Boosted Massive Jets @ CDF
and
Template Overlap Method for Massive Jets

Gilad Perez

Weizmann Institute

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

L. Almeida, S.J. Lee, GP, G. Sterman, & I. Sung, arXiv:1006.2035

The Dalitz Institute
Oxford University

Boost 2010

Outline

- Semi-analytical dist' for inner-jet energy flow:
  (i) jet mass => perturbative @ high mass =>
  (ii) angularity <-> 2-body (iii) planar flow <-> 3 body.
- First measurements: CDF preliminary.
- Can improve systematically? Template method.
- Summary

Jet Mass-Overview

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

- 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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+ detector smearing.

Pure kinematical bW(qq) dist'
in/out cone
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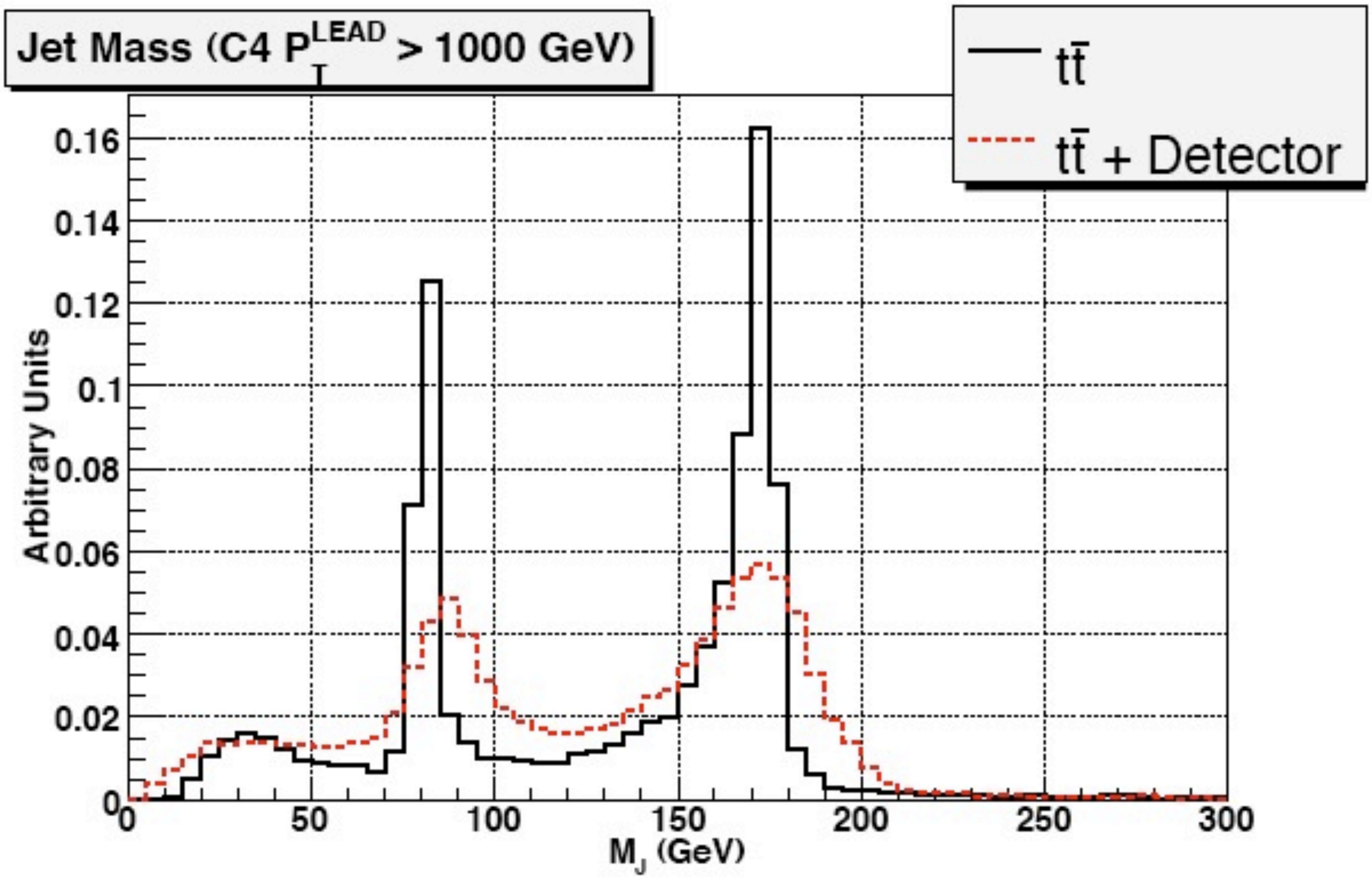
(Fleming, Hoang, Jain, Mantry, Scimemi, Stewart) Almeida, Lee, Perez, Sung,& Virzi (08).

Sherpa => Transfer functions,
(CKKW)



QCD jet mass distribution

✦Boosted QCD Jet via factorization:

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

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

- 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:

$$\frac{d\sigma_{H_AH_B\to J_1J_2}}{dm^2_{J_1}dm^2_{J_2}d\eta} = \sum_{abcd}\int dx_a\,dx_b\,\phi_a(x_a,p_T)\,\phi_b(x_b,p_T)\frac{d\hat{\sigma}_{ab\to cd}}{dp_Td\eta}(x_a,x_b,\eta,p_T)$$
$$S\left(m^2_{J_1},m^2_{J_2},\eta,p_T,R^2\right)\;J_1^{(c)}(m^2_{J_1},\eta,p_T,R^2)J_2^{(d)}(m^2_{J_2},\eta,p_T,R^2)$$

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

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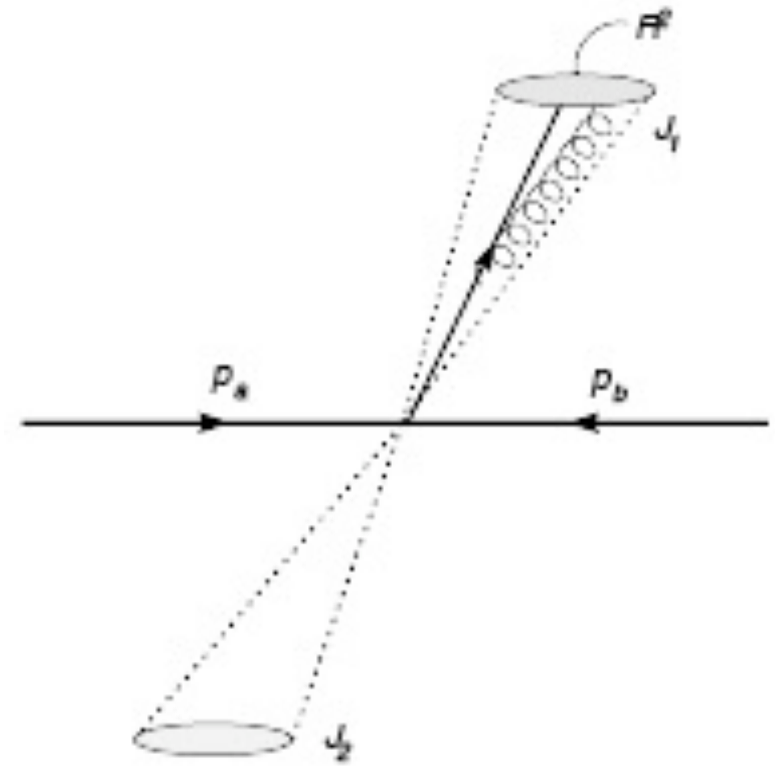
QCD jet mass distribution, Q+G

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



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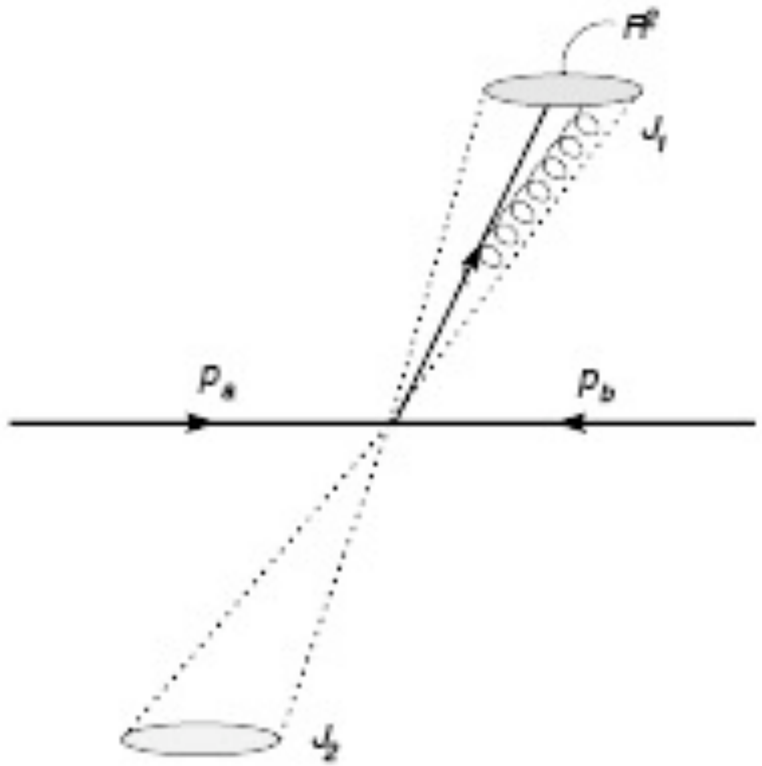

$$J^{(eik),c}(m_J, p_T, R) \simeq \alpha_S(p_T)\frac{4\,C_c}{\pi m_J}\log\left(\frac{R\,p_T}{m_J}\right)$$

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

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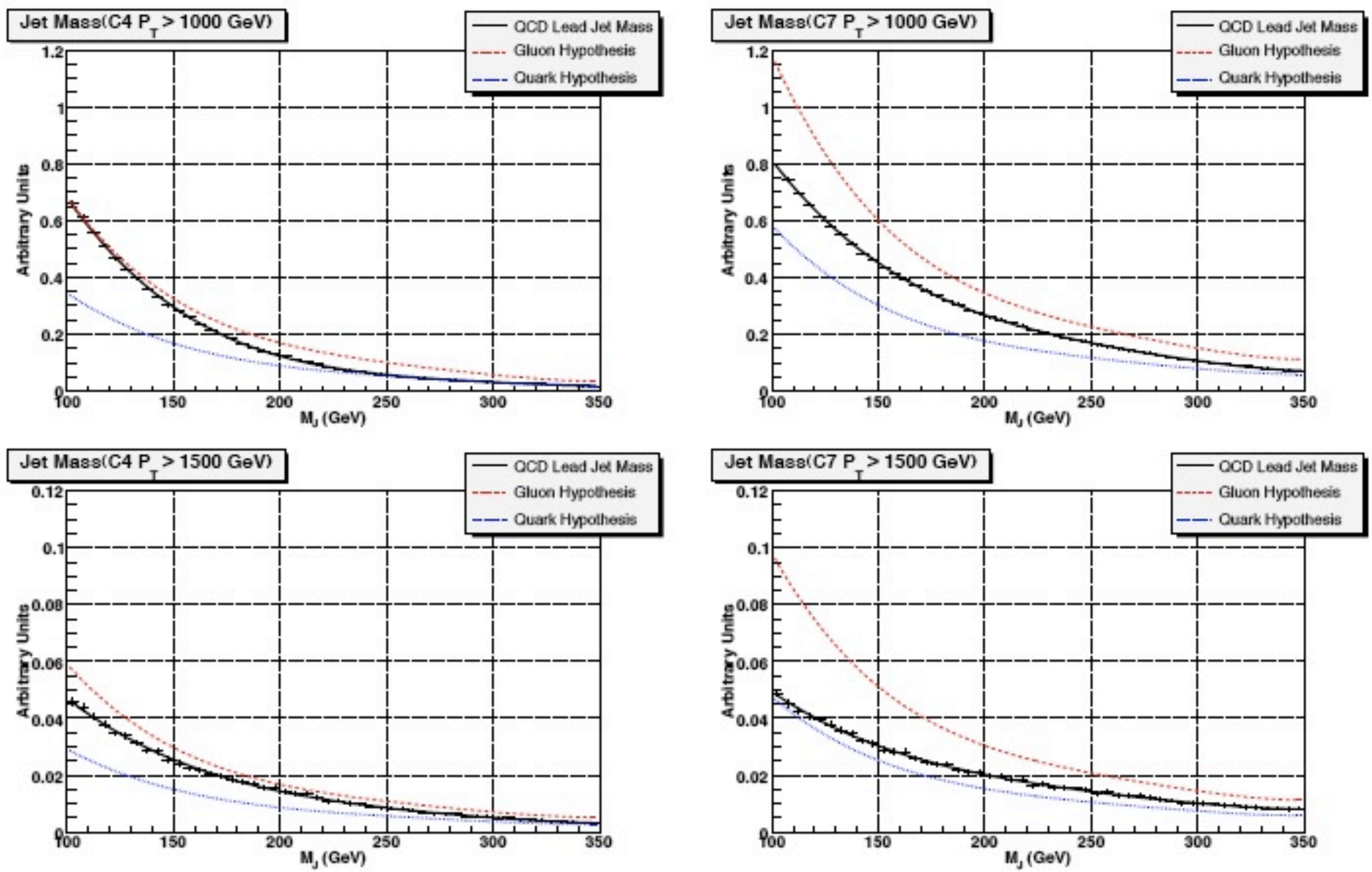
Data is admixture of the two, should be bounded by them:

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

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

Jet mass distribution theory vs. MC

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



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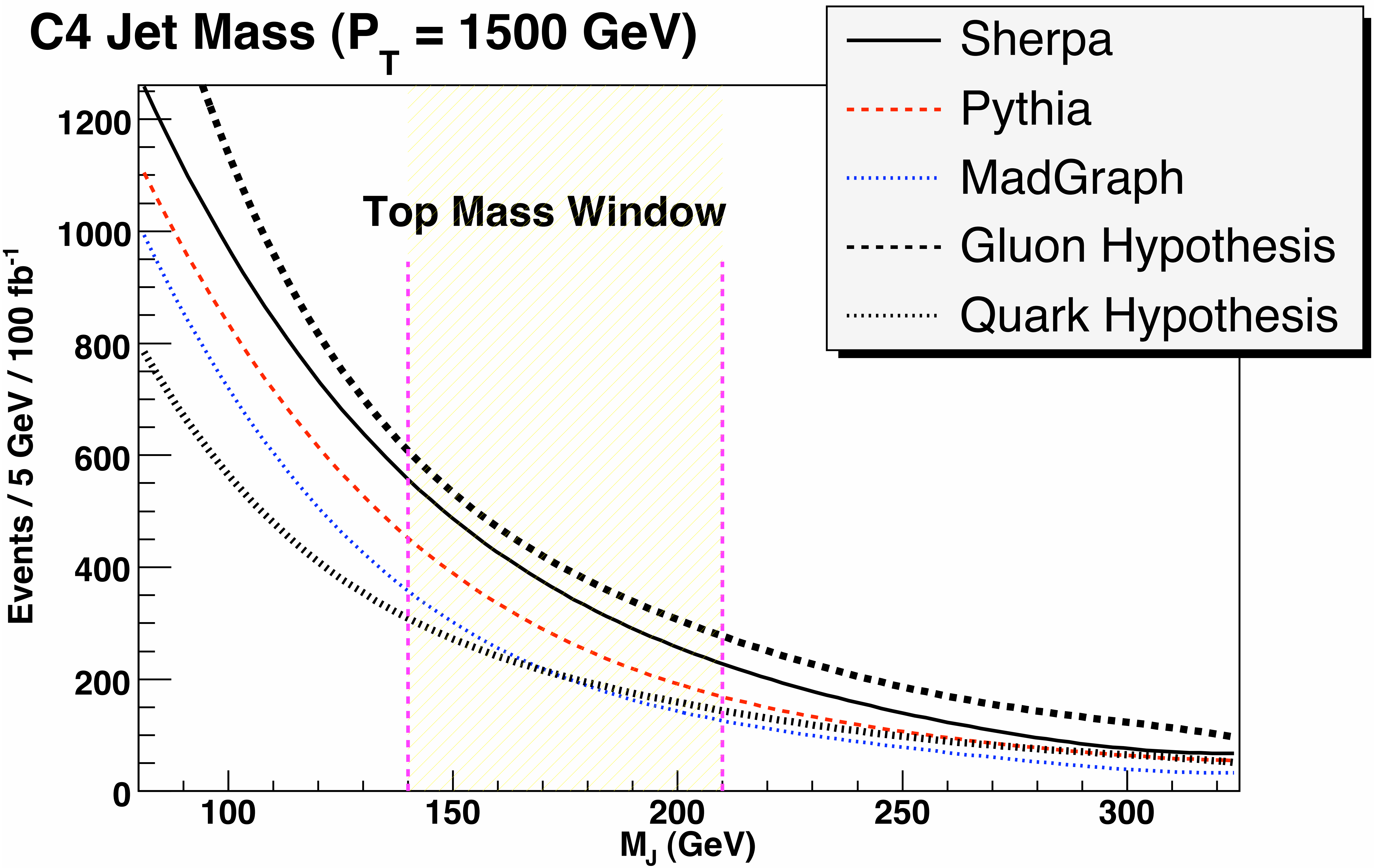

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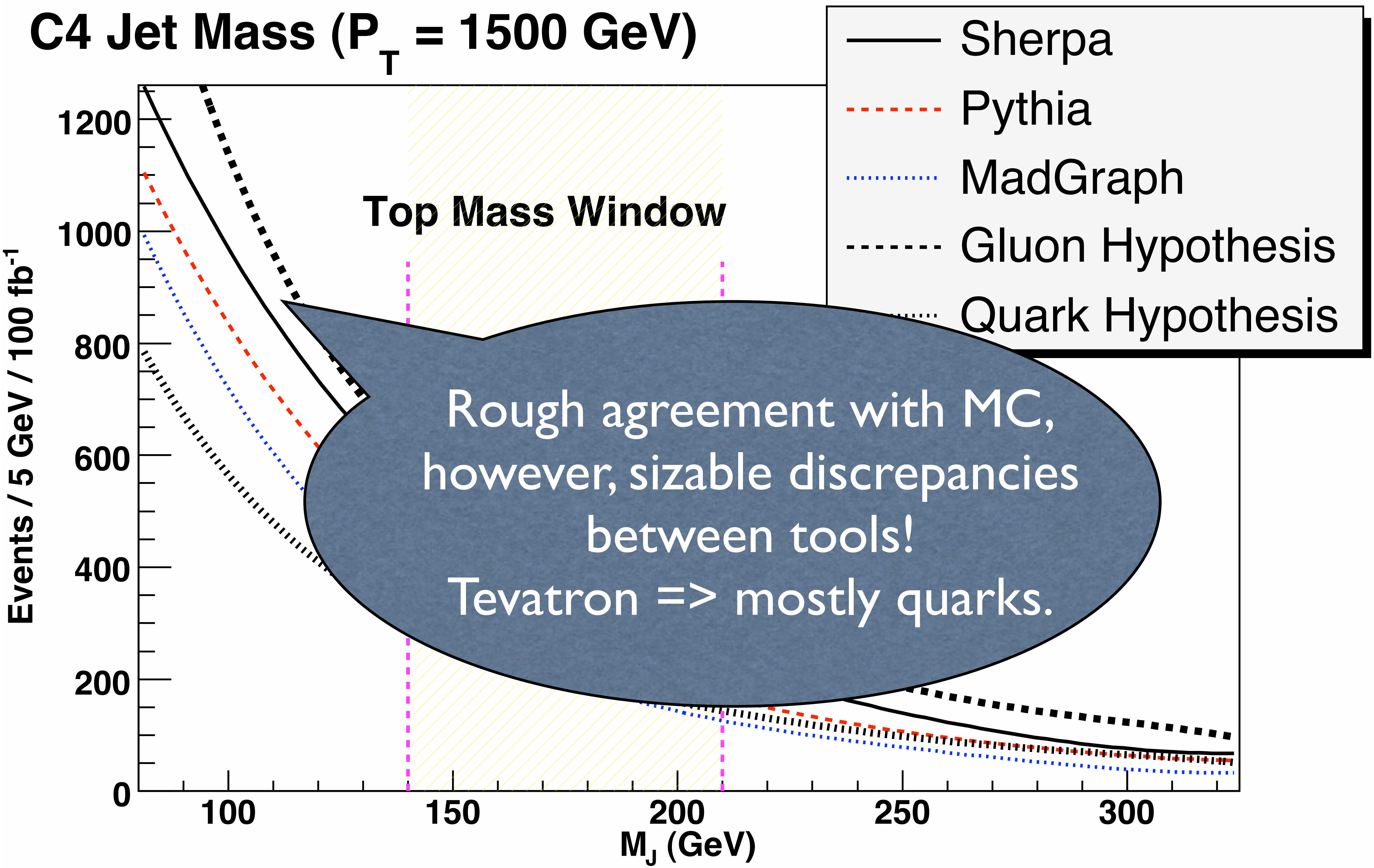
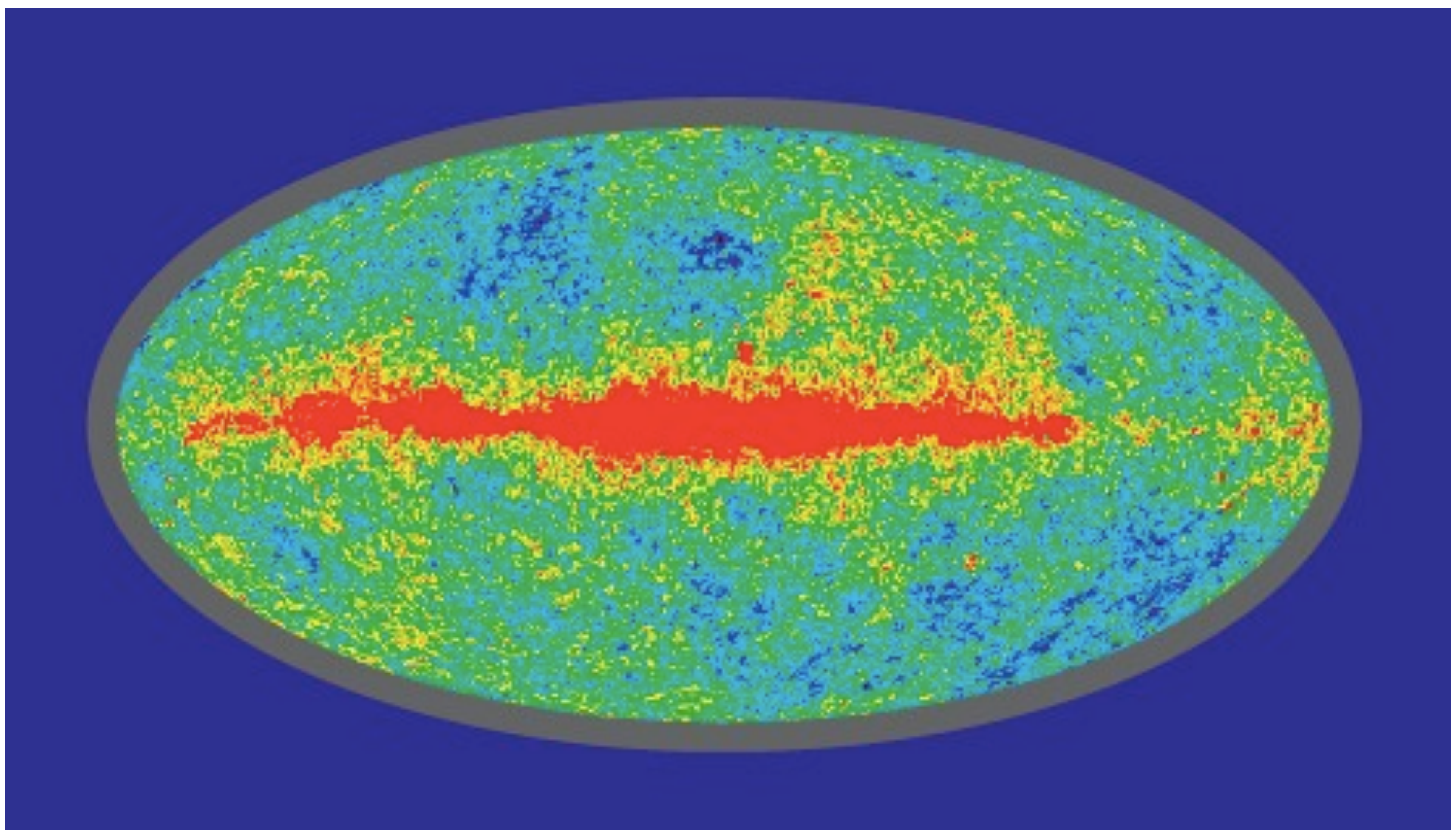


Jet sub-structure



angularity; planar flow <=> no manipulation of jet energy deposition

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

✦ Successes in high jet mass => jet function well described by single gluon radiation.

