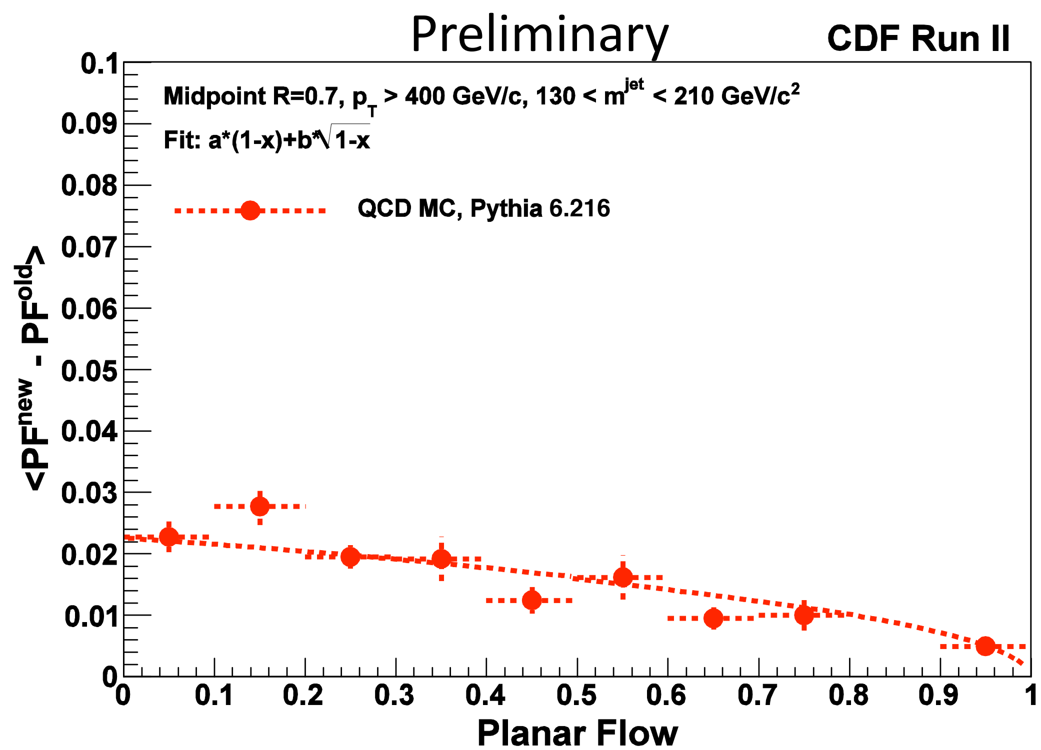
$$\Delta Pf \;=\; \frac{\sqrt{2}\,P_J}{m_J}\left[(1-Pf)\delta p_0 \oplus \sqrt{1-Pf}\,\delta p_i\right]\,.$$

# Data-driven method of pile-up correction for planar flow

- **PF:** $Pf = 4\,\frac{\det}{\mathrm{tr}(}$ … , $p_0 \simeq \frac{m_J}{\sqrt{2}\,P_J}$

  … $\delta p_i \Big]$ .



# Classification of LO jet shapes (brief)

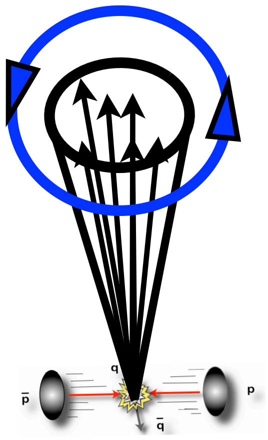
*G. Gur-Ari, M. Papucci & GP,* arXiv:1101.xxxx;

$$I_{i_1 \dots i_n} = \int d^2x \, \varepsilon(x) \, x_{i_1} \cdots x_{i_n} \, .$$

$$I_w^{kl} = \sum_{i \in \text{particles}} E_i \frac{p_{i,k}^{\perp}}{E_i} \frac{p_{i,l}^{\perp}}{E_i} \approx \sum_{i \in \text{particles}} E_i \, \theta_i f_k(\phi_i) \, \theta_i f_l(\phi_i) \, ,$$

$\phi$ is the azimuthal angle, and $f_1(\phi) = \cos(\phi)\, , f_2(\phi) = \sin(\phi)\, .$

$$I_{k_1,\dots,k_n} \equiv \int d^2x \, \varepsilon(x) \, x_{k_1} \cdots x_{k_n} = \frac{1}{E_J} \sum_{i \in \text{particles}} E_i \, x_{k_1}^{(i)} \cdots x_{k_n}^{(i)} \, .$$



invariance under the little group SO(2) (same \w splitting function of QCD)

$$I_0 = 1 \, , \quad I_1 = 0 \, . \;\; I_{ii} \approx \frac{m_J^2}{E_J^2} \, .$$

Next, consider a tensor product $I_2 \otimes I_2$. There are three nontrivial scalars one may construct,

$$I_{ii} I_{jj} \, , \quad I_{ij} I_{ij} \, , \quad \epsilon_{ij} \epsilon_{kl} I_{ik} I_{jl} \, .$$

