Boosted Massive Jets @ the LHC

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מכון ויצמן למדע
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L. Almeida, SL, G. Perez, G. Sterman, I. Sung, & J. Virzi

PRD 79, 074017 (2009);

L. Almeida, SL, G. Perez, I. Sung, & J. Virzi

PRD 79, 074012 (2009);

L. Almeida, SL, G. Perez, G. Sterman, & I. Sung

PRD 82, 054034 (2010)

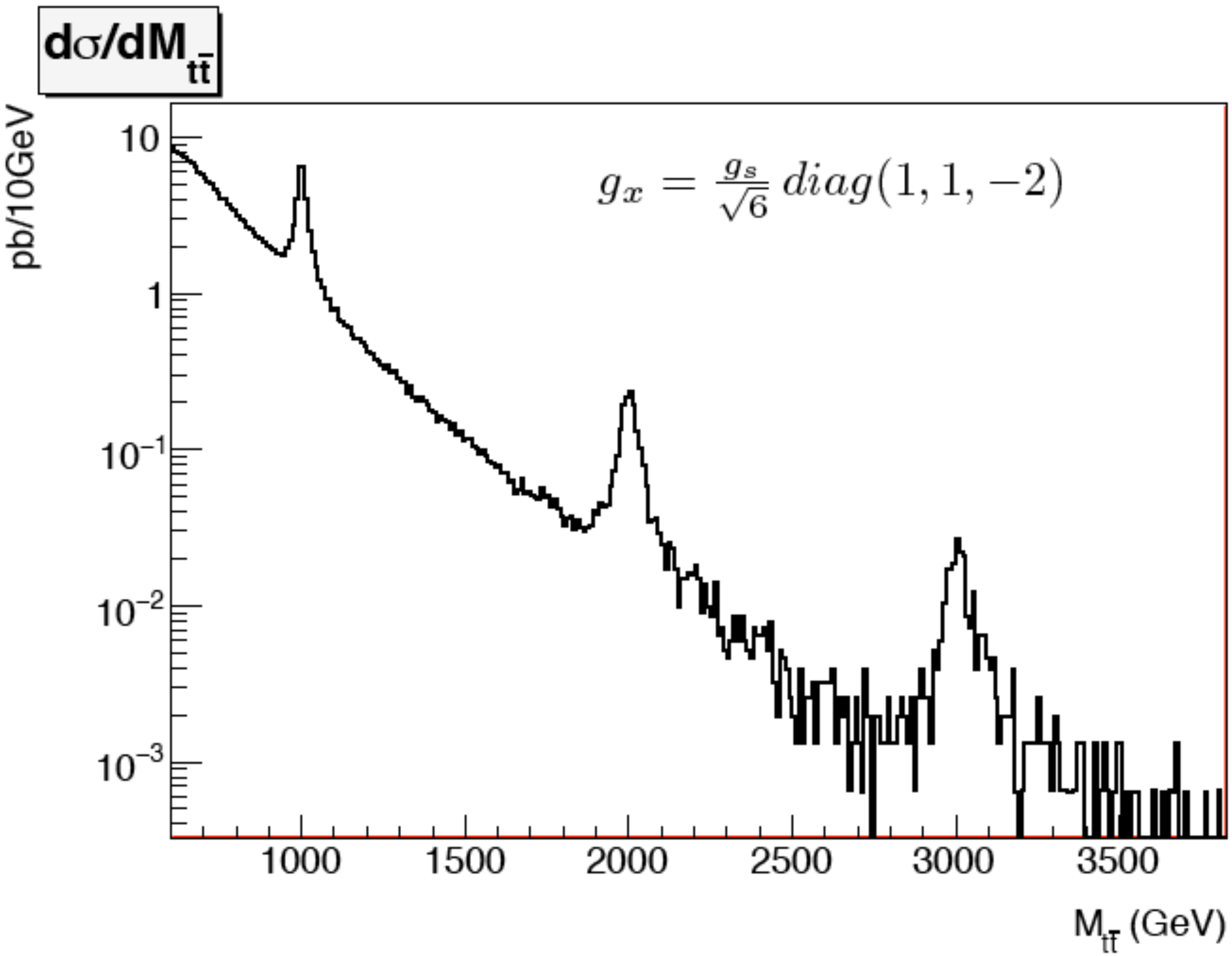
IPNL, Lyon, December 15, 2010

Outline

- Intro: emergence of massive jets @ LHC & the nature of the problem (finite resolution)
- Theory of massive jets:
  - jet mass
  - substructure: angularities, planar flow
- Template Overlap Method
- Summary

High P_T tops (or massive jets), might be crucial signal for various NP models

Z': Butterworth, Cox & Forshaw; KK gluon: Agashe, Belyaev, Krupovnickas, GP & Virzi (06); Lillie, Randall & Wang (07); KK graviton: Fitzpatrick, Kaplan, Randall & Wang (07); Agashe, Davoudiasl, GP & Soni (07).



C. Csaki, SL, G. Perez, & A. Weiler (Flavor gauge bosons: to appear)

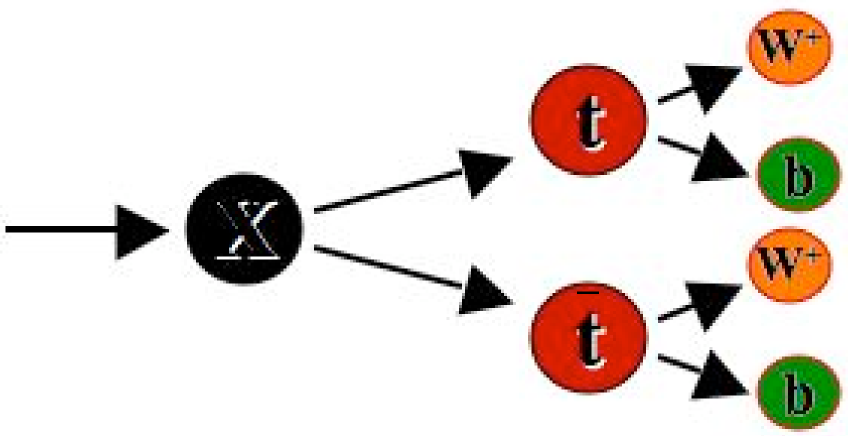
C. Delaunay, SL, & G. Perez (Extraordinary Phenomenology from Flavor Triviality: to appear)

The challenge of highly boosted Massive Jets

✦ High PT massive jets such as tops, might be crucial signal for various NP models (X ->ttbar +Y):

e.g. KK states decaying into top pair

$m_{\mathrm{KK}} \gtrsim 1\,\mathrm{TeV}$



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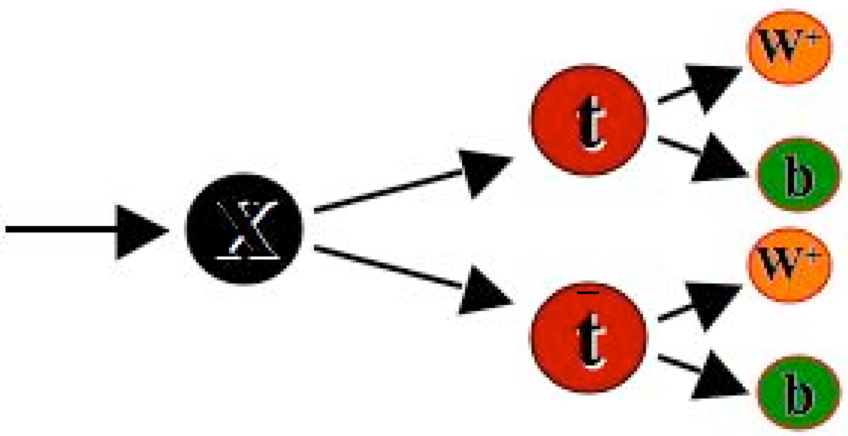

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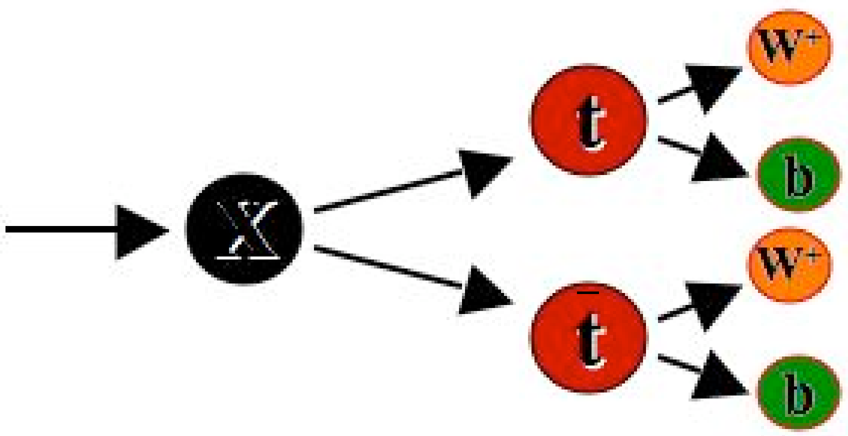

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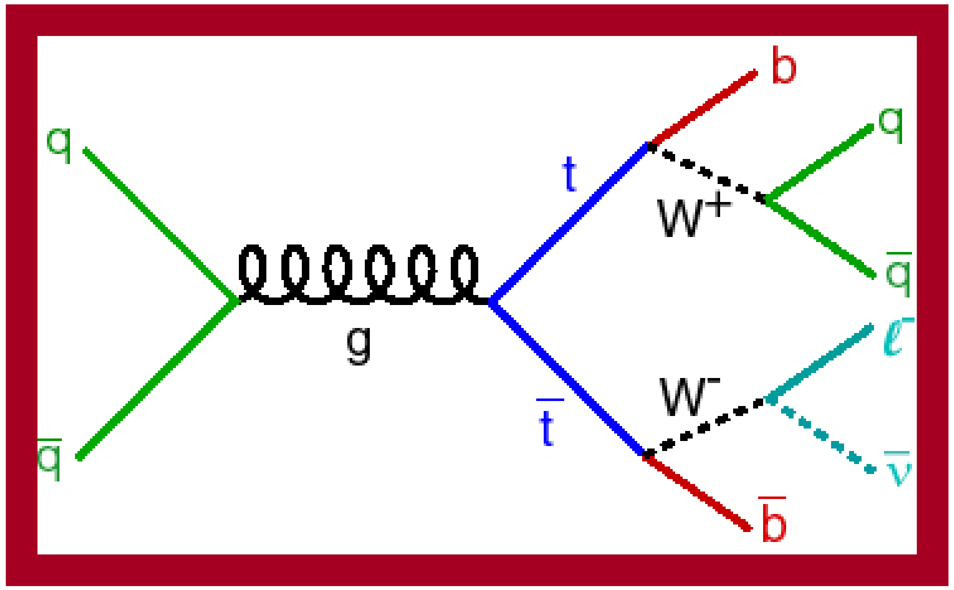

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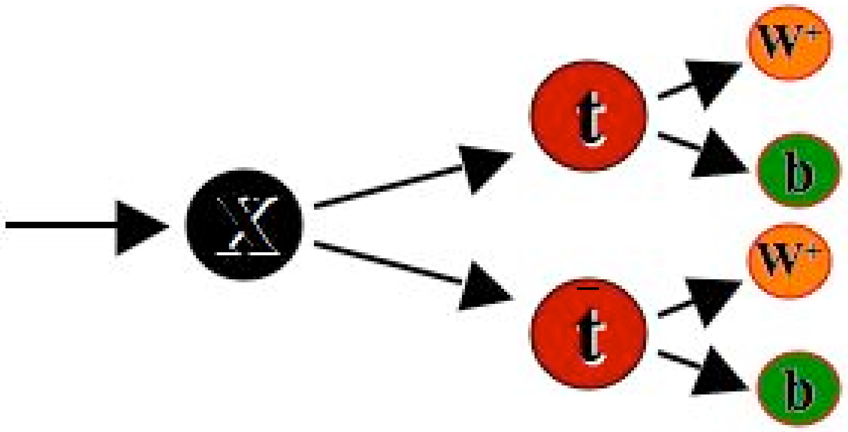

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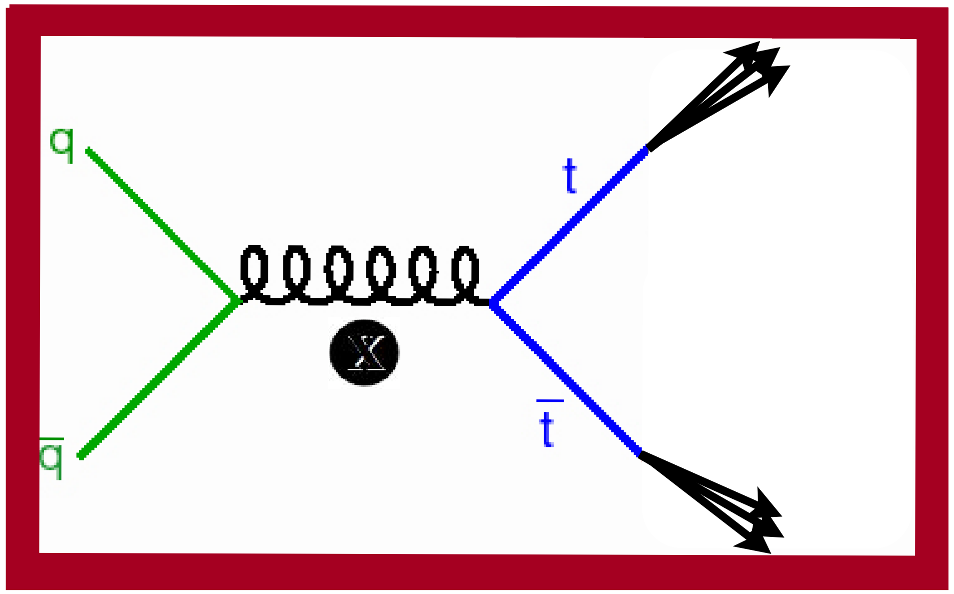

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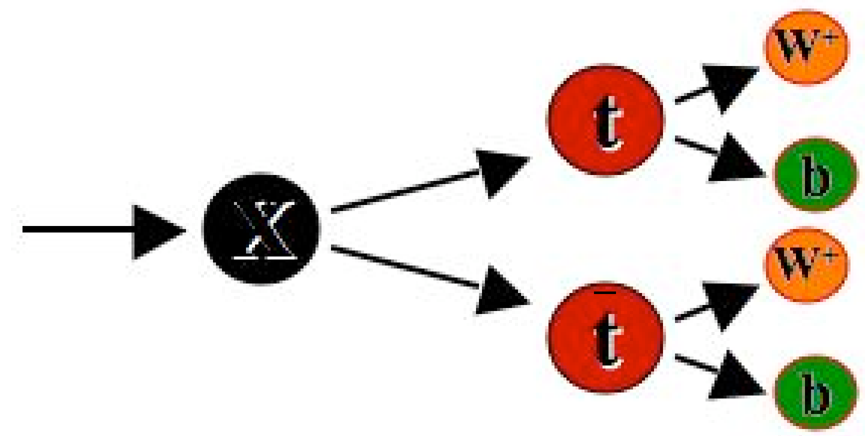

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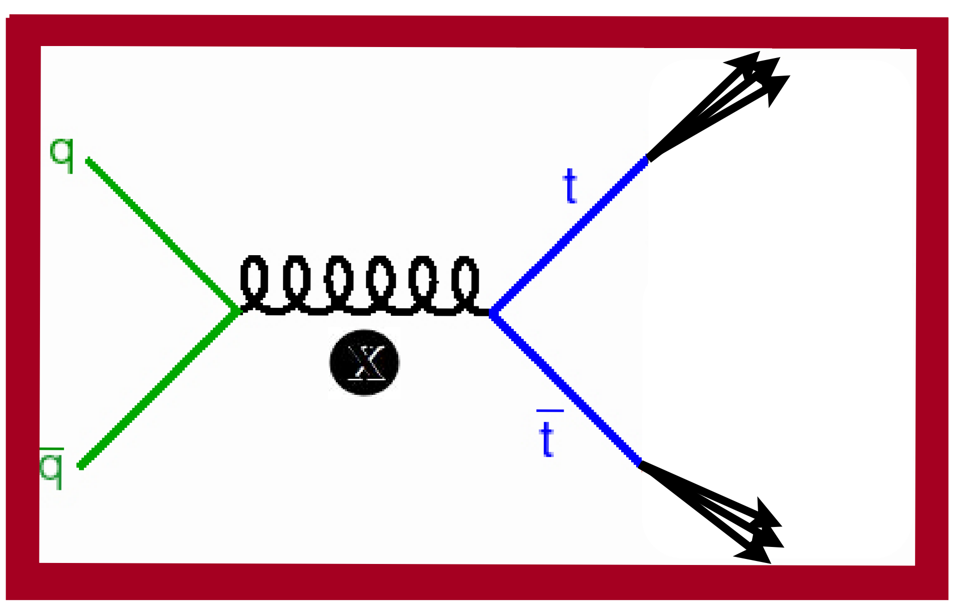
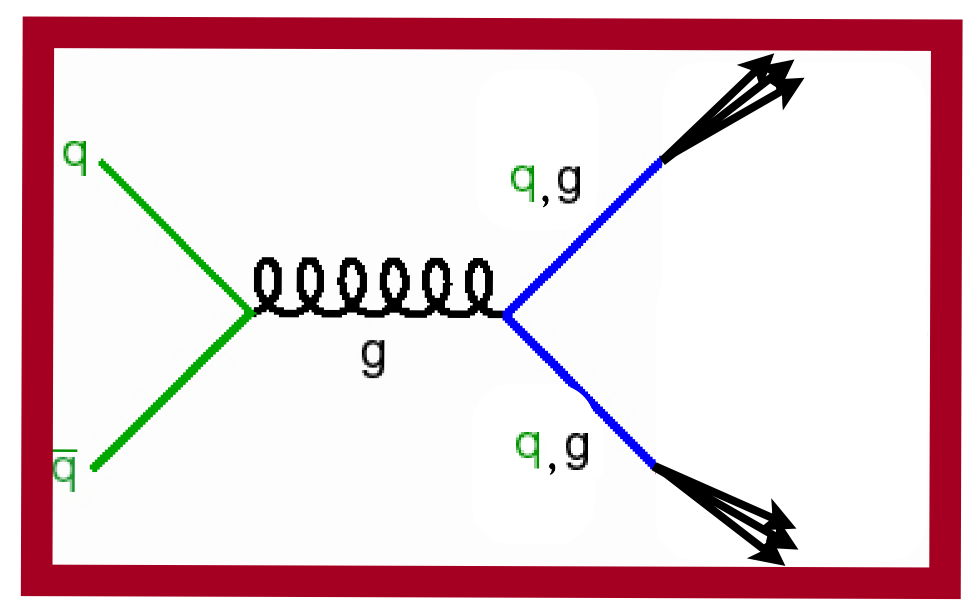
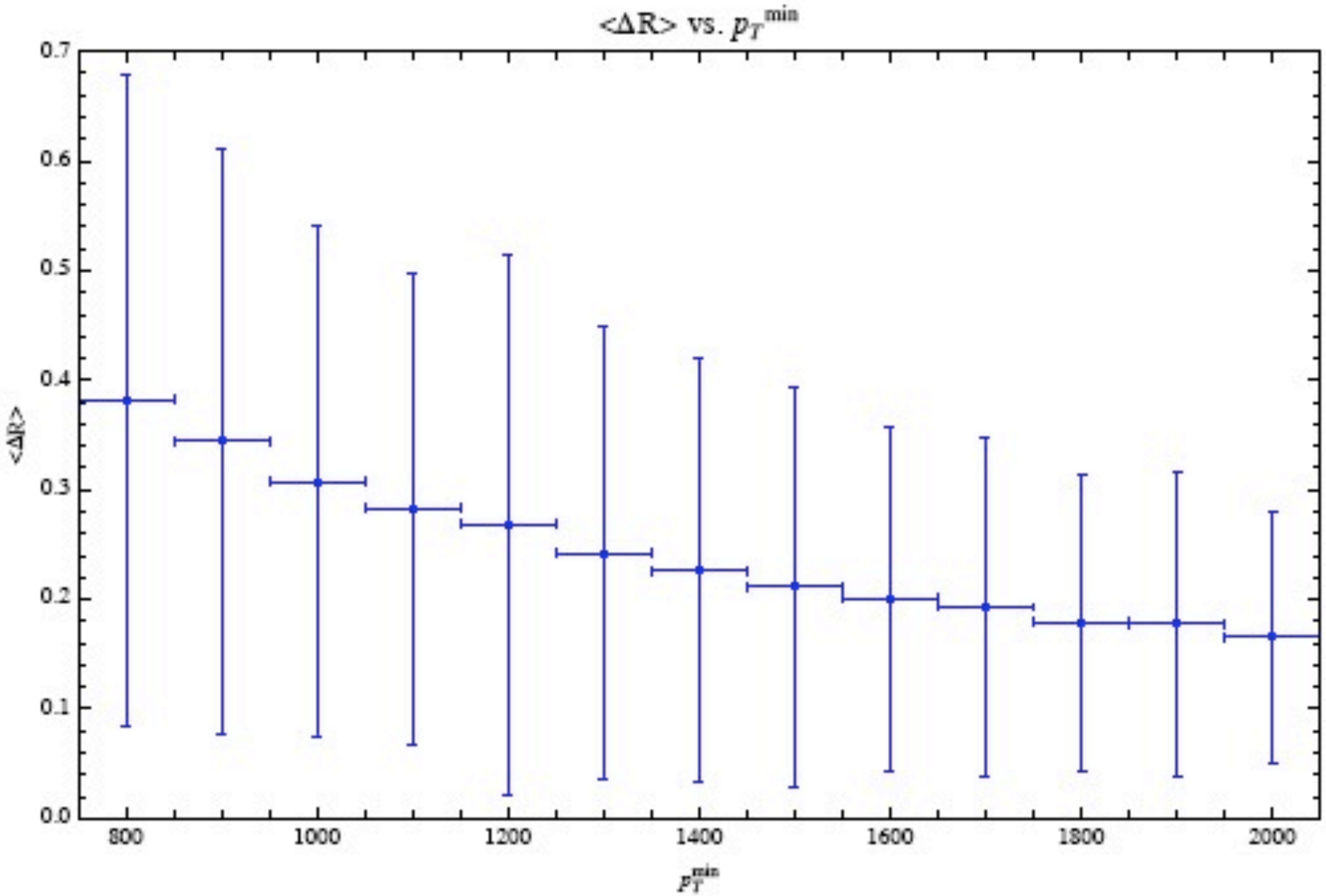


Similar to ordinary 2-jet QCD process impossible to observe ⁉



Boosted top (w/z/h) jets & collimation



Partonic Level

Highly Boosted Tops:
High Collimations!

ΔR vs. P_T $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

Why not use scaled-down conventional methods?

- ✦ IRC (IR & collinear) safety require inclusive observables (e.g. cone or kt jets).

- ✦ Hadronic calorimeter tower has an hard angular size R~0.1

- ✦ Radial shower of energetic hadrons are very large (require 1 full cell of H-cal to capture single PT=100 GeV pion)

✦R=0.4 smallest cone used so far. A careful th'+exp' effort required to go beyond that.

Top jet & di-jet @ the LHC

Almeida, SL, Perez, Sung, & Virzi.