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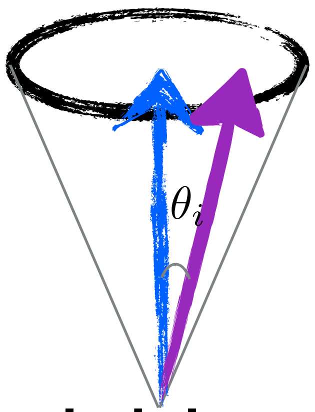

- Once jet mass fixed @ high scale
  - Large class of jet-shapes become perturbatively calculable

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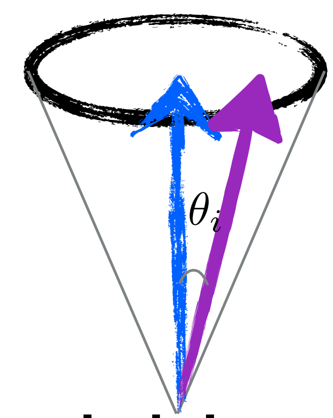

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  - ➡ Large class of jet-shapes become perturbatively calculable

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

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

emphasize cone-edge radiation

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

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

✦Angularities distinguish between Higgs and QCD jets (2-body only one variable<=>ysplitter):

$$\frac{dJ^h}{d\tilde{\tau}_a} \propto \frac{1}{|a|\left(\tilde{\tau}_a\right)^{1-\frac{2}{a}}}$$

vs.

$$\frac{dJ^{\mathrm{QCD}}}{d\tilde{\tau}_a} \propto \frac{1}{|a|\,\tilde{\tau}_a}$$

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

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

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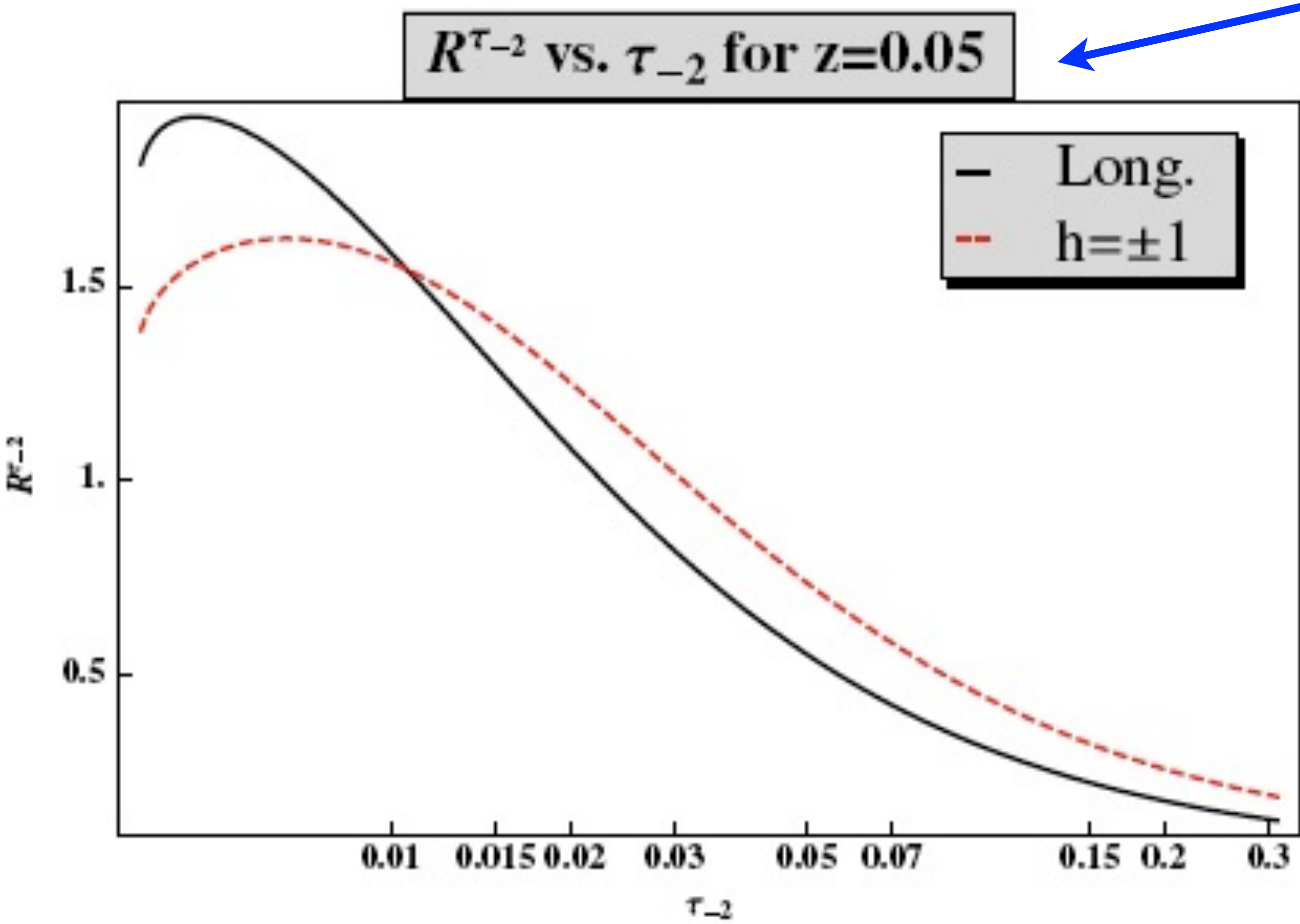

FIG. 3 (color online). The ratio between the signal and background probabilities to have jet angularity $\tilde{\tau}_{-2}$, $R^{\tilde{\tau}_{-2}}$.

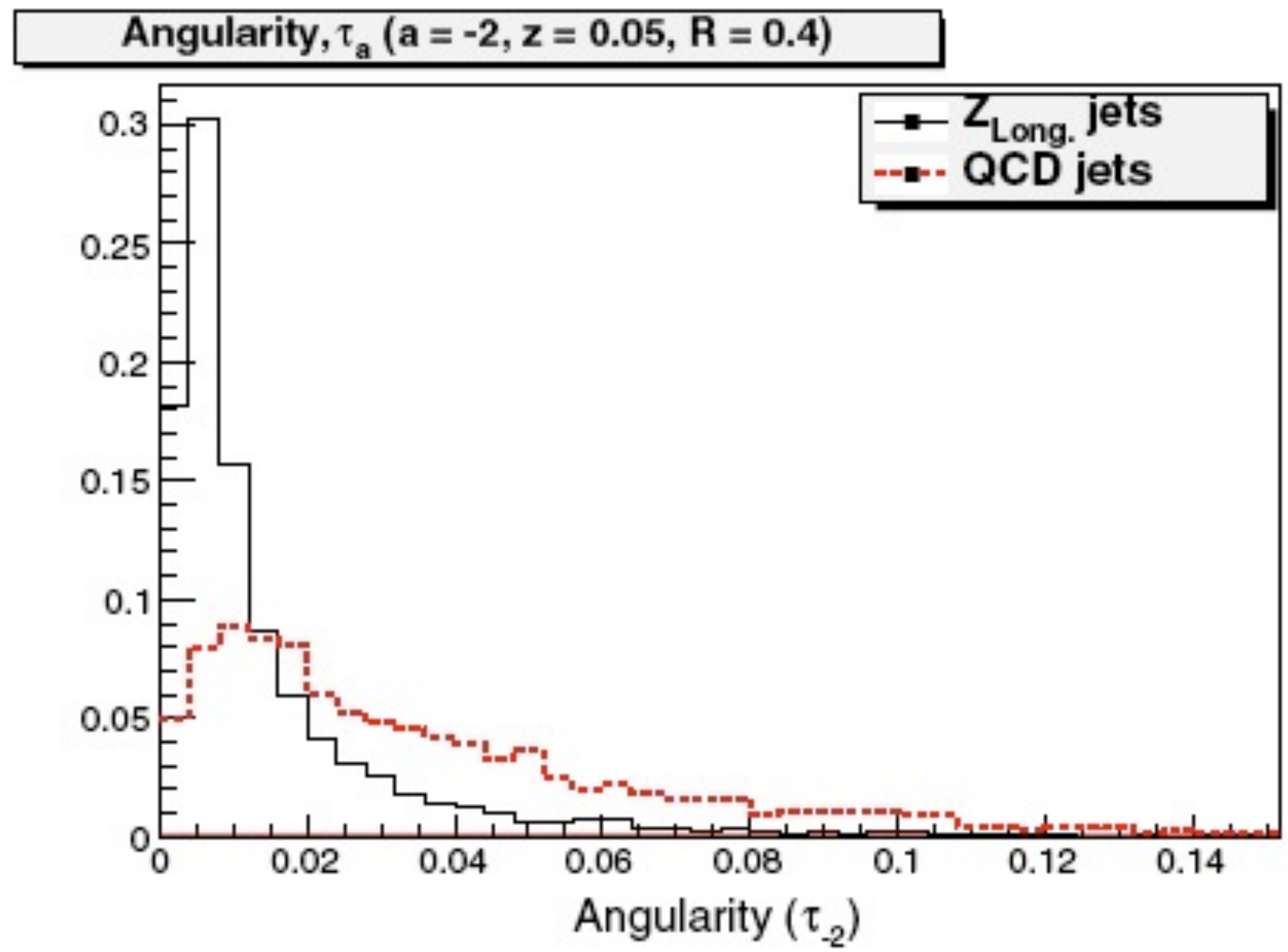

FIG. 4 (color online). The angularity distribution for QCD (red-dashed curve) and longitudinal Z (black-solid curve) jets obtained from MADGRAPH. Both distributions are normalized to the same area.

$$(z = m_J/p_T)$$

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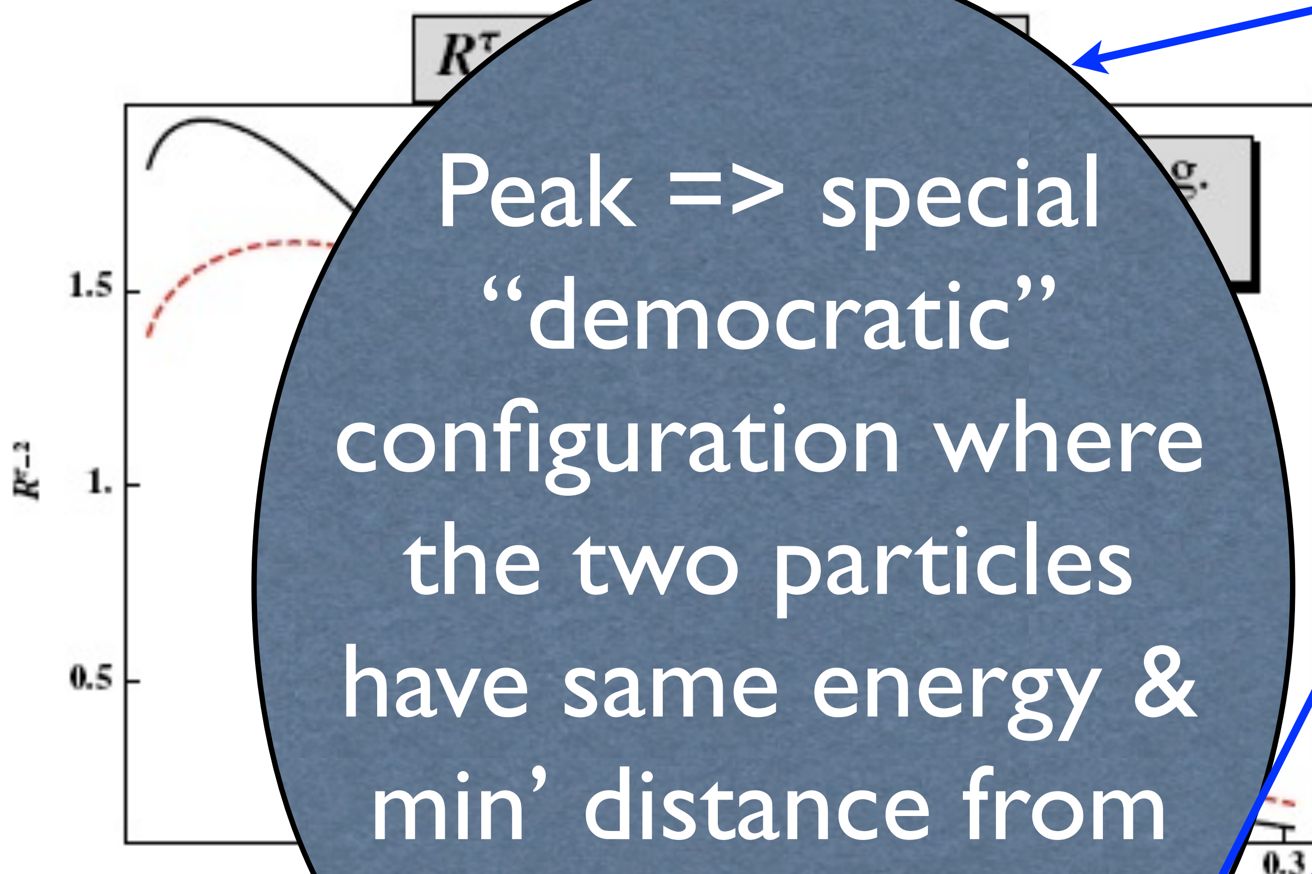
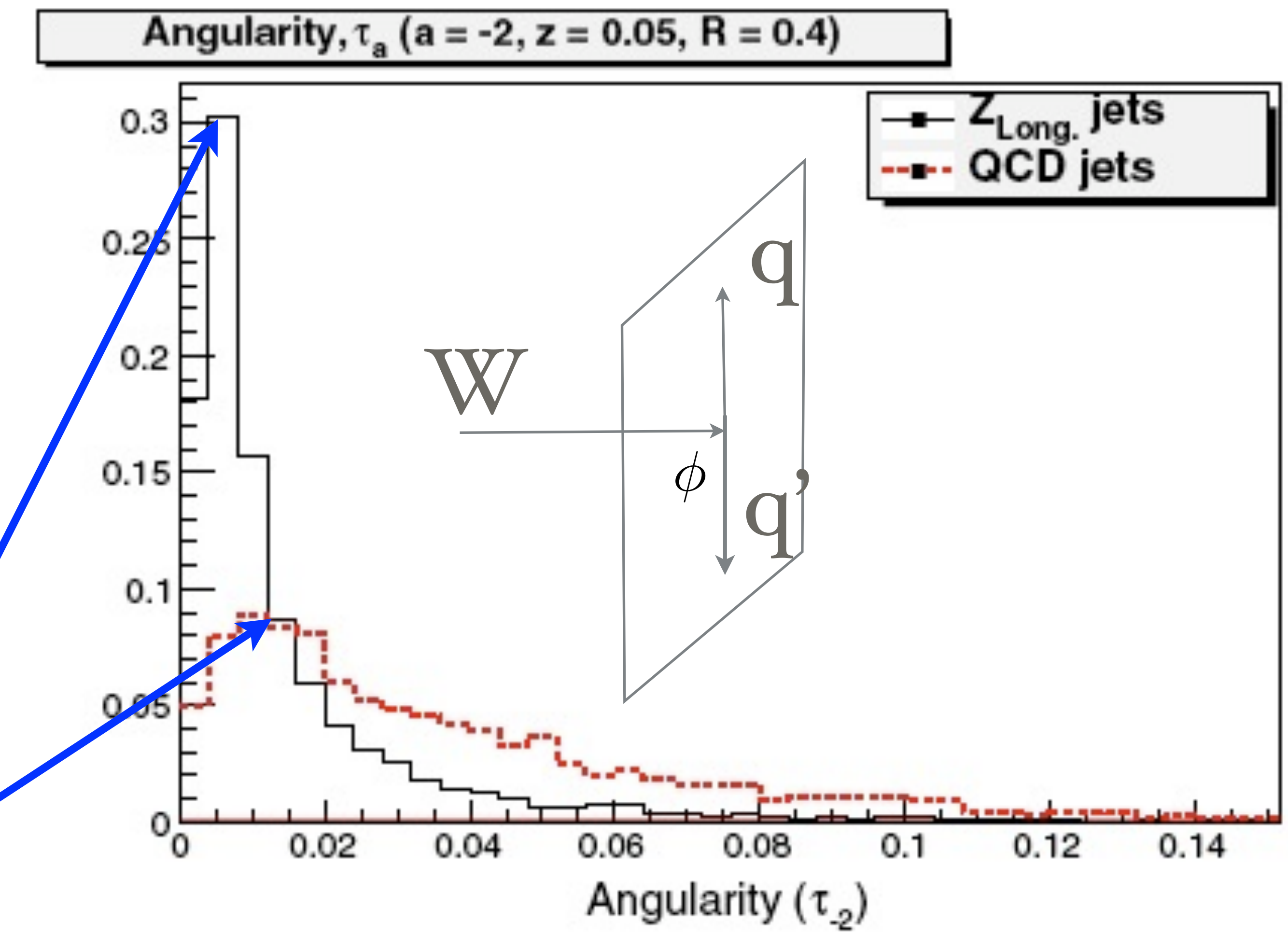


Peak => special "democratic" configuration where the two particles have same energy & min' distance from jet axis $\theta_m \approx z$.

$(z = m_J/p_T)$

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



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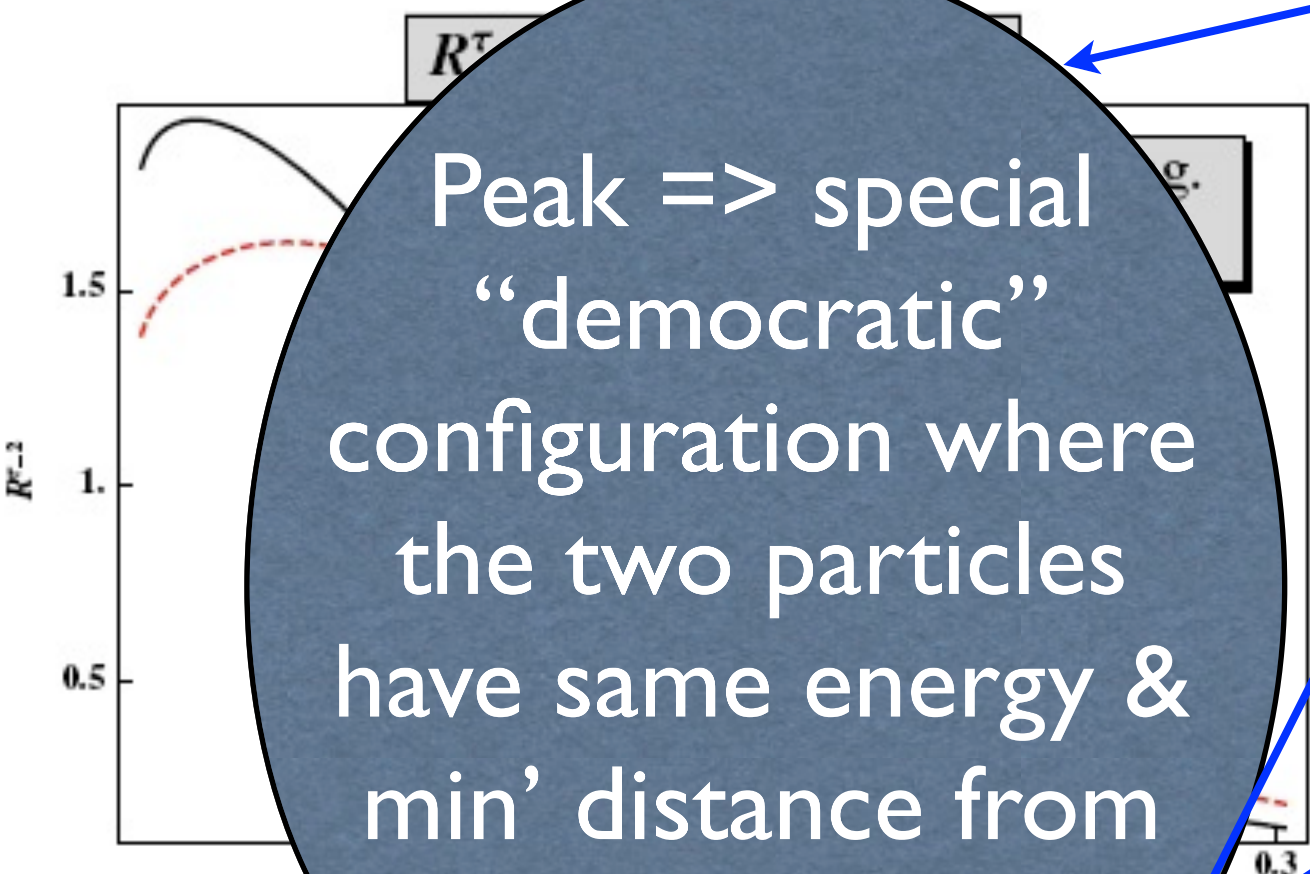

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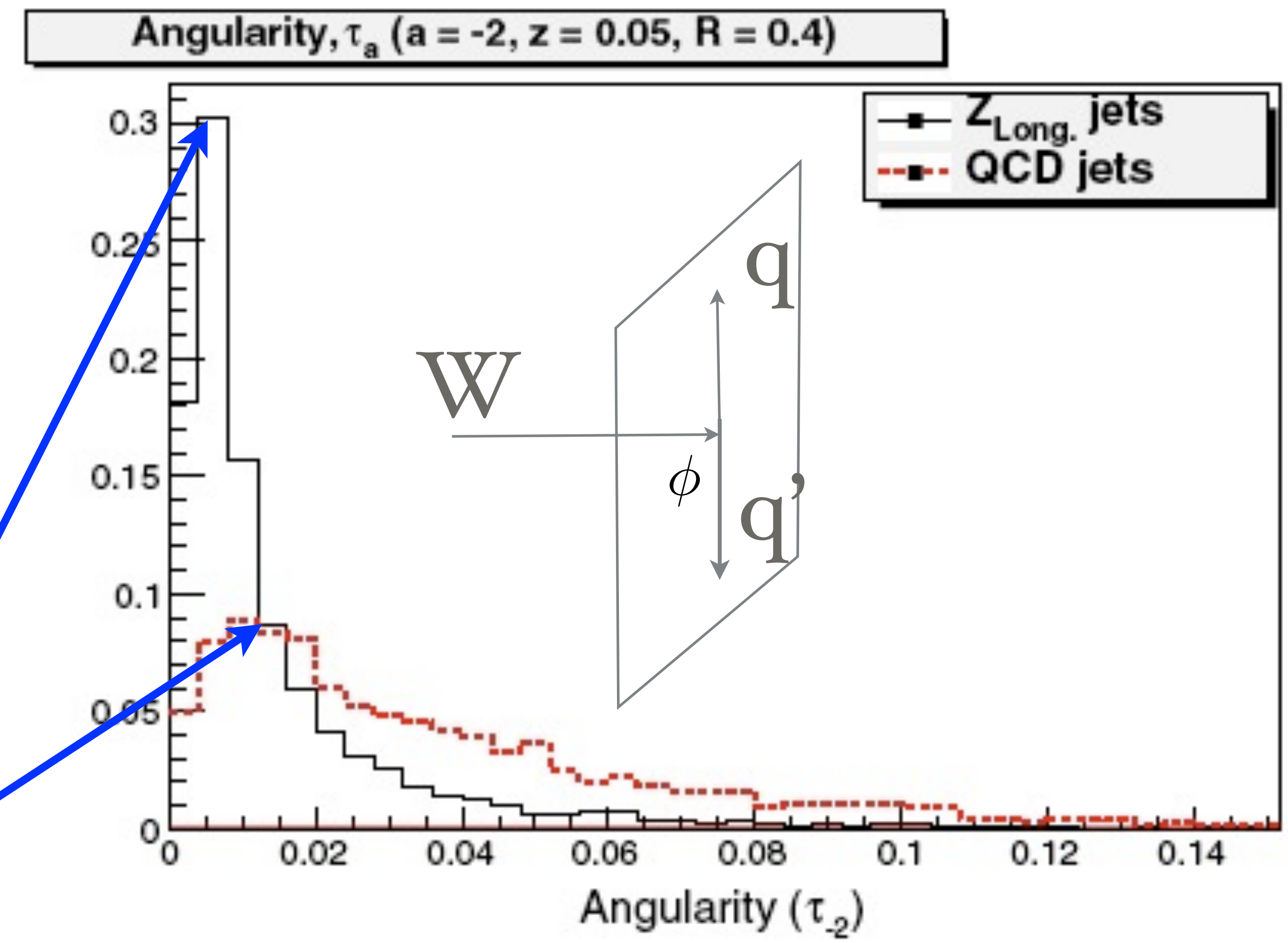


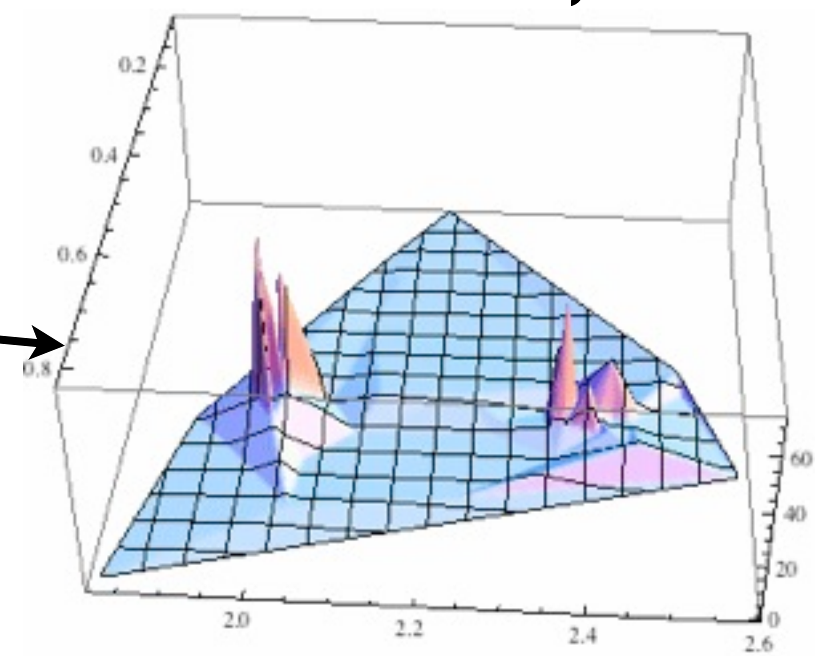
FIG. 4 (color online). The angularity distribution for QCD

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

QCD jets vs top jets via planar flow

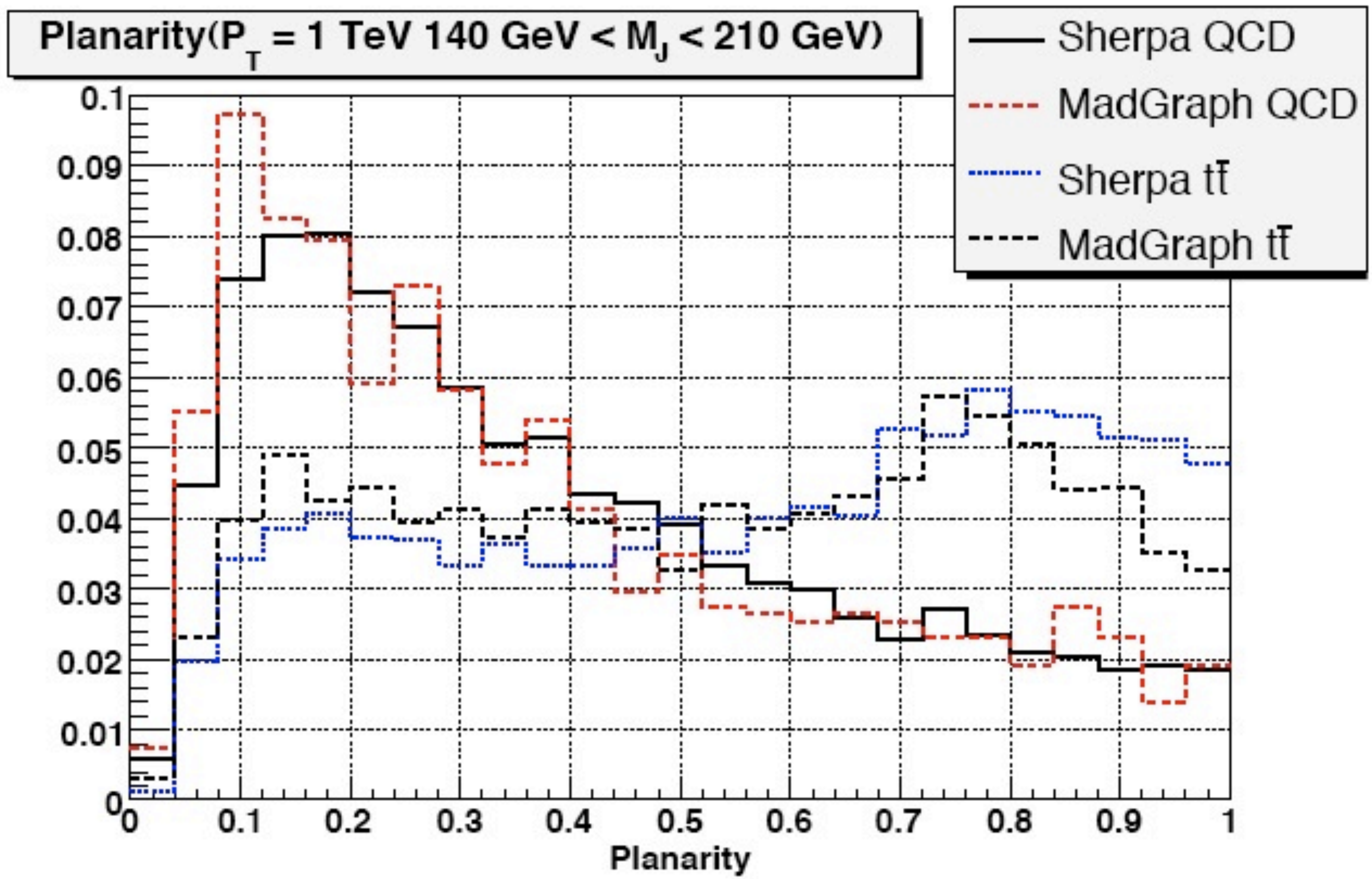
- QCD jets are democratic & broad, shown both for cone & anti-kt jets.