Of these, only two are independent, since

$$\epsilon_{ij} \epsilon_{kl} I_{ik} I_{jl} = 2(I_{ii} I_{jj} - I_{ij}^2) = 2 \det I \propto \text{ Pf}$$

# Classification of LO jet shapes (brief)

$$I_{iijj} = \frac{1}{E_J} \sum_{i \in \text{particles}} E_i \theta_i^4 \quad \propto \quad \tau_{-2} \qquad I_{iijjkk} = \frac{1}{E_J} \sum_{i \in \text{particles}} E_i \theta_i^6 \quad \propto \quad \tau_{-4}$$

At the next order we find $I_2 I_4$, $(I_3)^2$, and $I_8$, with the following independent contractions:

$$I_2 I_4 : \; \epsilon_{ij}\epsilon_{kl} I_{ik} I_{jlmm} \; , \; \epsilon_{ij} I_{ik} I_{jkll}$$
$$(I_3)^2 : \; \epsilon_{ij}\epsilon_{kl} I_{ikm} I_{jlm} \; , \; I_{ijk} I_{ijk}$$
$$I_8 : \; I_{iijjkkll}$$

| $R$ \ $\Delta\varepsilon$ | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 2 | $I_2$ | - | - | - |
| 4 | $I_4$ | $(I_2)^2$ | - | - |
| 6 | $I_6$ | $I_2 I_4, (I_3)^2$ | $(I_2)^3$ | - |
| 8 | $I_8$ | $I_2 I_6, I_3 I_5, (I_4)^2$ | $I_2 (I_3)^2, (I_2)^2 I_4$ | $(I_2)^4$ |

# Zernike polynomials

$$\varepsilon(r,\phi) = \frac{a_{0,0}}{R^2} + \frac{1}{R^2}\sum_{n=1}^{\infty}\sum_{\substack{0\le m\le n,\\ n-m\ \text{even}}}\left[a_{n,m}R_n^m\left(\frac{r}{R}\right)\cos(m\phi) + a_{n,-m}R_n^m\left(\frac{r}{R}\right)\sin(m\phi)\right],$$

where $R_n^m(\rho)$ are a set of polynomials of degree $n$ respecting the orthogonality condition

$$\int_0^1 \mathrm{d}\rho\,\rho R_n^m(\rho)R_{n'}^m(\rho) = \frac{1}{2n+2}\delta_{n,n'}\,.$$

$$\frac{m_J^2}{E_J^2} = \frac{\pi}{6}R^2\left(a_{2,0}+3a_{0,0}\right),$$

$$\frac{8s}{E_J}\tau_{-2} = \frac{\pi}{30}R^4\left(a_{4,0}+5a_{2,0}+10a_{0,0}\right),$$

$$\frac{32s}{E_J}\tau_{-4} = \frac{\pi}{140}R^6\left(a_{6,0}+7a_{4,0}+21a_{2,0}+35a_{0,0}\right),$$

$$(\mathrm{Pf}-1)\,\frac{m_J^4}{E_J^4} = \frac{\pi^2}{36}R^4\left(a_{2,2}^2-a_{2,-2}^2\right).$$