- S/B < 10^{-2}, for pt(j)>1000GeV, R=0.4

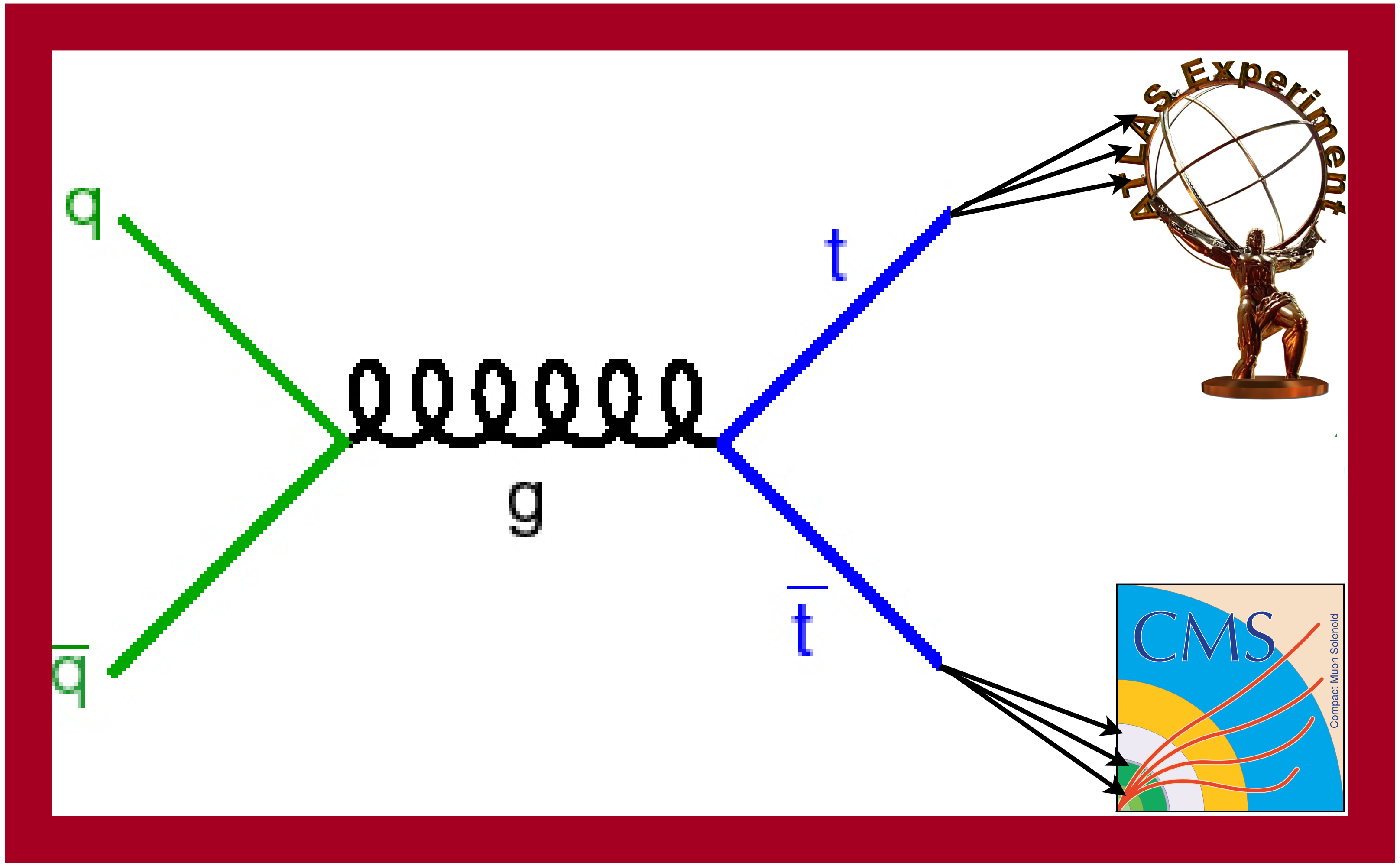
  (10pb for jj+X, 100fb for ttbar+X)

Process	Generator	PDF	Matching	Cross Section
$pp \to t\bar{t}(j)$	SHERPA 1.0.9	CTEQ6M	CKKW	135 fb
$pp \to t\bar{t}(j)$	SHERPA 1.1.2	CTEQ6M	CKKW	149 fb
$pp \to t\bar{t}(j)$	MG/ME 4	CTEQ6M	MLM	68 fb
$pp \to t\bar{t}(j)$	MG/ME 4	CTEQ6L	MLM	56 fb
$pp \to t\bar{t}$	Pythia 6.4	CTEQ6L	-	157 fb
$pp \to t\bar{t}$	Pythia 8.1	CTEQ6M	-	174 fb
$pp \to jj(j)$	SHERPA 1.1.0	CTEQ6M	CKKW	10.2 pb
$pp \to jj(j)$	MG/ME 4	CTEQ6L	MLM	8.54 pb
$pp \to jj(j)$	MG/ME 4	CTEQ6M	MLM	9.93 pb
$pp \to jj$	Pythia 6.4	CTEQ6L	-	13.7 pb
$pp \to jj$	Pythia 8.1	CTEQ6M	-	13.3 pb

"Theory" of massive jets @ the LHC

Other works:

Butterworth, Cox, Forshaw;
Thaler & Wang; Conway; Vos; Brooijmans
Kaplan, Rehermann, Schwartz & Tweedie. ...
Butterworth, Davison, Rubin, Salam,...



(I) Jet mass.

(II) Jet substructure:

(i) angularity (ii) Planar flow (iii) Template Overlap

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

(naively: QCD jets are massless while top jets ~ m_t)

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- Jet mass is non-trivial both for S & B
- Simple mass tagging tricky (counting in mass window)
- S&B distributions via 1st principles & compare to Monte-Carlo.
- Allow to improve S/B & yield insights!

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/out cone
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+ detector smearing.

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Pure kinematical bW(qq) dist'
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Non trivial top-jet mass distribution

- $$J^t(m_J, R, p_T) \sim \int d(\delta m_{EW}) dm_{QCD}\, \delta(m_J - m_{QCD} - \delta m_{EW}) \times J^t_{QCD}(m_{QCD}, R, p_T)\, \mathcal{F}_{EW}(\delta m_{EW}, m_{QCD}/(p_T R))$$
- In practice: $m_J^t \sim m_t + \delta m_{QCD} + \delta m_{EW}$

+ detector smearing.

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Pure kinematical bW(qq) dist'
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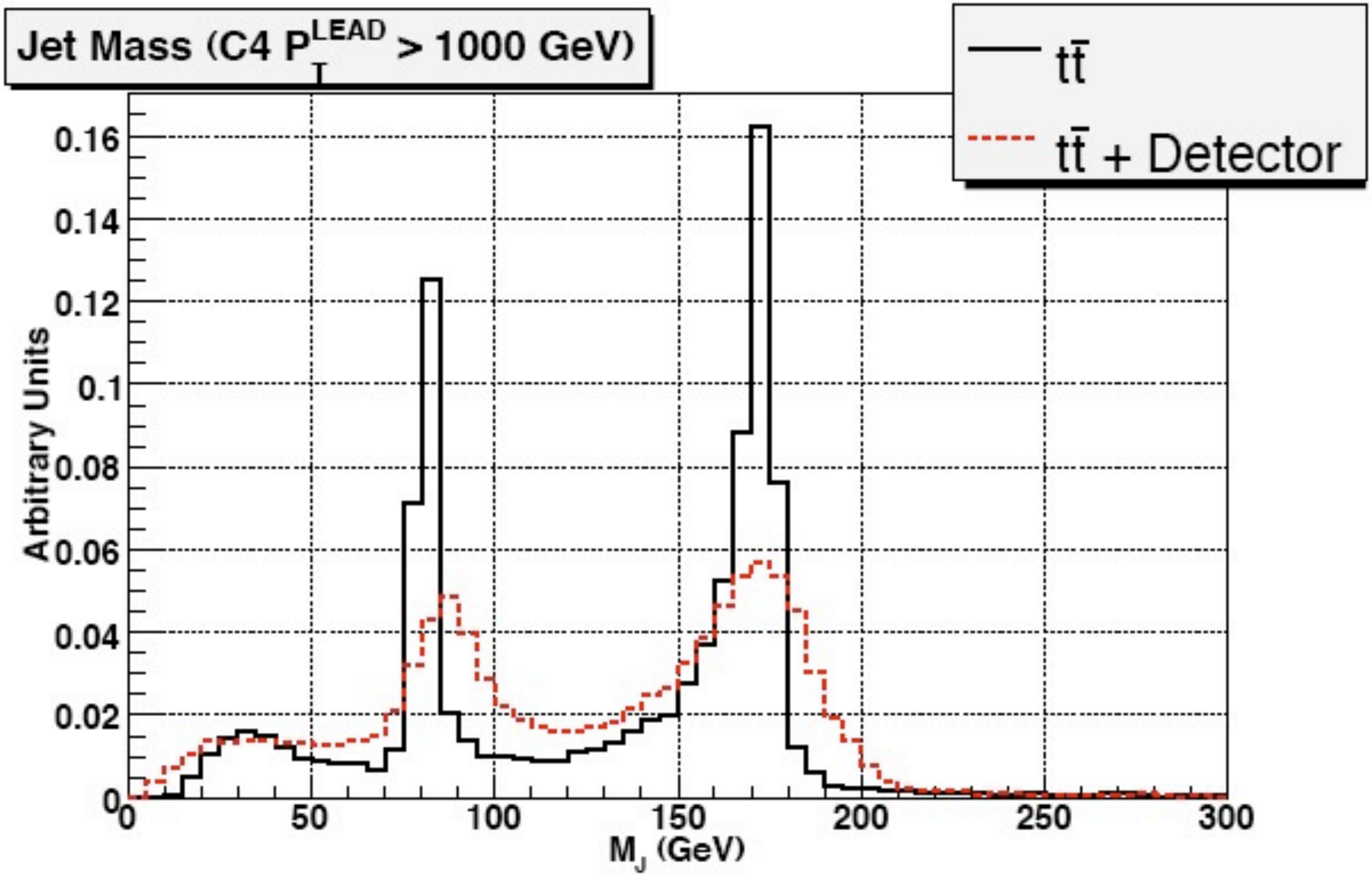
(Fleming, Hoang, Jain, Mantry, Scimemi, Stewart) Almeida, SL, Perez Sung, & Virzi.

Sherpa => (CKKW) Transfer functions, JES



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 pT to acquire a mass between mJ and mJ + δmJ

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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$$\int dm_J\, J \quad \ldots \quad i = Q, G$$

- can interpret the jet functio… …quire a mass between mJ and mJ + …

For large jet mass & small R,
no big logs =>
can be calculated via
perturbative QCD!

Full expression:

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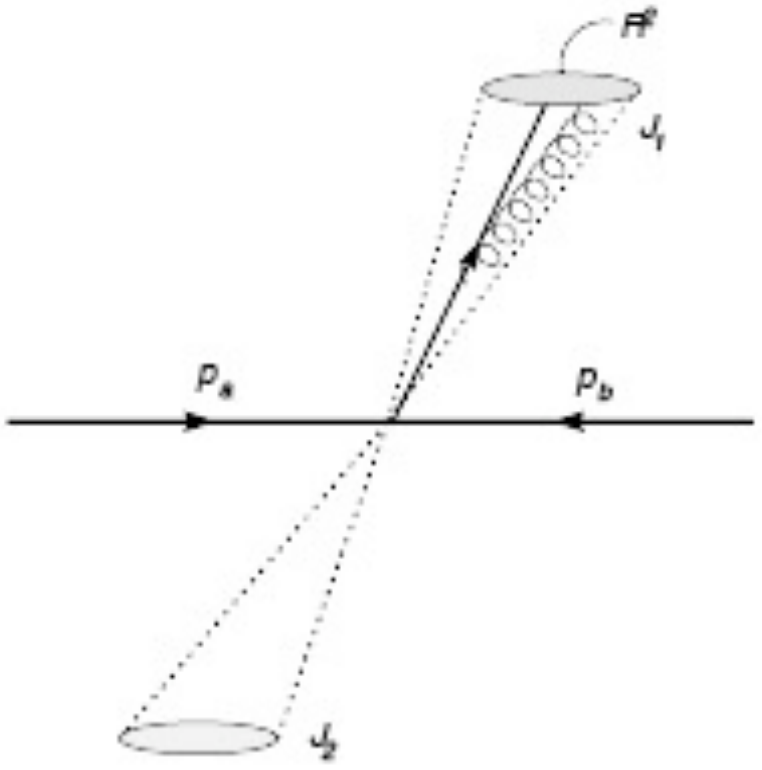
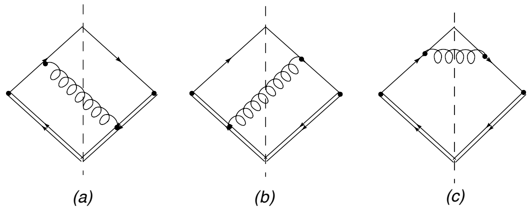
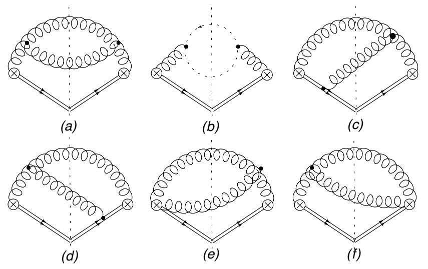
$$S\,(m^2_{J_1},m^2_{J_2},\eta,p_T,R^2)\;J_1^{(c)}(m^2_{J_1},\eta,p_T,R^2)J_2^{(d)}(m^2_{J_2},\eta,p_T,R^2)$$

QCD jet mass distribution, Q+G

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







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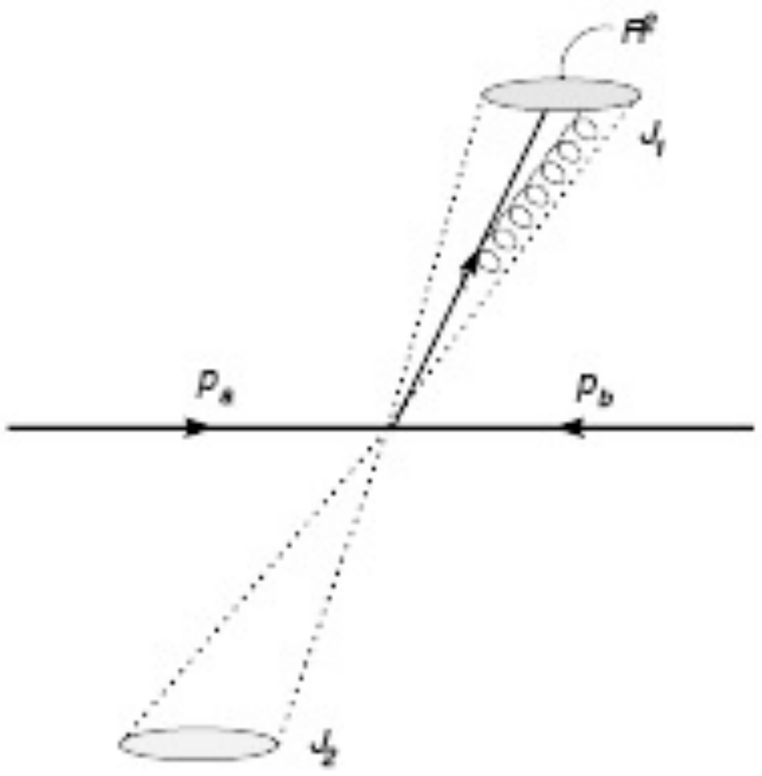
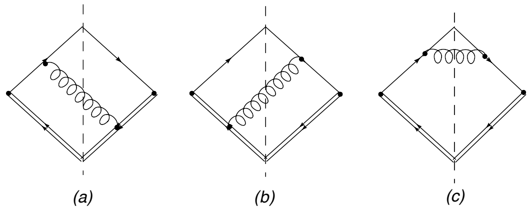
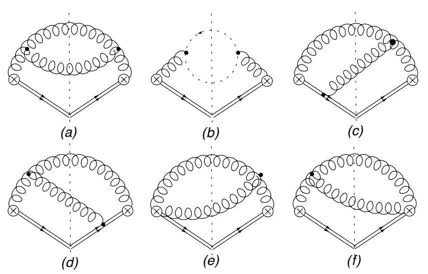


Main idea: calculating mass due to two-body QCD bremsstrahlung:

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

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



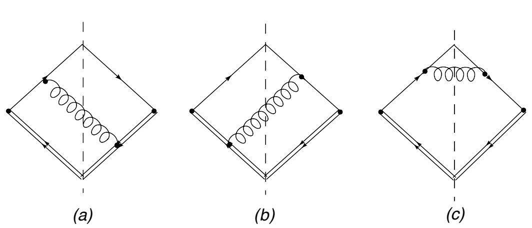


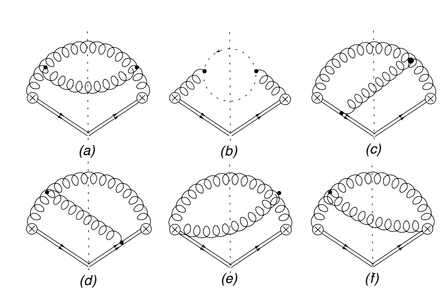
QCD jet mass distribution, Q+G

$$
\begin{aligned}
J_i^{q(1)}(m_J^2, p_{0,J_i}, R) &= \frac{C_F \beta_i}{4 m_{J_i}^2} \int_{\cos(R)}^{\beta_i} \frac{d\cos\theta_S}{\pi} \frac{\alpha_S(k_0)\, z^4}{(2(1-\beta_i\cos\theta_S) - z^2)\,(1-\beta_i\cos\theta_S)} \times \\
&\left\{ z^2 \frac{(1+\cos\theta_S)^2}{(1-\beta_i\cos\theta_S)} \frac{1}{(2(1+\beta_i)(1-\beta_i\cos\theta_S) - z^2(1+\cos\theta_S))} + \right. \\
&\left. \frac{3(1+\beta_i)}{z^2} + \frac{1}{z^4} \frac{(2(1+\beta_i)(1-\beta_i\cos\theta_S) - z^2(1+\cos\theta_S))^2}{(1+\cos\theta_S)(1-\beta_i\cos\theta_S)} \right\},
\end{aligned}
$$

$$
\beta_i = \sqrt{1 - m_{J_i}^2/p_{0,J_i}^2} \quad z = \frac{m_{J_i}}{p_{0,J_i}},\ p_{0,J_i} = \sqrt{m_{J_i}^2 + p_T^2},\ \text{and}\ k_0 = \frac{p_{0,J_i}}{2}\frac{z^2}{1-\beta_i\cos\theta_S}.
$$

$$
\begin{aligned}
J_i^{g(1)}(m_J^2, p_{0,J_i}, R) &= \frac{C_A \beta_i}{16 m_{J_i}^2} \int_{\cos(R)}^{\beta_i} \frac{d\cos\theta_S}{\pi} \frac{\alpha_S(k_0)}{(1-\beta\cos\theta_S)^2(1-\cos^2\theta_S)(2(1+\beta)-z^2)} \\
&\times \left(z^4(1+\cos\theta_S)^2 + z^2(1-\cos^2\theta_S)(2(1+\beta_i)-z^2) + (1-\cos\theta_S)^2(2(1+\beta_i)-z^2)^2\right)^2
\end{aligned}
$$





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

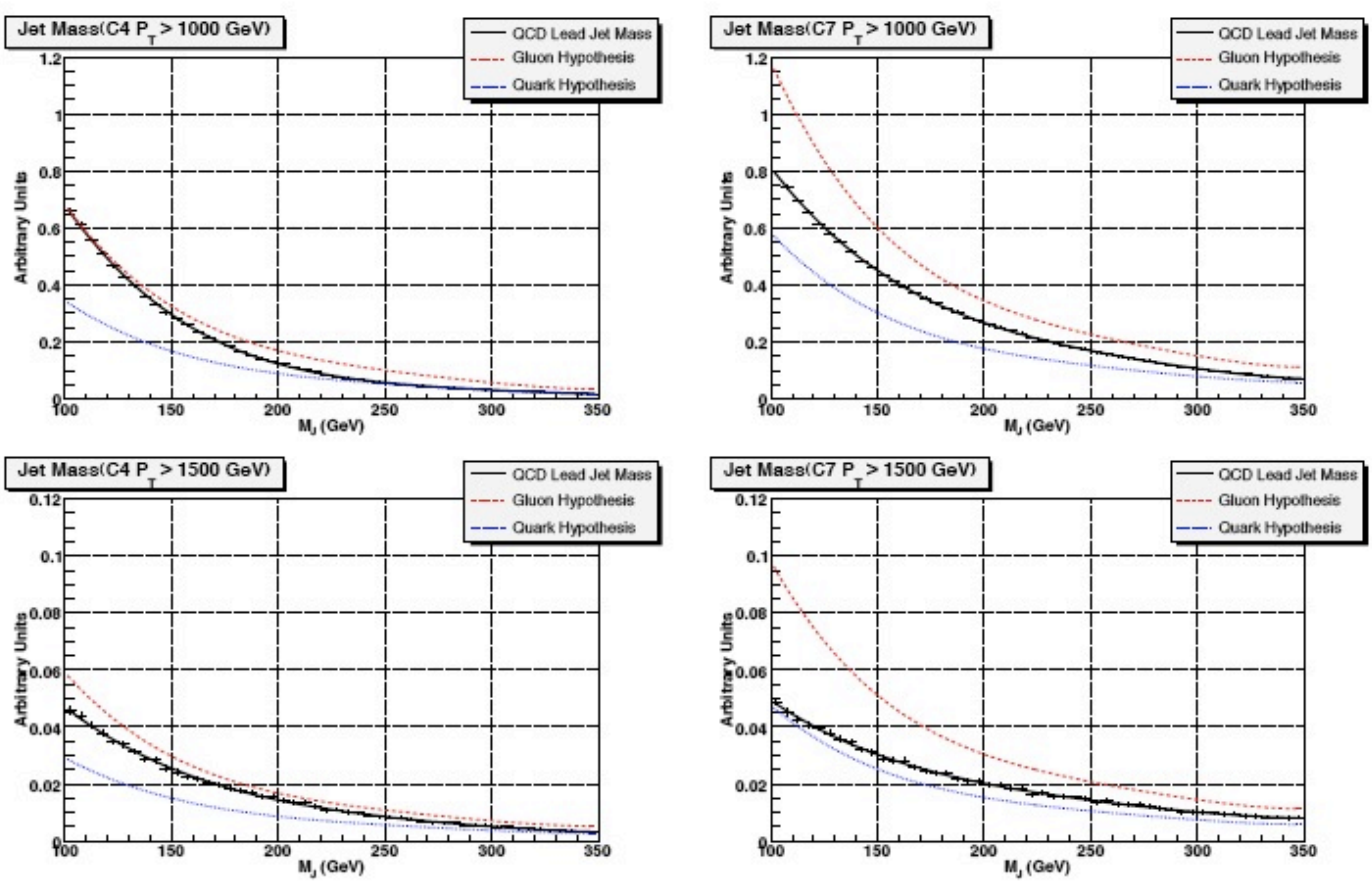
Data is admixture of the two, should be bounded by them:

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

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

Jet mass distribution theory vs. MC

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



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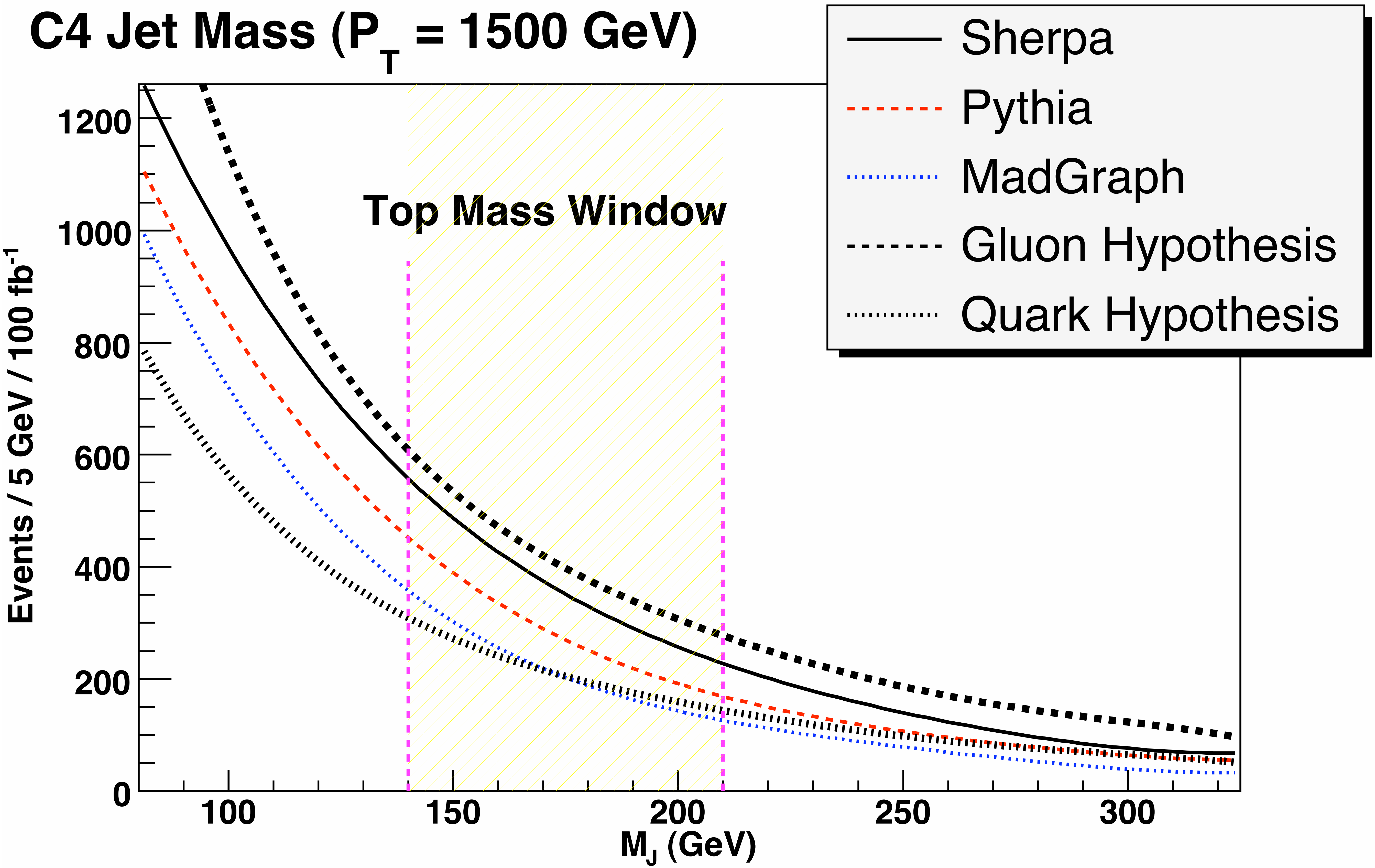

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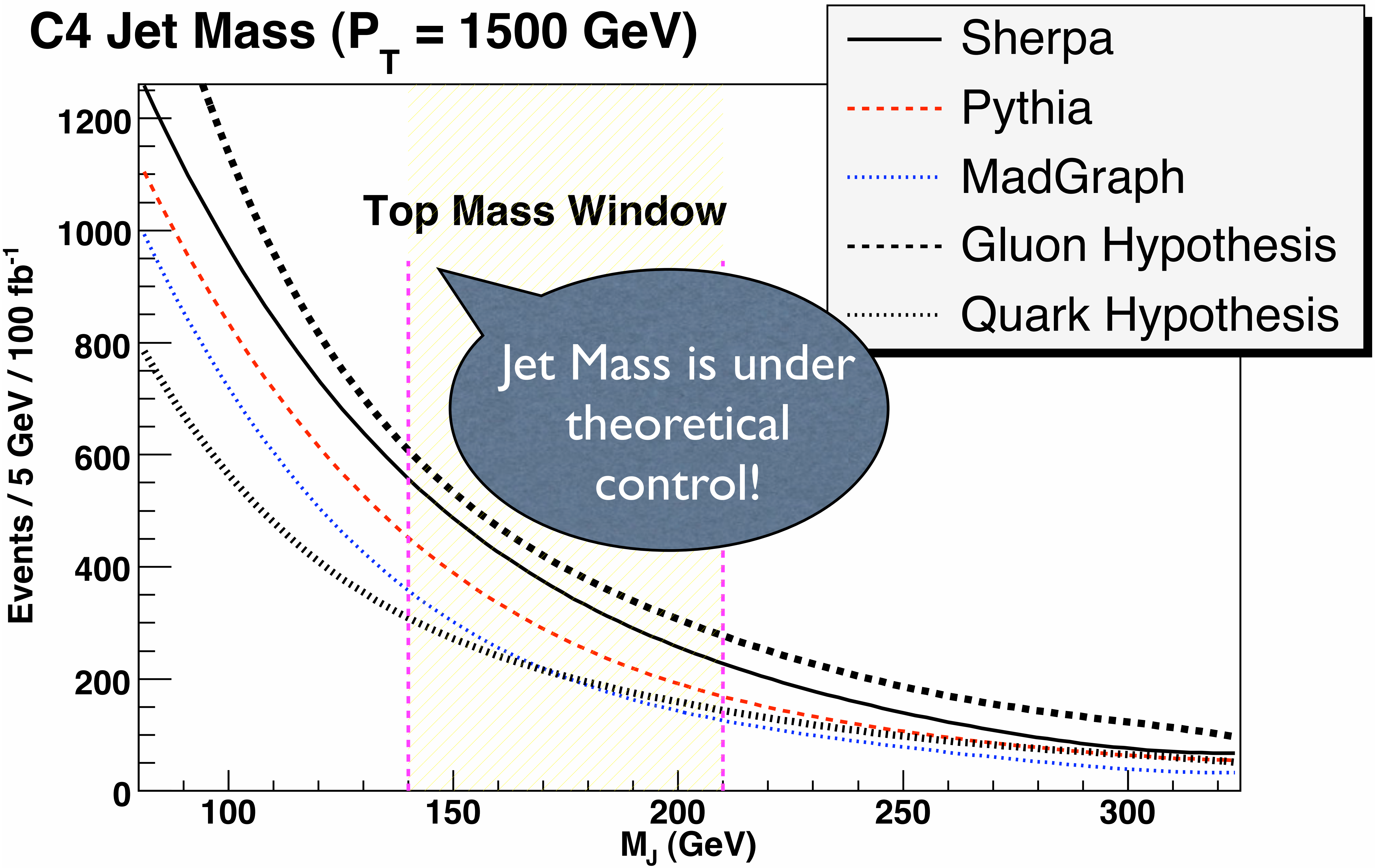
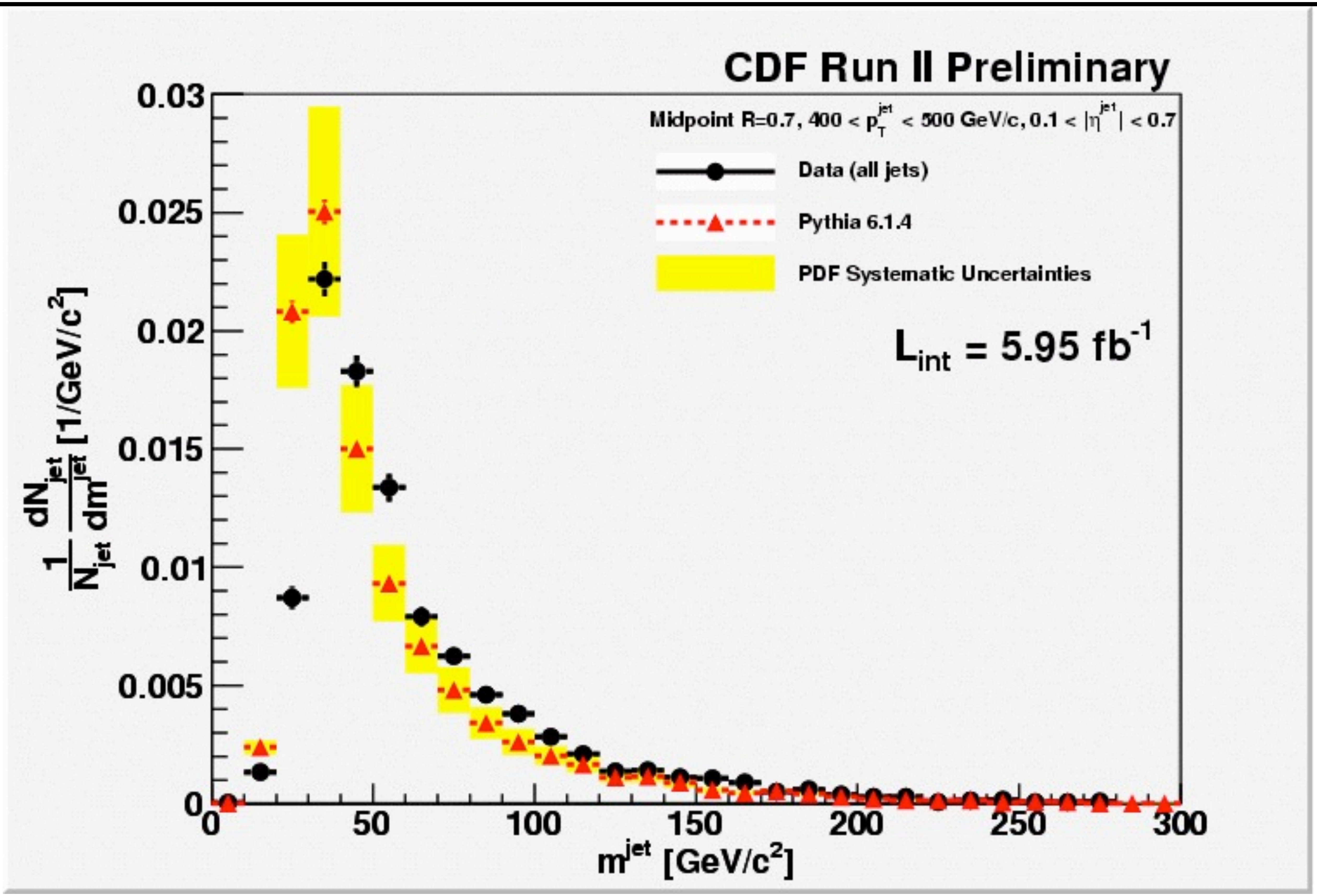
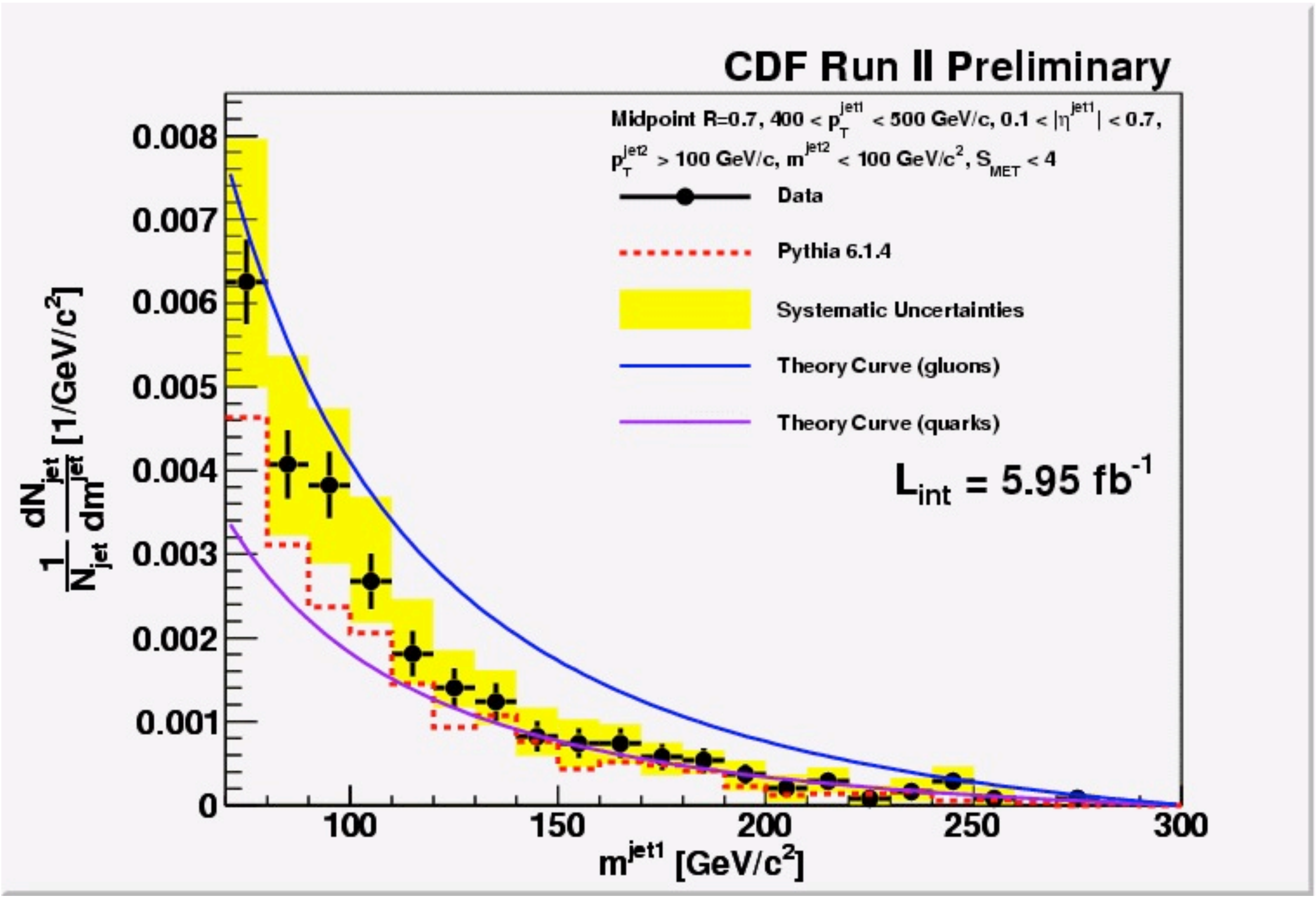


Jet mass distribution



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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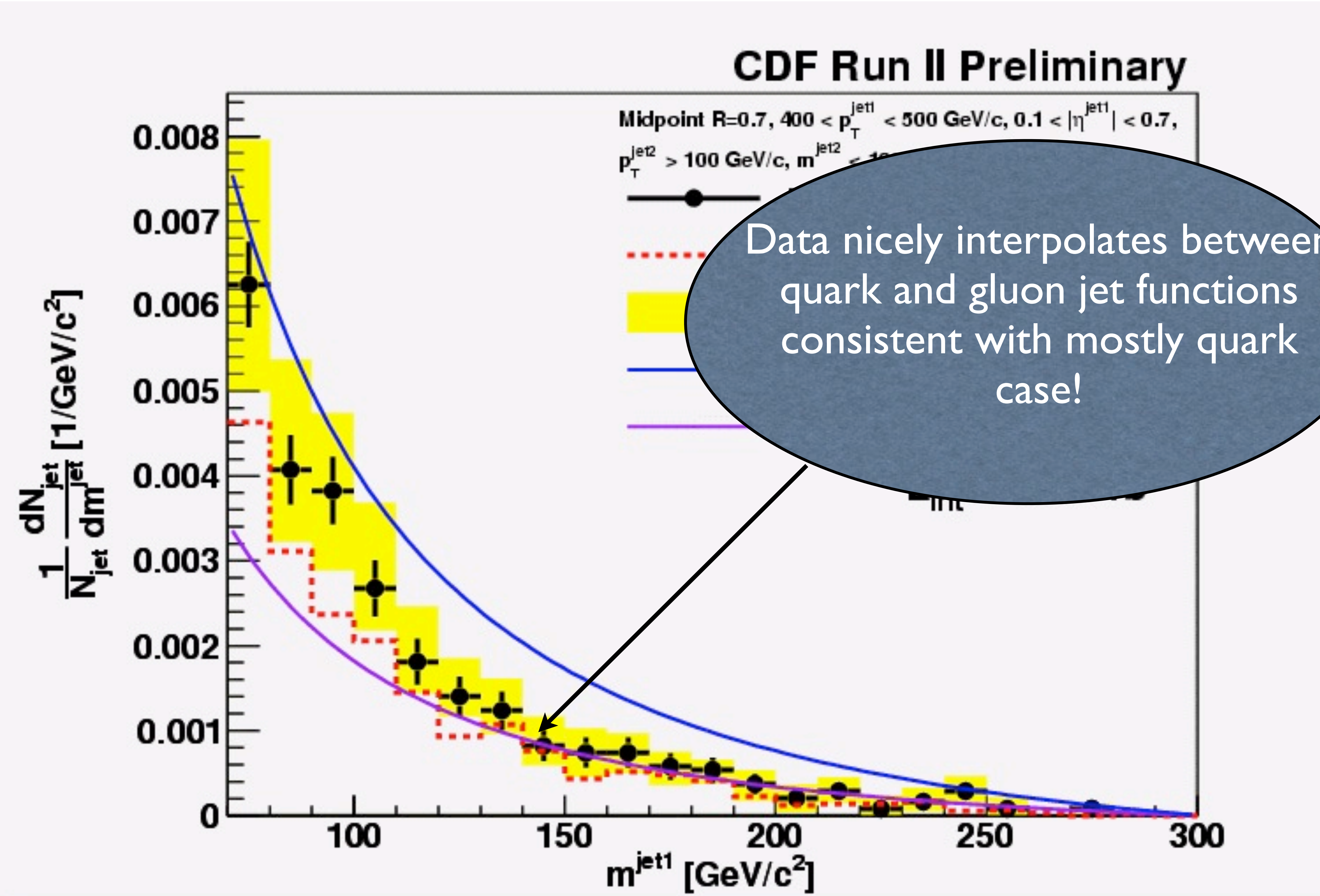


SM ttbar vs dijet: jet mass tagging

Resolve signal from dijet background:

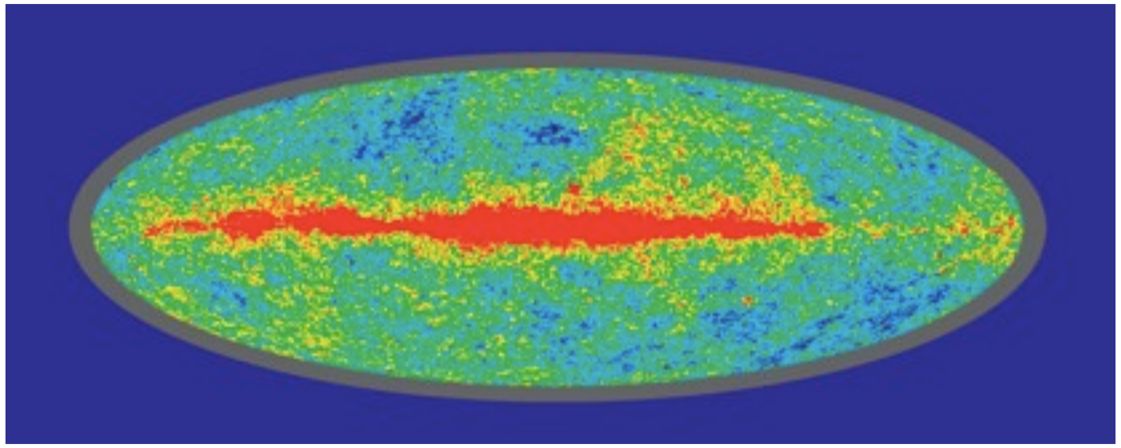
$$p_T^{min} \sim 1\ \text{TeV} \ \text{ and } \ 25\ \text{fb}^{-1}$$

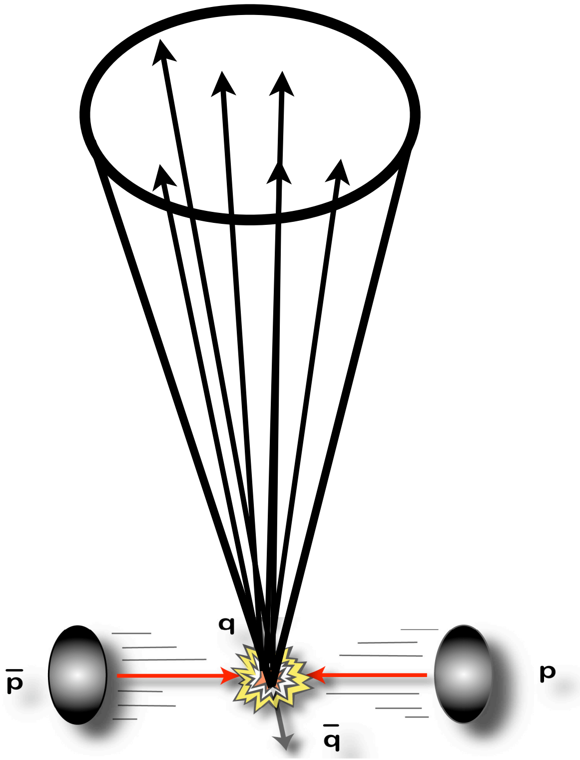
$$p_T^{min} \sim 1.5\ \text{TeV} \ \text{ with } \ 100\ \text{fb}^{-1}$$

without jet substructure or b-tagging

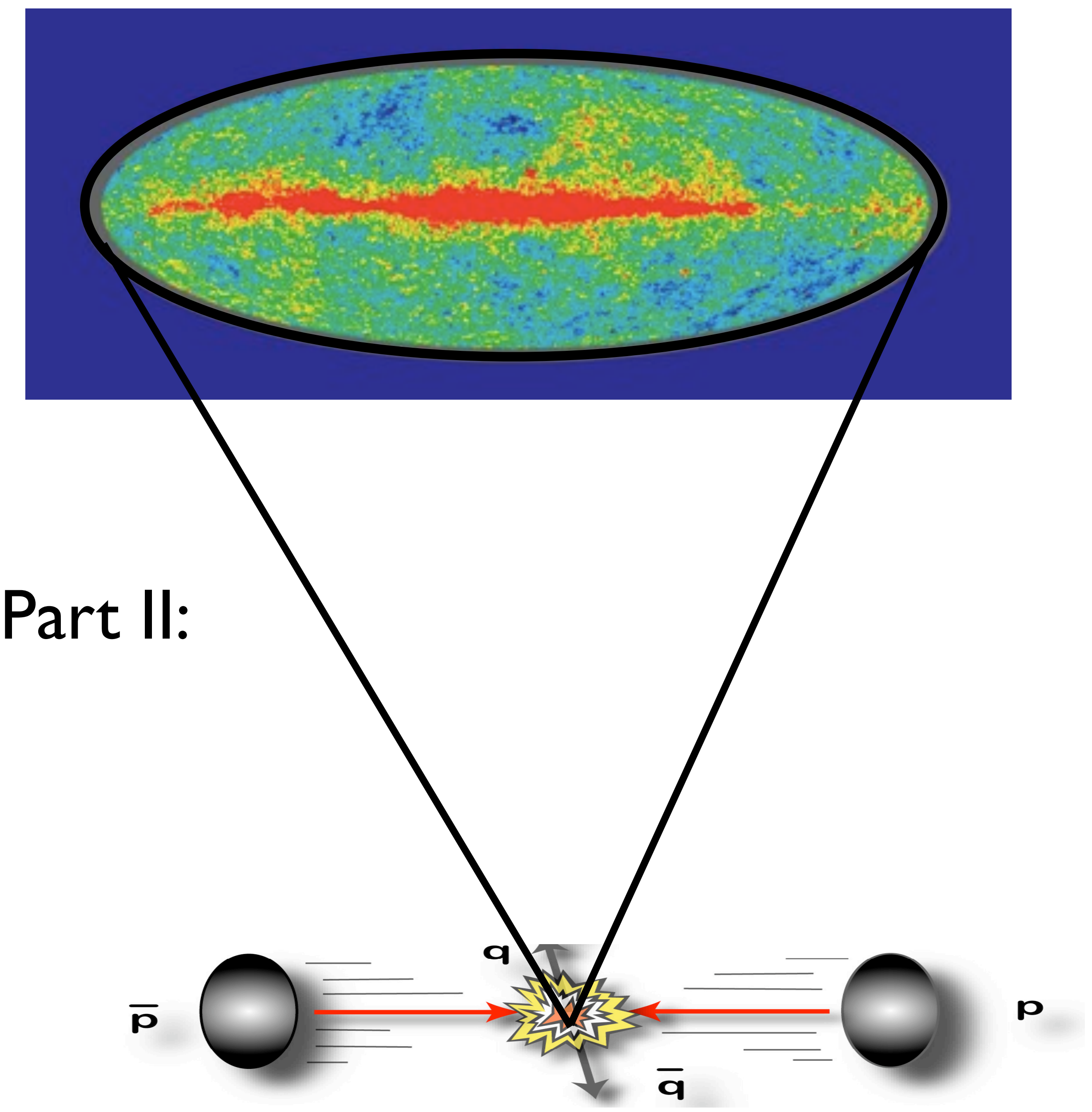
Note that if S/B is enhanced,
as in RS or other NP models reach is better.