SISCone
QCD Jet



- QCD-linear, top-planar E-deposition in the cone
- IR-safe E-flow tensor: $$I_w^{kl} = \frac{1}{m_J} \sum_i w_i \frac{p_{i,k}}{w_i} \frac{p_{i,l}}{w_i}$$
- Planar flow: $$Pf = \frac{4\det(I_w)}{\mathrm{tr}(I_w)^2} = \frac{4\lambda_1 \lambda_2}{(\lambda_1 + \lambda_2)^2}$$

Planar flow, QCD vs top jets



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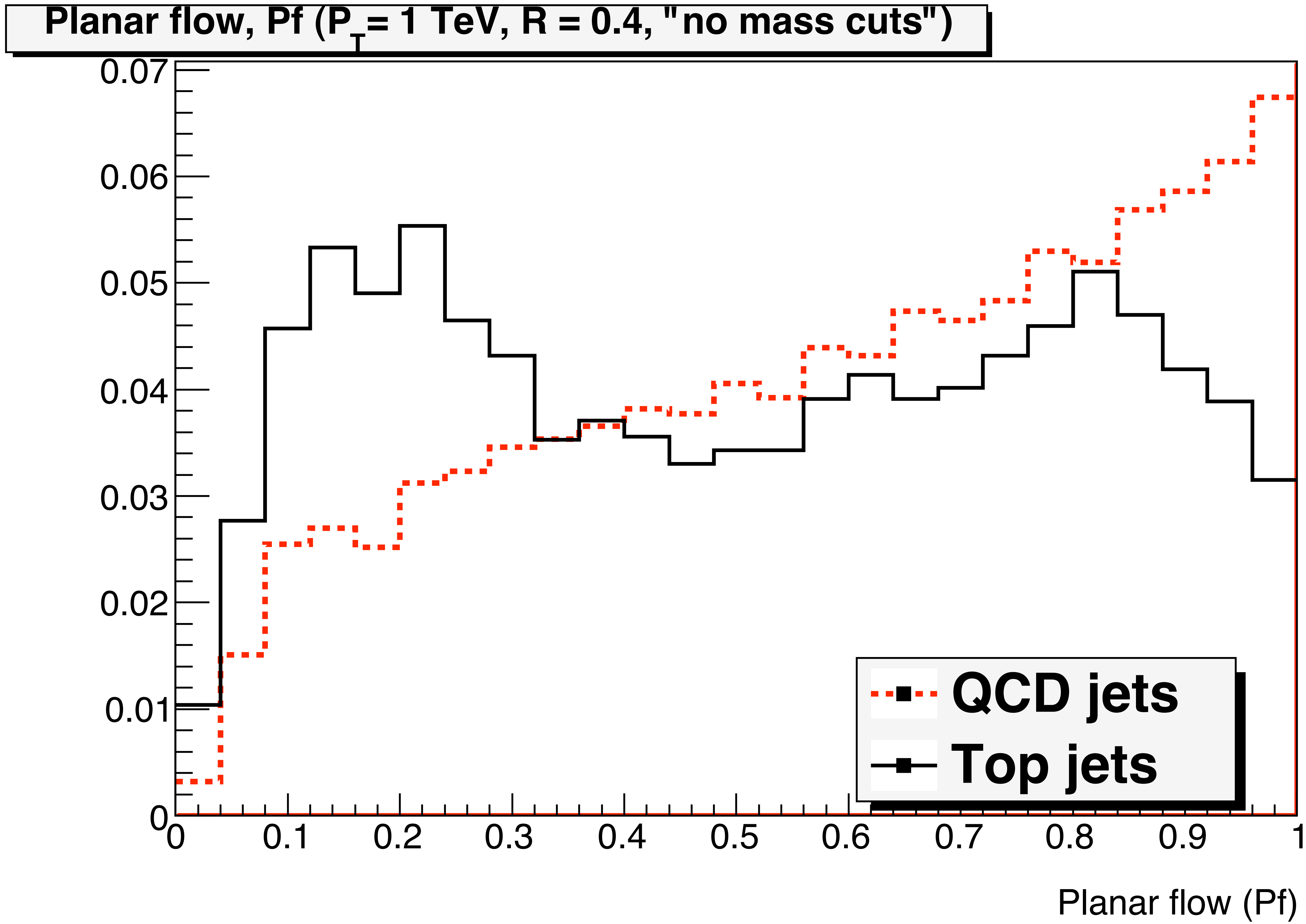

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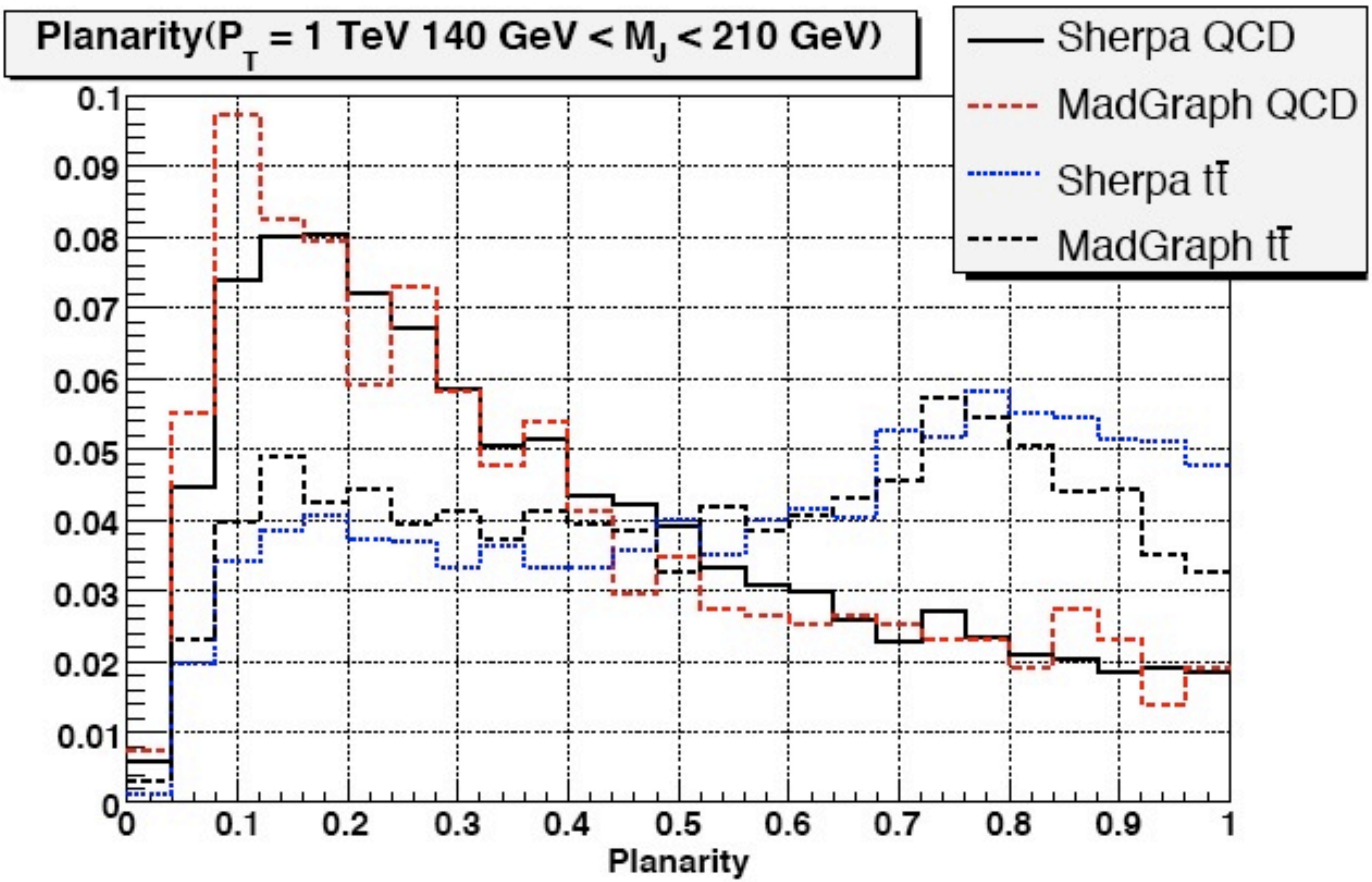
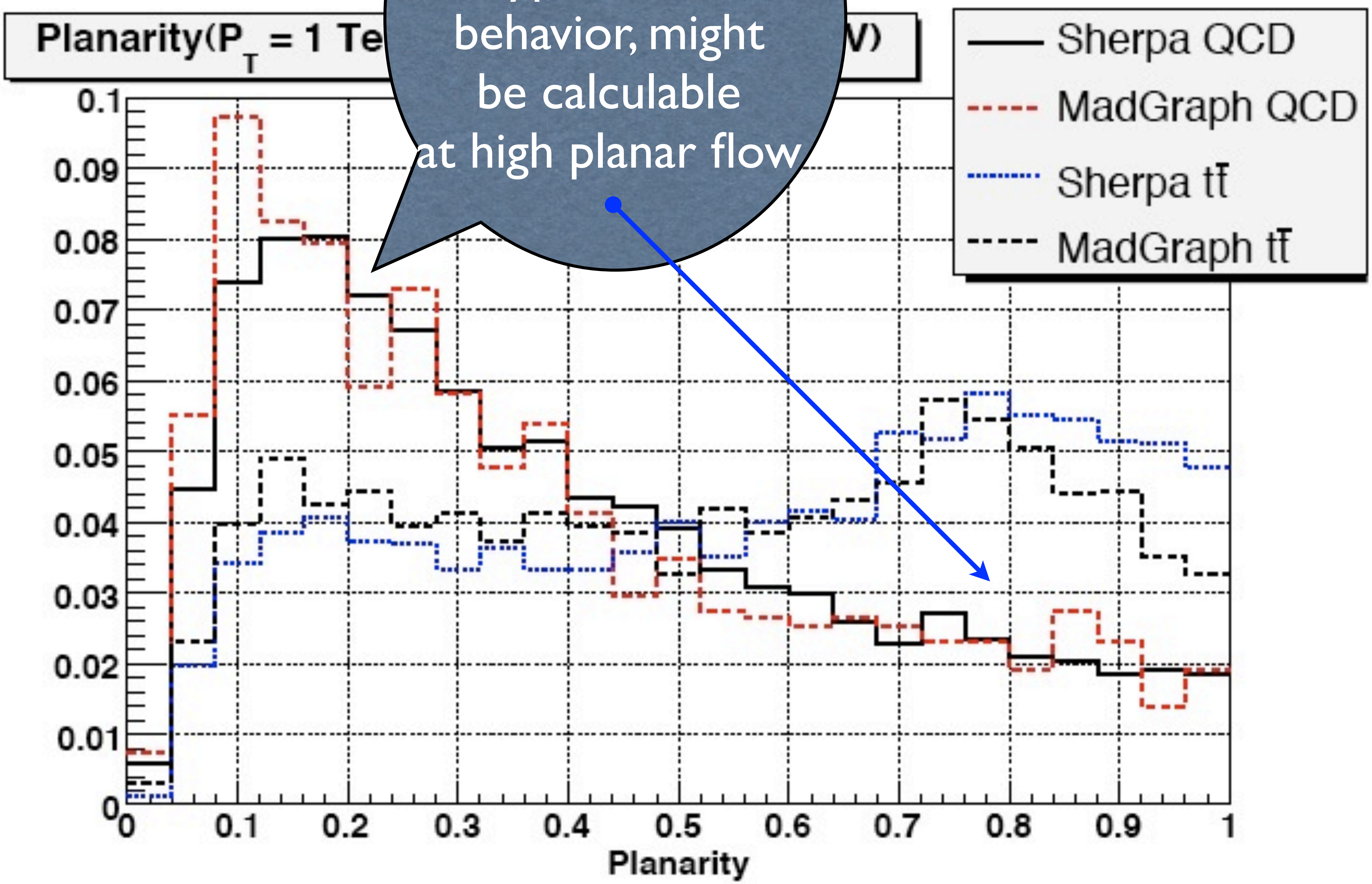


Planar flo CD vs top jets

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



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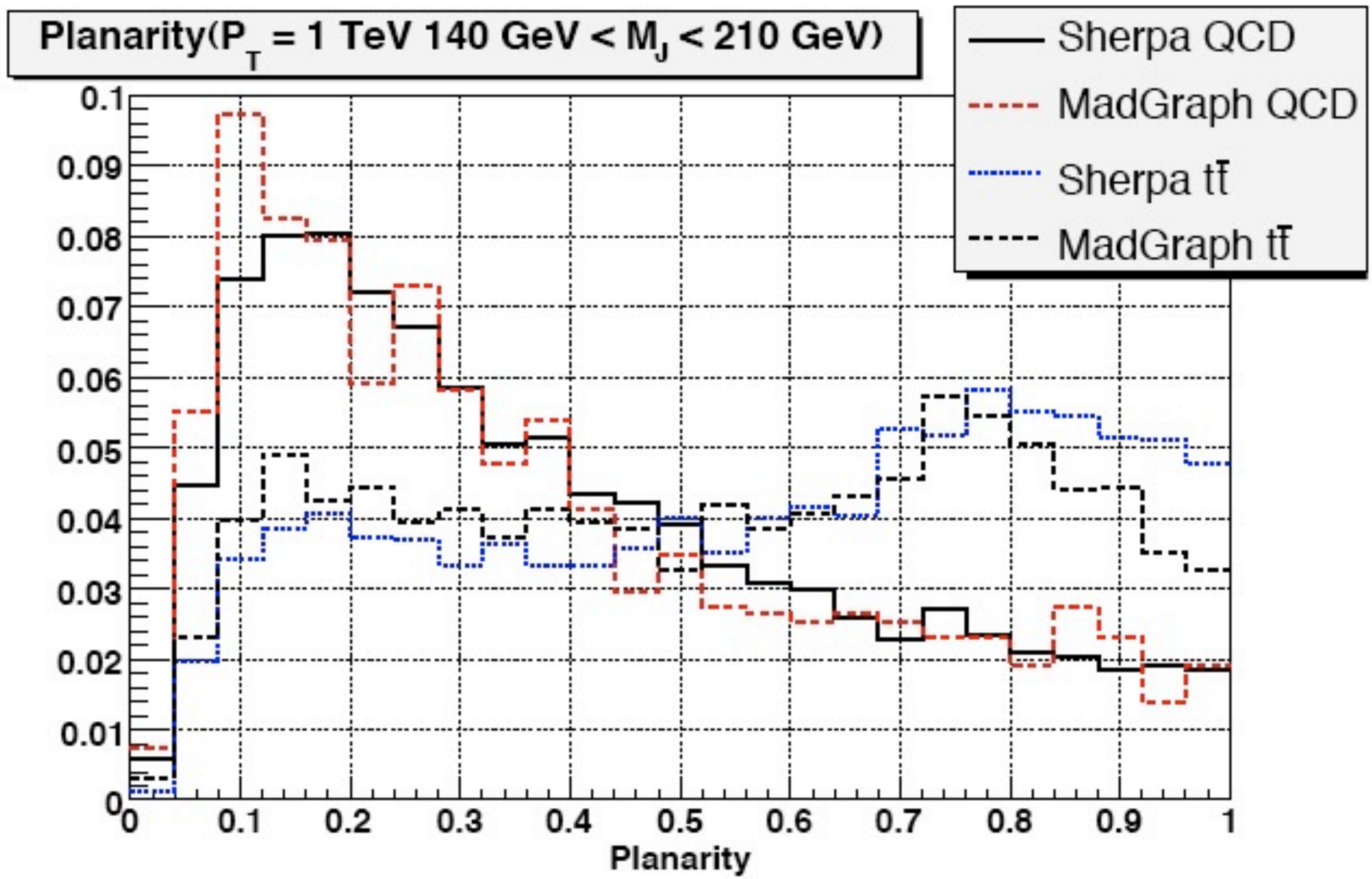

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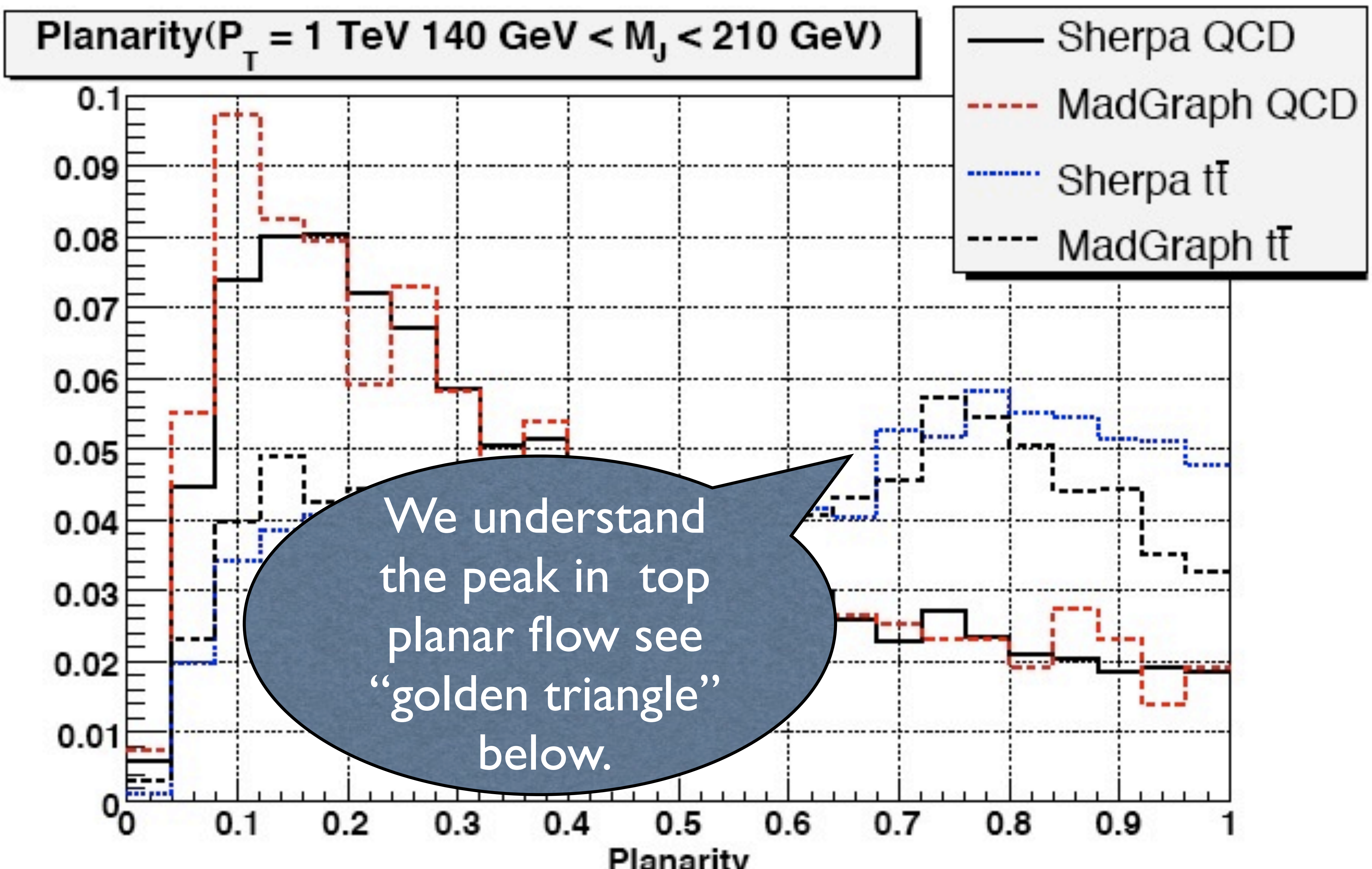


Boosted massive jets @ CDF

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

The data to be looked at

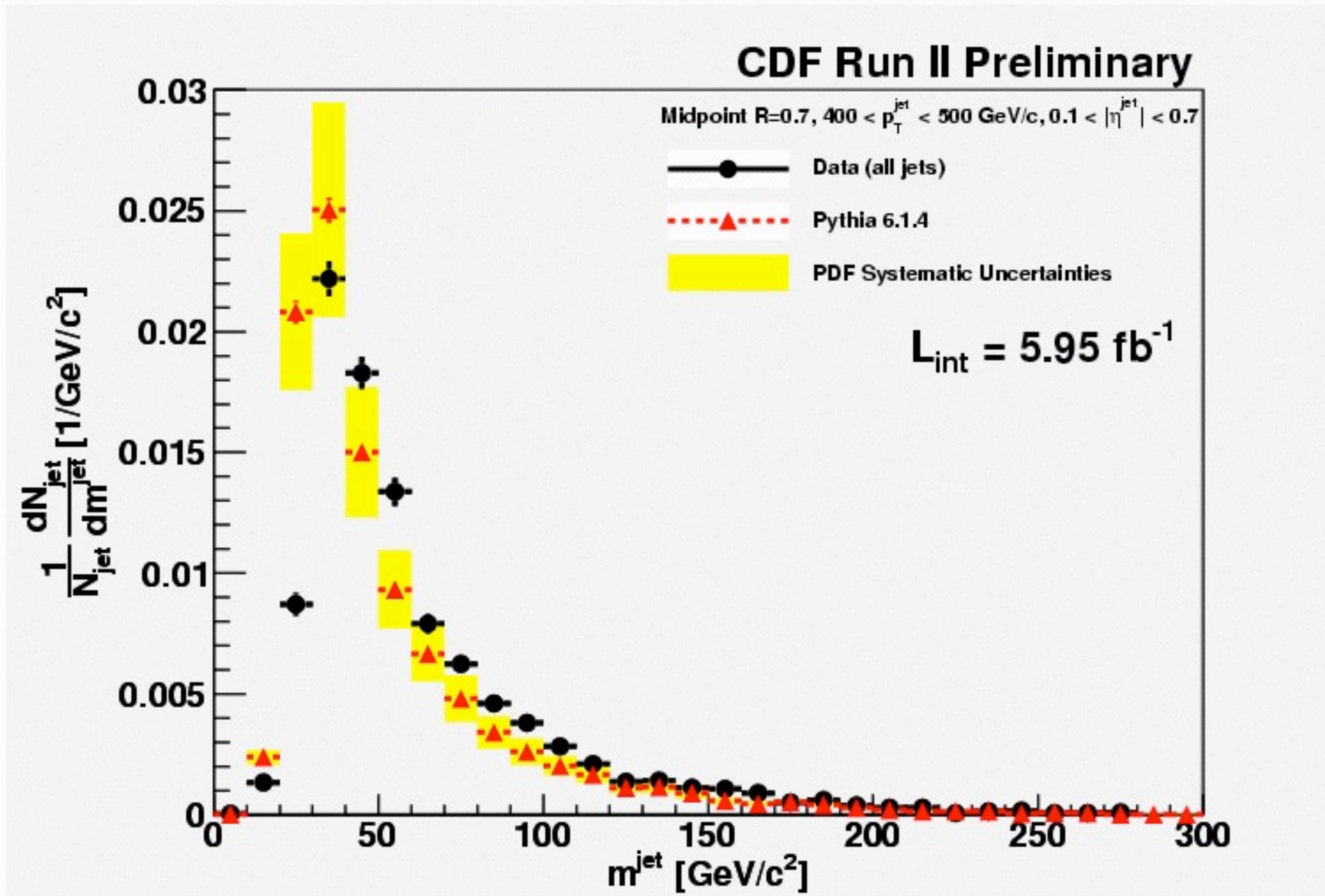
CDF Preliminary

Cut Flow		
All Data, 5.95 fb^{-1}	75,764,270 events	
	R = 0.4	**R = 0.7**
At least one jet with $p_T > 400$ GeV/c, $0.1 < \|\eta\| < 0.7$, and event quality cuts	3136 events	3621 events
$m^{jet2} < 100$ GeV/c^2 and $S_{MET} < 4$ (with $p_T^{jet2} > 100$ GeV/c and MI corrections)	2579 events	2576 events

CDF Preliminary

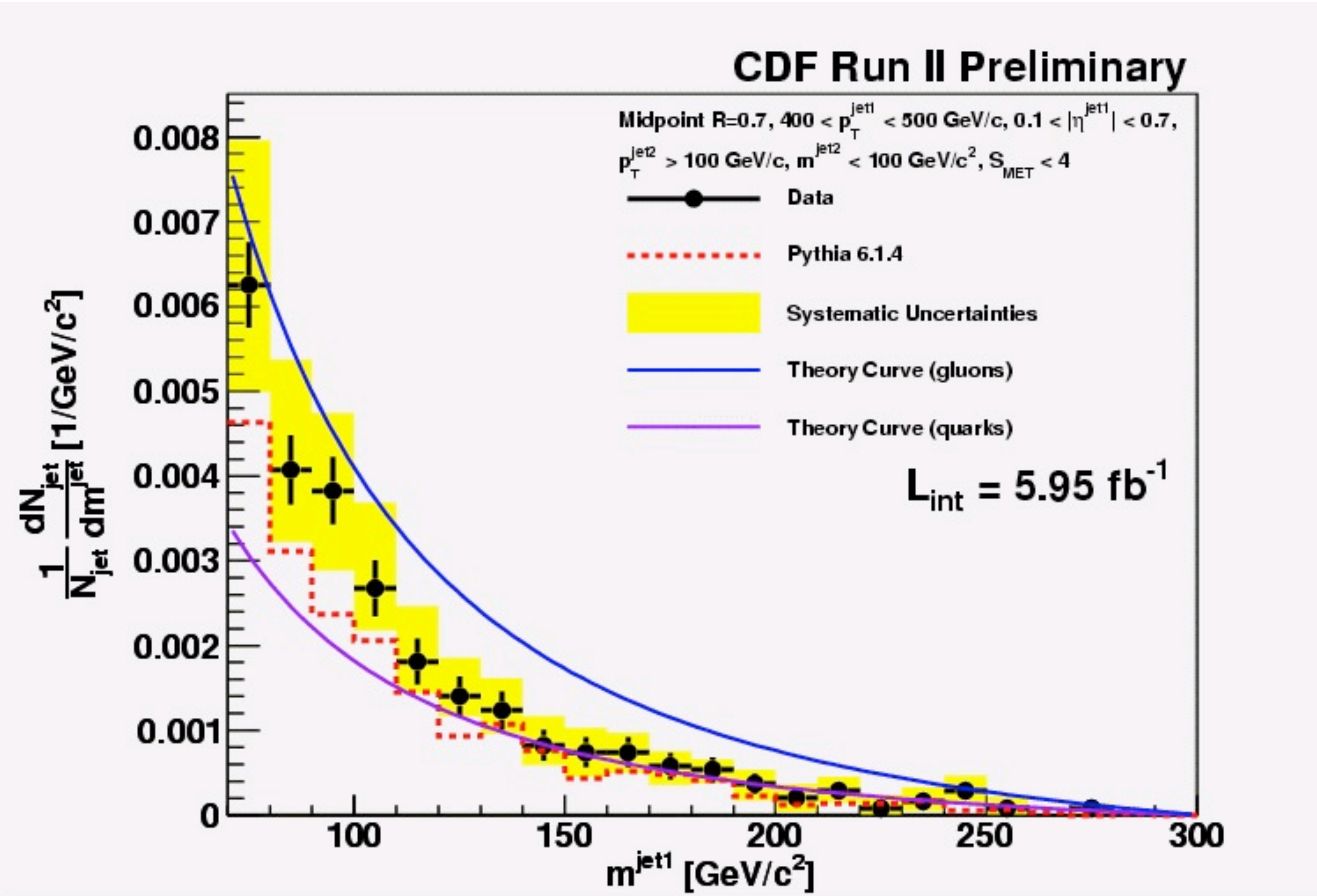
Events with at least one jet within p_T interval and $0.1 < \|\eta\| < 0.7$ and passing top rejection cuts		
p_T interval (GeV/c)	**R = 0.4**	**R = 0.7**
$400 < p_T < 500$	2428 events	2431 events
$p_T > 500$	151 events	145 events