## Rotation Moment Invariants for Recognition of Symmetric Objects

Jan Flusser, *Senior Member, IEEE*, and Tomáš Suk

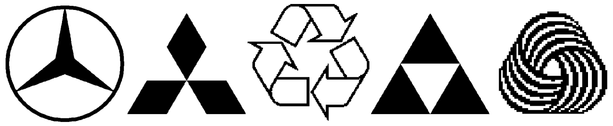
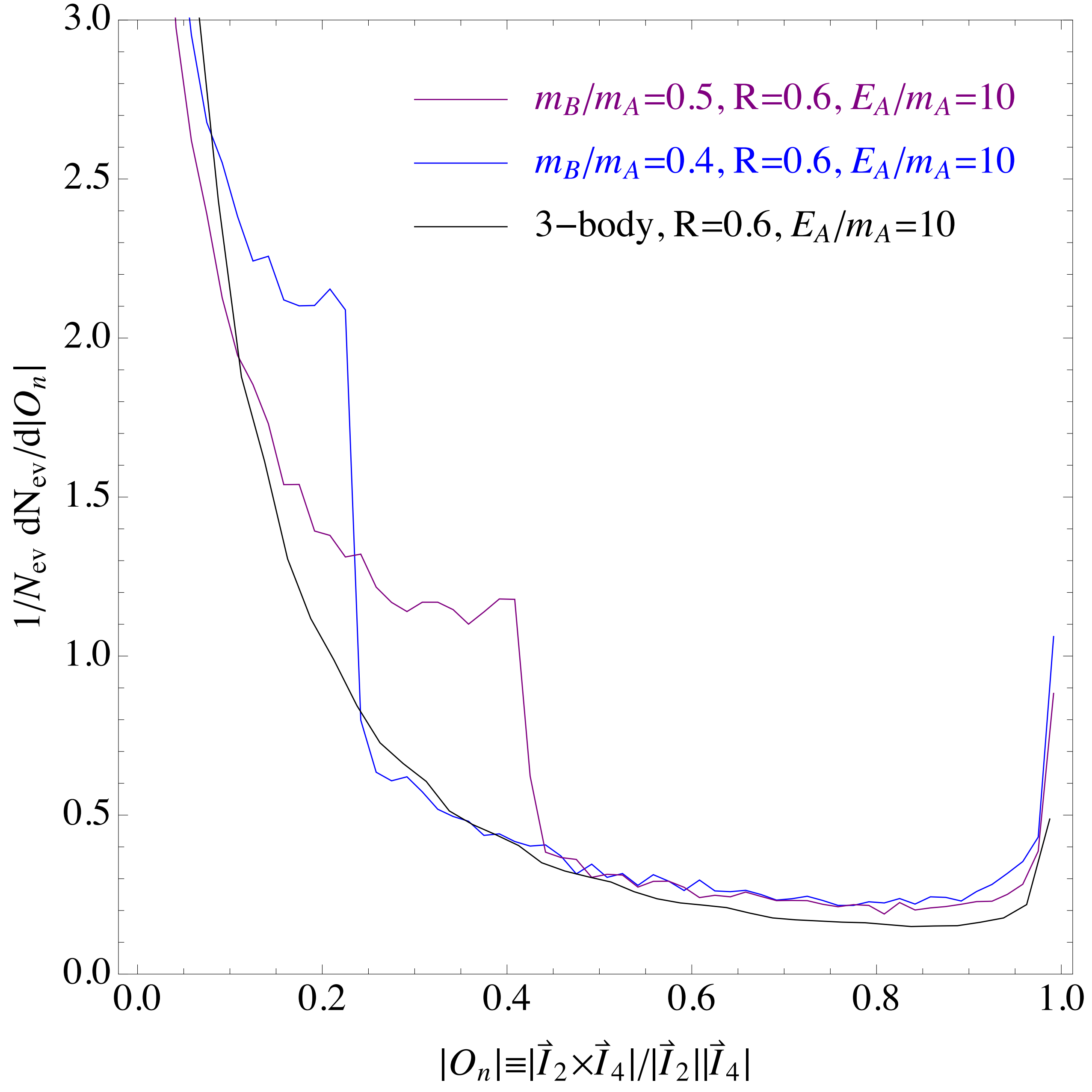


Fig. 1. Test trademarks (from left to right): Mercedes-Benz, Mitsubishi, Recycling, Fischer, and Woolen Stuff.

***Abstract*—In this paper, a new set of moment invariants with respect to rotation, translation, and scaling suitable for recognition of objects having $N$-fold rotation symmetry are presented. Moment invariants described earlier cannot be used for this purpose because most moments of symmetric objects vanish. The invariants proposed here are based on complex moments. Their independence and completeness are proven theoretically and their performance is demonstrated by experiments.**

# The pseudo scalar jet shape variable?

$$\mathcal{O} = 2\epsilon_{ij} I_{ik} I_{jkmm} = 2\,\mathrm{Tr}(I_2 \epsilon I_4') = \epsilon_{ij} I_{2,i} I_{4,j} = \vec{I}_2 \times \vec{I}_4 \,,$$



# Some Interpretation of CDF's di-mass boosted jet excess

- Simplest explanation is QCD: $R_{\rm mass} \equiv \frac{n_B n_C}{n_A n_D} = 1\,,$
  not coming from PDF, since the ratio is close to unity.
  (thanks to S. Ellis for questioning)

- Requires 7-14 fb of hadronic top equivalence Xsec.

- Assuming new source of tops, tension with "SL" sample is~1.4σ

- Pf: Deviation from MC is reduced when looking at new Pythia, MG/ME+matching & Herwig (however none includes 1->3 SF).

# Summary

- LHC => new era, boosted massive jets important for studying QCD & NP discoveries.
- Jet function (gluon emission) gives correct qualitative description of data => 2 body physics; quark jets.
- Angularity distribution further confirmed this description, affected by jet algorithm (due to IR safety issues).
- Interesting excess of di-massive jet events (not in ones \w MET).
- Planar flow (3 body) shows larger deviation at large masses.
- Data driven pile up corrections works, jet-shape classification.