Need to distinguish between top & ordinary QCD jet





Need to understand the energy flow inside jet
jet shapes or jet substructure



Theory of ultra massive boosted jets Part II:

(ii) Angularity & Planar flow.

(iii) Template Overlap Method

Why jets? What else?

- QCD amplitudes have soft-collinear singularity
- Observable: IR safe, smooth function of E flow

Sterman & Weinberg, PRL (77)

- Jet is a very inclusive object, defined via direction + p_T (+ mass)
- Even R=0.4 contains O(50) had-cells => huge amount of info' is lost

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n & Weinberg, PRL (77)

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direction
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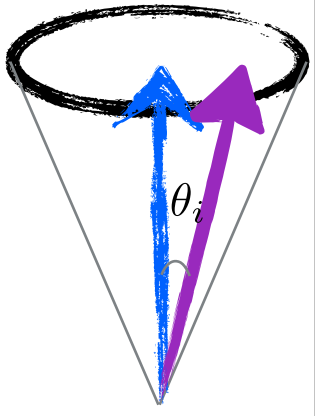
jet shape = inclusive observables
dependent on energy flow
within individual jets

IR-safe jet-shapes which know top from QCD jets?

- Successes in high jet mass => jet function is well described by single gluon radiation



IR-safe jet-shapes which know top from QCD jets?

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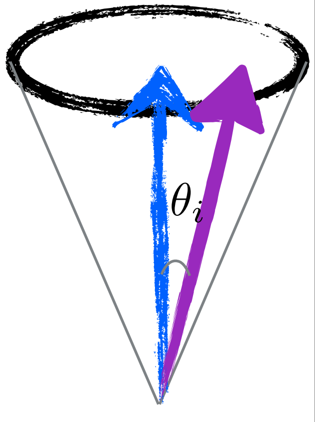
- Once jet mass is fixed at a high scale
  - ➡ Large class of jet-shapes become perturbatively calculable



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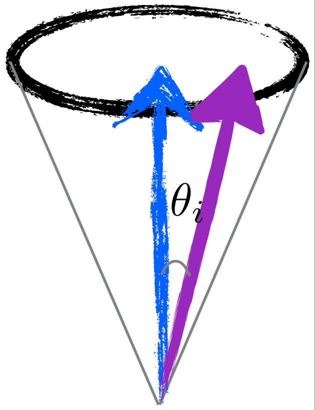
- Once jet mass is fixed at a high scale
  - Large class of jet-shapes become perturbatively calculable

- As a warm-up consider angularity (2-body final state):

Berger, K´ucs and Sterman (03)

Angularities on a cone:

Almeida, SL Perez, Sterman, Sung, & Virzi.



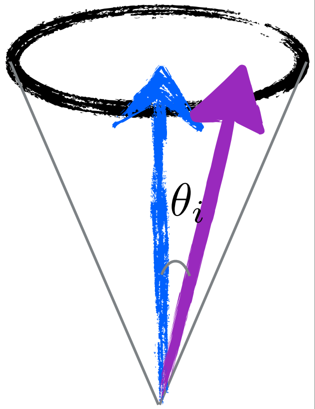
IR-safe jet-shapes which know top from QCD jets?

- Successes in high jet mass => jet function is well described by single gluon radiation
- Once jet mass is fixed at a high scale
  - ➡ Large class of jet-shapes become perturbatively calculable
- As a warm-up consider angularity (2-body final state):

Berger, K´ucs and Sterman (03)

Angularities on a cone:

$$\tilde{\tau}_a(R, m_J) = \frac{1}{m_J} \sum_{i \in \text{jet}} \omega_i \sin^a\left(\frac{\pi\theta_i}{2R}\right)\left[1 - \cos\left(\frac{\pi\theta_i}{2R}\right)\right]^{1-a} \sim \frac{1}{m_J} \frac{1}{2^{1-a}} \sum_{i \in \text{jet}} \omega_i \left(\frac{\pi\theta_i}{2R}\right)^{2-a}$$



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

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a ≤2 for IR safety

✦Angularities distinguish between Higgs and QCD jets:

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

v.s.

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

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

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

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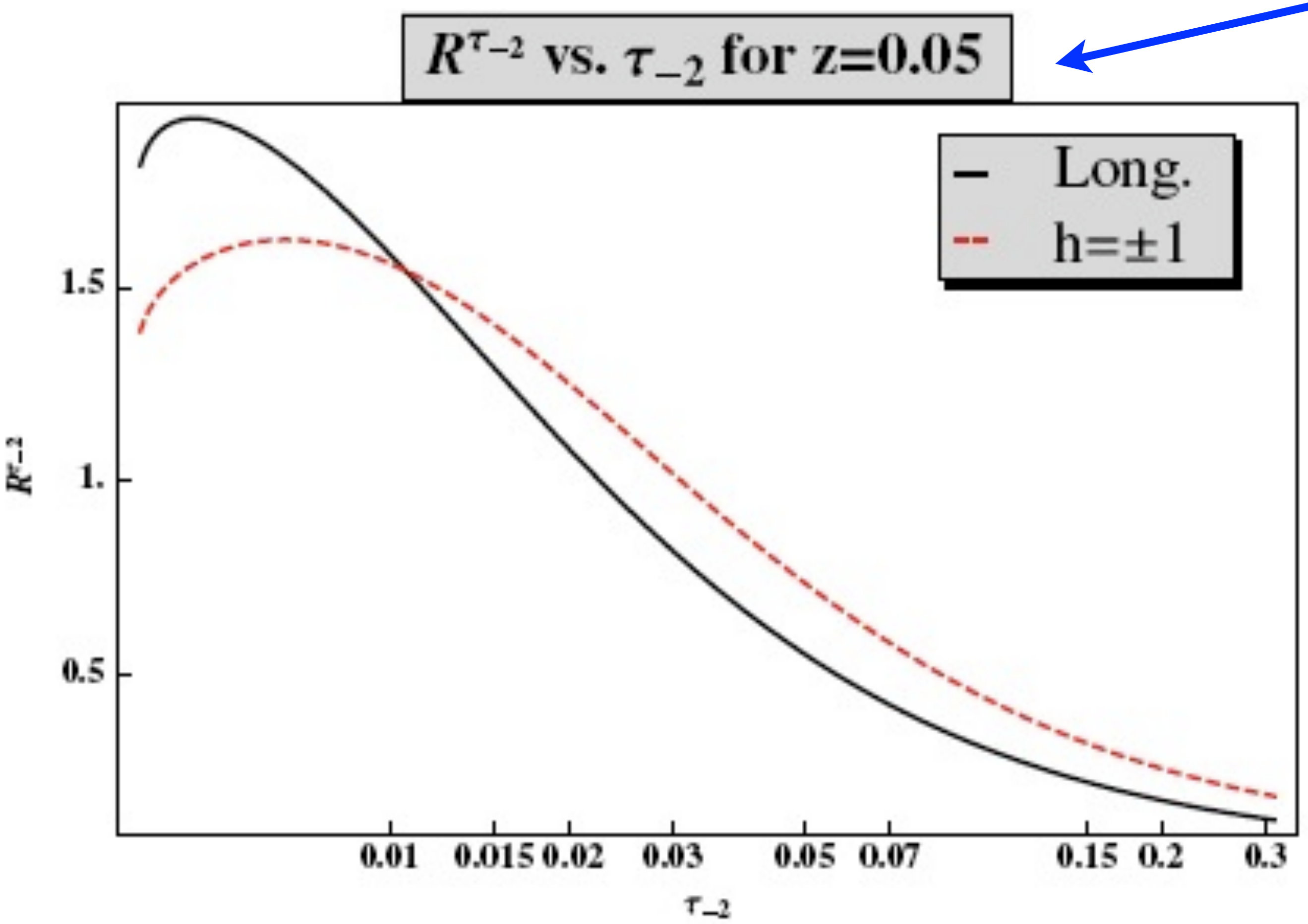


FIG. 3 (color online). The ratio between the signal and background probabilities to have jet angularity $\tilde{\tau}_{-2}$, $R^{\tilde{\tau}_{-2}}$.

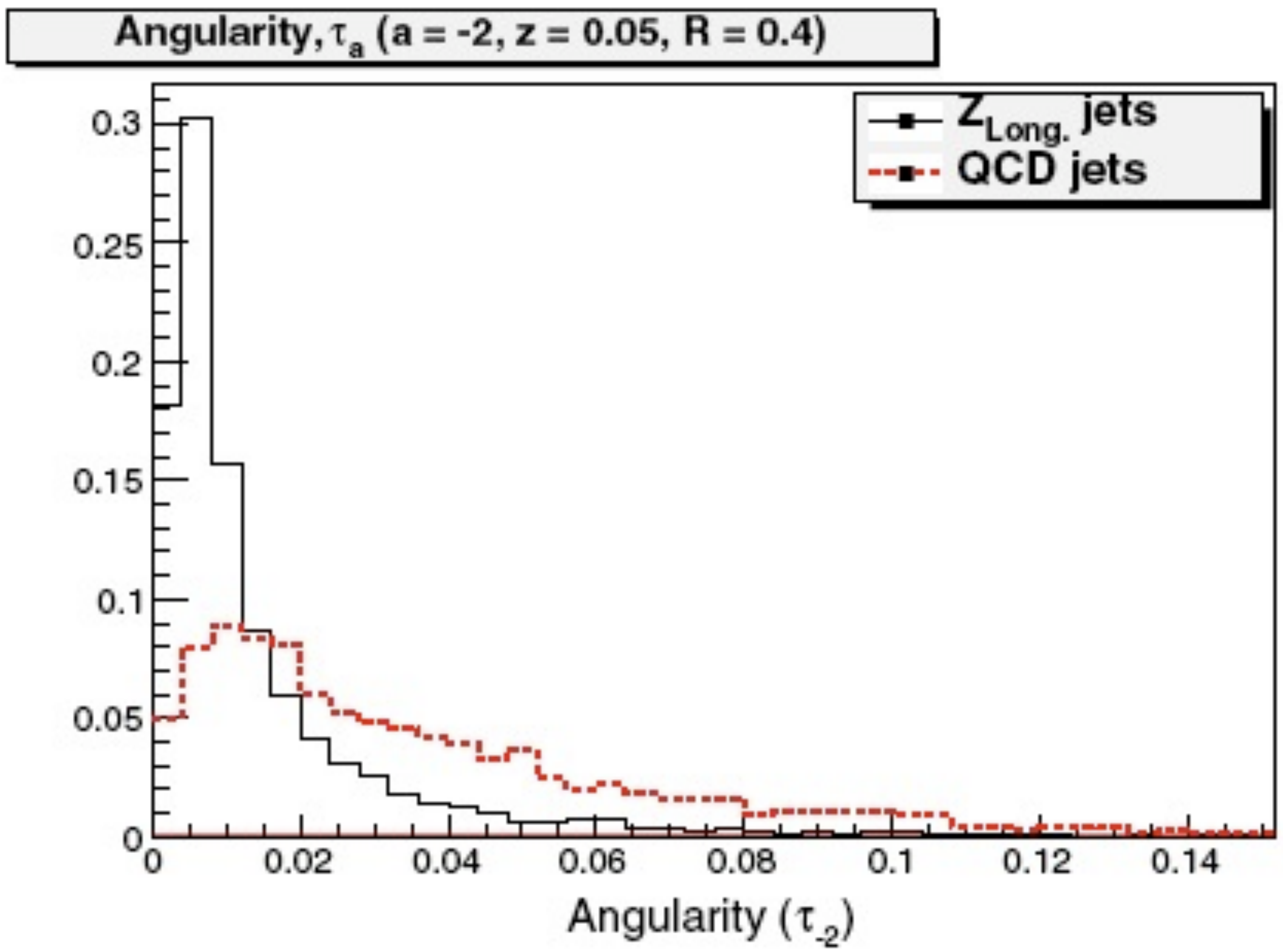
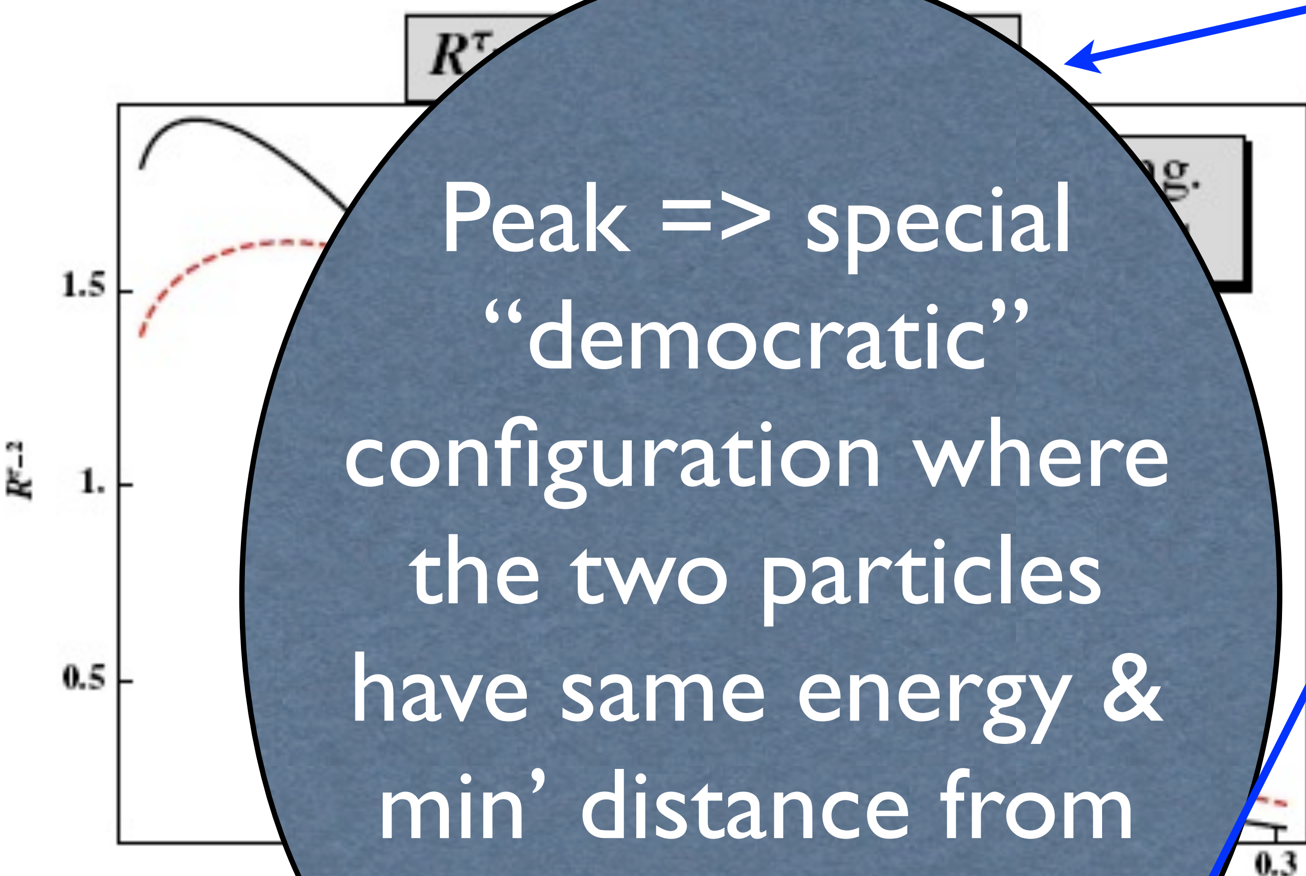


FIG. 4 (color online). The angularity distribution for QCD (red-dashed curve) and longitudinal Z (black-solid curve) jets obtained from MADGRAPH. Both distributions are normalized to the same area.

$(z = m_J/p_T)$

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

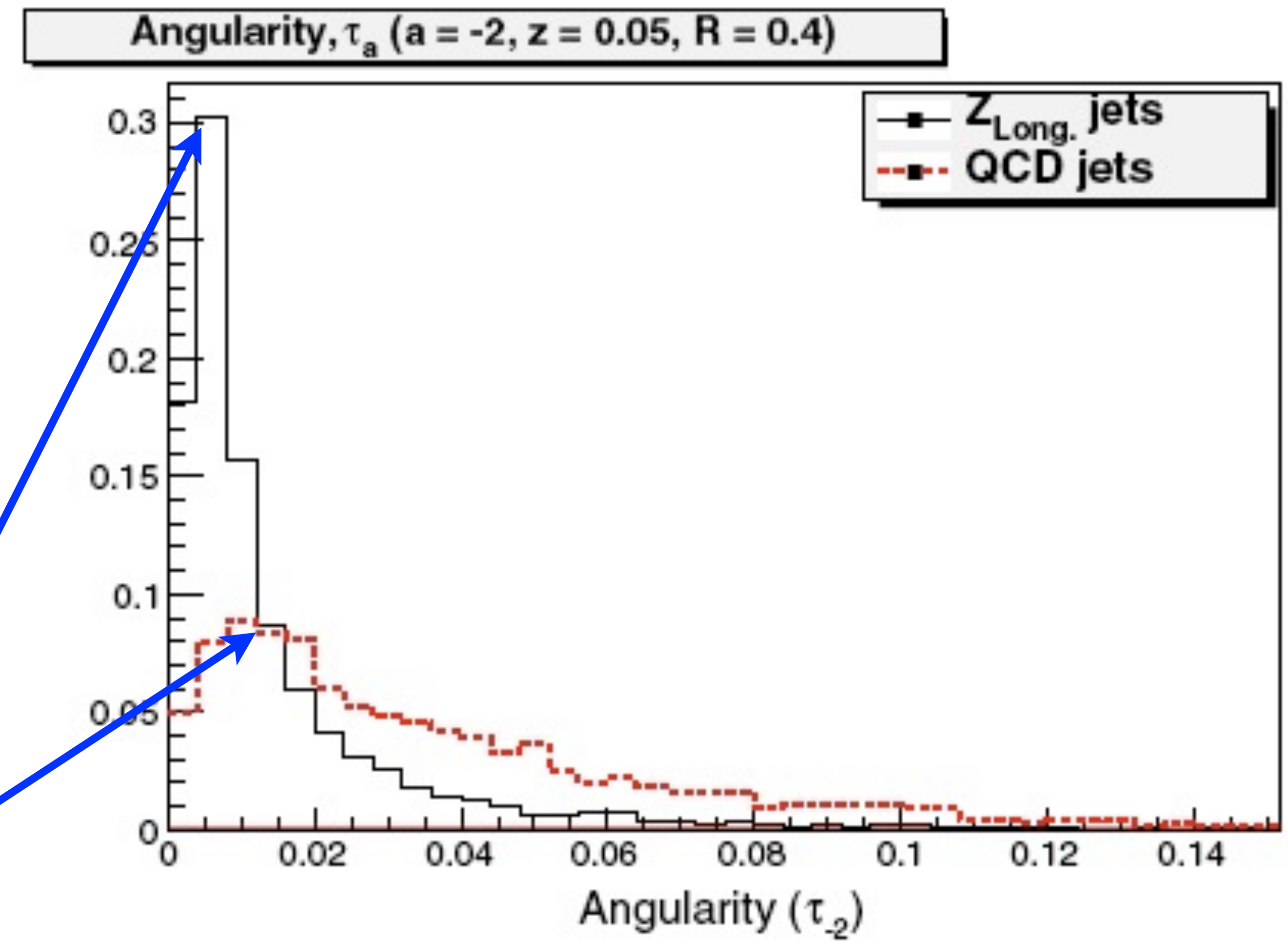
$$P^x(\theta_s) = (dJ^x/d\theta_s)/J^x \Rightarrow P^x(\tilde{\tau}_a)\,; \quad R(\tilde{\tau}_a) = \frac{P^{\rm sig}(\tilde{\tau}_a)}{P^{\rm QCD}(\tilde{\tau}_a)}$$