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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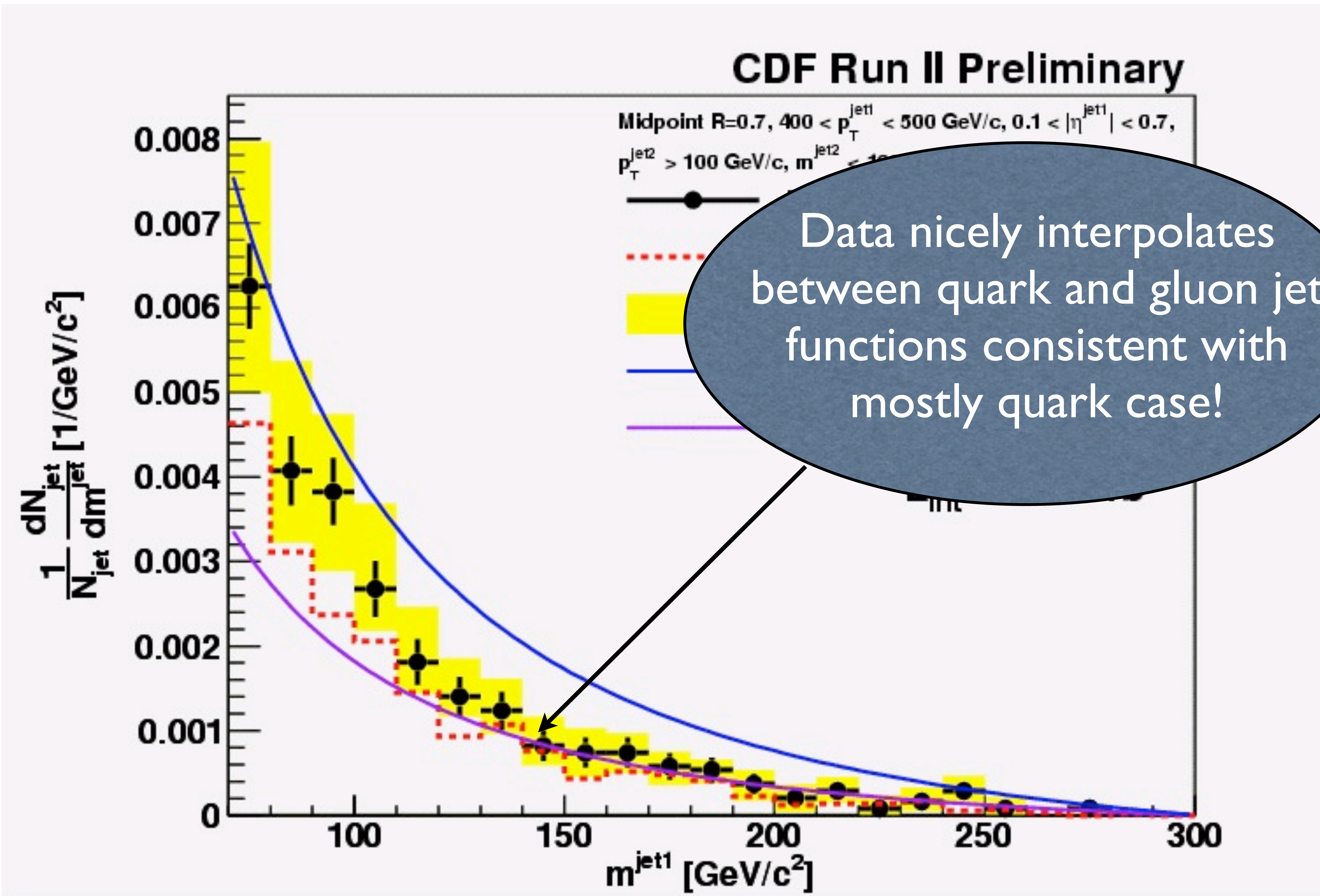
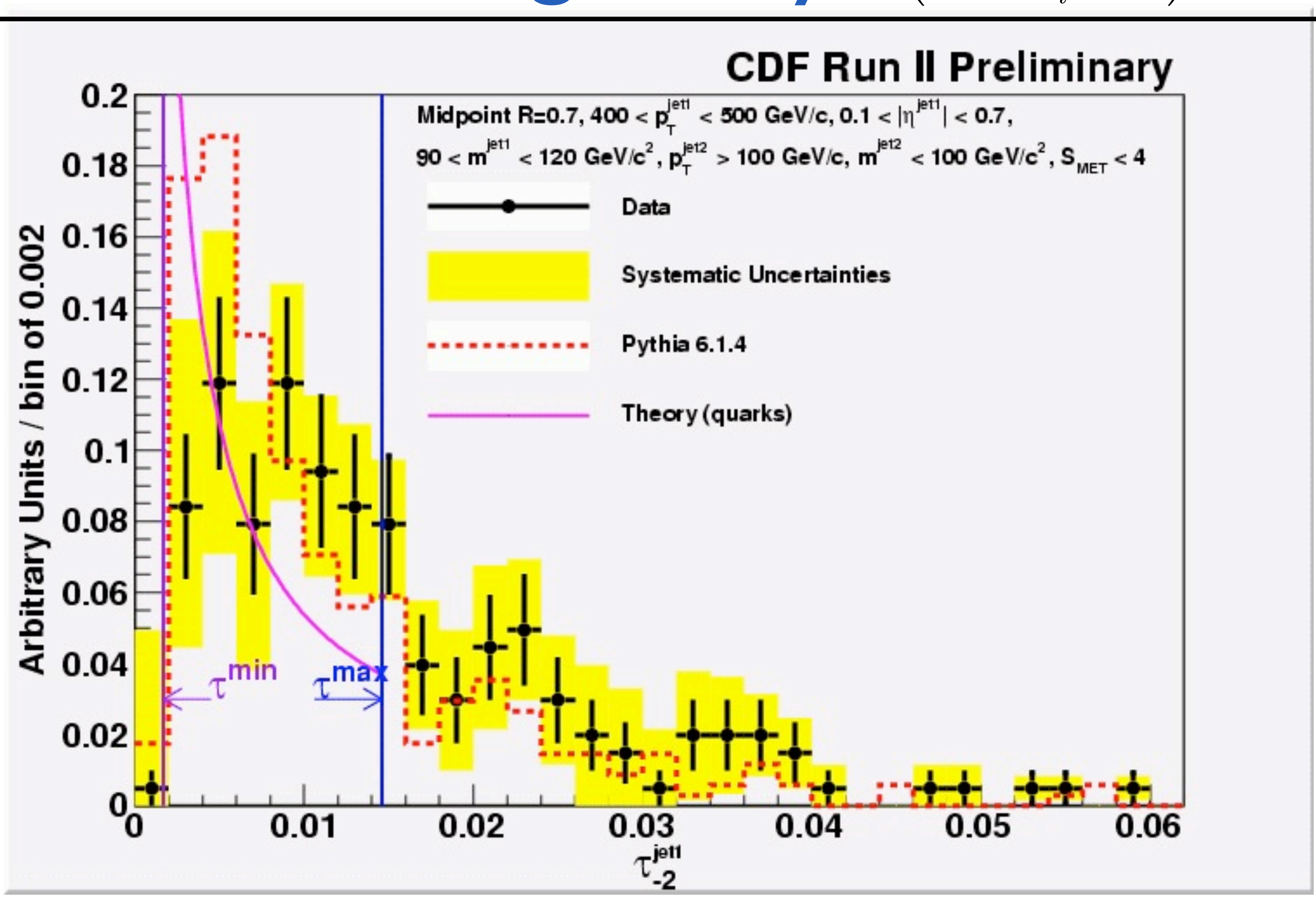


Angularity $\left(\propto_{a=-2} \sum_i \omega_i \theta_i^4\right)$



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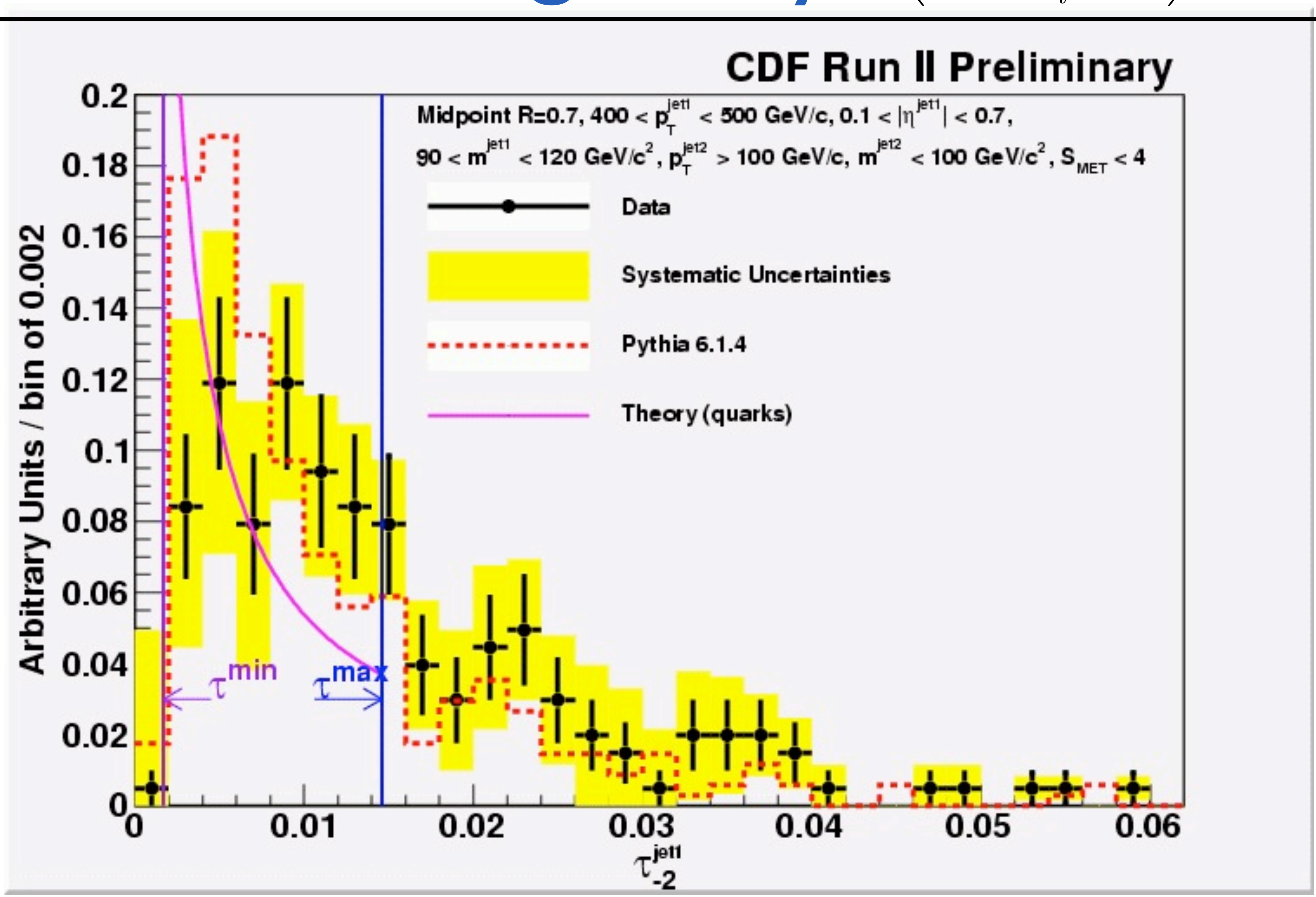

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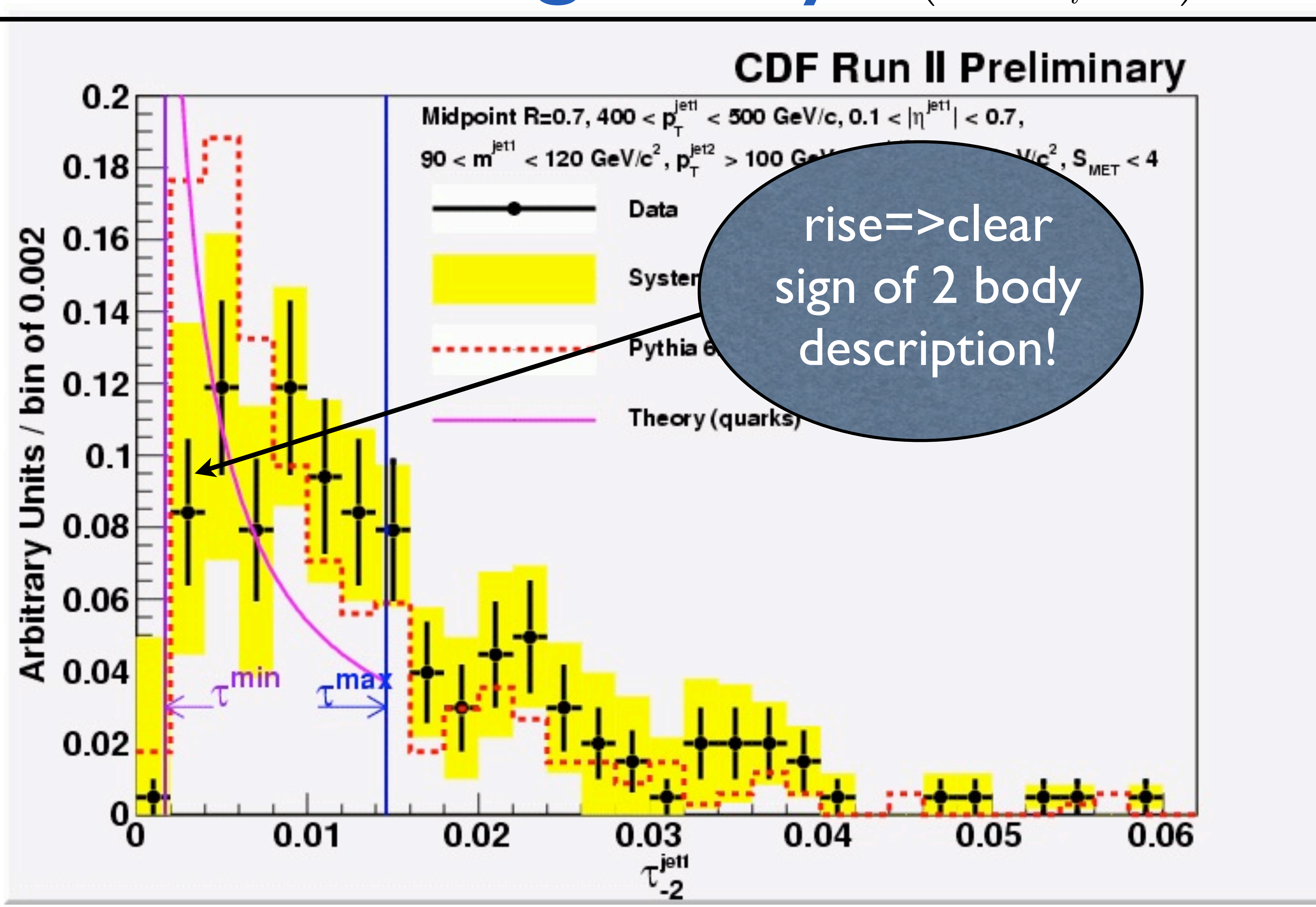

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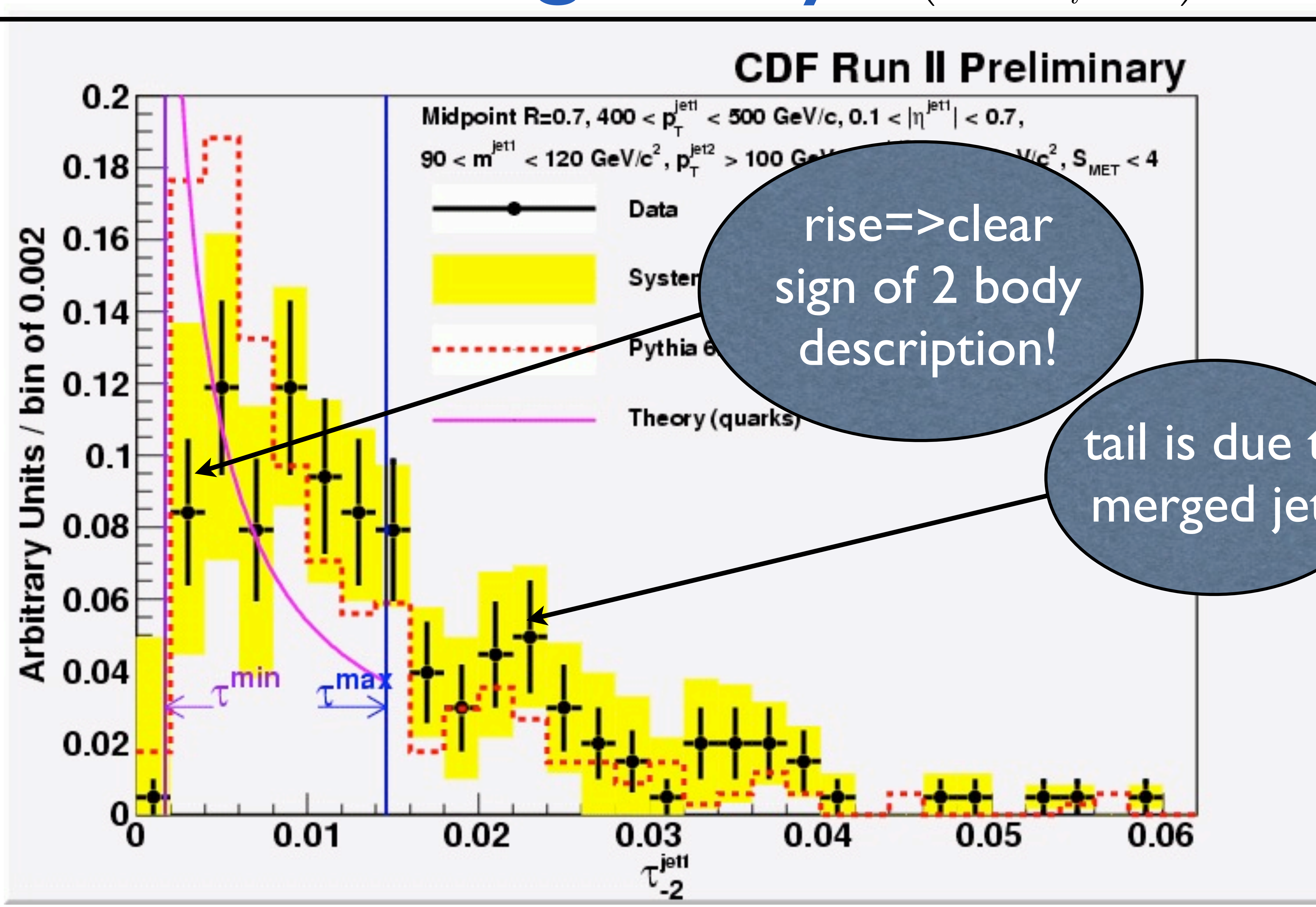

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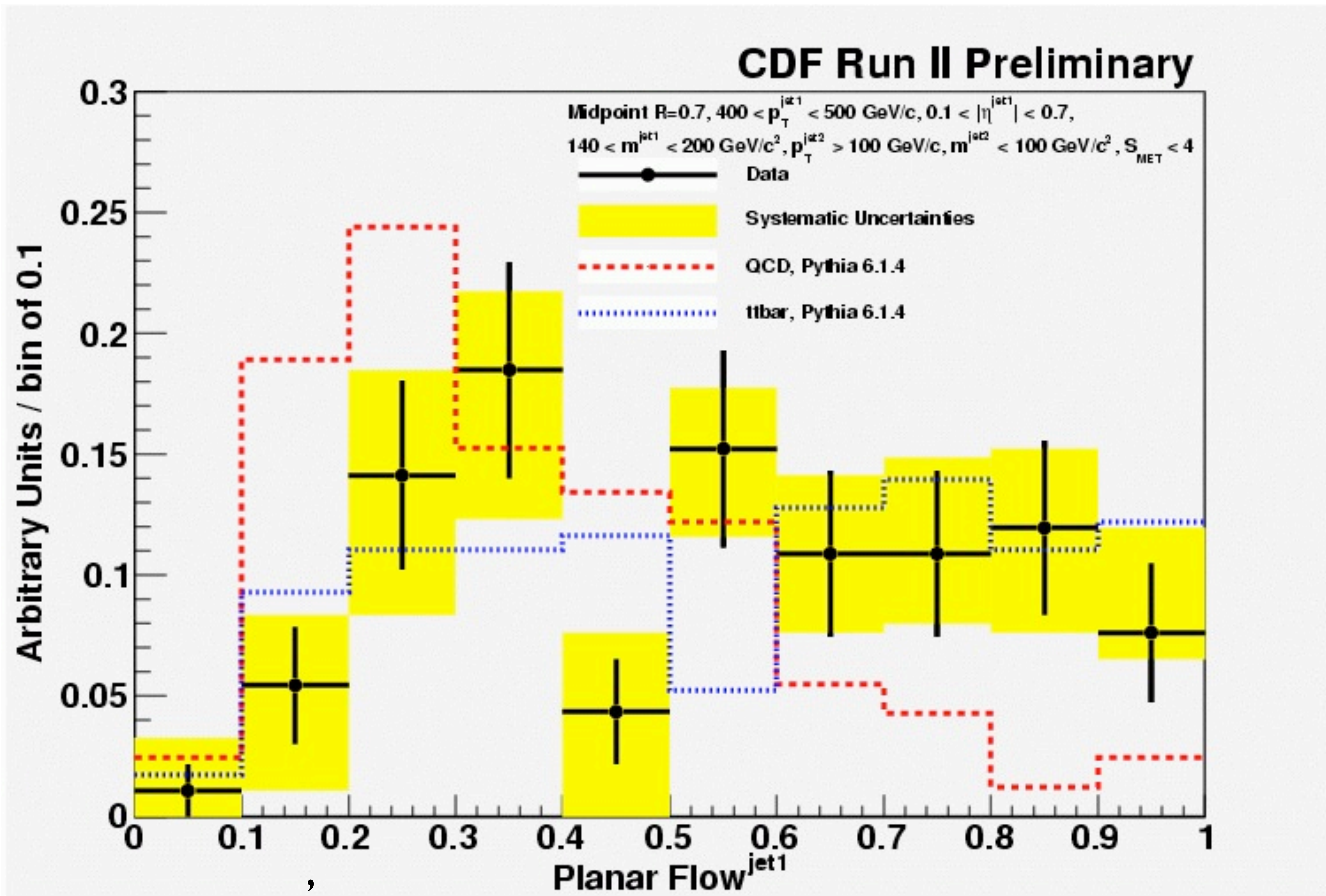
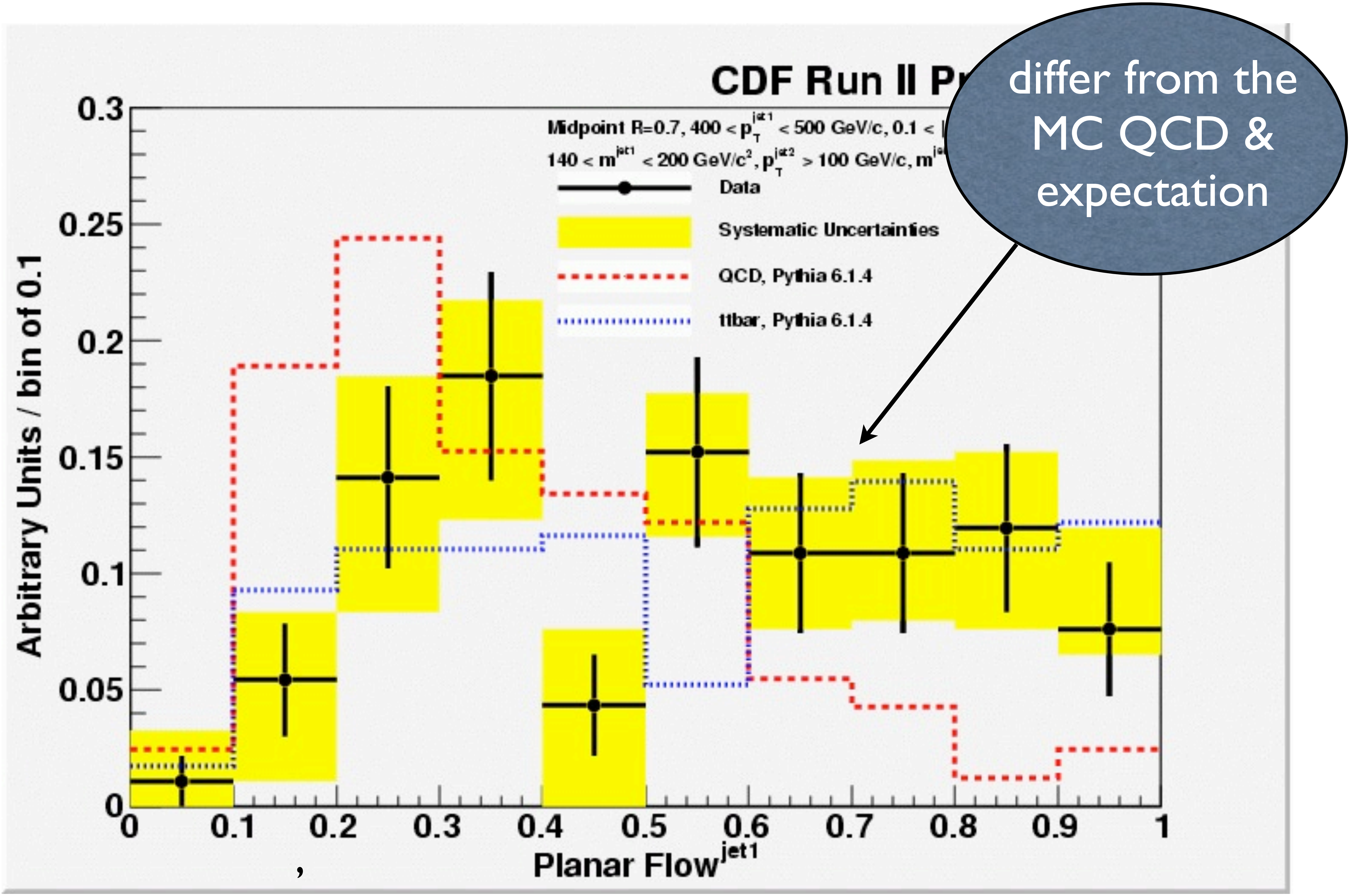
Planar flow


CDF Run II Preliminary
Midpoint R=0.7, $400 < p_T^{jet1} < 500$ GeV/c, $0.1 < |\eta^{jet1}| < 0.7$,
$140 < m^{jet1} < 200$ GeV/c^2, $p_T^{jet2} > 100$ GeV/c, $m^{jet2} < 100$ GeV/c^2, $S_{MET} < 4$
Data
Systematic Uncertainties
QCD, Pythia 6.1.4
ttbar, Pythia 6.1.4
Arbitrary Units / bin of 0.1
Planar Flow^{jet1}
0
0.05
0.1
0.15
0.2
0.25
0.3
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Planar flow


CDF Run II Pr
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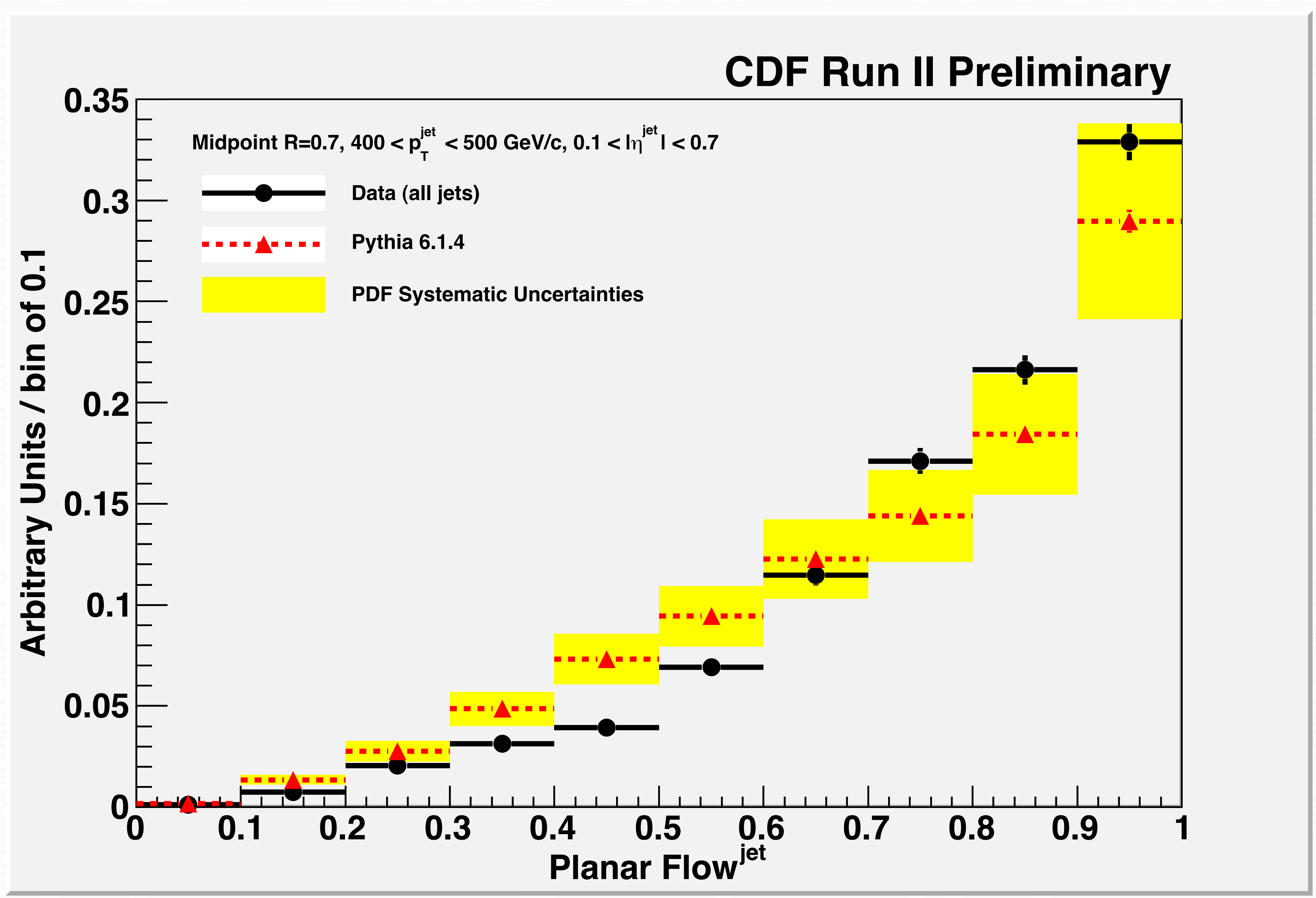
140 < m^{jet1} < 200 GeV/c^2, p_T^{jet2} > 100 GeV/c, m
Data
Systematic Uncertainties
QCD, Pythia 6.1.4
ttbar, Pythia 6.1.4
Arbitrary Units / bin of 0.1
Planar Flow^{jet1}
differ from the MC QCD & expectation

Planar flow, no mass cut



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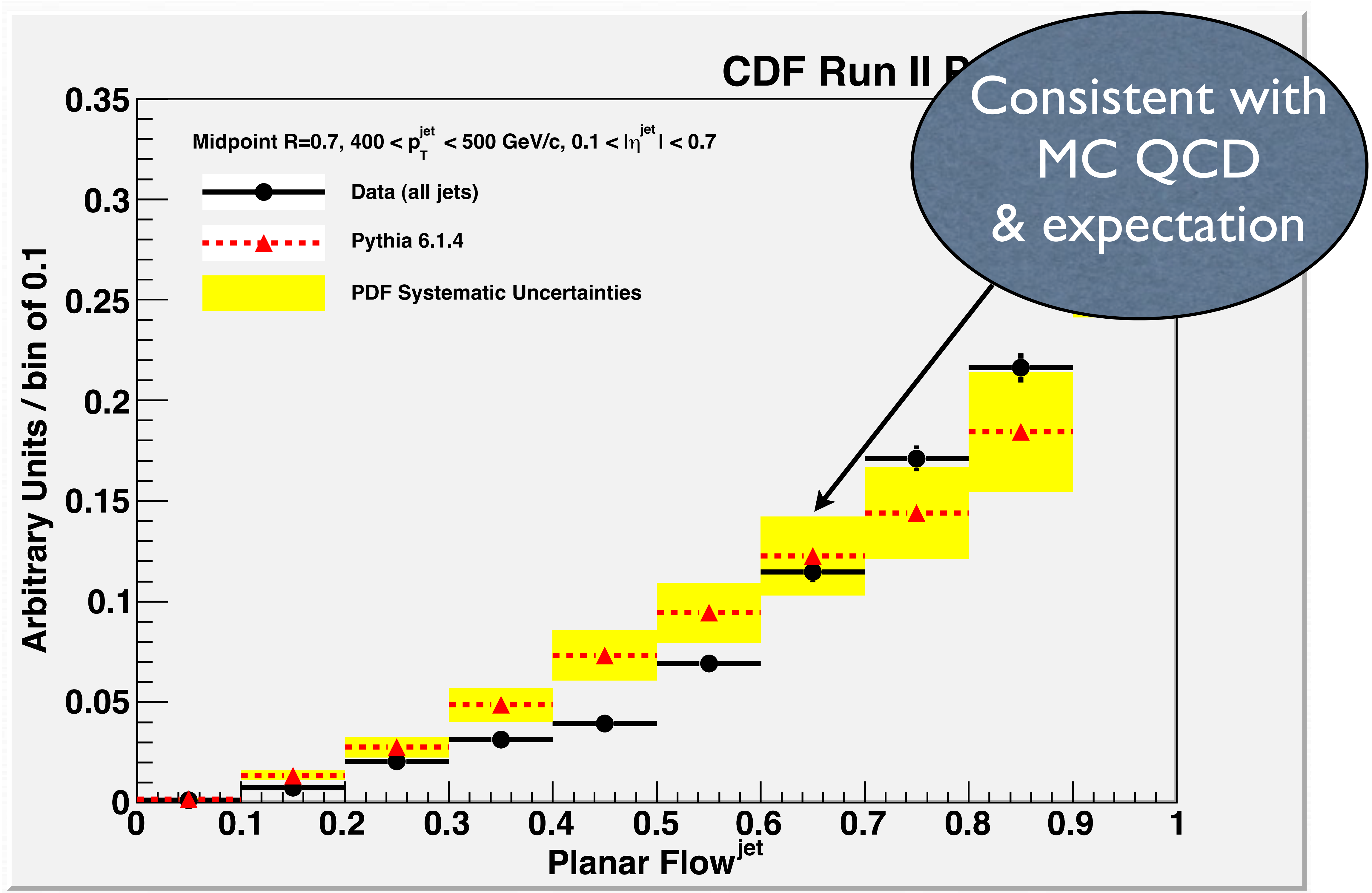

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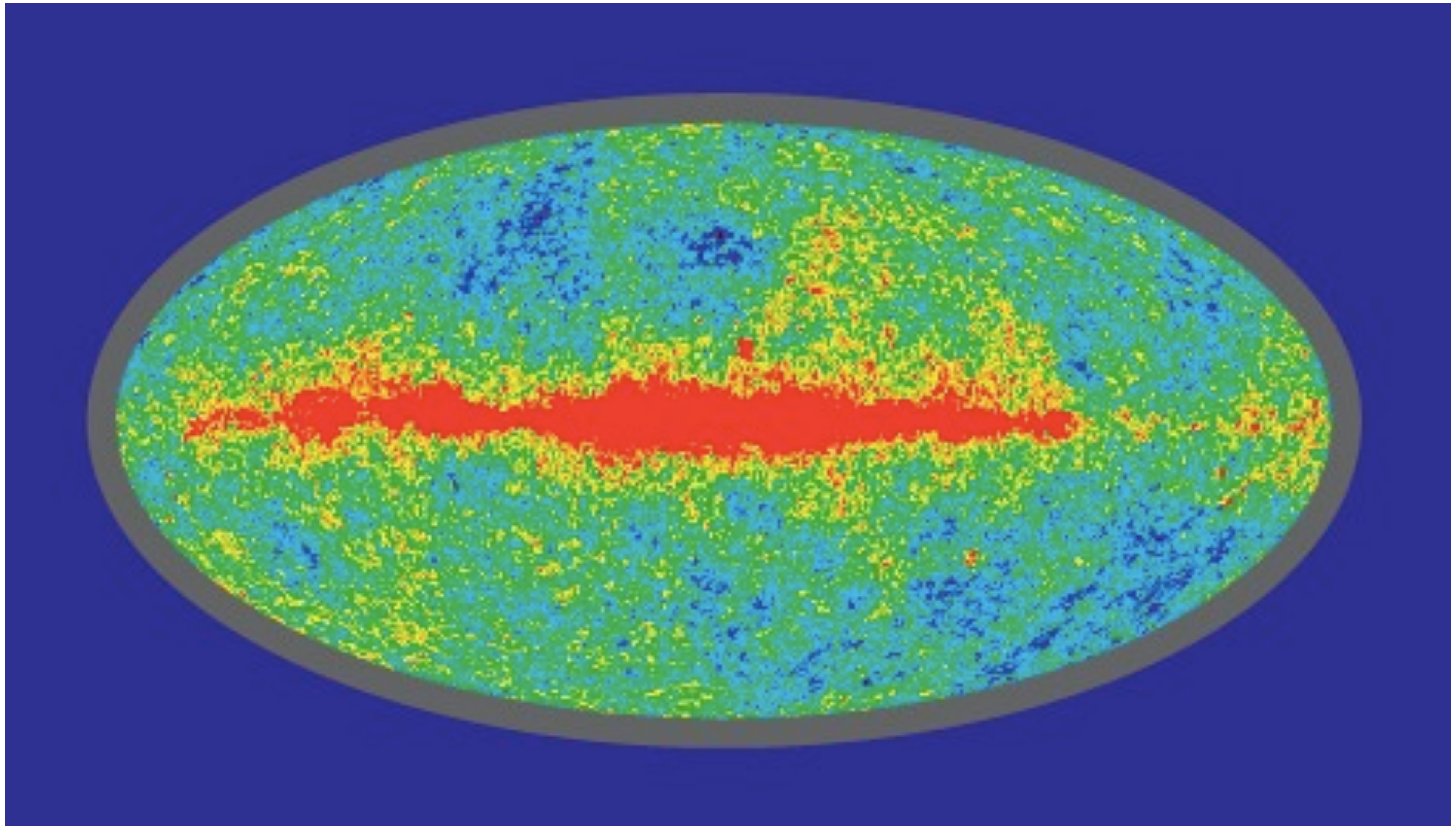
Template Method



Template Overlap Method

- Pf / angularity are 2 variables in a multi-body kinematical-variable phase-space => info' is lost.

- Can we be more systematic in our approach?

Fixing jet mass & pT @ LO in PQCD:
single parameter for 2-pronged decay;
four (5 without W mass) parameters for 3 pronged decay.

Template Overlap Method

♦ Template overlap: functional measure of how well jet-energy-flow matches flow of a certain template calculated from 1st principle (LO, partonic)

$$|t> \;=\; \text{top distribution}$$
$$|g> \;=\; \text{massless QCD distribution}$$

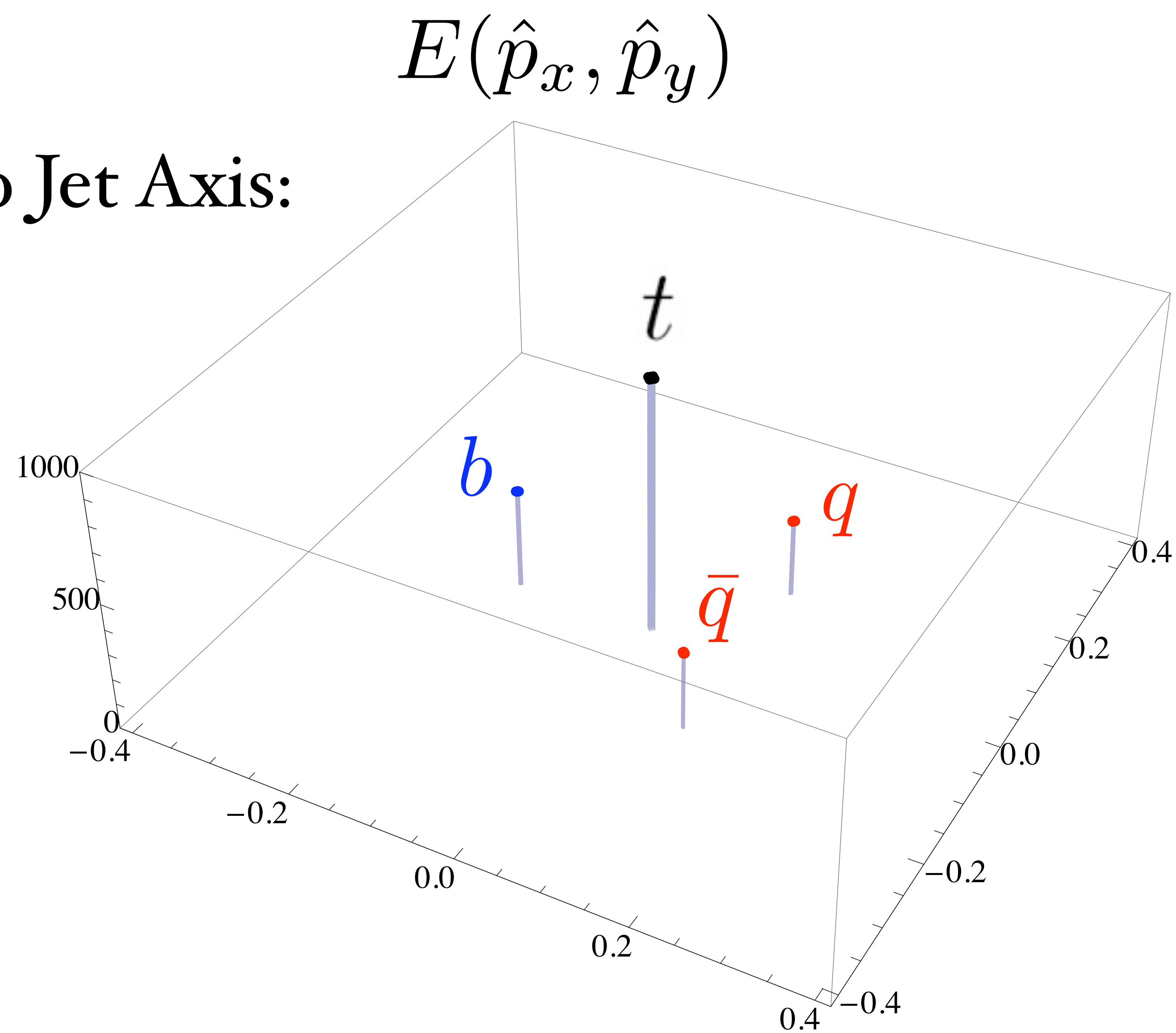
We need a probe distribution, $|f>$, such that

$$R = \left(\frac{<f|t>}{<f|g>}\right) \text{ is maximized.}$$

general overalp functional: $Ov(j,f) = \langle j|f\rangle = \mathcal{F}\left[\frac{dE(j)}{d\Omega}, \frac{dE(f)}{d\Omega}\right]$

Example, top jet: "Golden Triangle"

Plane $\perp$ to Jet Axis:



Template Overlap Method

- Any region of partonic phase space for the boosted decays, {f}, defines a template
- Ansatz: good (if not best) rejection power using signal distribution for templates
- Define "template overlap" as the maximum functional overlap of j to a state f[j]:

$$Ov(j, f) = \max_{\{f\}} \mathcal{F}(j, f)$$

- Can match arbitrary final states *j* to partonic partners *f[j]* at any given order in PQCD.

Constructing a functional

- A natural measure of the matching between state j and the template: weighted difference of their energy flows (employ a Gaussian)

$$Ov^{(F)}(j,f) = \max_{\tau_n^{(R)}} \exp\left[-\frac{1}{2\sigma_E^2} \left(\int d\Omega \left[\frac{dE(j)}{d\Omega} - \frac{dE(f)}{d\Omega} \right] F(\Omega, f) \right)^2 \right]$$

Alternatively, we may choose F to be a normalized step function around the directions of the template momenta p_i

for a given template, with direction of particle a, $\hat{n}_a$ & its energy $E^{(f)}_a$:

$$Ov(j, p_1 \ldots p_n) \;=\; \max_{\tau_n^{(R)}} \exp\left[-\sum_{a=1}^{n} \frac{1}{2\sigma_a^2} \left(\int d^2\hat{n}\, \frac{dE(j)}{d^2\hat{n}} \theta(\hat{n}, \hat{n}_a^{(f)}) - E_a^{(f)} \right)^2 \right]$$

for an n-particle final state

Three-particle Templates and Top Decay

- Construct template: three particle phase space

for top decay $t \to b + W \to b + q + \bar{q}$.

with $(p_q + p_{\bar{q}})^2 = M_W^2$

4 d.o.f.: most straightforward method by 4 angles:

1)polar and azimuthal angles that define b and W directions in the top rest frame

2)polar and azimuthal angles that define q and qbar directions relative to the boost axis from the W rest frame

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Lorentz transformations => 4 angles identified determine the energies and directions of the three decay products of the top at LO

Three-particle Templates and Top Decay

- jet mass window 160 GeV $< m_J <$ 190 GeV,

cone size R = 0.5 (D = 0.5 for anti-kT jet),
jet energy 950 GeV $< E_J <$ 1050 GeV.

- Template Overlap with data discretization

$$Ov(j,f) = \max_{\tau_n^{(R)}} \exp\left[-\sum_{a=1}^{3}\frac{1}{2\sigma_a^2}\left(\sum_{k=i_a-1}^{i_a+1}\sum_{l=j_a-1}^{j_a+1} E(k,l) - E(i_a,j_a)^{(f)}\right)^2\right]$$

$$\sigma_a = E(i_a,j_a)^{(f)}/2 \,.$$

Ov with top-jet @ partonic level

Proof of principle, nearly a perfect match

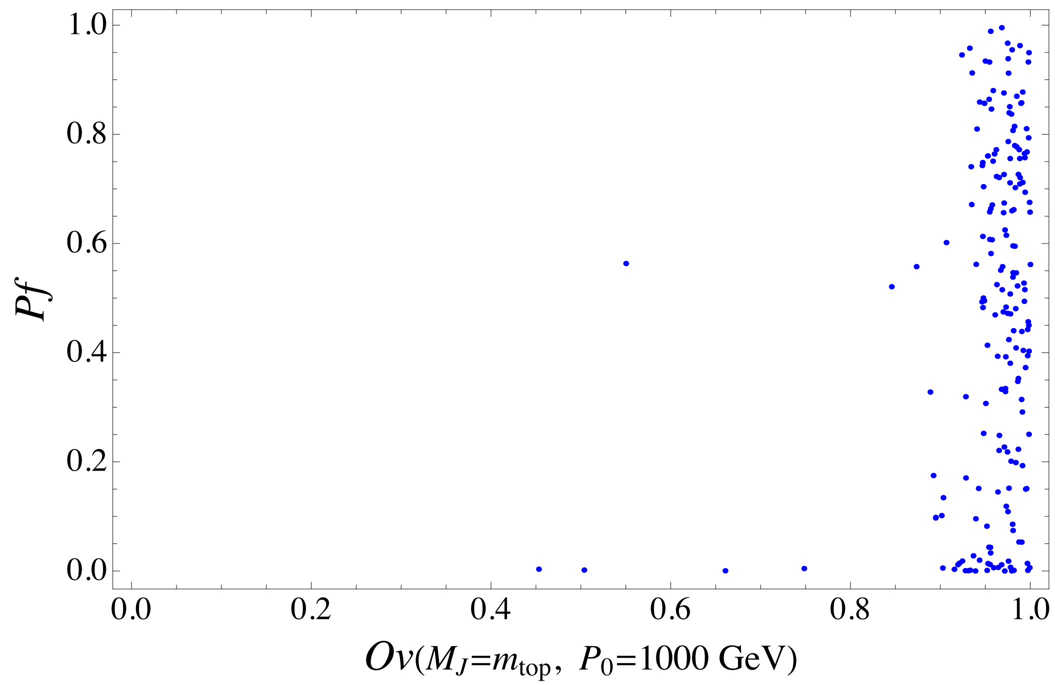
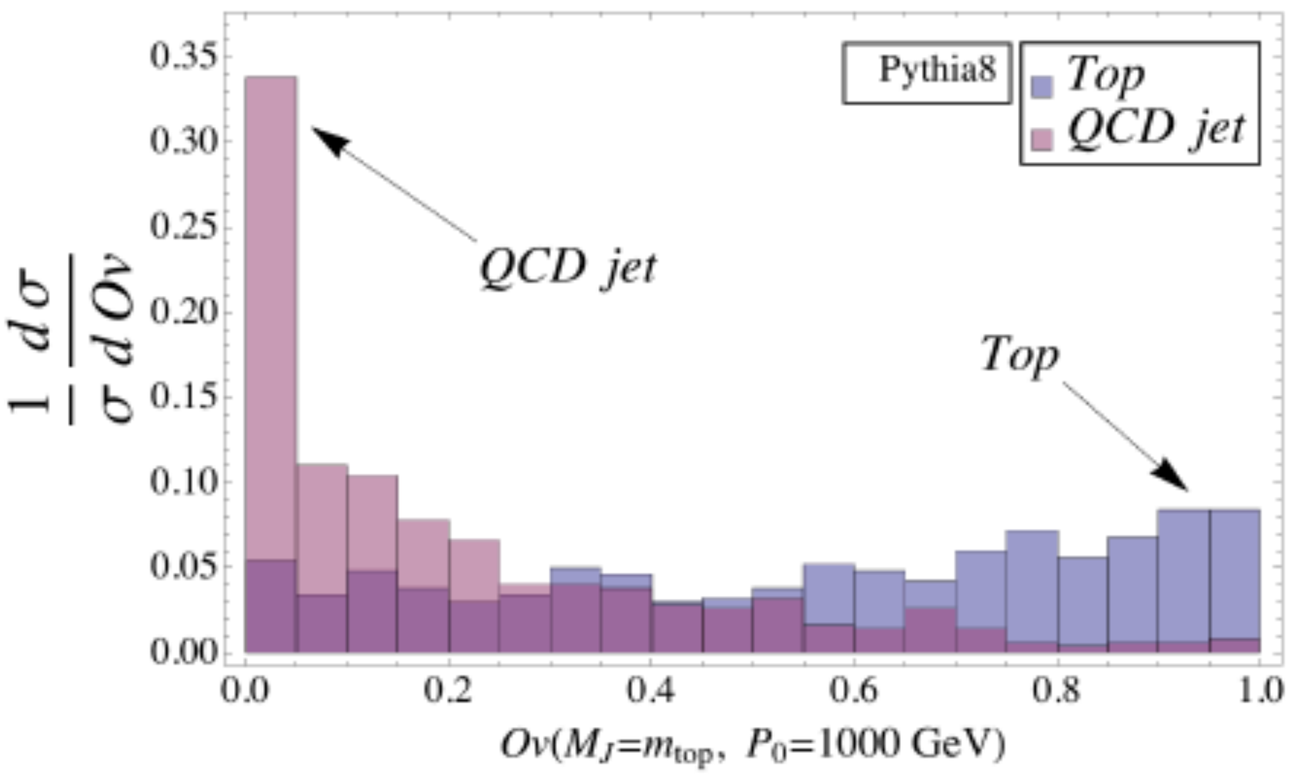
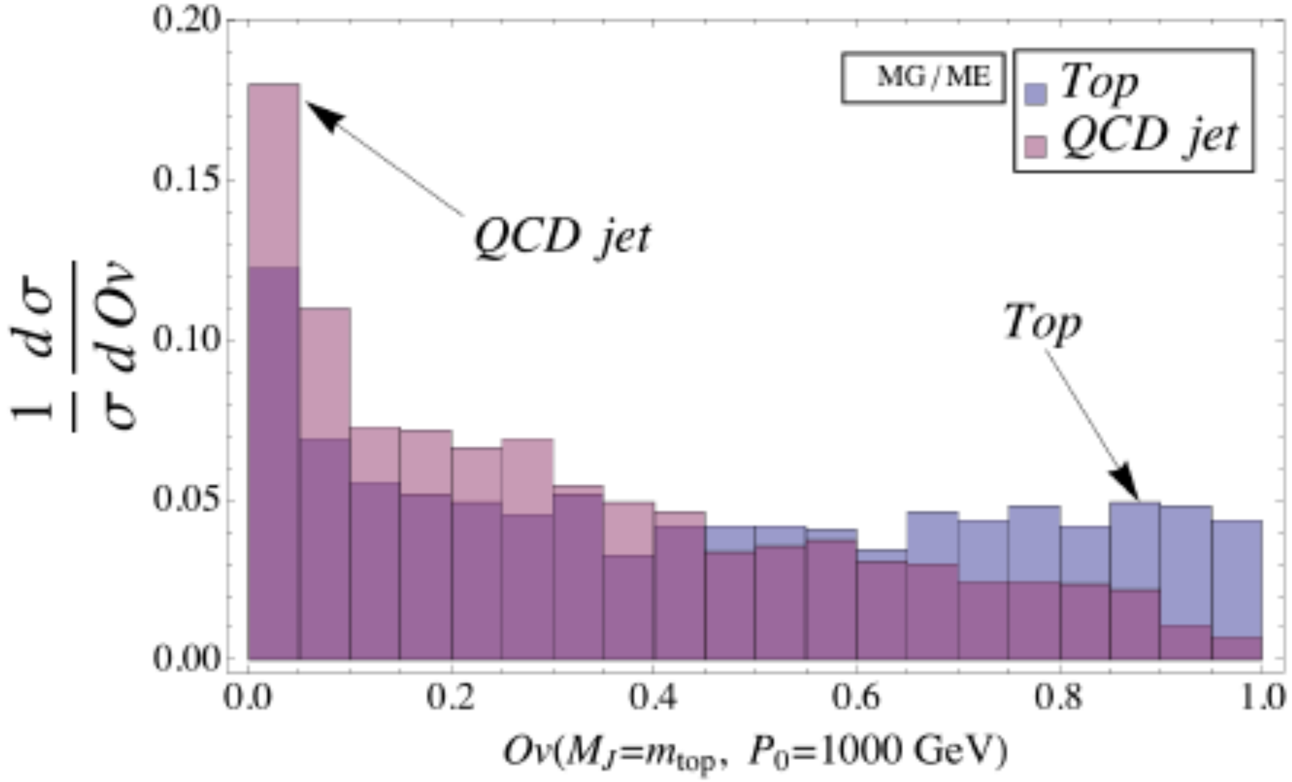
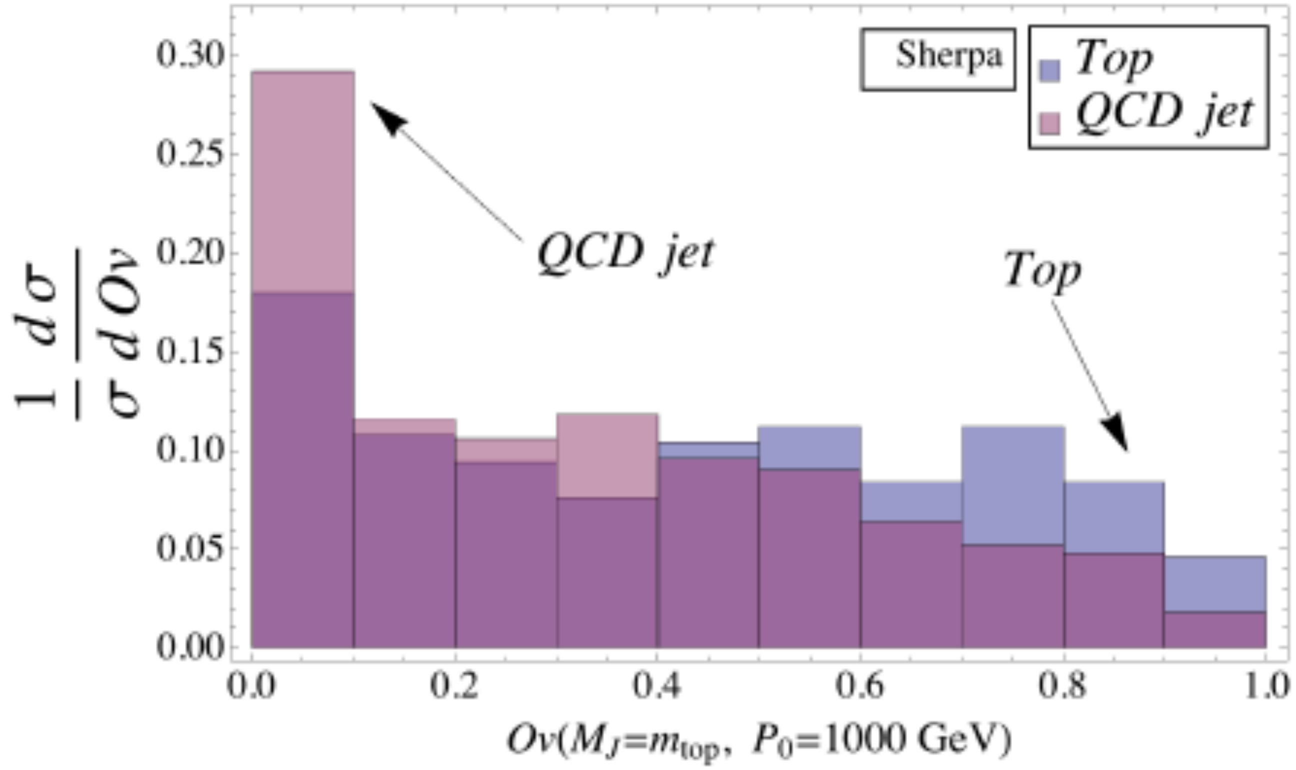