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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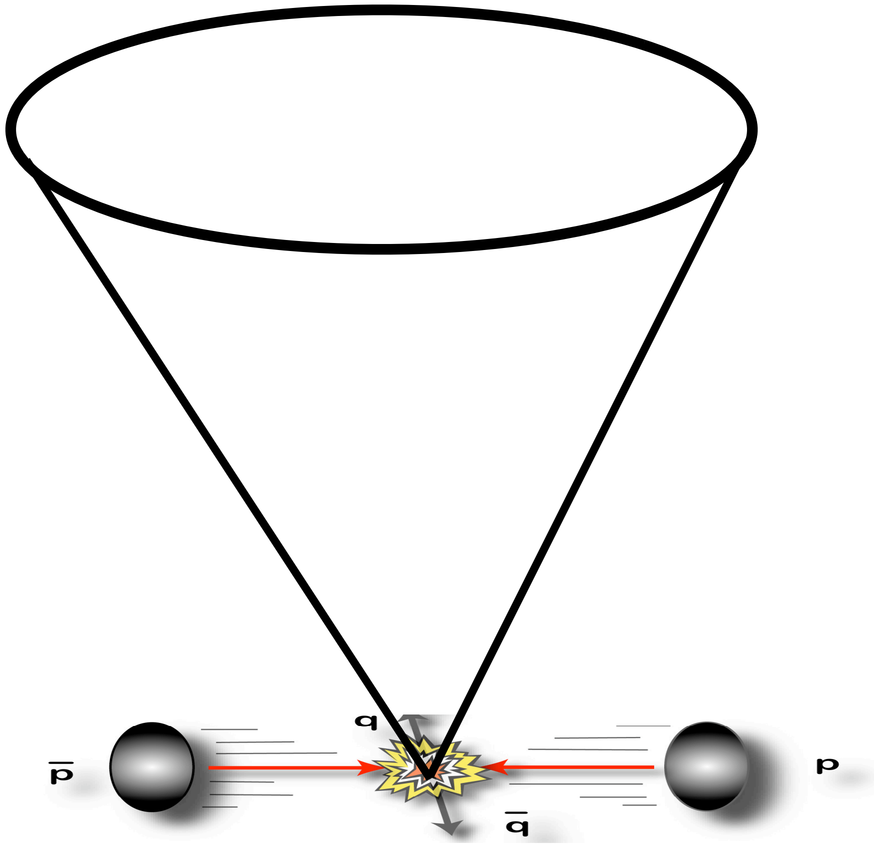
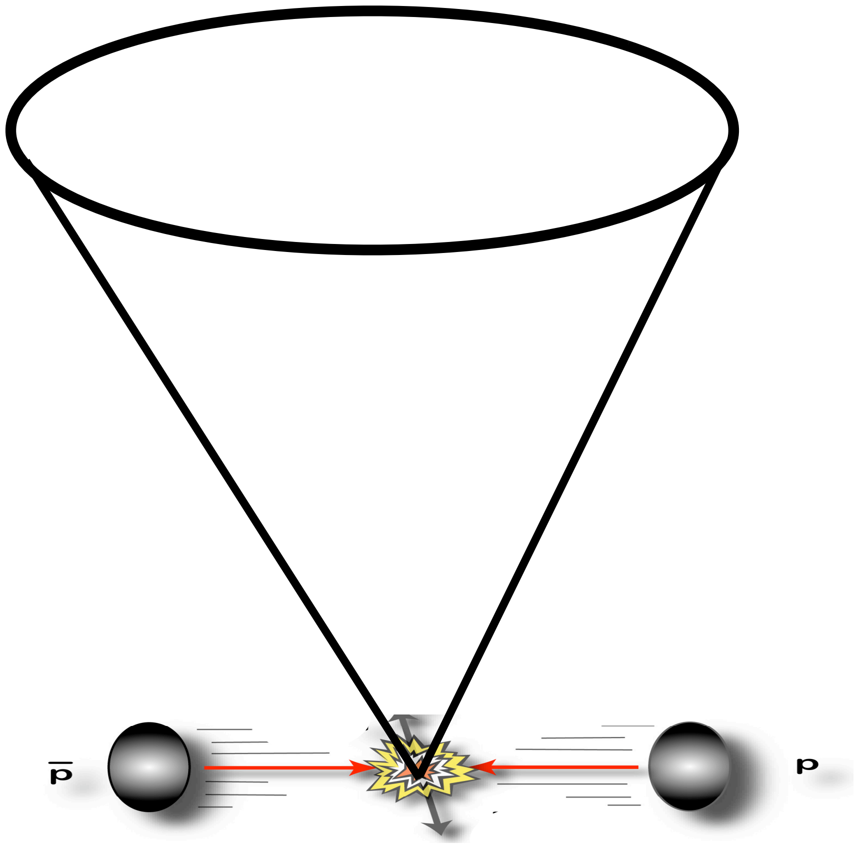
Planar flow

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

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



QCD massive jet



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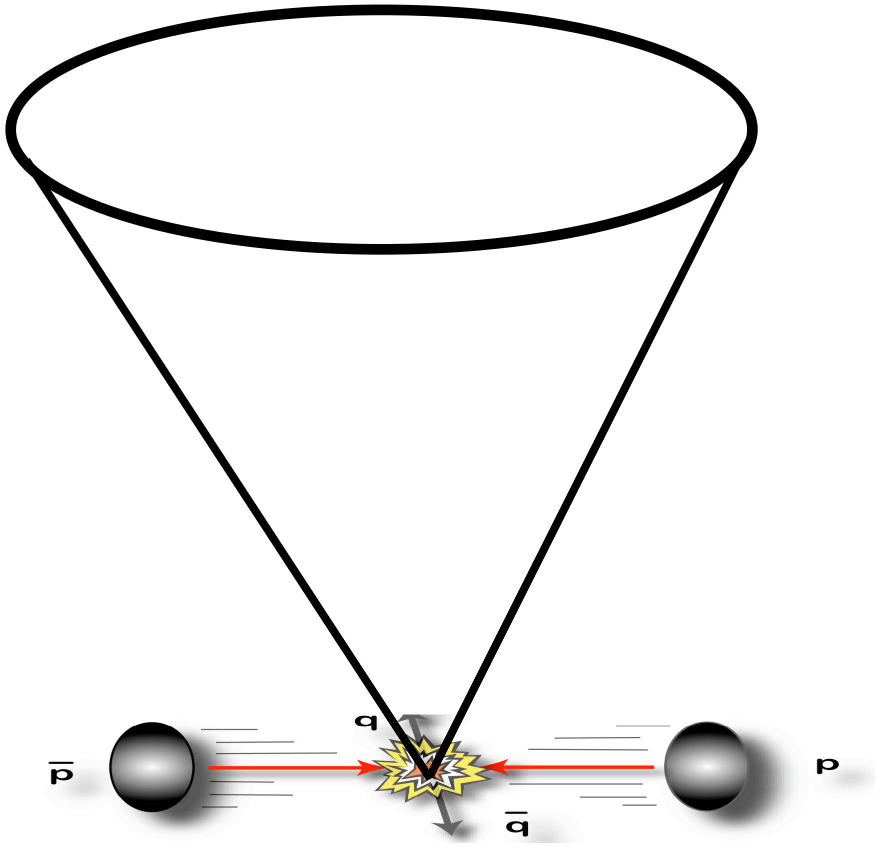

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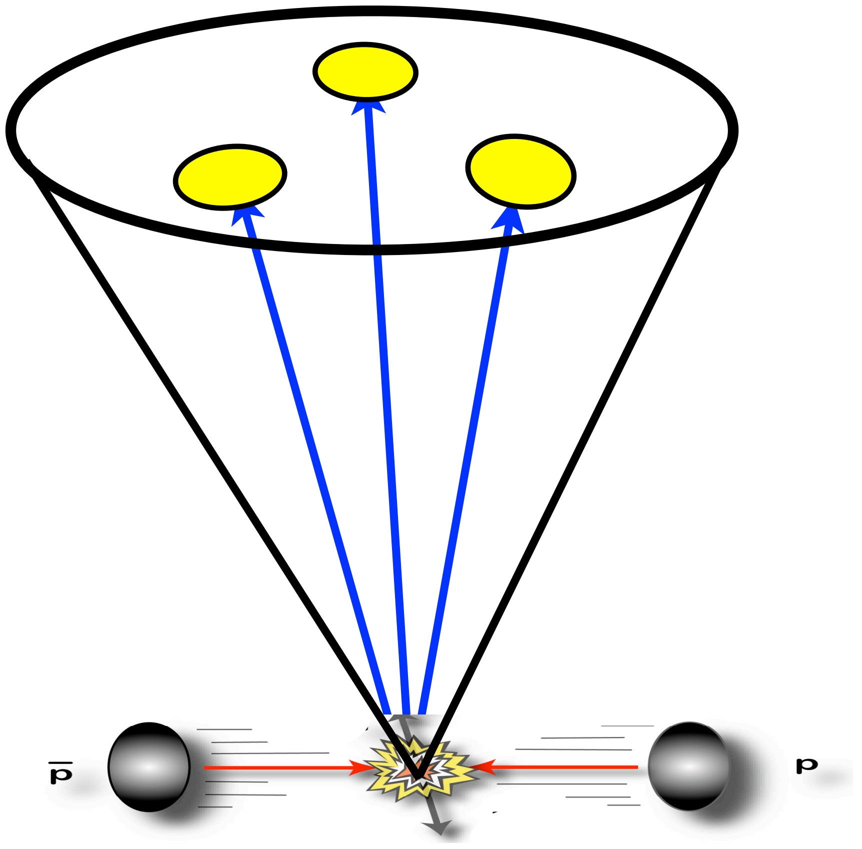

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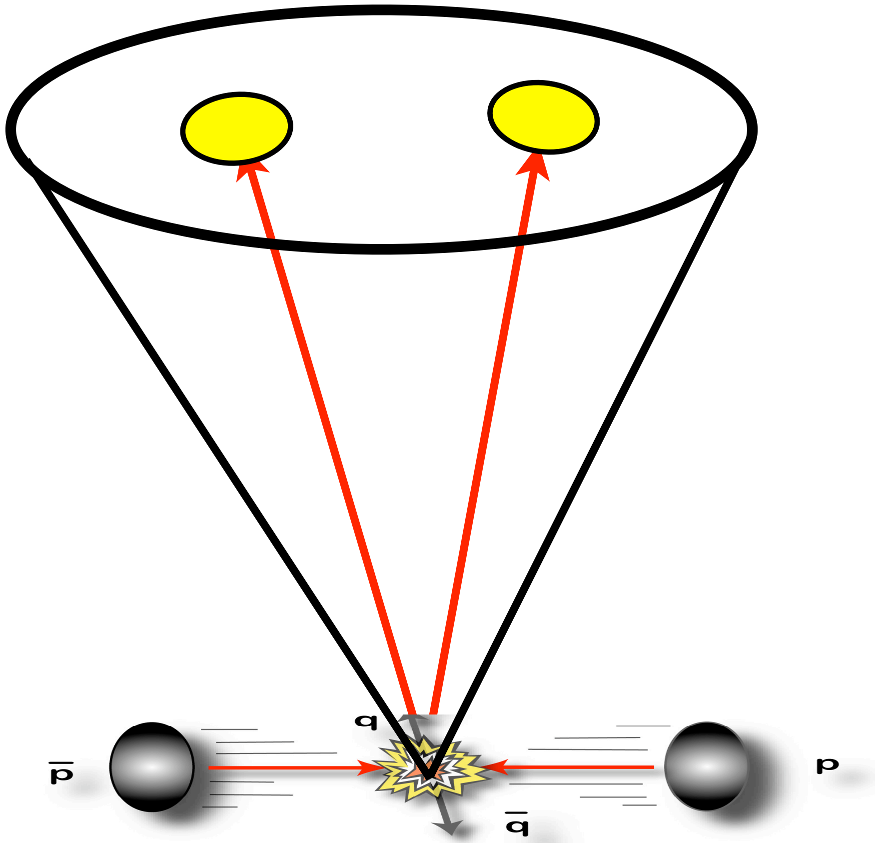

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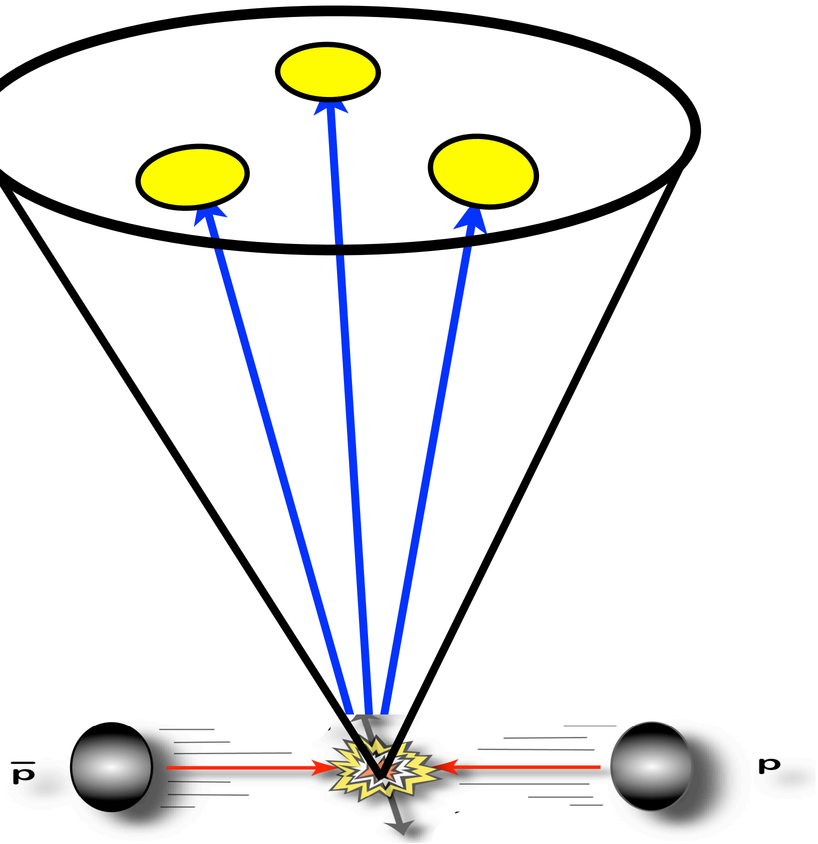

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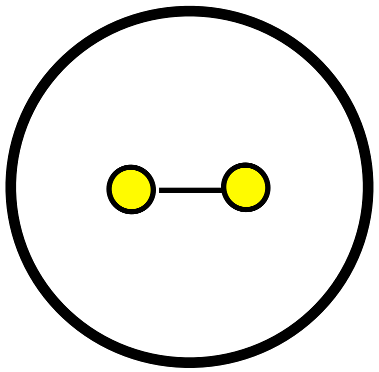
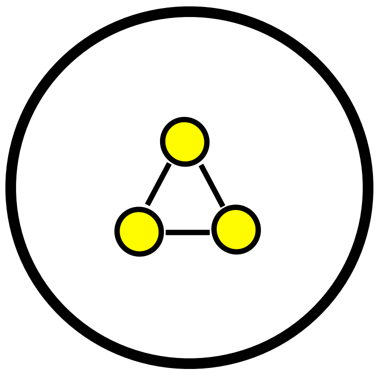
- Planar flow, *Pf*, measures the energy ratio between two primary axes of cone surface:

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



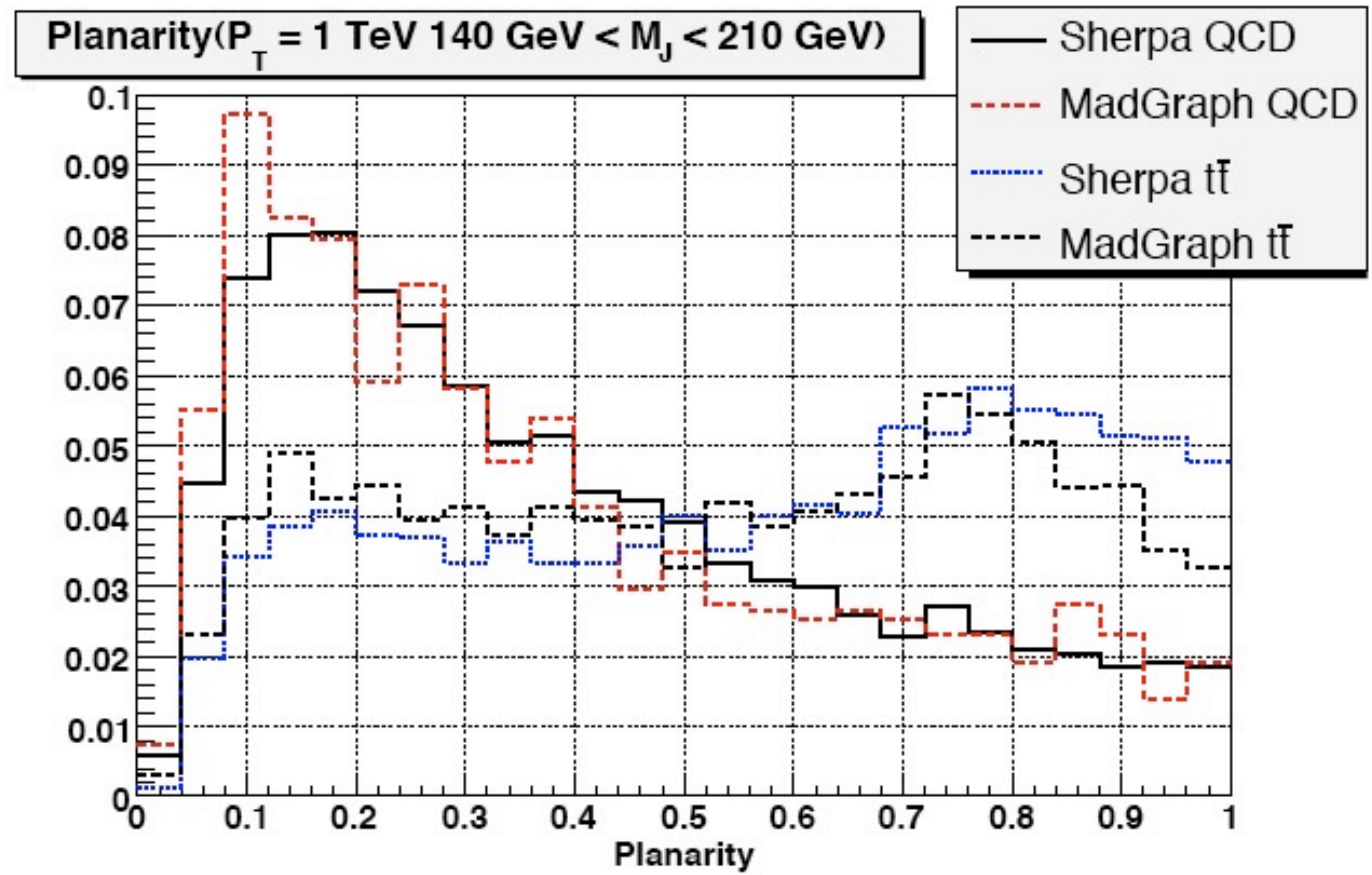
leading order QCD, *Pf=0*



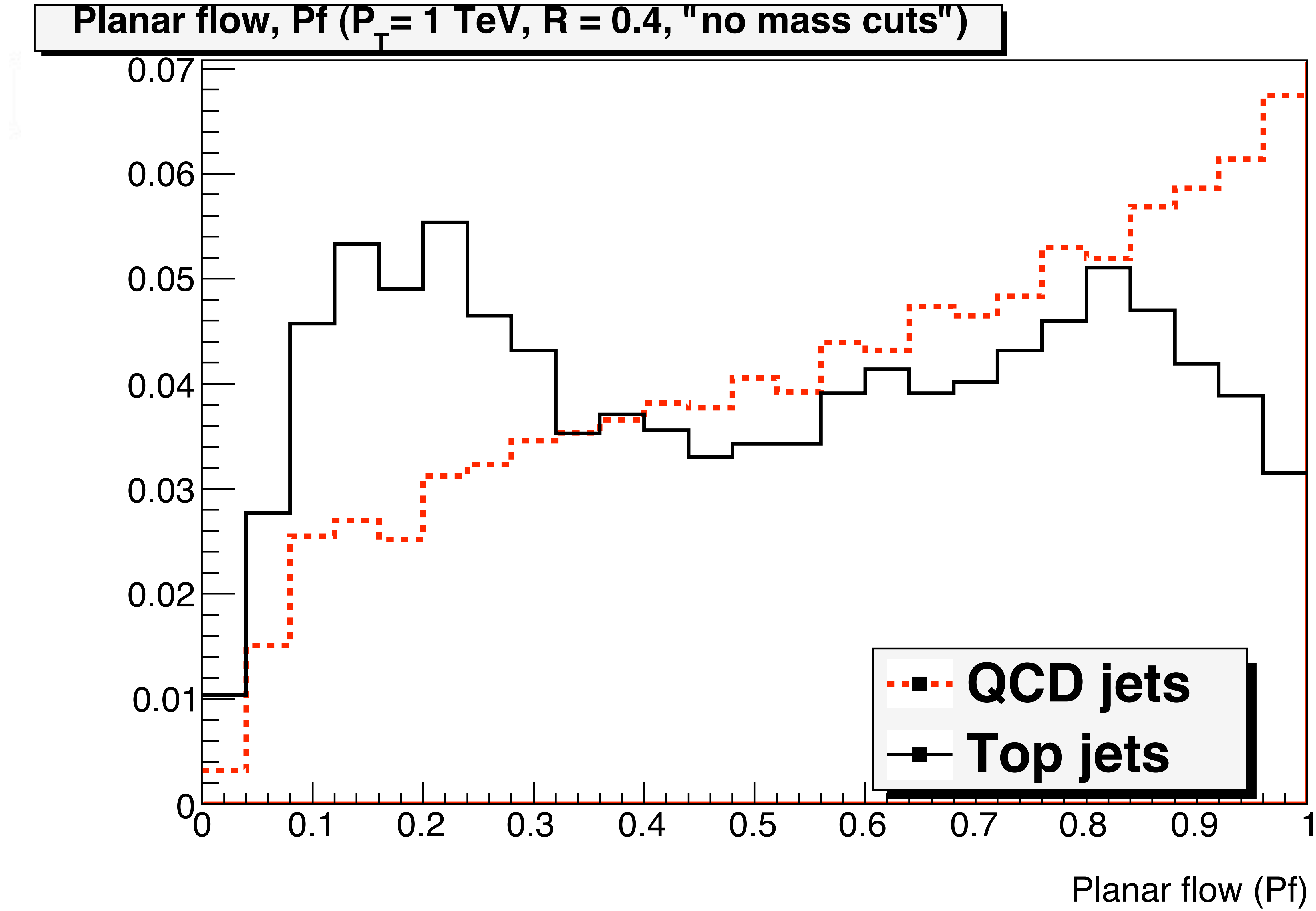
top jet, *Pf=1*

Planar flow, QCD vs top jets

Planar flow, QCD vs top jets



Planar flow, QCD vs top jets



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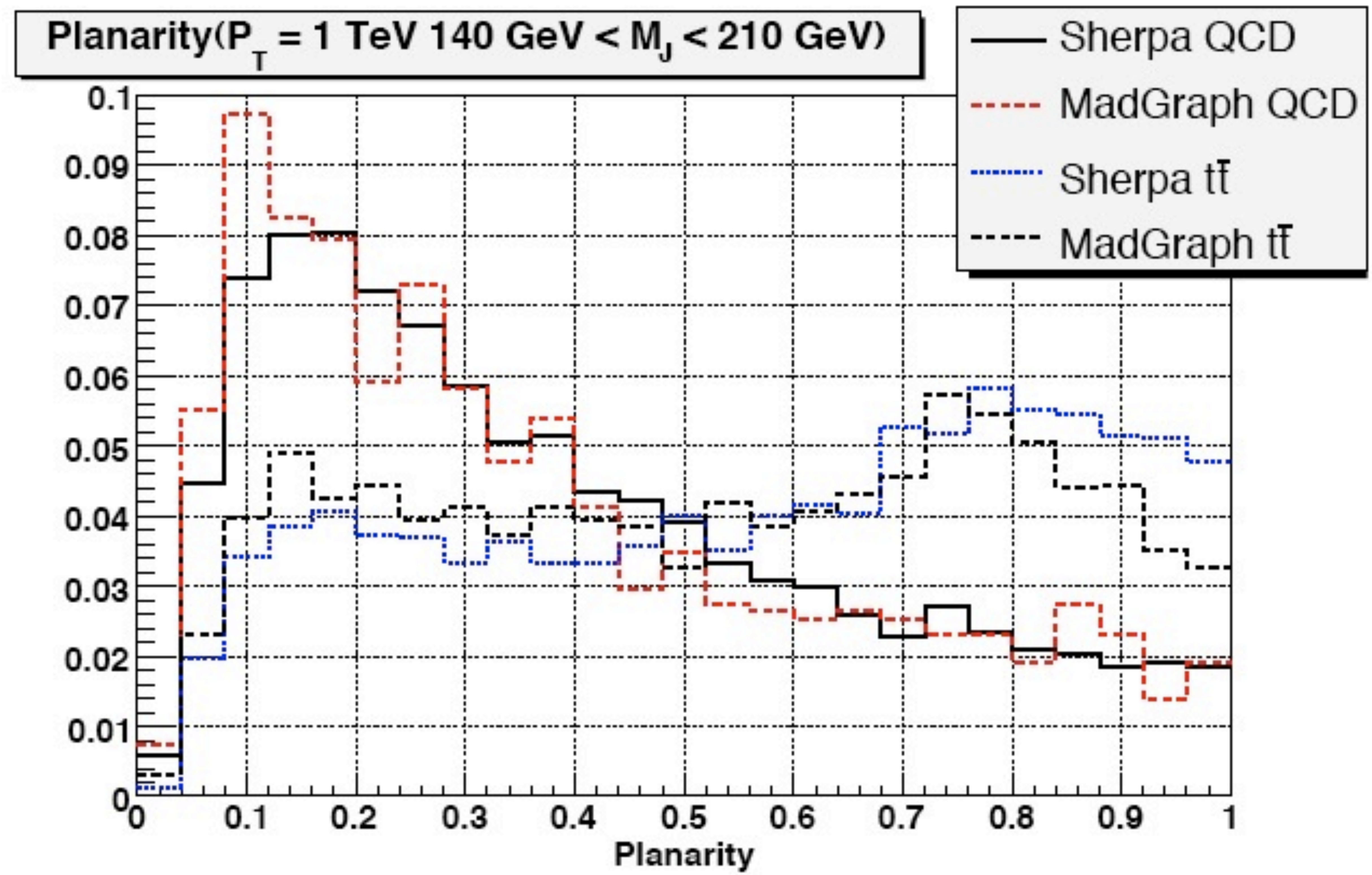
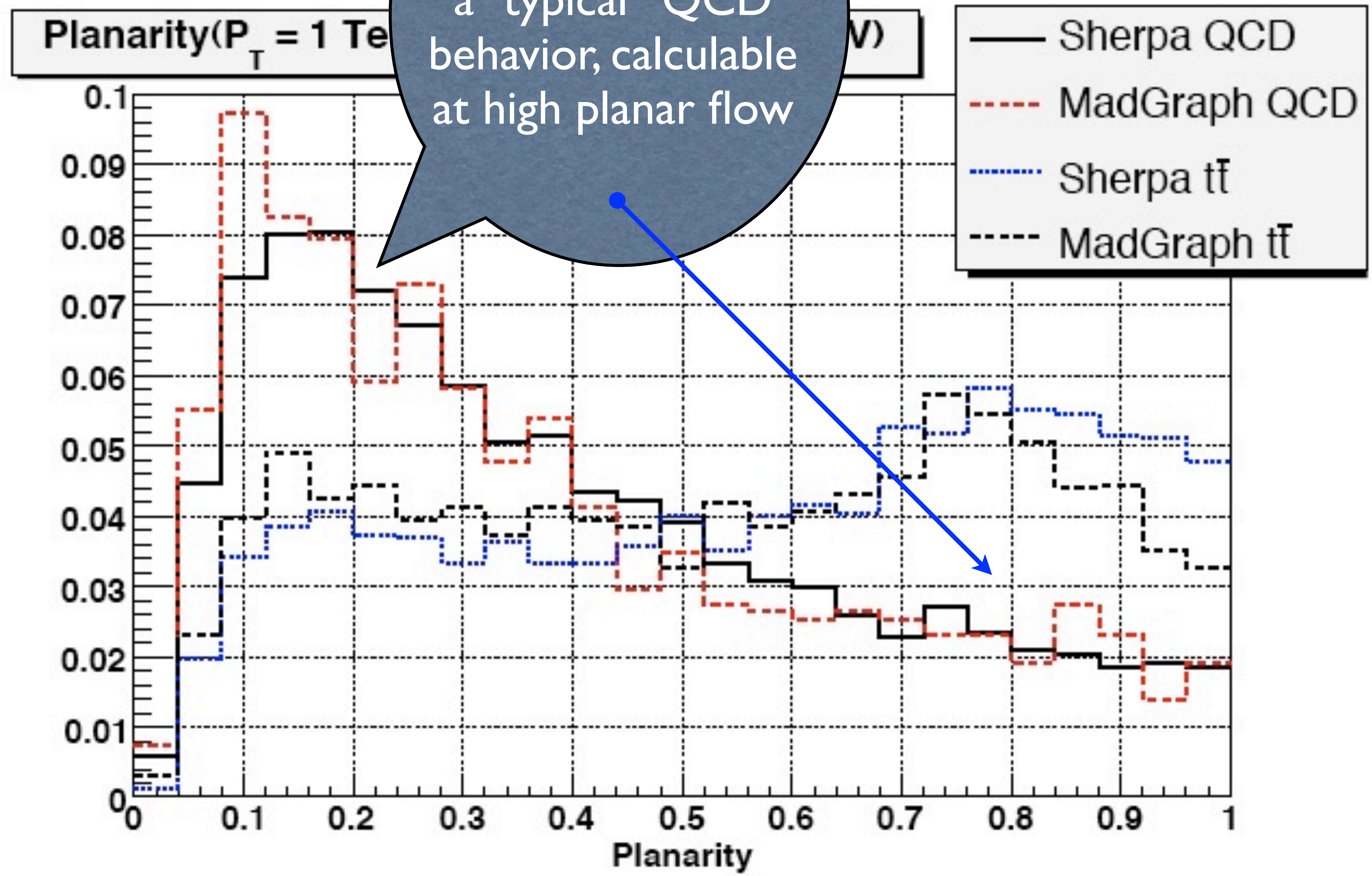
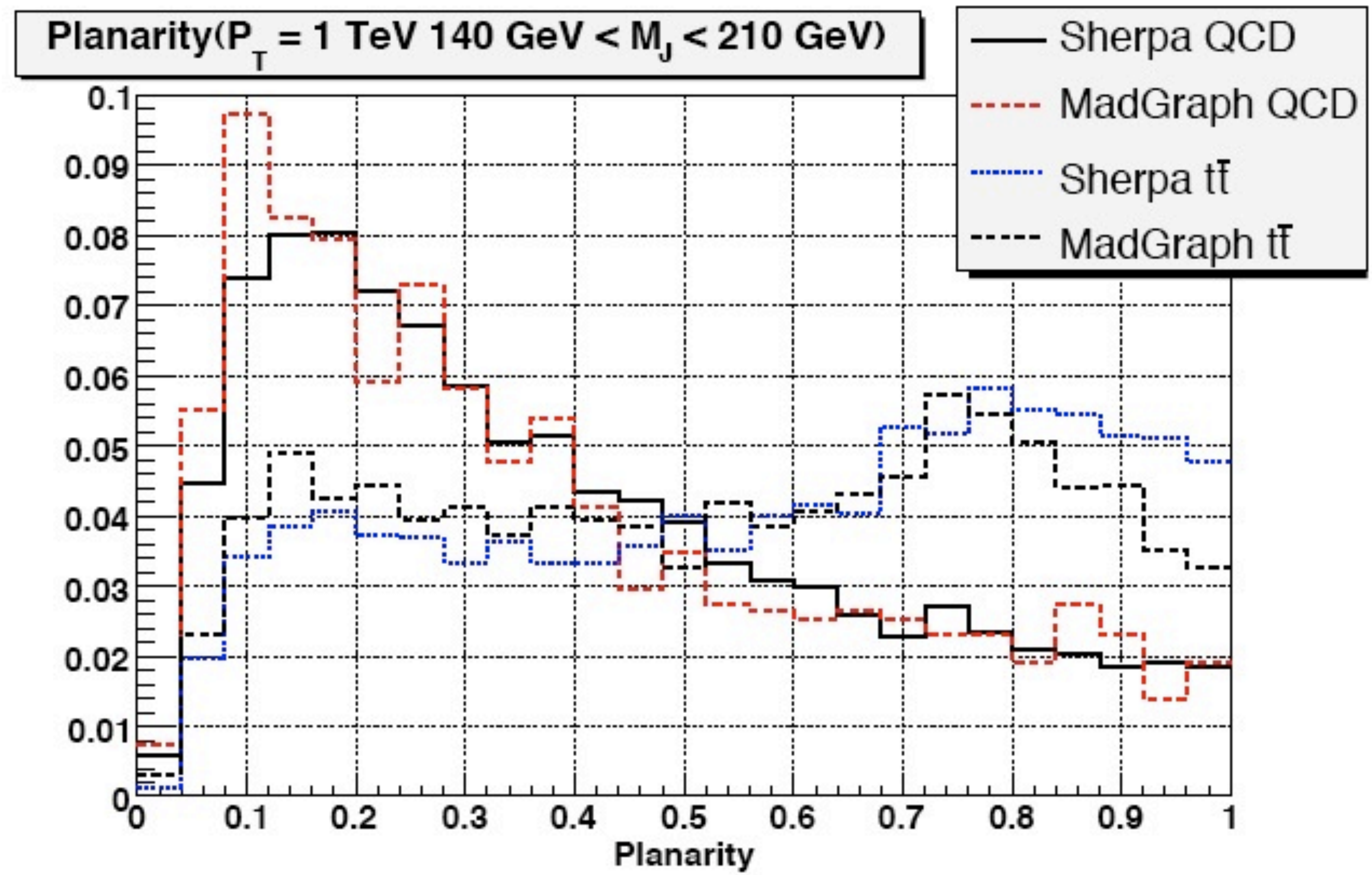


Planar flo… CD vs top jets

QCD
Planar flow shows a “typical” QCD behavior, calculable at high planar flow



Planar flow, QCD vs top jets



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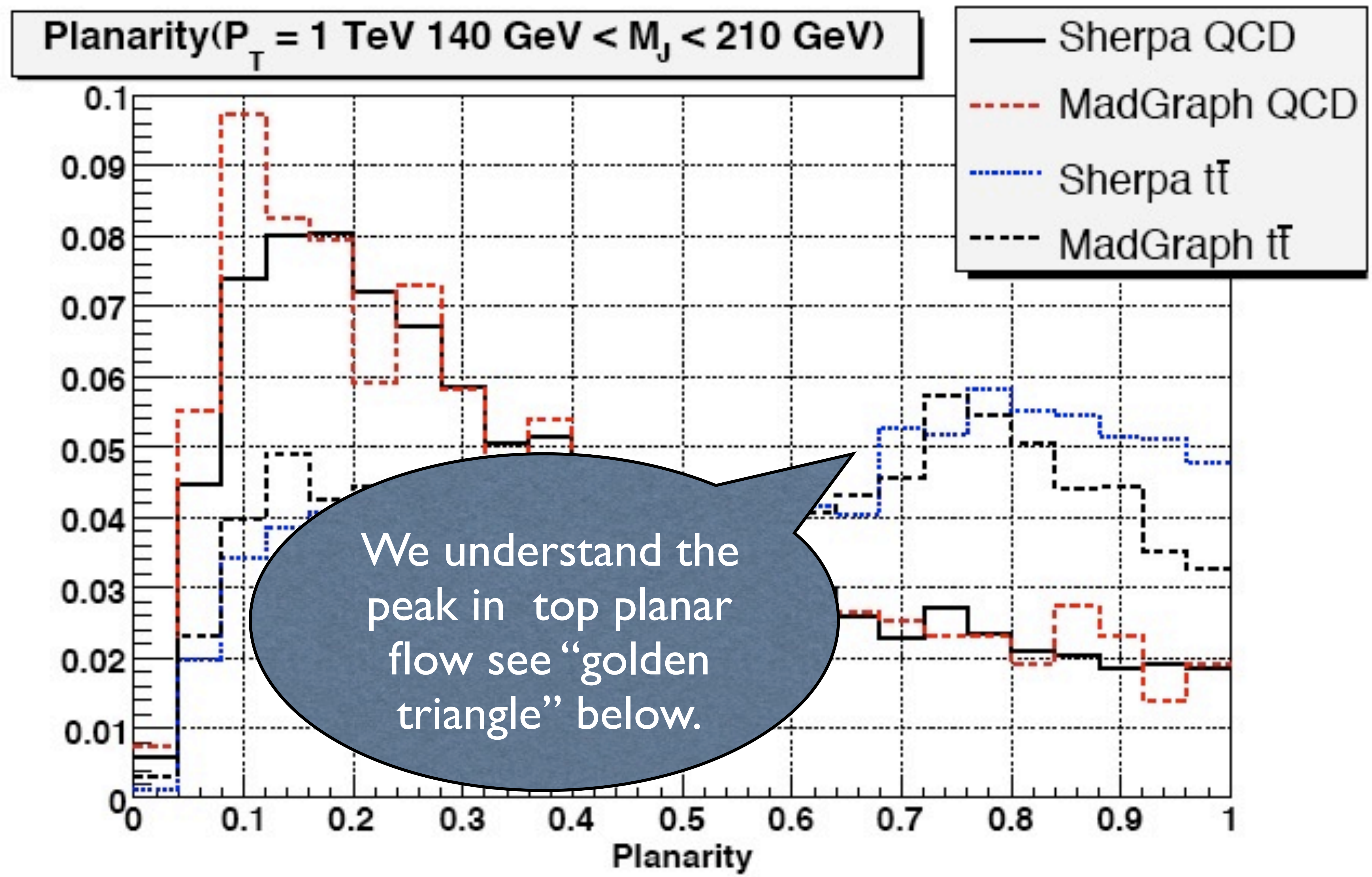
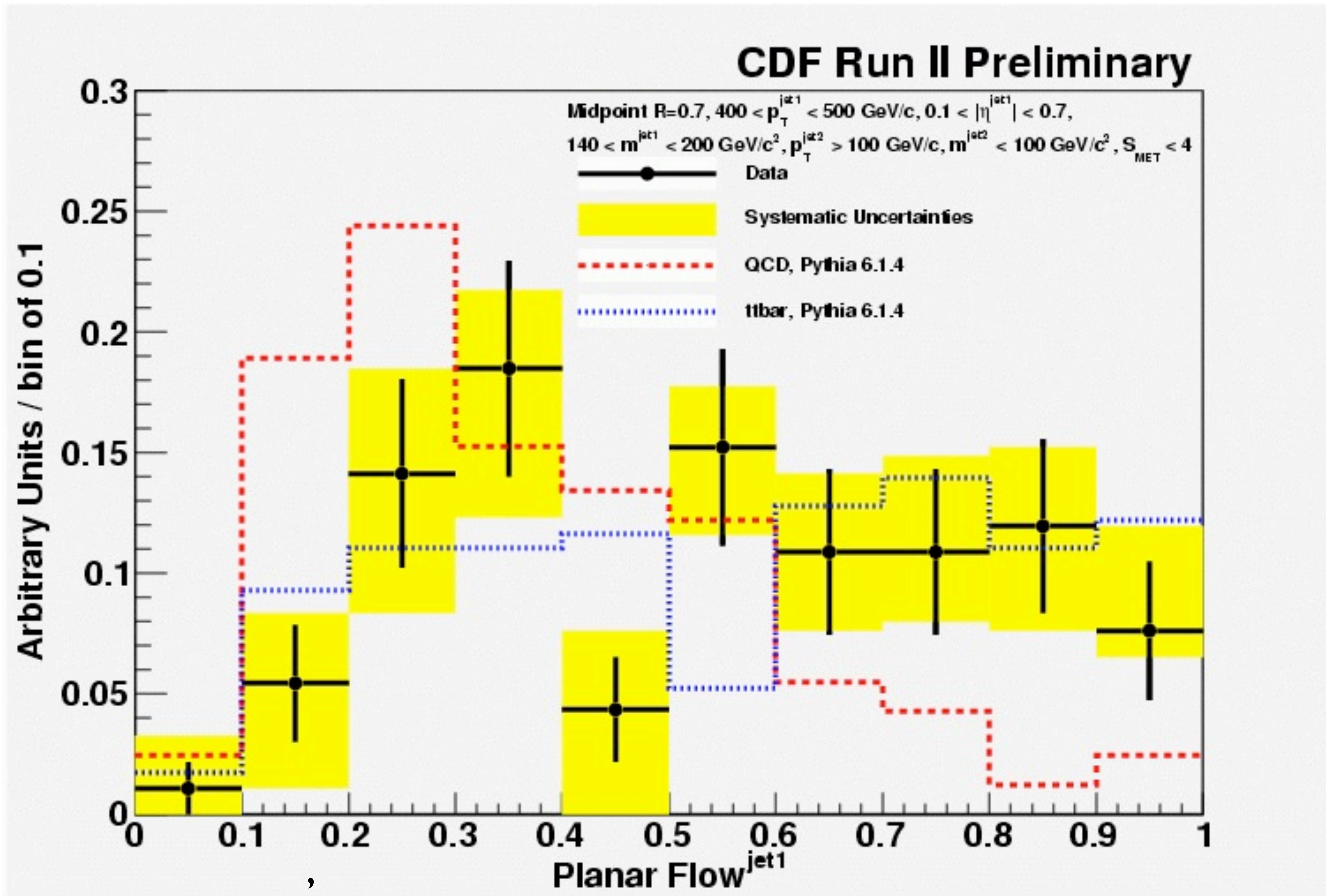
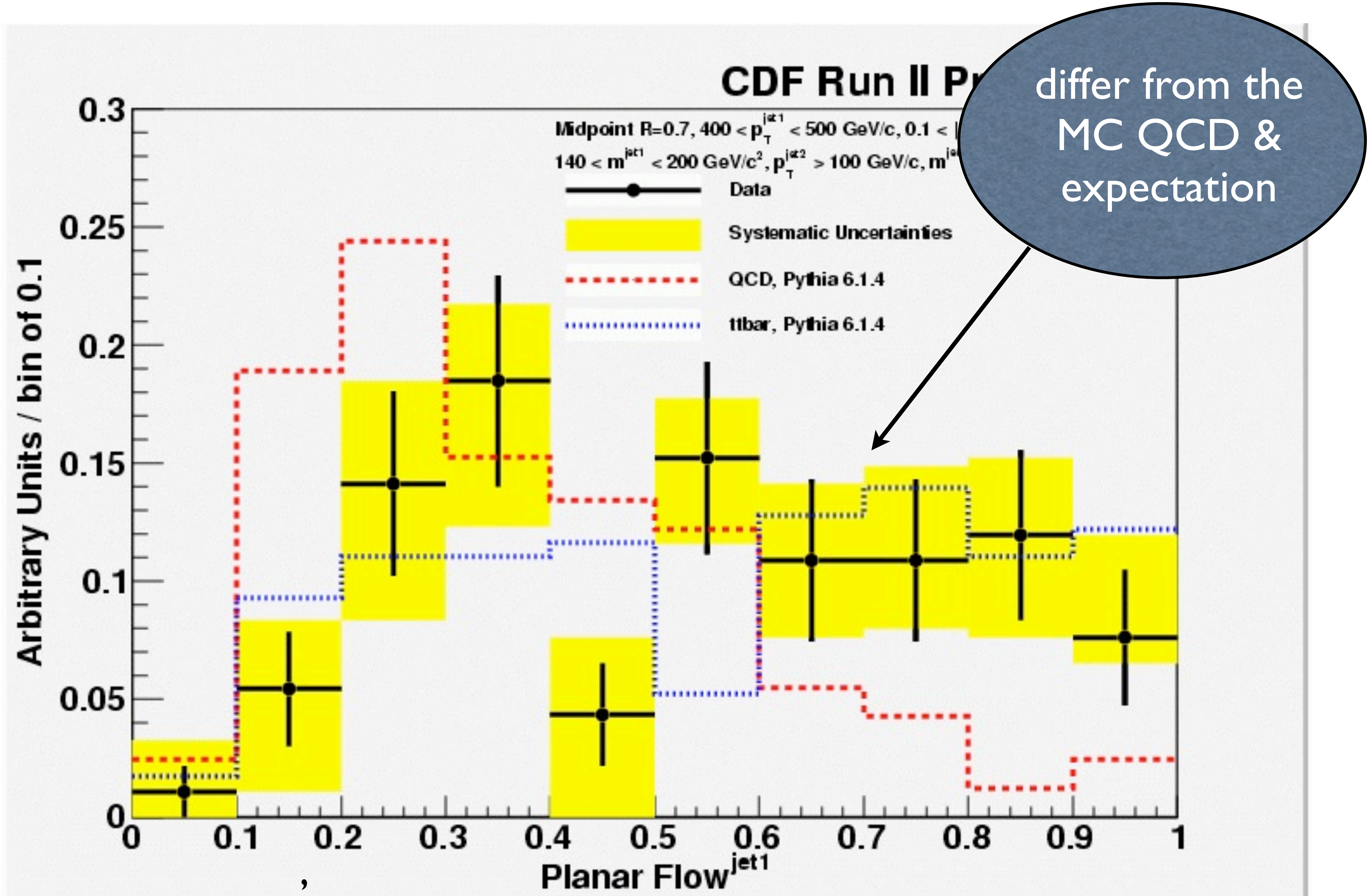


Planar flow



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
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
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Planar flow



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0.7
0.8
0.9
1
Planar Flow^{jet1}
differ from the
MC QCD &
expectation

Constraining New Physics

R, Alon, E. Duchovni, G. Perez & P. Sinervo, for the CDF, CDF\ANAL\TOP\PUBLIC \10234.