Figure 2: A scatter plot of template overlap, Eq. (6) and Pf for LO parton-level MC output for top quark decay, with $P_0 = 1$ TeV, $m_{top} = 174$ GeV.

Three-particle Templates @ Jet Level
(after showering, hadronization etc.)





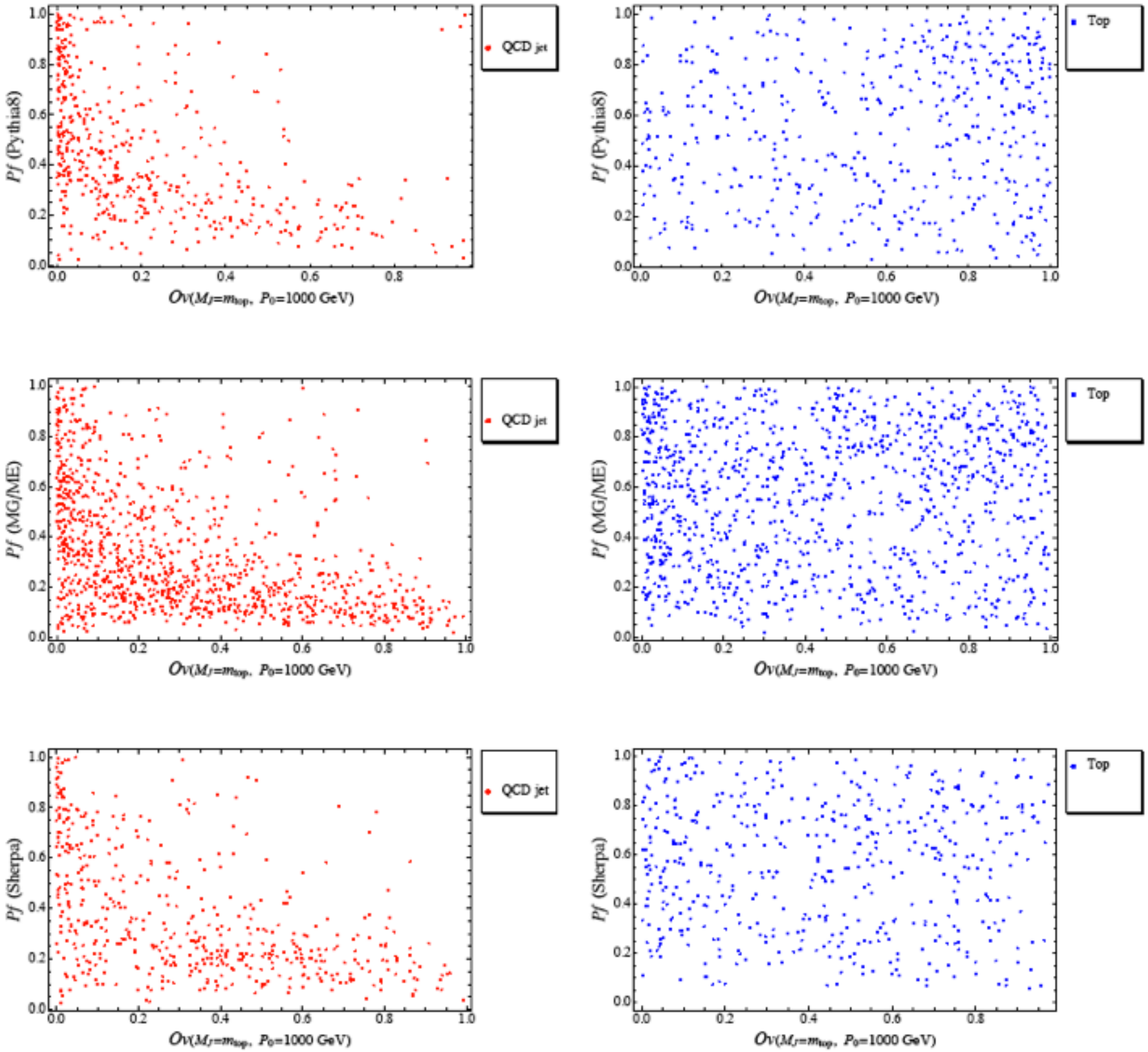


Three-particle Templates and Top Decay

- Combine with Planar flow- distinguish between “3-prong” events with large template overlaps.

- QCD jets with large *Ov* tend to have smaller planar flow than top decay events.

Three-particle Templates and Top Decay



Three-particle Templates and Top Decay

MC	Jet mass cut only		Mass cut + Ov + Pf	
	Top-jet efficiency [%]	fake rate [%]	Top-jet efficiency [%]	fake rate [%]
Pythia8	58	3.6	21	0.022
MG/ME	52	3.7	11	0.017
Sherpa	34	3.2	7	0.032

Table 1: Efficiencies and fake rates for jets with $R = 0.5$ (using anti-k_T: $D = 0.5$), 950 GeV$\leq P_0 \leq$1050 GeV, 160 GeV$\leq m_J \leq$190 GeV and $m_{top} = 174$ GeV. The left pair of columns shows efficiencies and fake rates found by imposing the jet mass window only. The right pair takes into account the effects of cuts in Ov and Pf in addition to the mass window. For the different MC simulations, we have imposed various cuts on Ov and Pf variables: for Pythia8 $Ov \geq 0.6$ and $Pf \geq 0.4$, for MG/ME $Ov \geq 0.7$ and $Pf \geq 0.39$ and for Sherpa $Ov \geq 0.6$ and $Pf \geq 0.48$.

Three-particle Templates and Top Decay

MC	Jet mass cut only		Mass cut + Ov + Pf	
	Top-jet efficiency [%]		Top-jet efficiency [%]	fake rate [%]
Pyth				0.022
MG/M				0.017
Sherpa				0.032

Table 1: .5), 950
GeV≤ pair of
column y. The
right pa window.
For the ariables:
for Pythia8 for Sherpa
$Ov \geq 0.6$ and

Rejection Power:
Pythia: 1 in 1000
MadGraph: 1 in 600
Sherpa: 1in 200

without optimization!

Three-particle Templates and Top Decay

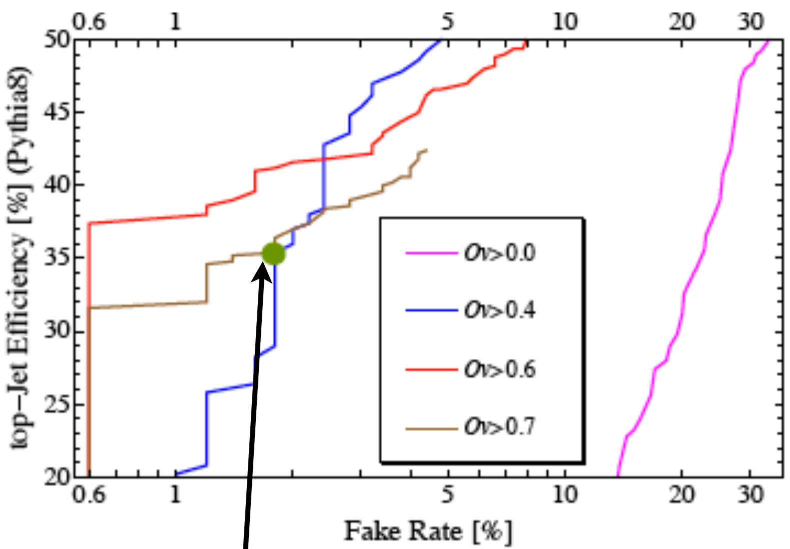
- Template method among highest rejection powers.

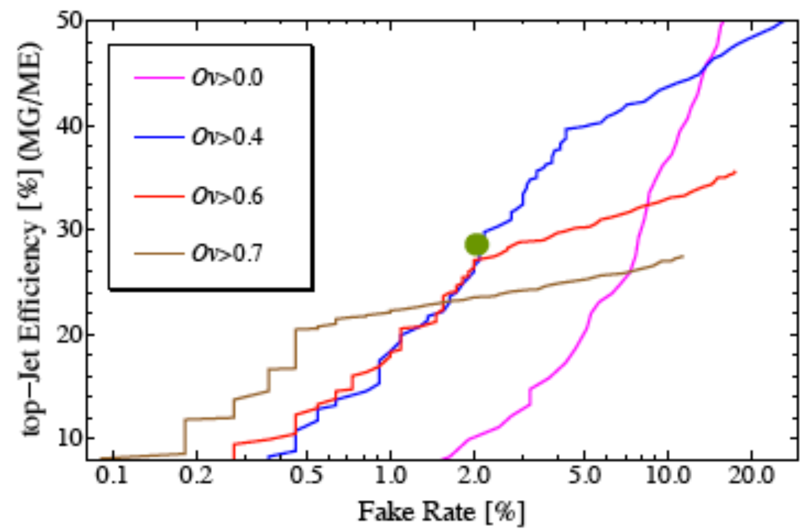
Three-particle Templates and Top Decay

- Template method among highest rejection powers.

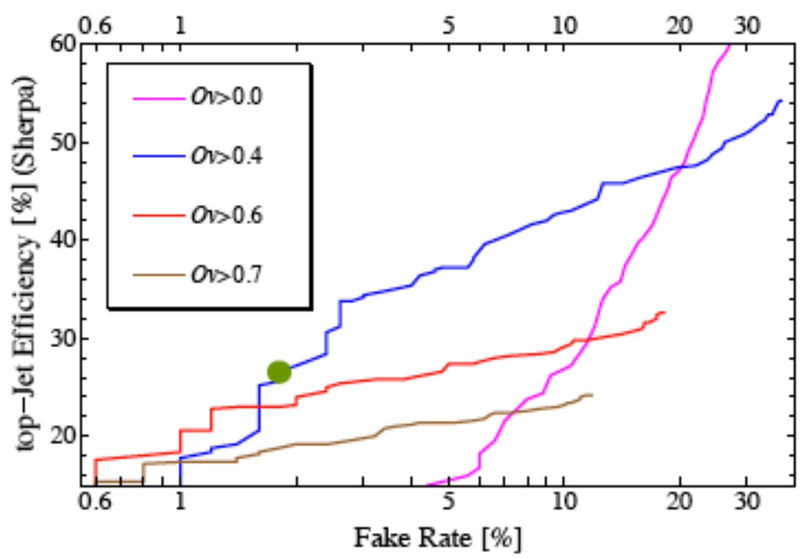
- Method theoretically defined, while no strong dependence on jet-reconstruction & no manipulation of soft radiation is made!

Three-particle Templates and Top Decay





$Pf > 0.6$ and $Ov > 0.4$



different generators yield different energy flow patterns.

caution regarding interpretation of tests for all methods; especially those that rely heavily on the anticipated structure of soft radiation in final states

Three-particle Templates and Top Decay

- Template method allows for systematic improvement:
  e.g. by incorporating the effect of gluon emission in the template, or by weighting phase space by squared matrix elements.

Three-particle Templates and Top Decay

- Template method allows for systematic improvement:
e.g. by incorporating the effect of gluon emission in the template, or by weighting phase space by squared matrix elements.

- Can also optimize the cut for getting higher rejection power

Two-particle Templates and Higgs Decay

- Construct template: two particle phase space for top decay $|f\rangle = |h\rangle^{(\mathrm{LO})} = |p_1, p_2\rangle$
- Higgs: at fixed $z = m_J/P_0 << 1$, Θ_s distribution is peaked around Θ_s in its minimum value

=> decays "democratic" (sharing energy evenly)

$$\frac{dJ^h}{d\theta_s} \propto \frac{1}{\theta_s^3}$$

- lowest-order QCD events is also peaked, but much less so $$\frac{dJ^{\mathrm{QCD}}}{d\theta_s} \propto \frac{1}{\theta_s}$$

Two-particle Templates and Higgs Decay

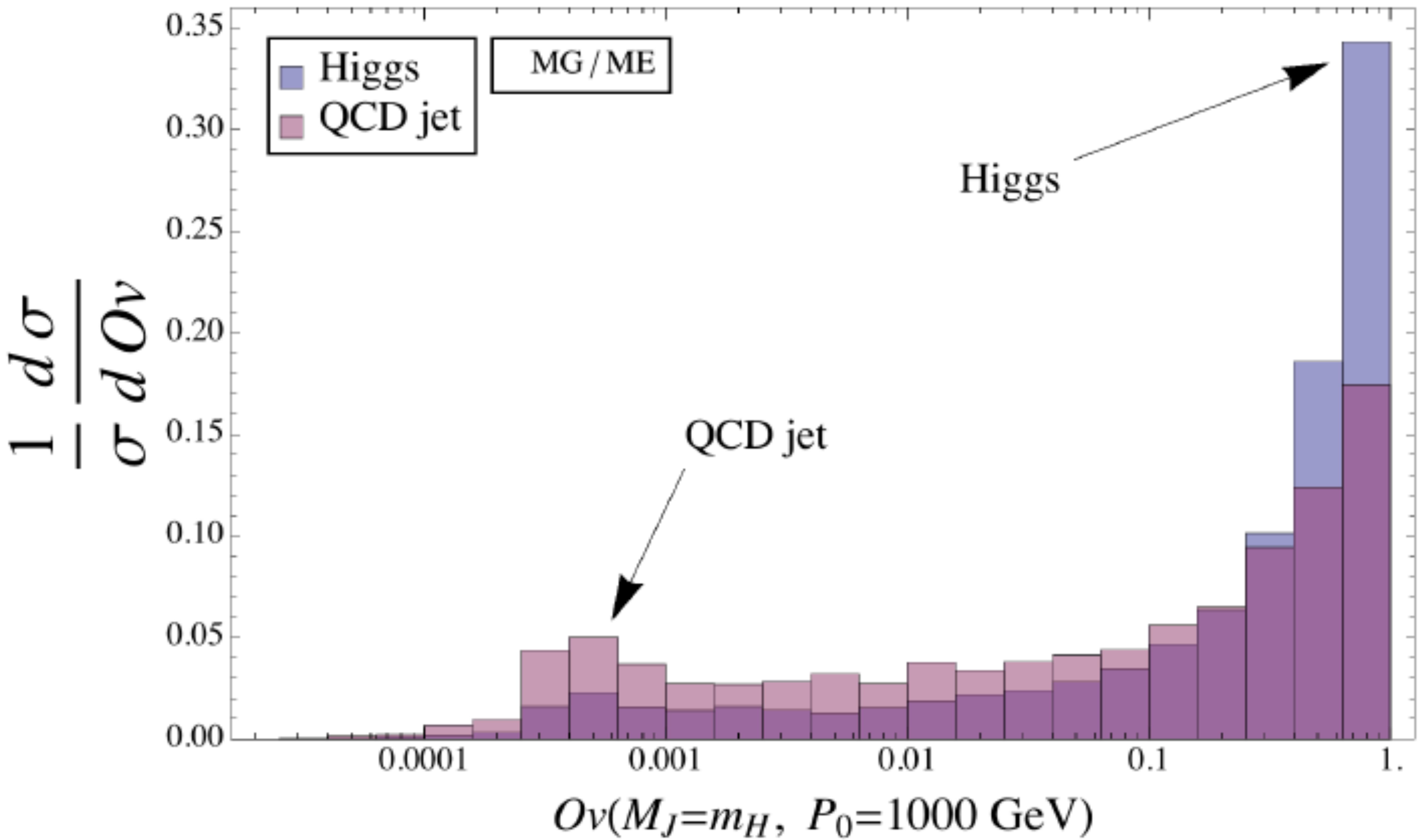
- jet mass window 110 GeV < m_J <130 GeV,

cone size R = 0.4 (D = 0.4 for anti-kT jet),
jet energy 950 GeV < E_J < 1050 GeV.

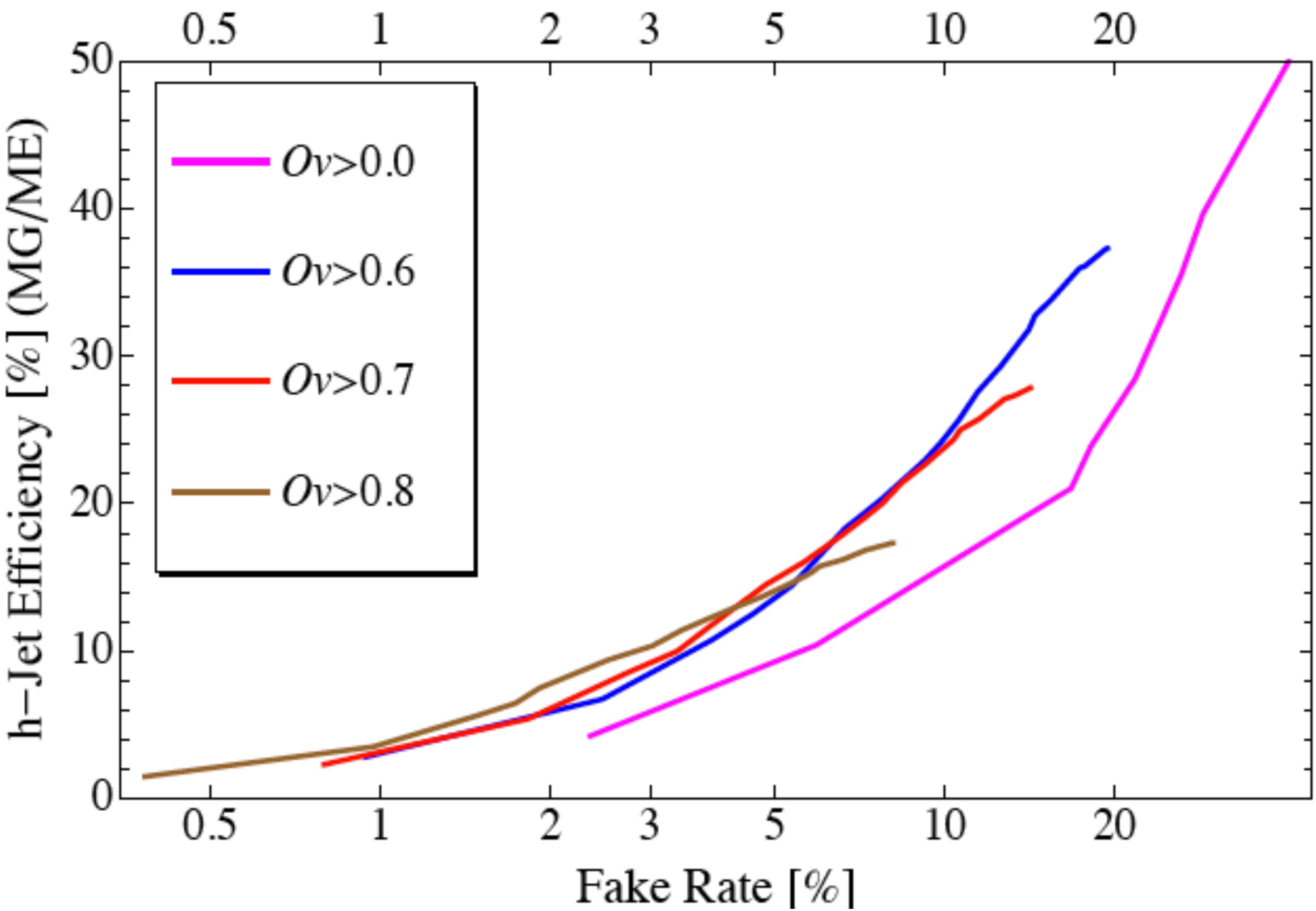
- Template Overlap with data discretization

$$Ov(j,f) = \max_{\tau_n^{(R)}} \exp\left[- \sum_{a=1}^{2} \frac{1}{2\sigma_a^2} \left(\sum_{k=i_a-1}^{i_a+1} \sum_{l=j_a-1}^{j_a+1} E(k,l) - E(i_a,j_a)^{(f)} \right)^2 \right]$$

Two-particle Templates and Higgs Decay



Two-particle Templates and Higgs Decay



Two-particle Templates and Higgs Decay

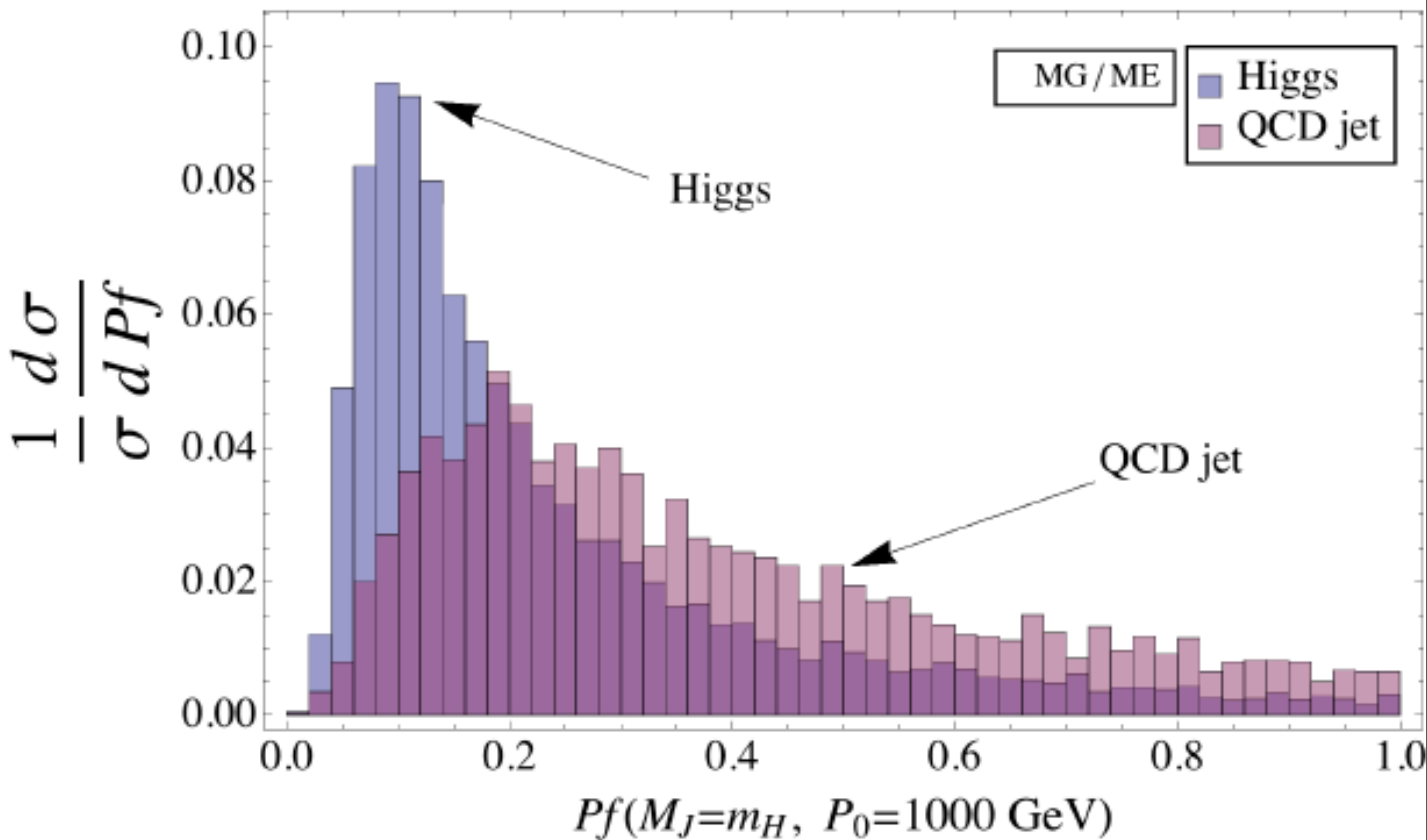
- The templates can be systematically improved by including the effects of gluon emissions, which contain color flow information

Two-particle Templates and Higgs Decay

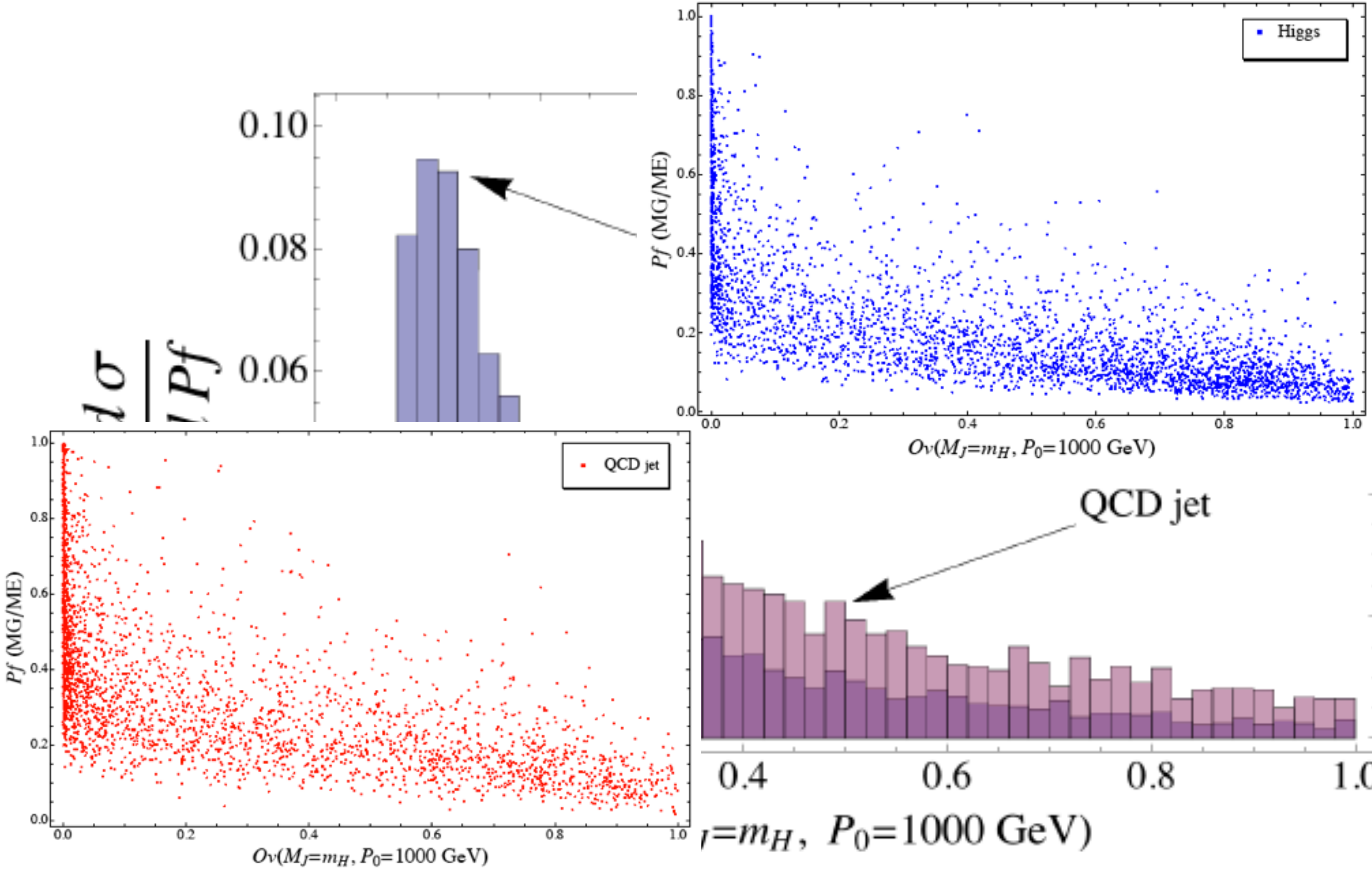
- The templates can be systematically improved by including the effects of gluon emissions, which contain color flow information
- The effects of higher-order effects can be partly captured by using Planar flow

(expect soft radiation from the boosted color singlet Higgs to be concentrated between the b and bbar decay products, in contrast to QCD light jet)

Two-particle Templates and Higgs Decay



Two-particle Templates and Higgs Decay



Two-particle Templates and Higgs Decay

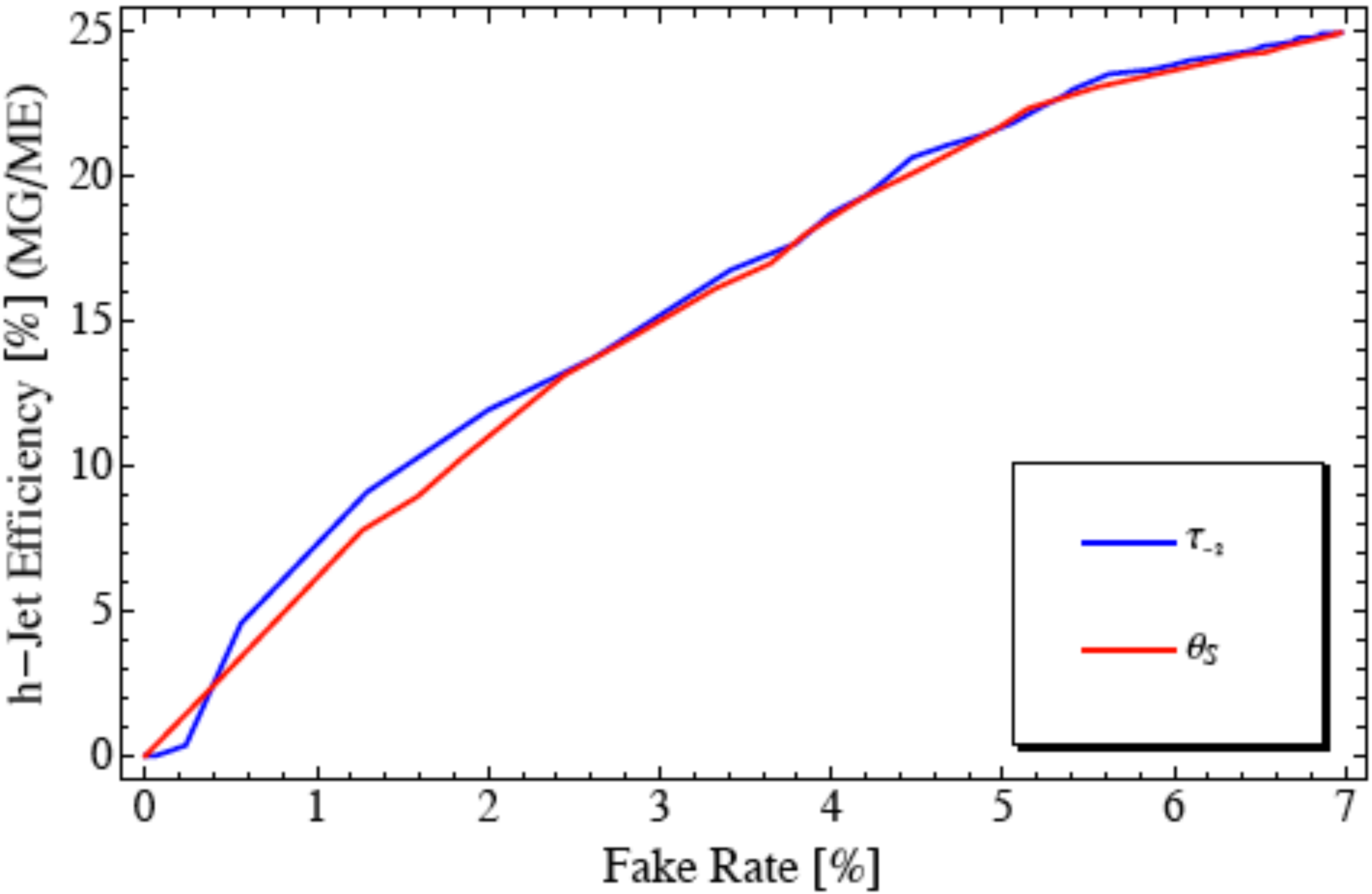
- Combined with angularity or Θ_s : can improved rejection power (Θ_s and angularities are related)

Two-particle Templates and Higgs Decay

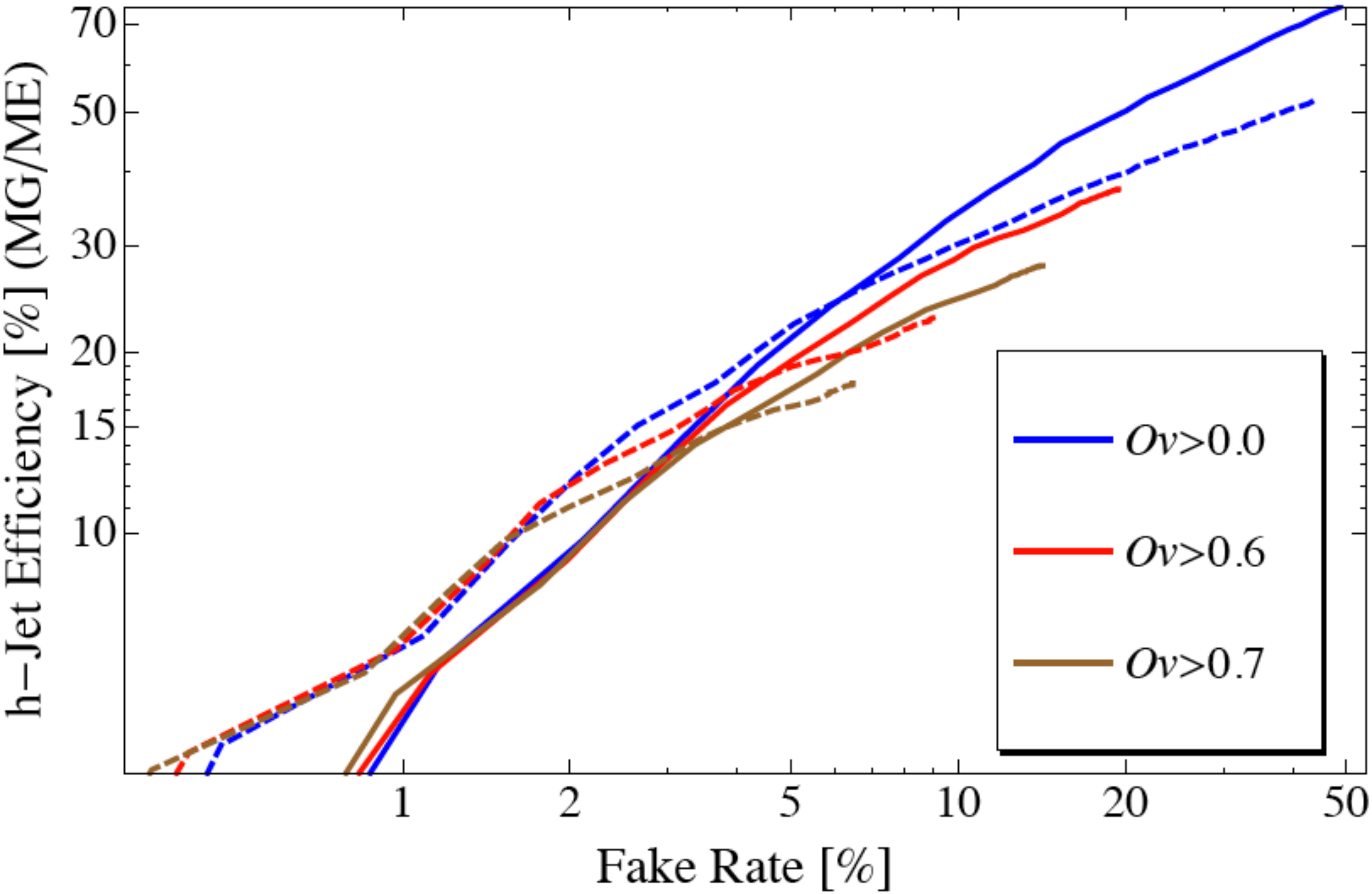
- Combined with angularity or Θ_s : can improved rejection power (Θ_s and angularities are related)

- Compared to angularities, Θ_s is a parameter for two-body template states, which already provides useful information on physical states, as well as a clear picture of their energy flow.

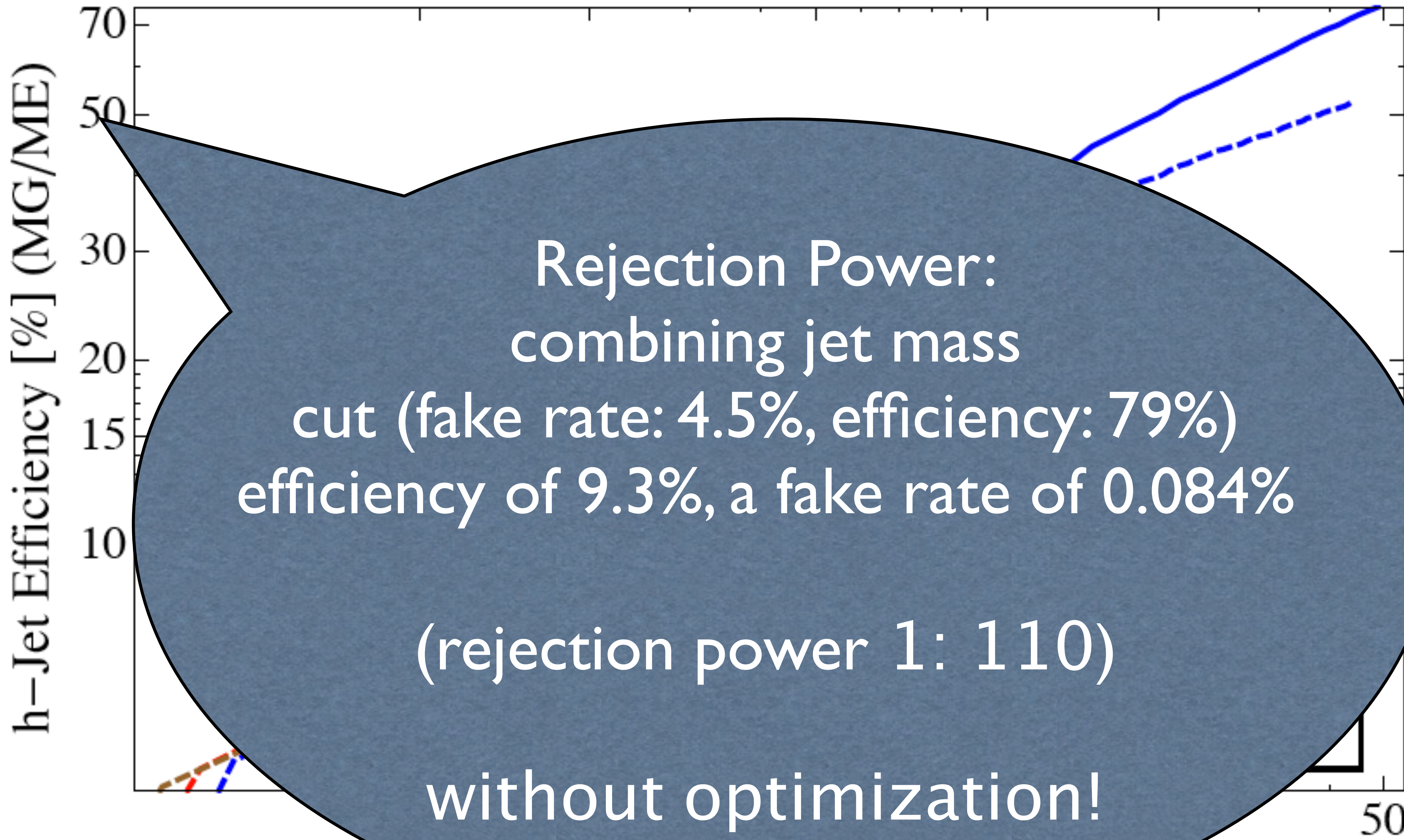
Two-particle Templates and Higgs Decay



Two-particle Templates and Higgs Decay



Two-particle Templates and Higgs Decay



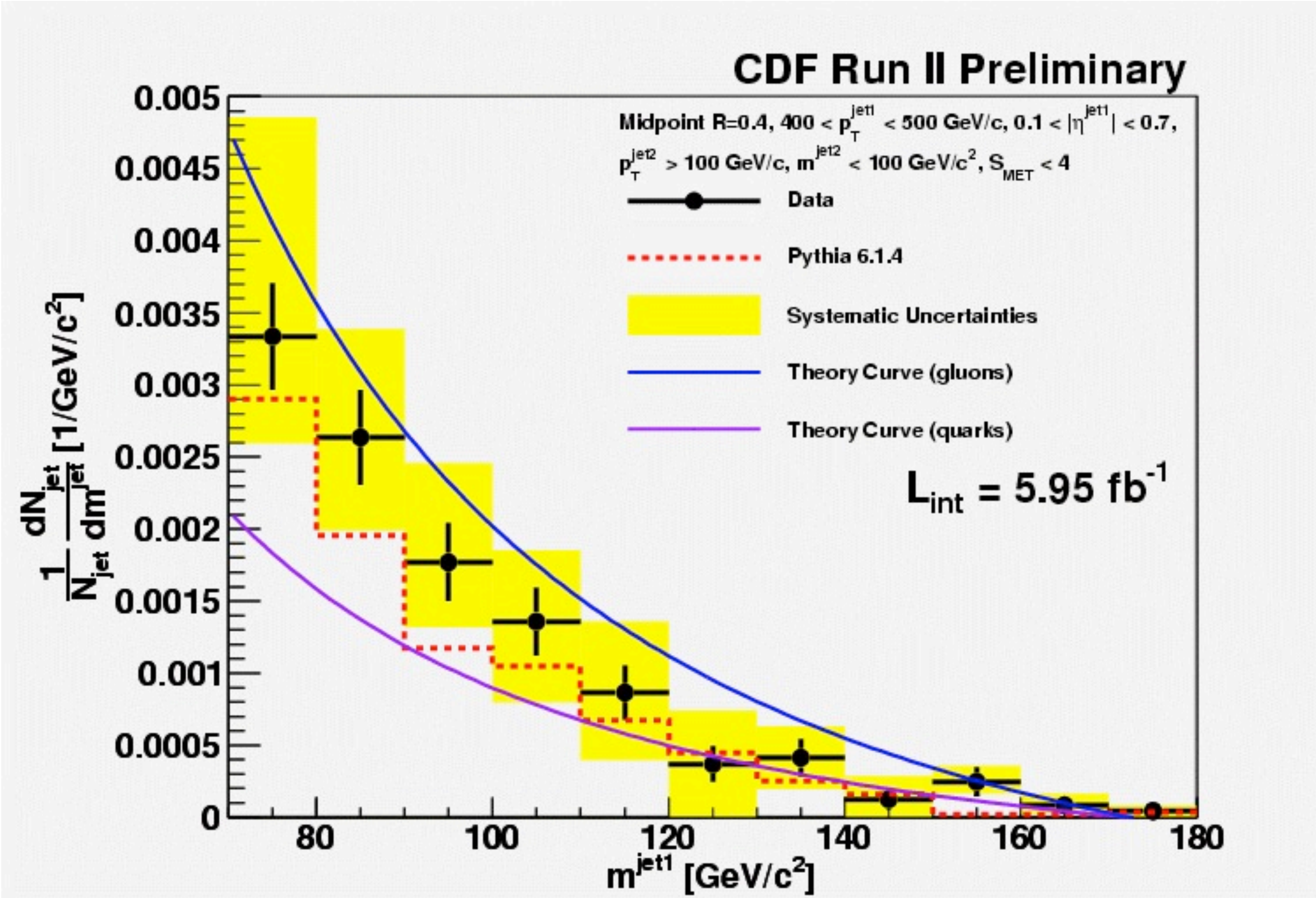
Rejection Power:
combining jet mass
cut (fake rate: 4.5%, efficiency: 79%)
efficiency of 9.3%, a fake rate of 0.084%

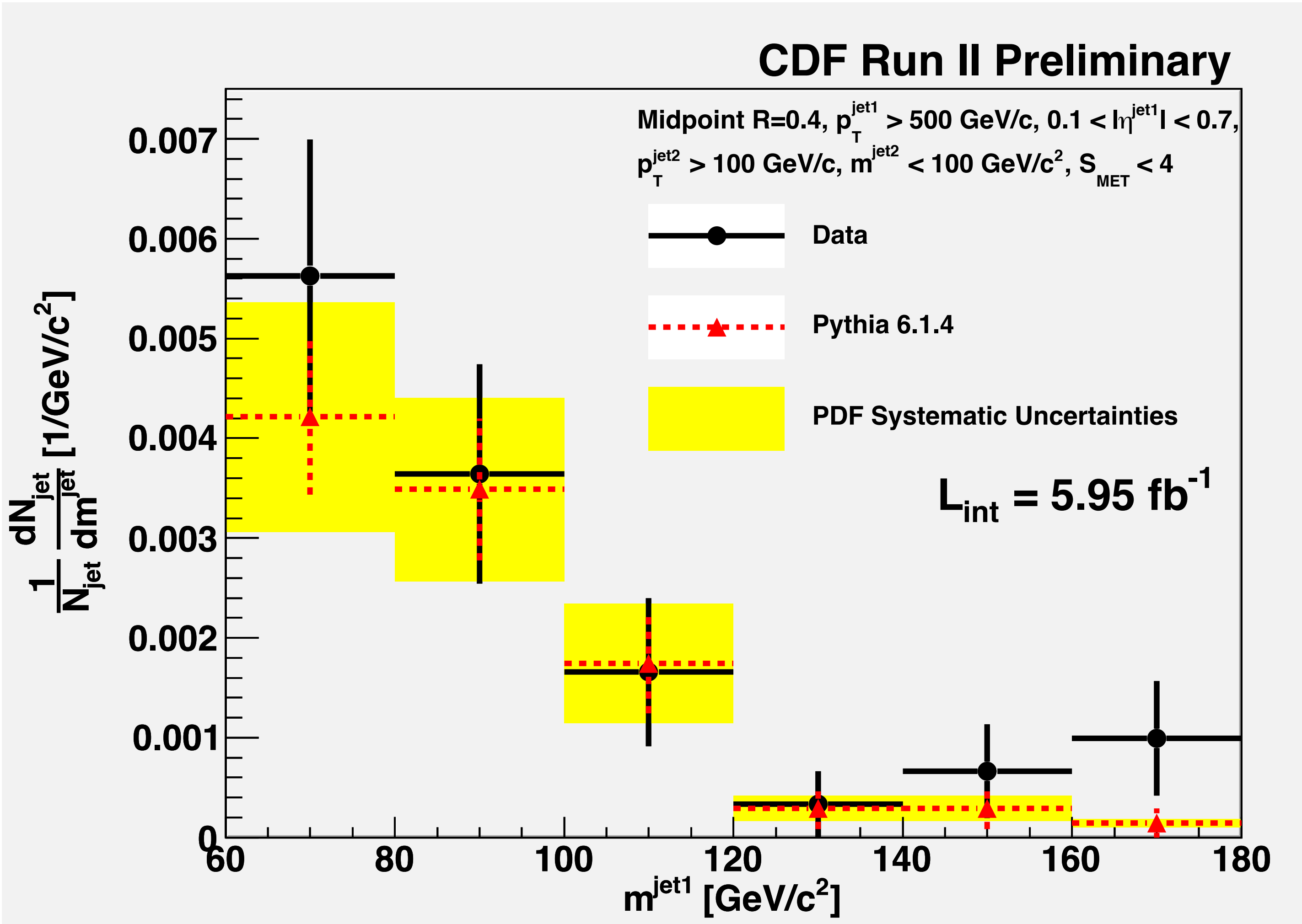
(rejection power 1: 110)

without optimization!