Best known bound on energetic tops:

Boosted Top (p_T > 400 GeV/c) Cross Section Upper Limit

– 54 fb @ 95% C.L. (c.f. SM prediction: 4.5 fb)

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and

Initial Result from CDF

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Total Number of Observed Events in Signal Region	**103**
Predicted Background from QCD Jets in Signal Region	**$76 \pm 10(\text{stat})^{+26}_{-20}(\text{syst})$**
Expected Number of ttbar Events in Signal Region	**5.75 ± 0.72**

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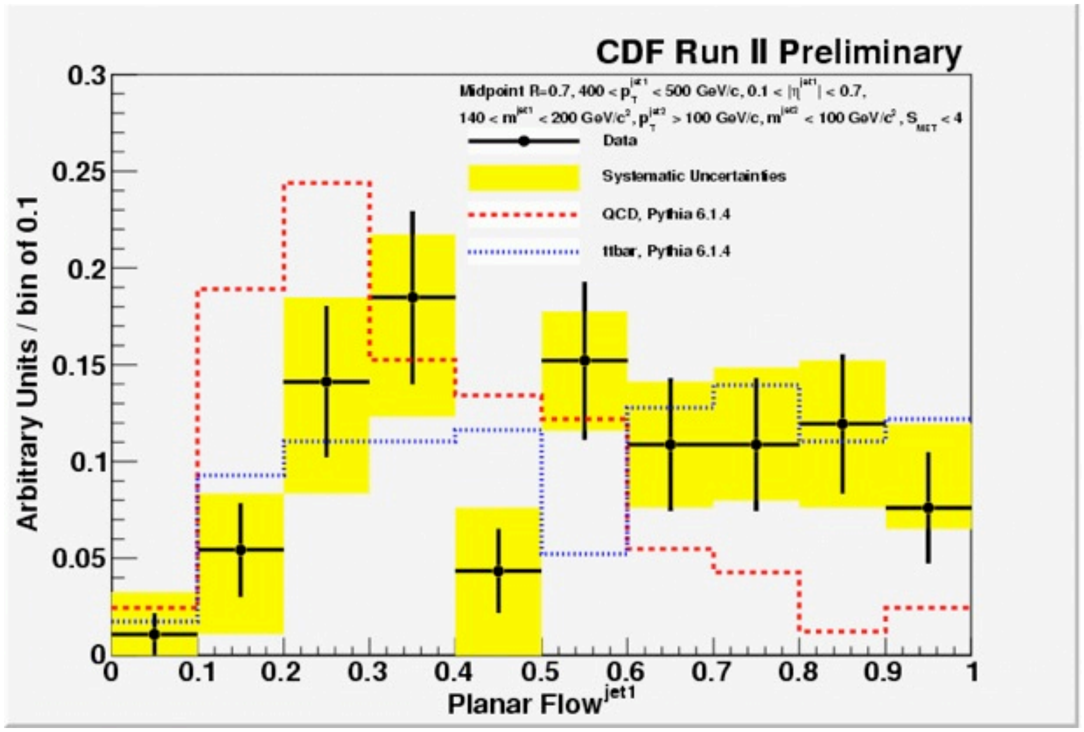
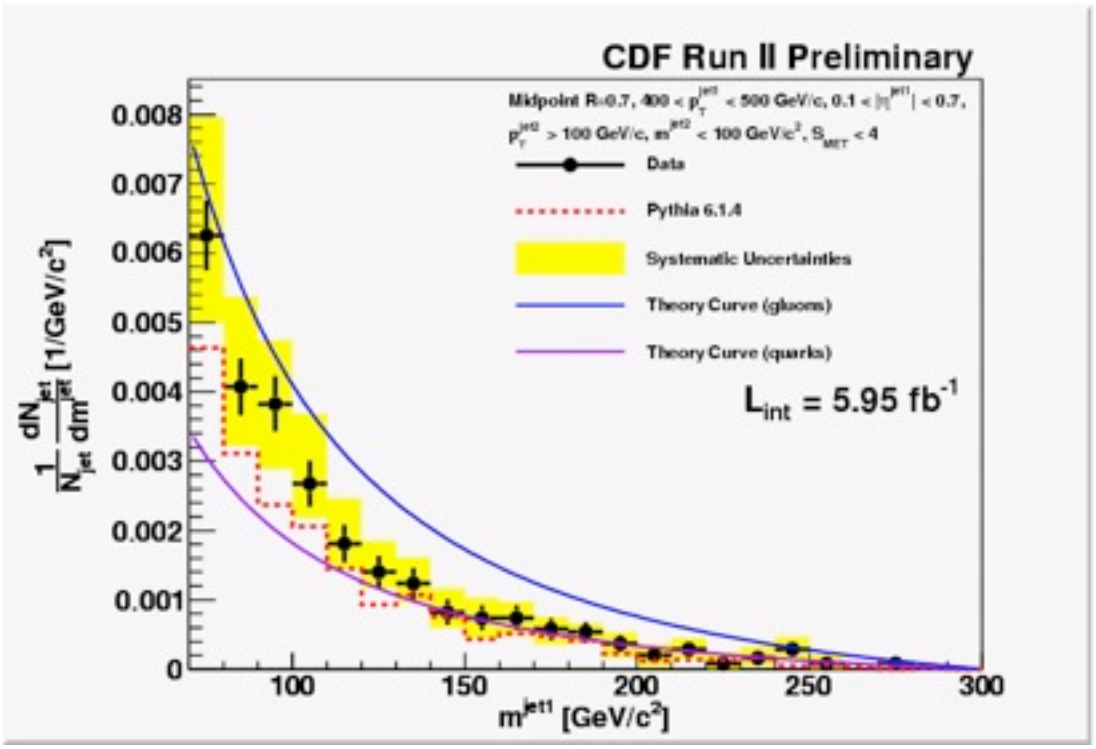


Jet mass distribution



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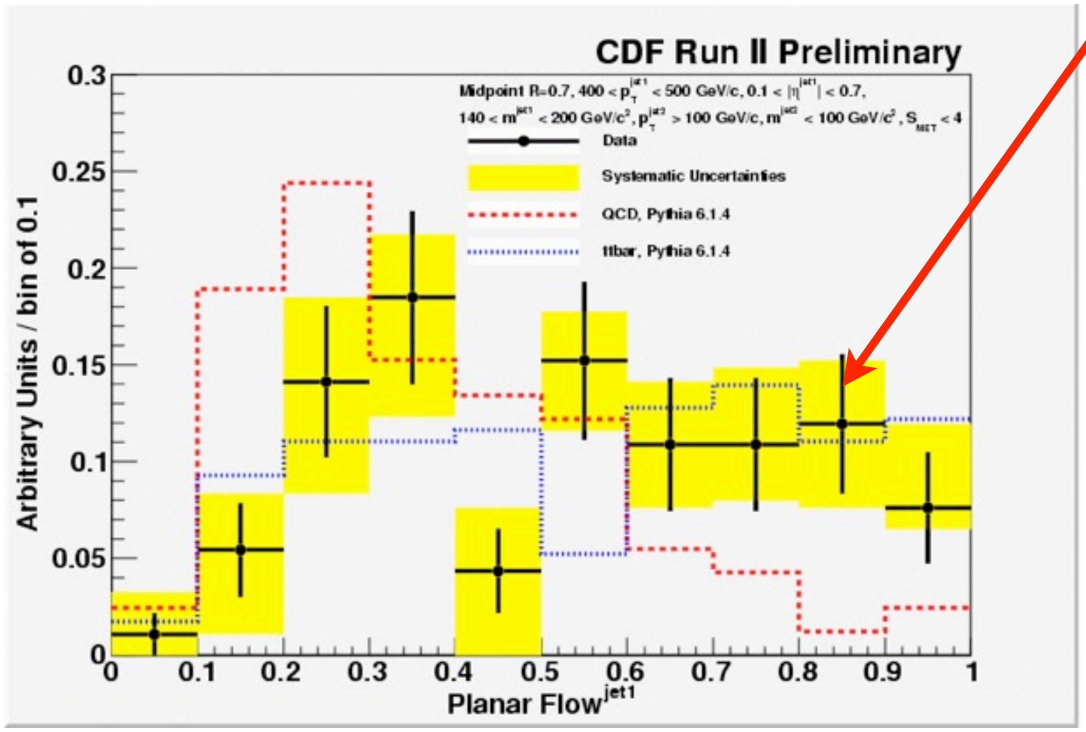

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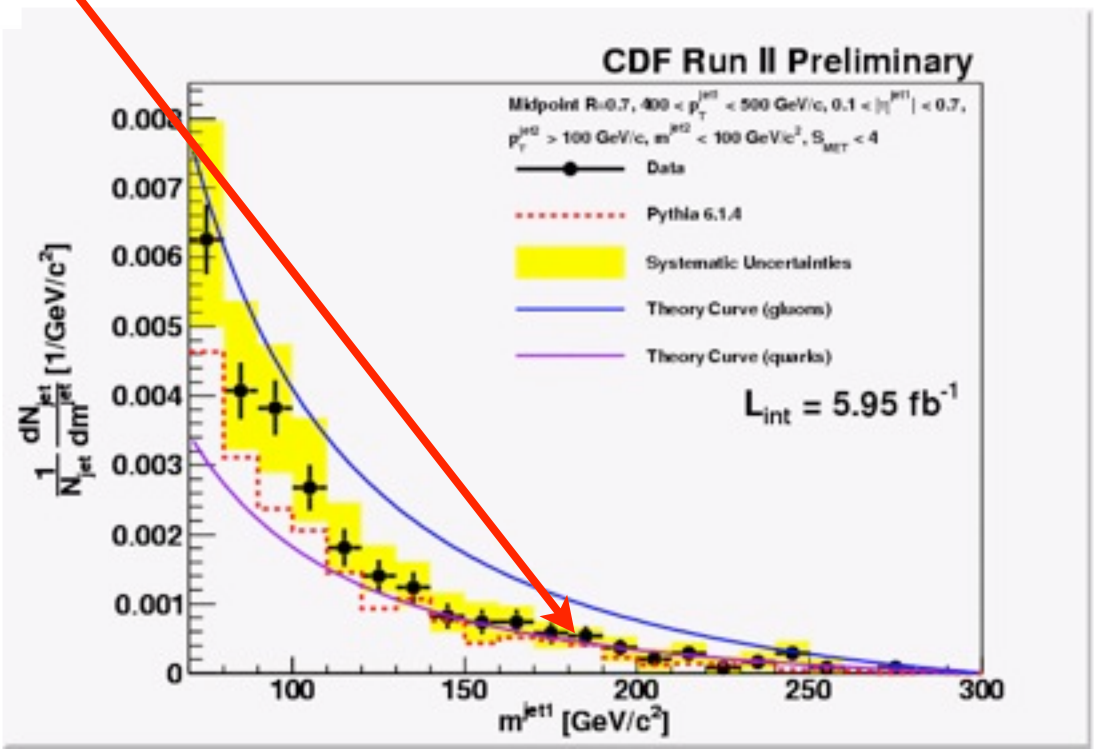

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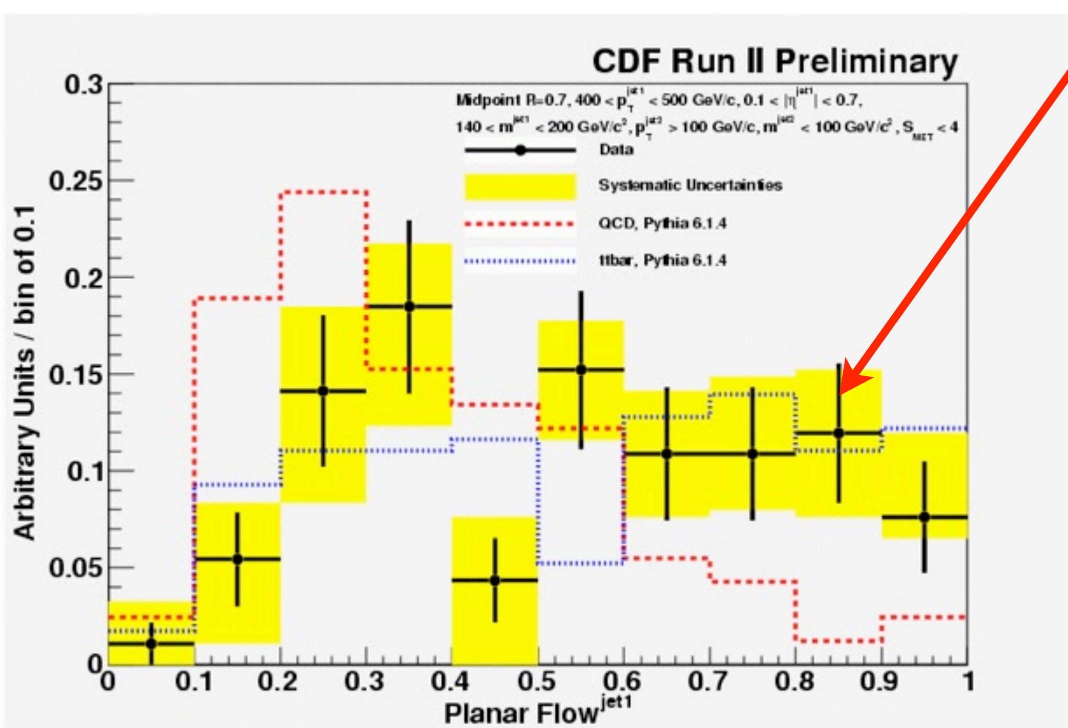
see Cédric Delaunay's talk on Friday for a possible NP explanation

Planar flow



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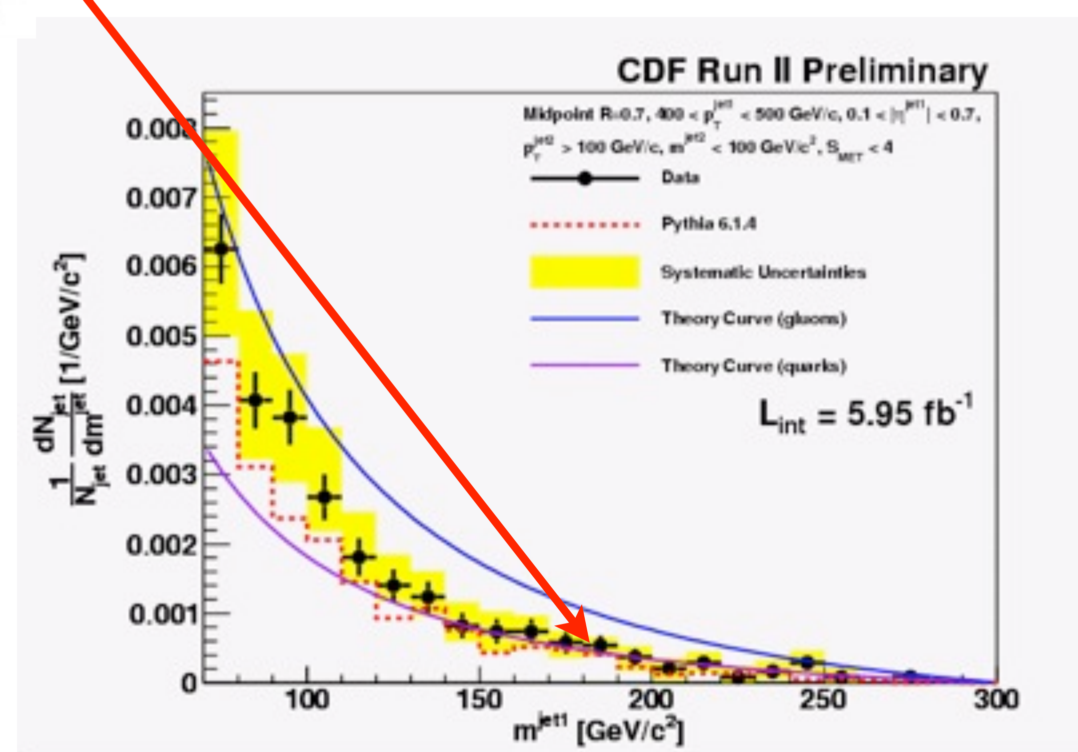

Template Overlap Method

- Planar flow is a single variable in a 4D 3-body kinematical-variable phase-space => info' is lost.

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- Can we be more systematic in our approach?

Template Overlap Method

- ♦Planar flow is a single variable in a 4D 3-body kinematical-variable phase-space => info' is lost.

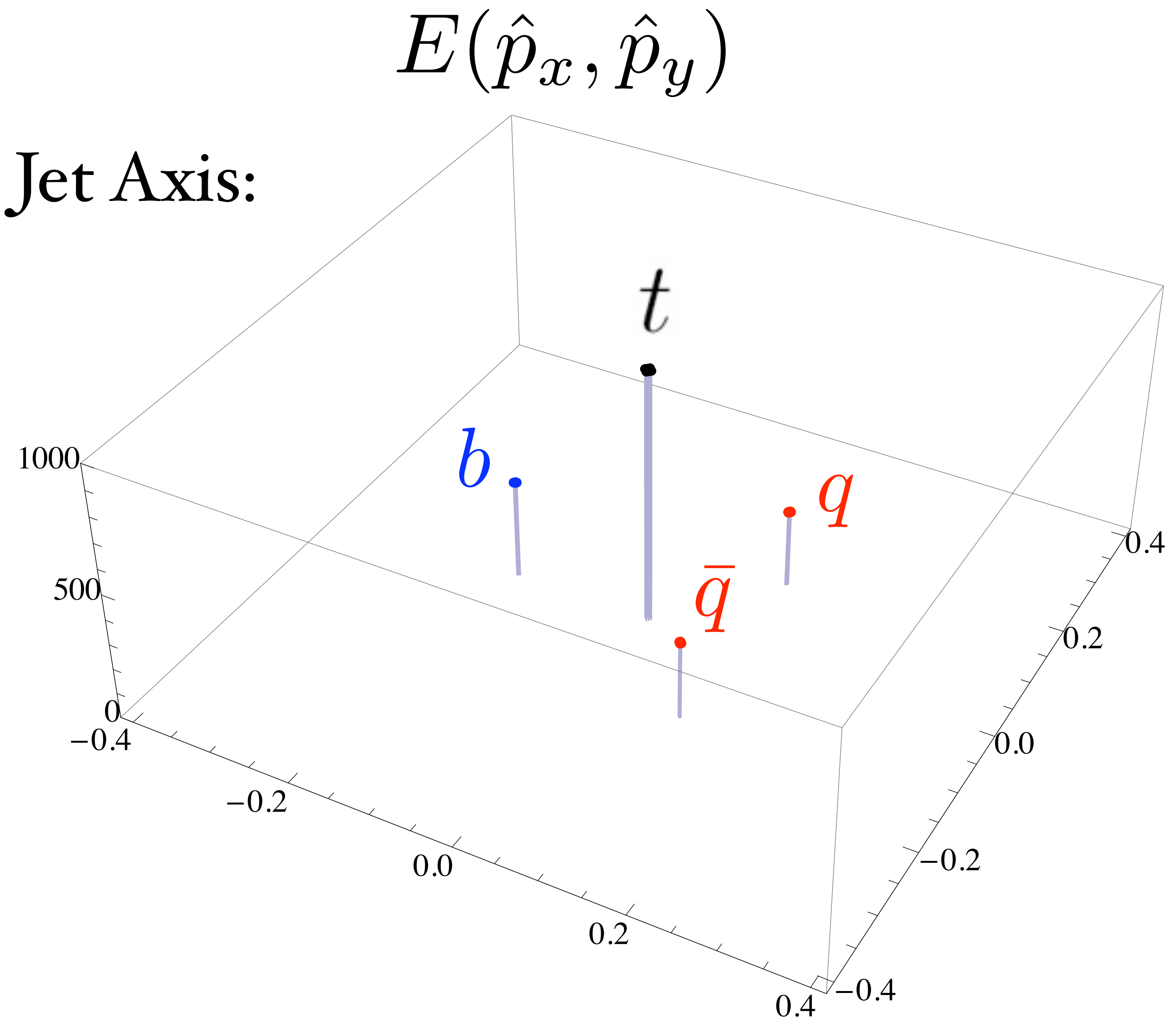
- ♦Can we be more systematic in our approach?

- ♦Energy flow is a natural language for the description of jet structure:

Jet cross sections are naturally described in terms of correlation functions of energy flow

Example: The Golden Triangle

Plane $\perp$ to Jet Axis:



Template Overlap Method

♦ Template overlaps: functional measures that quantify how well the energy flow of a physical jet matches the flow of a boosted partonic decay

|j>=set of particles or calorimeter towers that make up a jet. e.g. |j>=|t>,|g>,etc, where:

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

Lunch table discussion with Juan Maldacena

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

"template"

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

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

Template Overlap Method

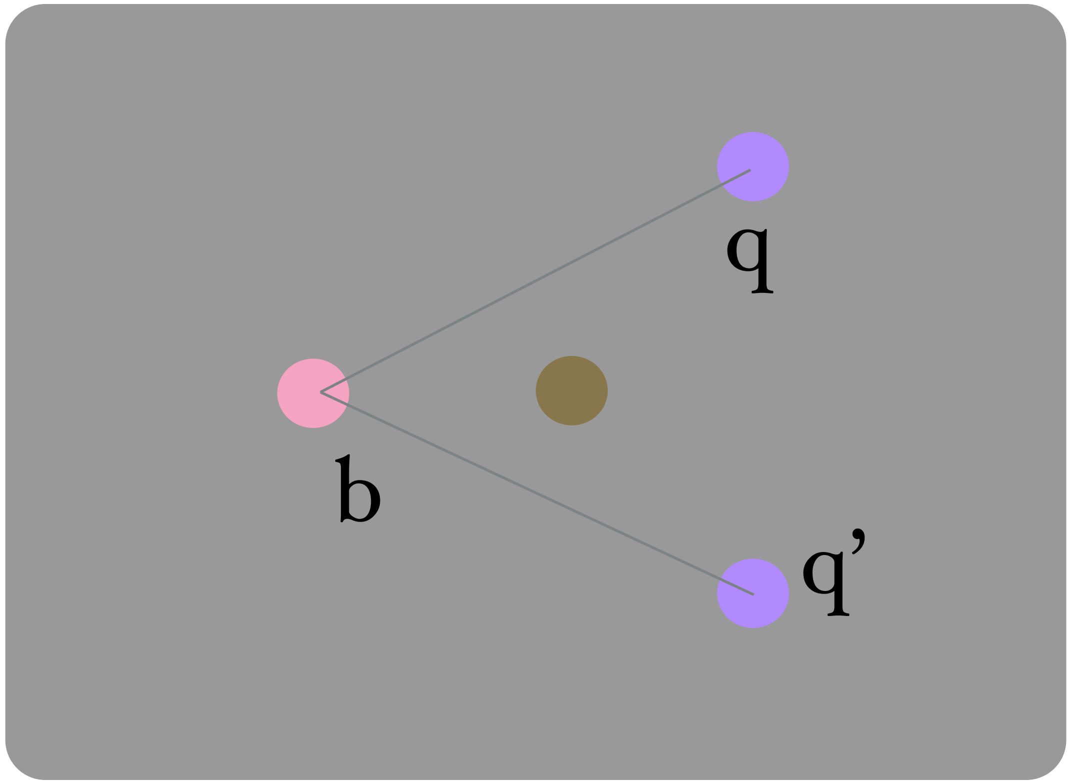
- Any region of partonic phase space for the boosted decays, {f}, defines a template
- our ansatz: a good (if not the best) rejection power is obtained when we use the signal distribution itself to construct our templates
- Define "template overlap" as the maximum functional overlap of j to a state f[j]:

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

- can match unequivocally arbitrary final states j to partonic partners f[j] at any given order

Template Overlap Method

Example:
Template Config. for top



Our templates will be a set of partonic momenta $f = p_1 \dots p_n$, with

$$\sum_{i=1}^{n} p_i = P\,, \quad P^2 = M^2\,,$$

Probe template configuration in the entire phase space

By weighting energy distribution on detector (EG),
by how close it is to our Template configuration

Constructing a functional

♦ A natural measure: weighted difference of their energy flows integrated over a region (simple example: Gaussian)

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

n-paritcle phase space:

$$\tau_n^{(R)} \equiv \int \prod_{i=1}^{n} \frac{d^3\vec{p}_i}{(2\pi)^3 2\omega_i} \, \delta^4(P - \sum_{i=1}^{n} p_i) \, \Theta(\{p_i\}, R)$$

IR safety: *F* should be a sufficiently smooth function of the angles for any template state f:

-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, $\hat{n}_a$ and its energy $E^{(f)}_a$:

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

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 relative to the direction of the boost

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 above 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.