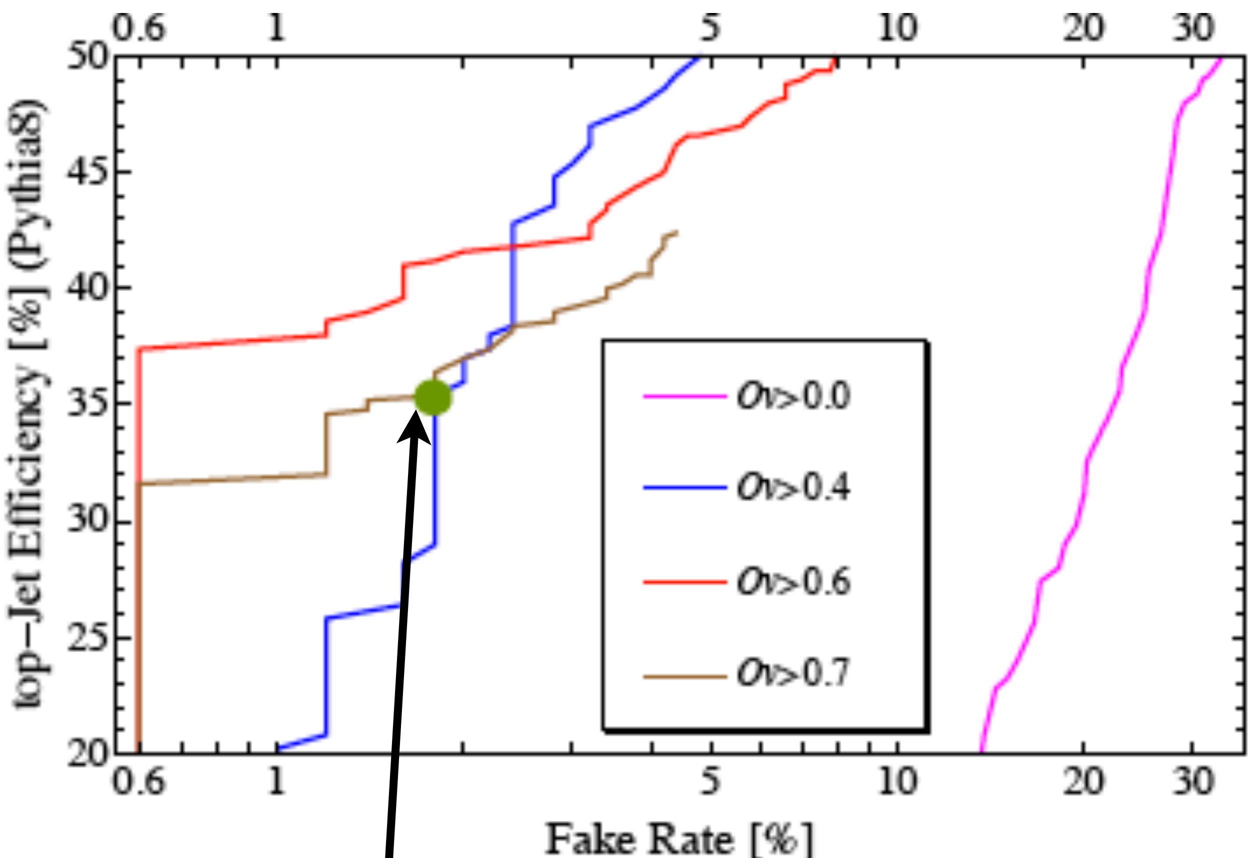
Summary

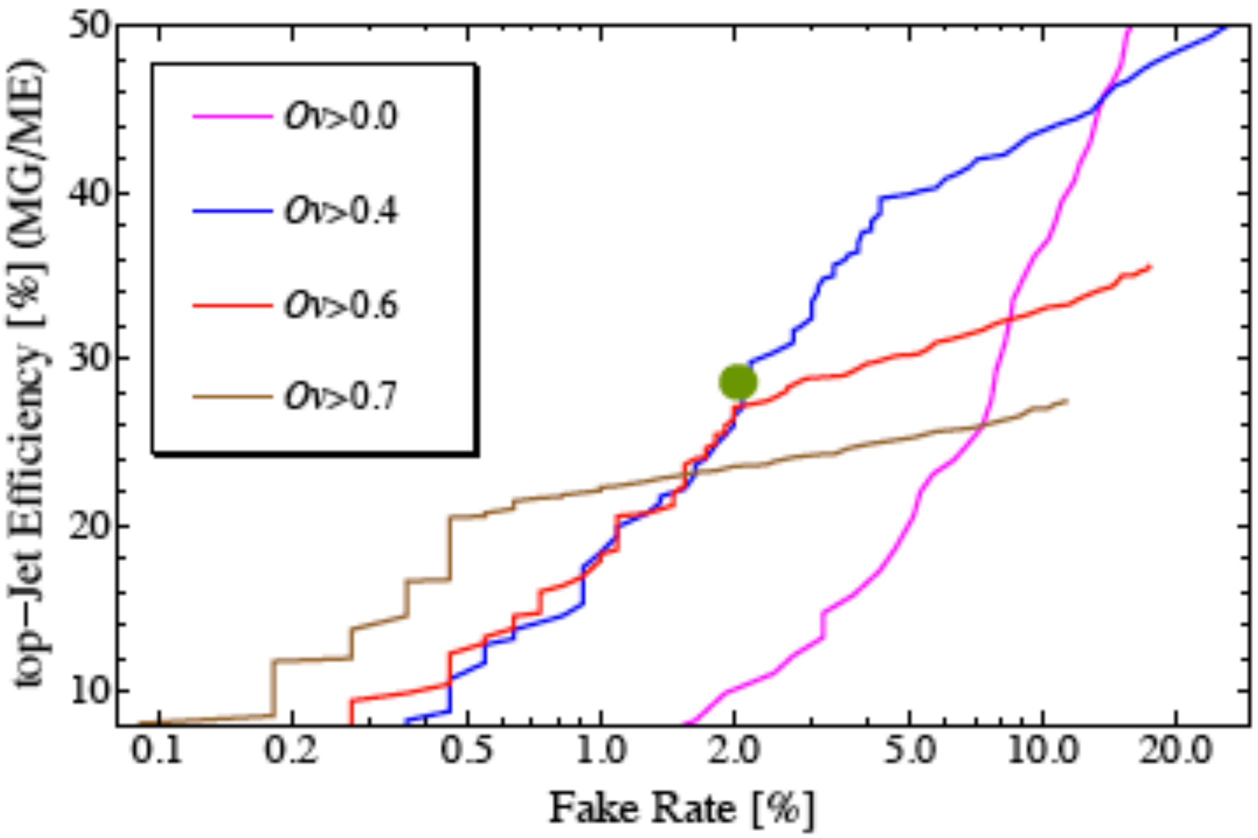
- LHC => new era, boosted massive jets important for studying QCD & NP discoveries.
- Jet function (gluon emission) gives correct qualitative description of data => 2 body physics; quark jets.
- Angularity distribution further confirmed this description, affected by jet algorithm, data differ from Pythia.
- Planar flow (3 body) shows larger deviation at large masses.
- Template Overlap method - provides a theoretical handle with good rejection power (systematically improvable).


CDF Run II Preliminary
Midpoint R=0.4, 400 < p_T^{jet1} < 500 GeV/c, 0.1 < $|\eta^{jet1}|$ < 0.7,
p_T^{jet2} > 100 GeV/c, m^{jet2} < 100 GeV/c^2, S_{MET} < 4
Data
Pythia 6.1.4
Systematic Uncertainties
Theory Curve (gluons)
Theory Curve (quarks)
L_{int} = 5.95 fb^{-1}
$\frac{1}{N_{jet}}\frac{dN_{jet}}{dm^{jet}}$ [1/GeV/c^2]
m^{jet1} [GeV/c^2]
0.005
0.0045
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
80
100
120
140
160
180

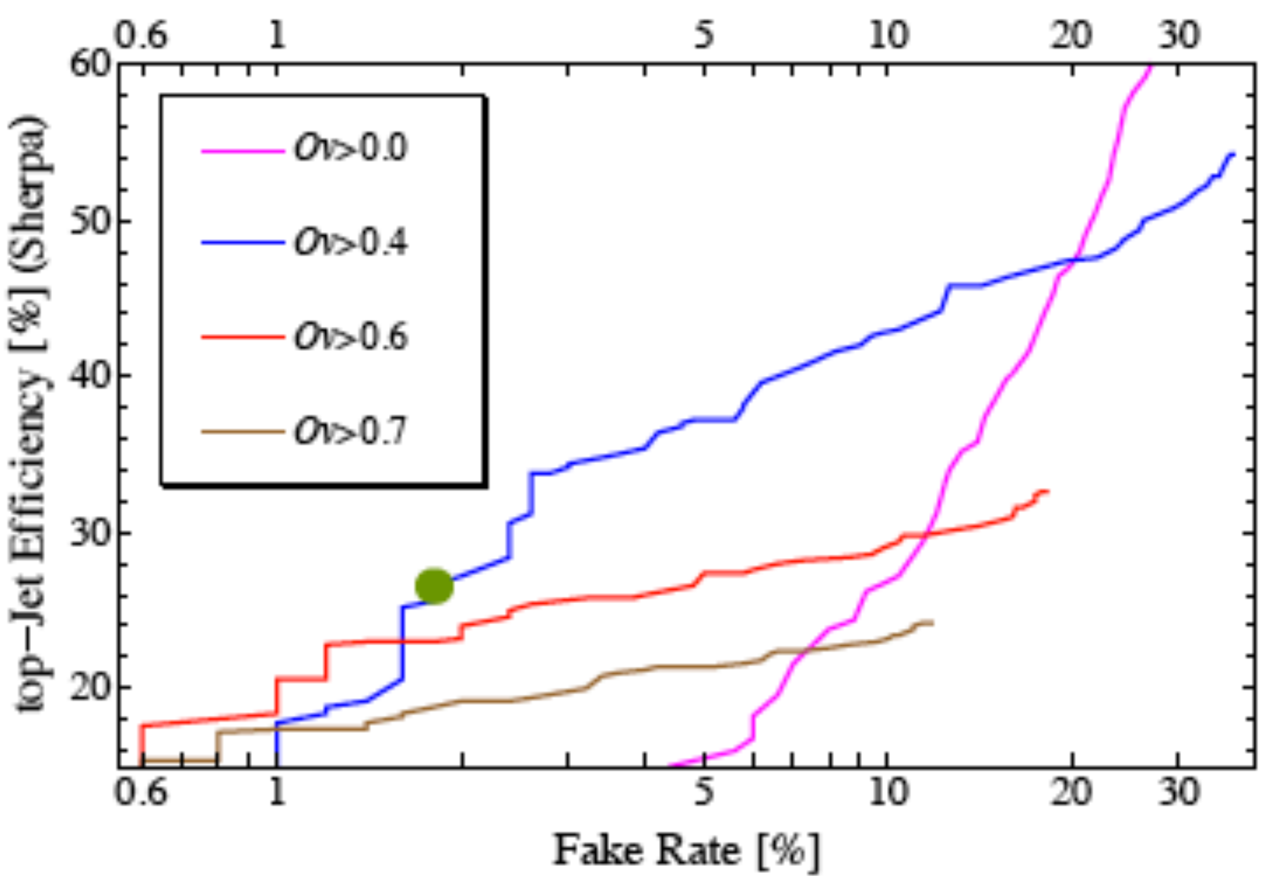

CDF Run II Preliminary
Midpoint R=0.4, p_T^{jet1} > 500 GeV/c, 0.1 < $|\eta^{jet1}|$ < 0.7,
p_T^{jet2} > 100 GeV/c, m^{jet2} < 100 GeV/c^2, S_{MET} < 4
Data
Pythia 6.1.4
PDF Systematic Uncertainties
L_{int} = 5.95 fb^{-1}
$\frac{1}{N_{jet}}\frac{dN_{jet}}{dm^{jet}}$ [1/GeV/c^2]
m^{jet1} [GeV/c^2]
0
0.001
0.002
0.003
0.004
0.005
0.006
0.007
60
80
100
120
140
160
180

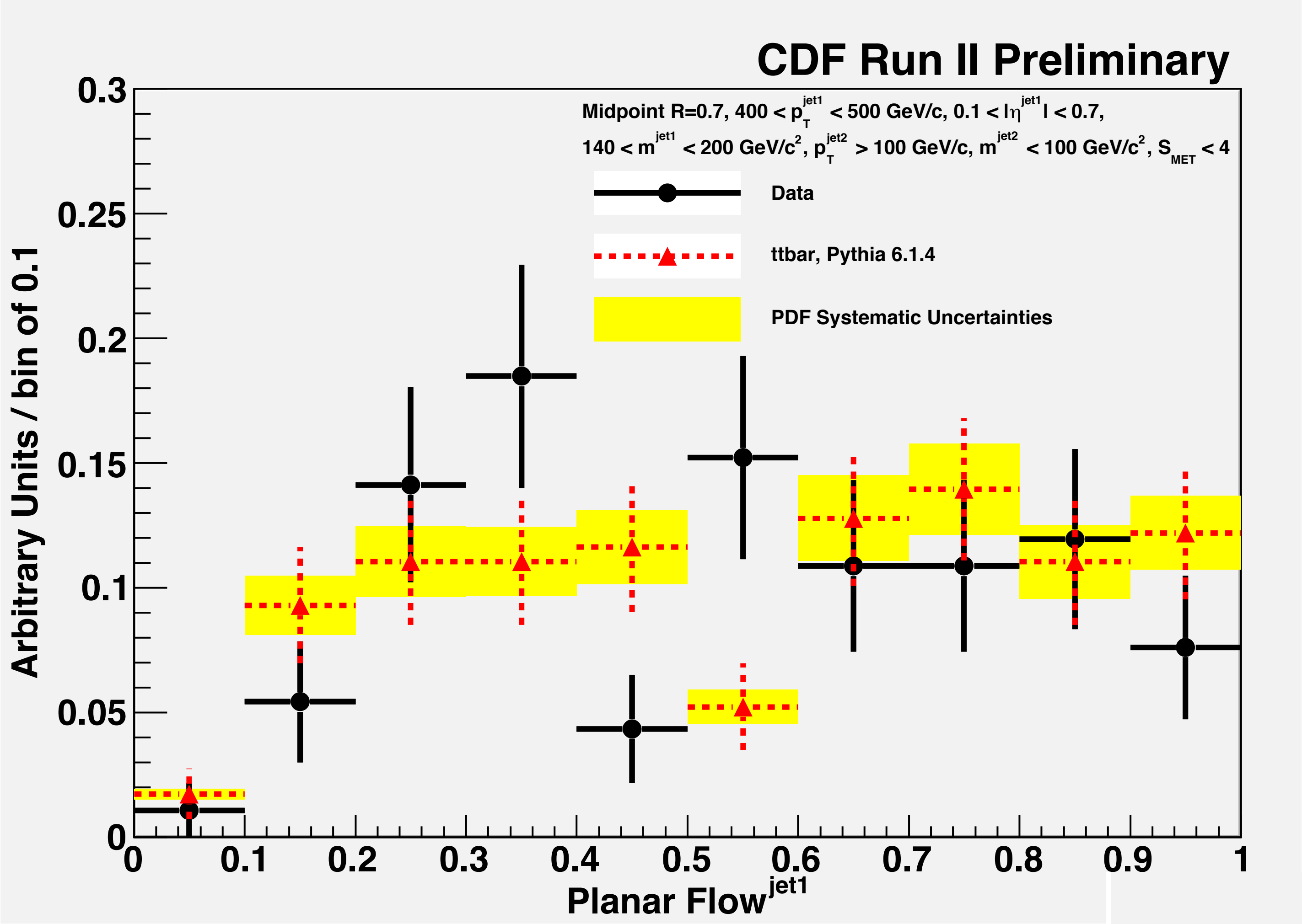
Three-particle Templates and Top Decay

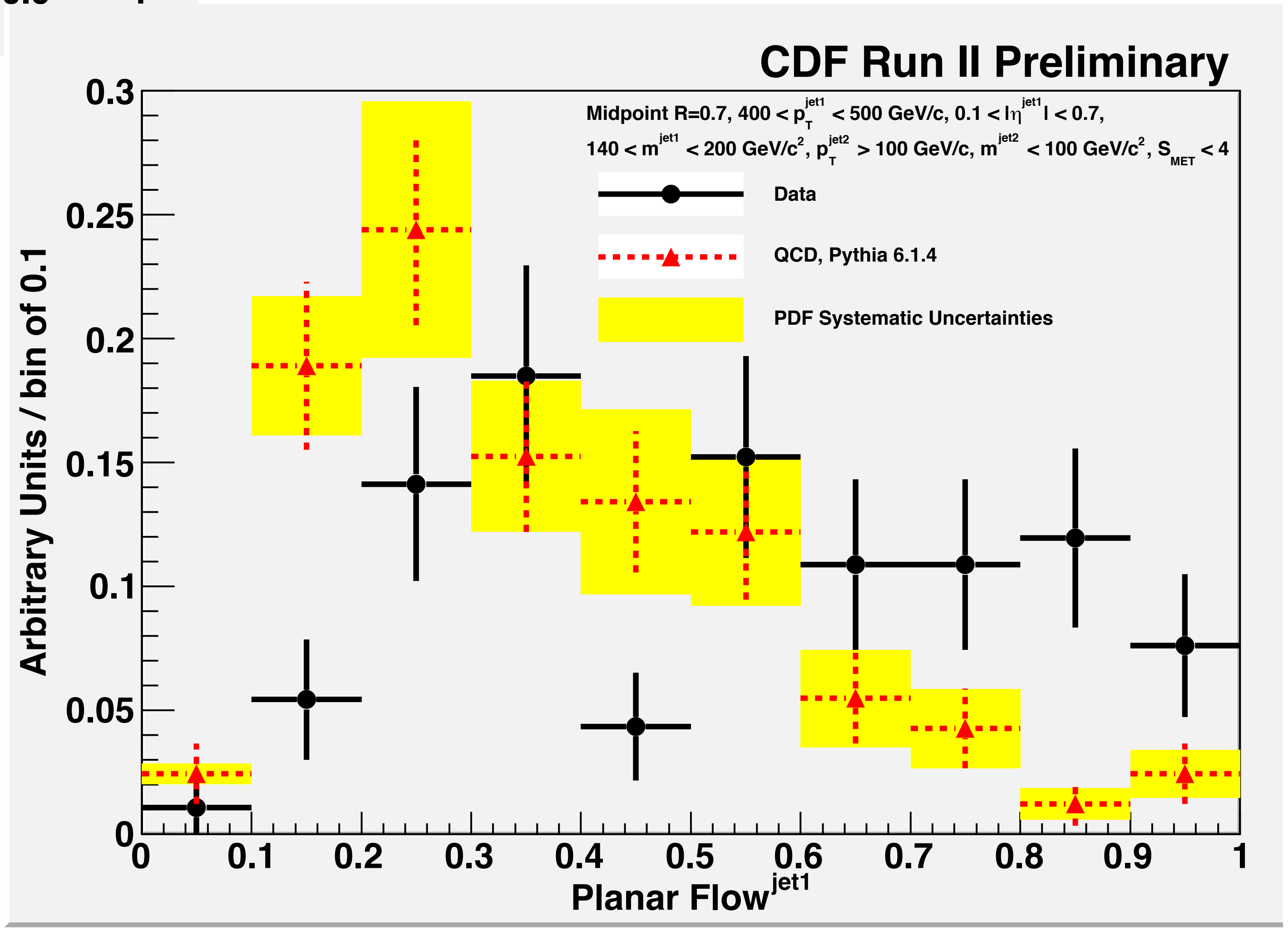




$Pf > 0.6$ and $Ov > 0.4$




CDF Run II Preliminary
Midpoint R=0.7, 400 < p_T^{jet1} < 500 GeV/c, 0.1 < |η^{jet1}| < 0.7,
140 < m^{jet1} < 200 GeV/c^2, p_T^{jet2} > 100 GeV/c, m^{jet2} < 100 GeV/c^2, S_{MET} < 4
Data
ttbar, Pythia 6.1.4
PDF Systematic Uncertainties
Arbitrary Units / bin of 0.1
Planar Flow^{jet1}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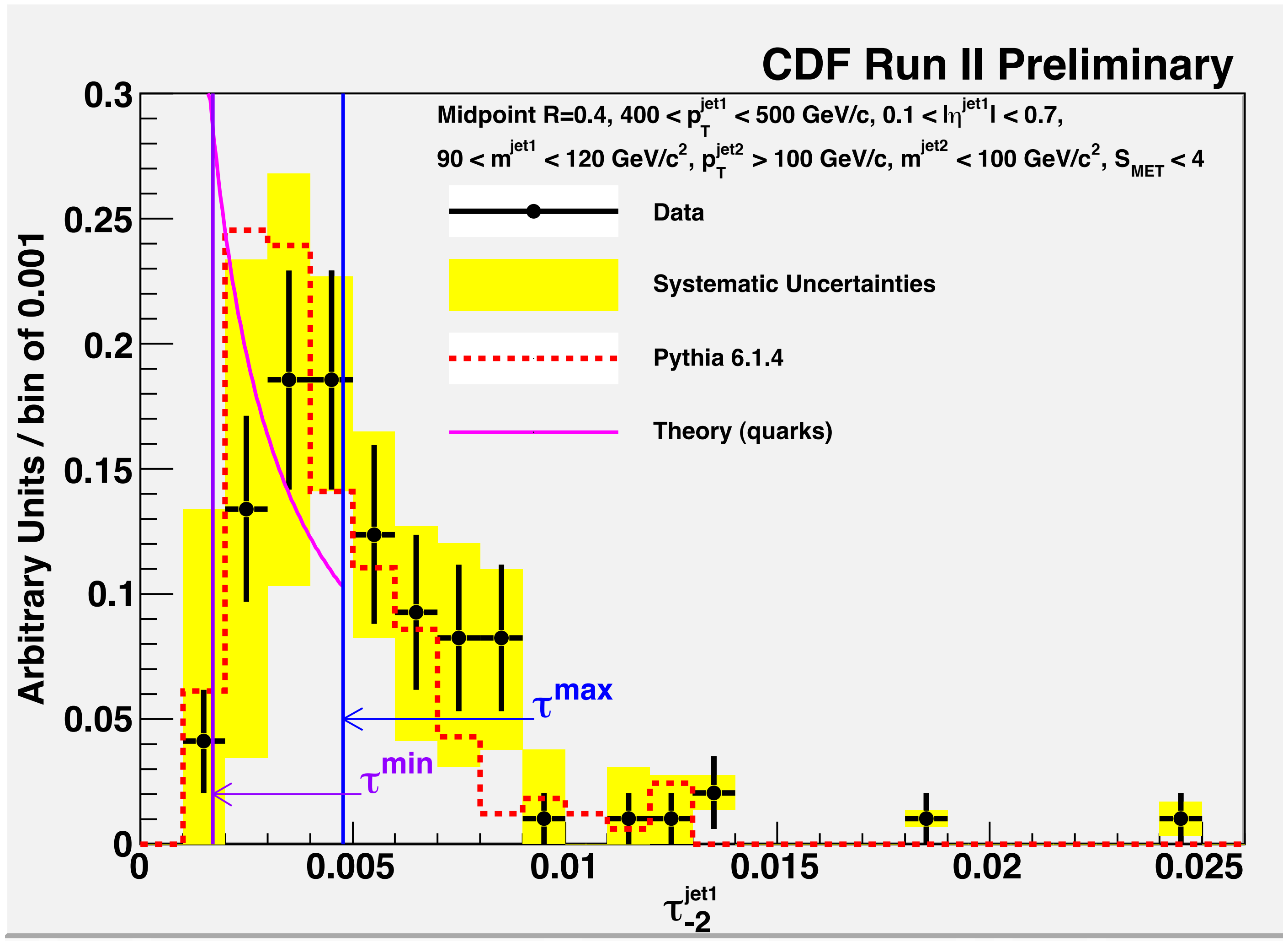
Data
QCD, Pythia 6.1.4
PDF Systematic Uncertainties
Arbitrary Units / bin of 0.1
Planar Flow^{jet1}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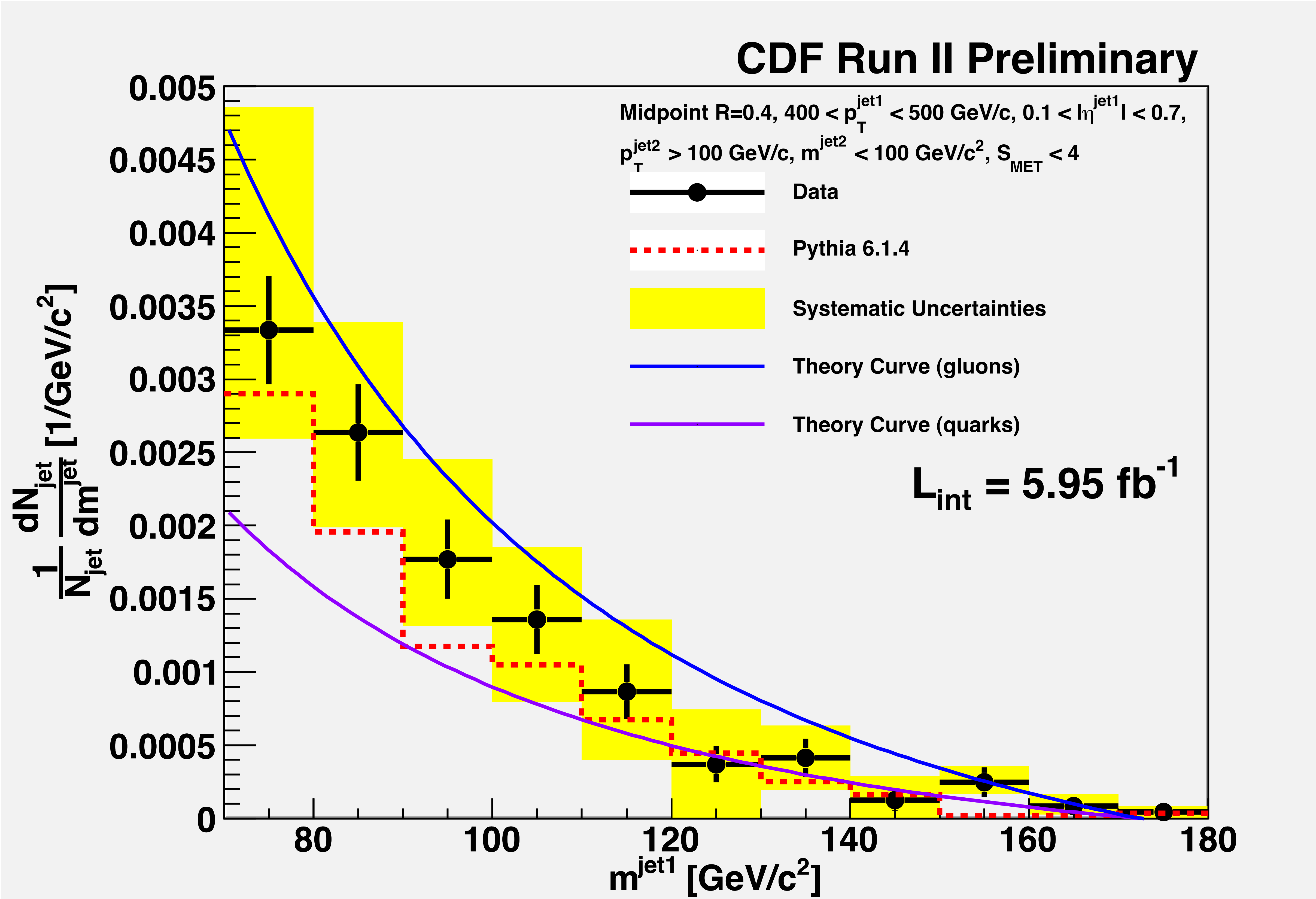
90 < m^{jet1} < 120 GeV/c^2, p_T^{jet2} > 100 GeV/c, m^{jet2} < 100 GeV/c^2, S_{MET} < 4
Data
Systematic Uncertainties
Pythia 6.1.4
Theory (quarks)
τ^{max}
τ^{min}
Arbitrary Units / bin of 0.001
τ_{-2}^{jet1}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