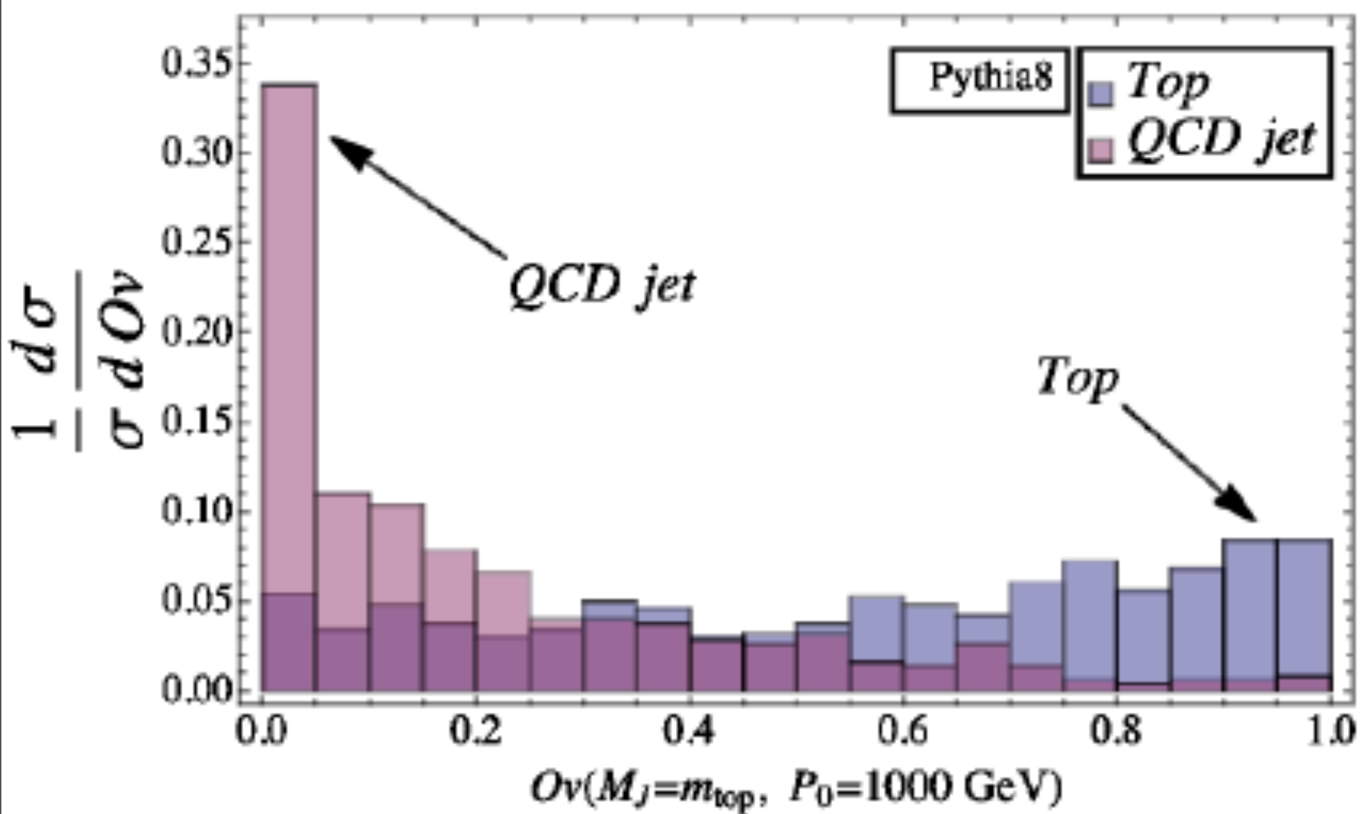
- Template Overlap with data discretization

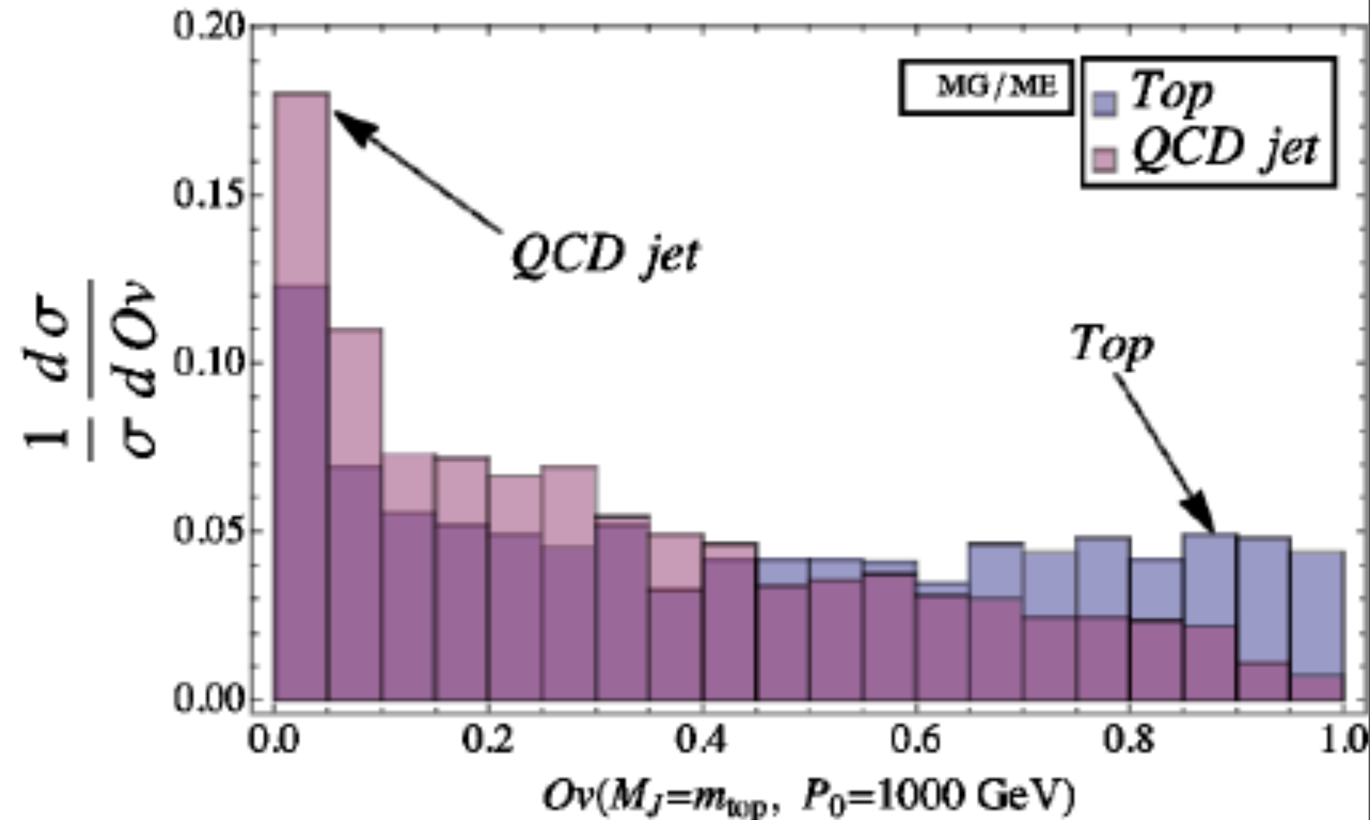
$$Ov(j,f) = \max_{\tau_n^{(R)}} \exp\left[-\sum_{a=1}^{3} \frac{1}{2\sigma_a^2} \left(\sum_{k=i_a-1}^{i_a+1} \sum_{l=j_a-1}^{j_a+1} E(k,l) - E(i_a,j_a)^{(f)} \right)^2 \right]$$

for data, we encode two physical angles in terms of row and column number

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

Three-particle Templates and Top Decay





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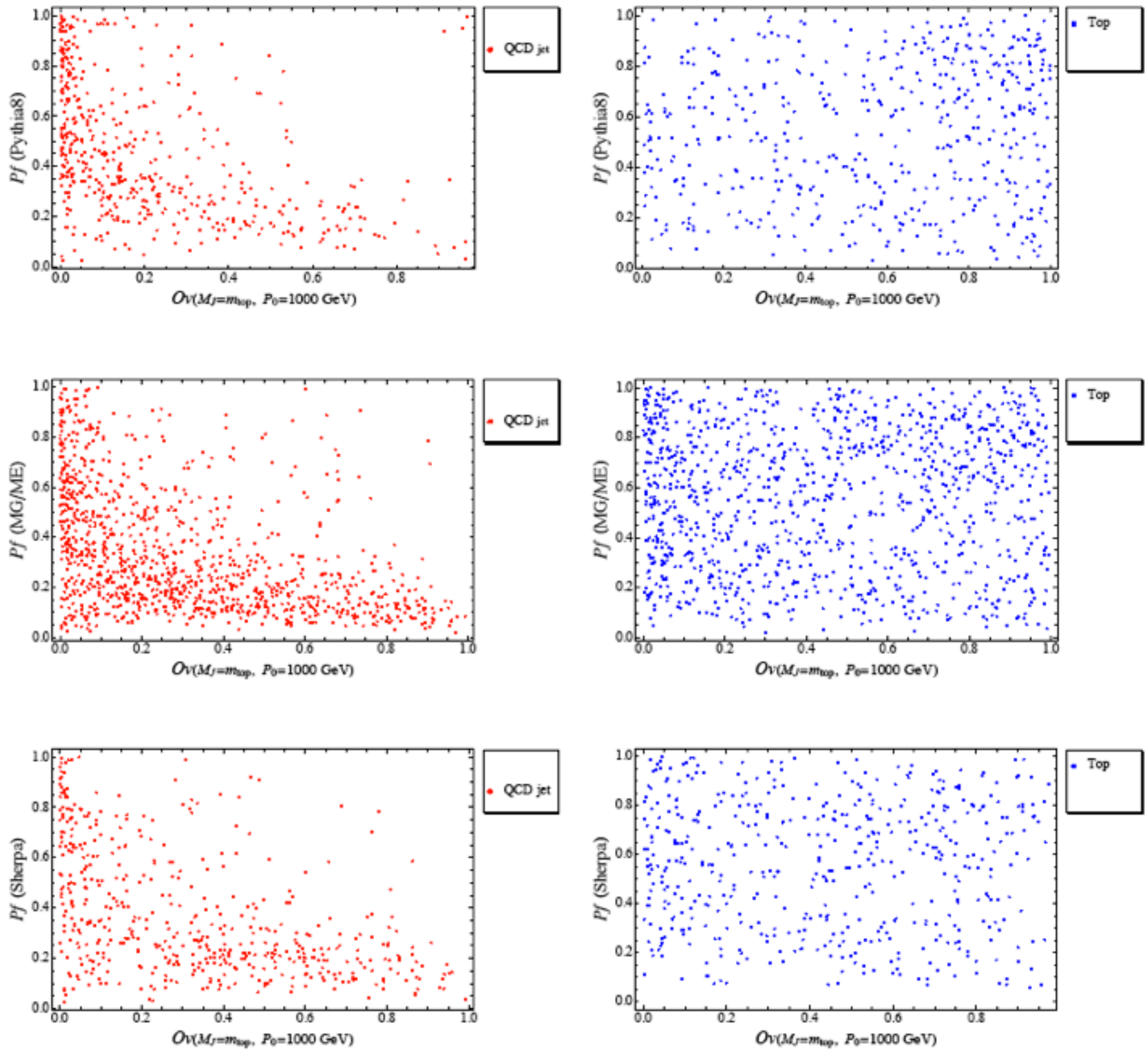
$$\sigma_a = E(i_a, j_a)^{(f)}/2 \, .$$

Three-particle Templates and Top Decay

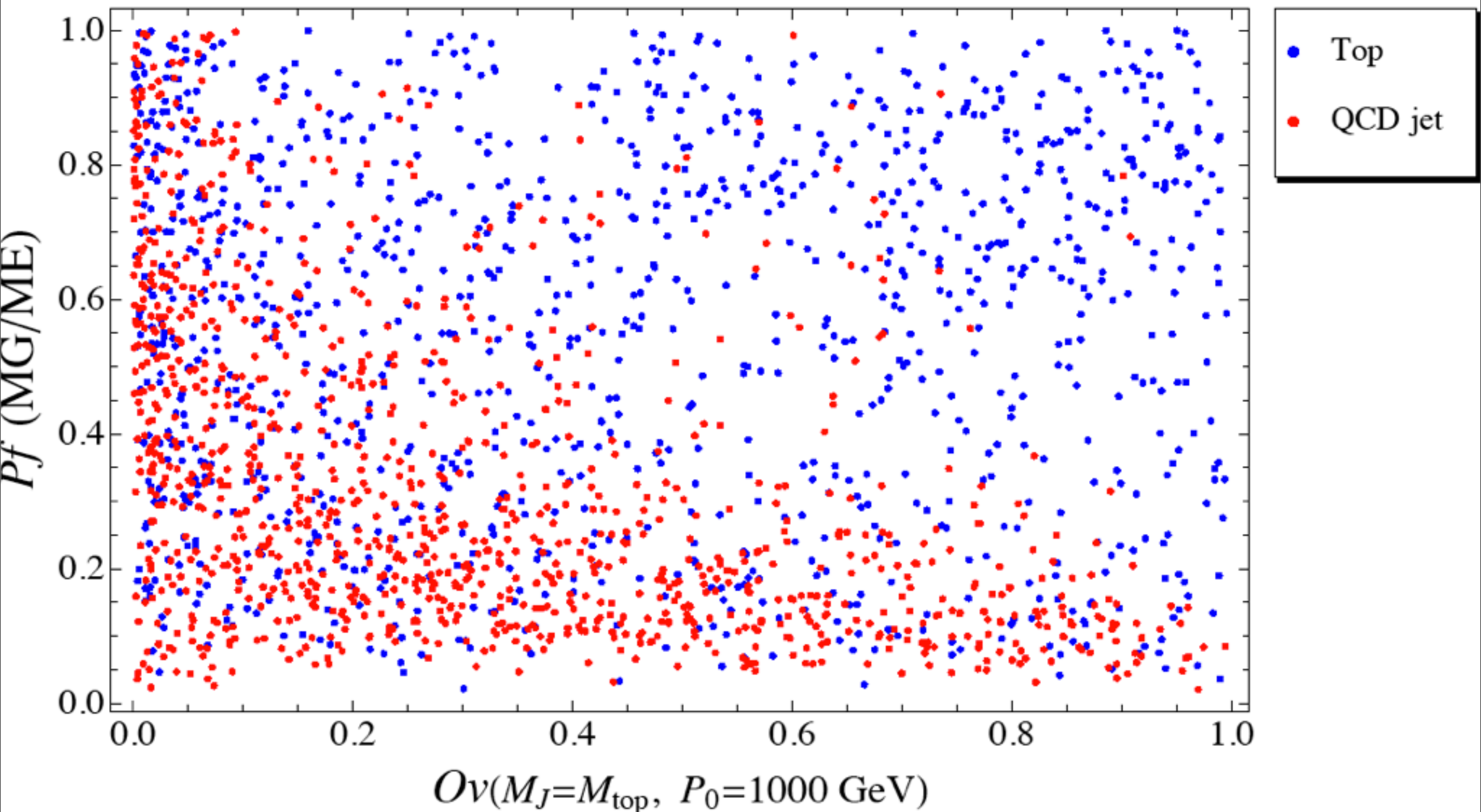
♦Combine with Planar flow-
distinguishes between many three-jet events with large template overlaps.

♦In general, QCD events with large *Ov* will have significantly smaller planar flow than top decay events; for the QCD jets a large overlap would be a result of a kinematic “accident”.

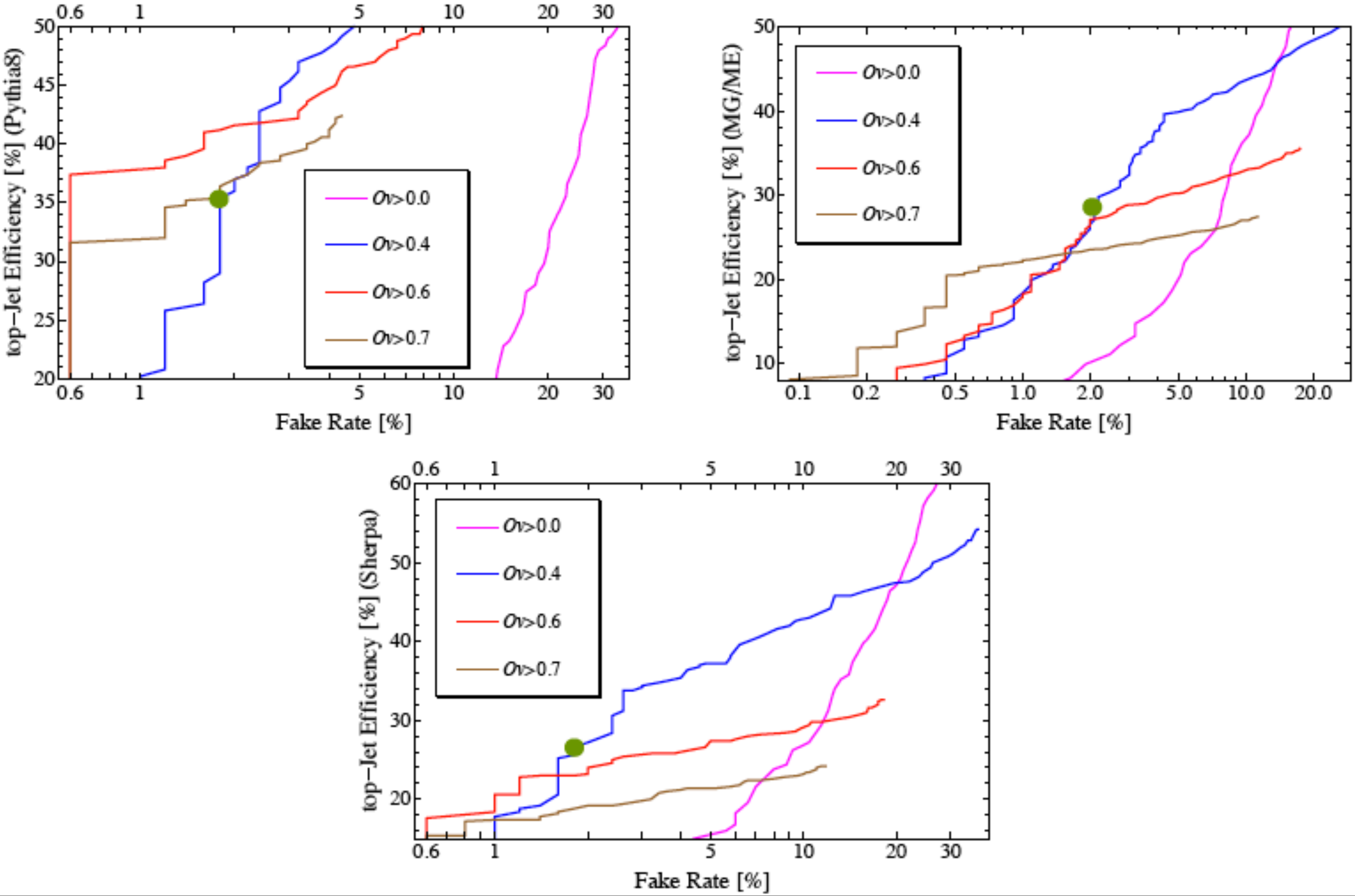
Three-particle Templates and Top Decay



Three-particle Templates and Top Decay



Three-particle Templates and Top Decay



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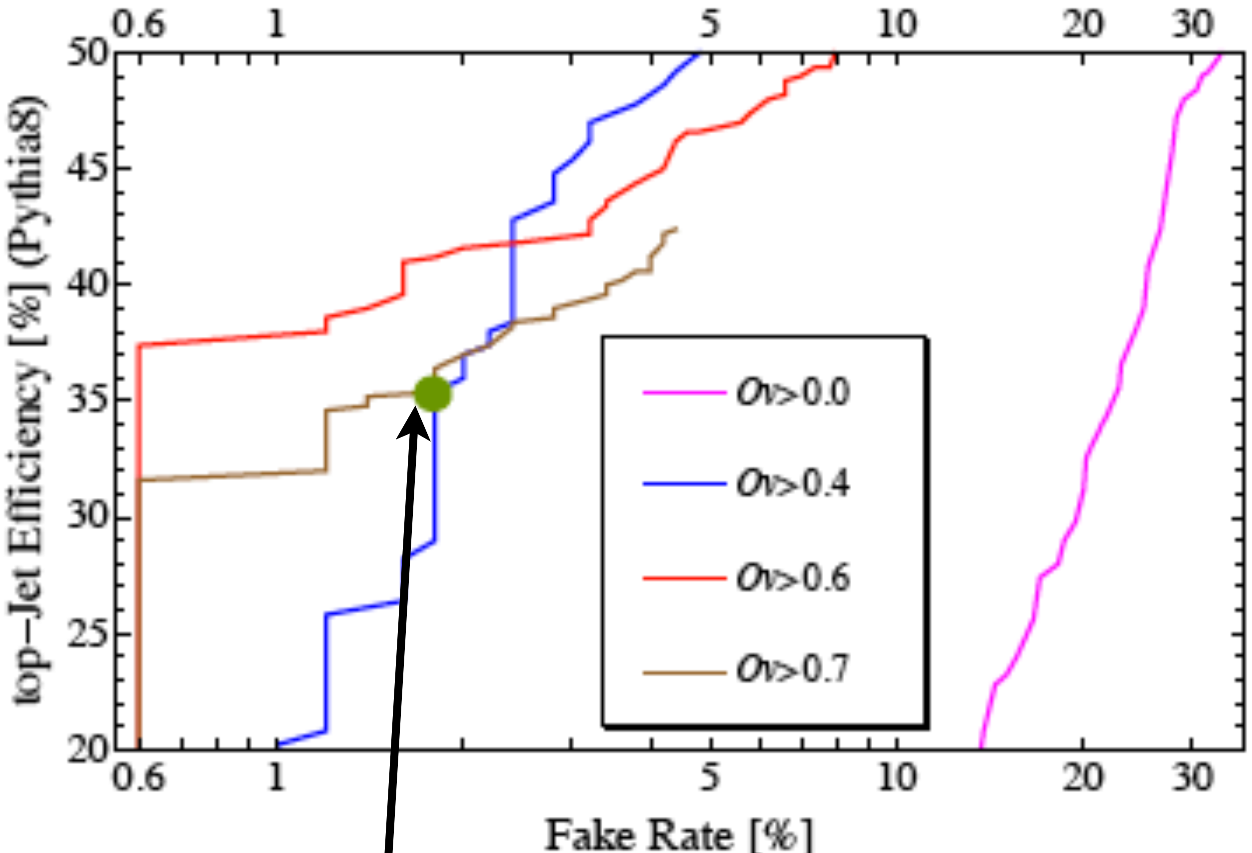
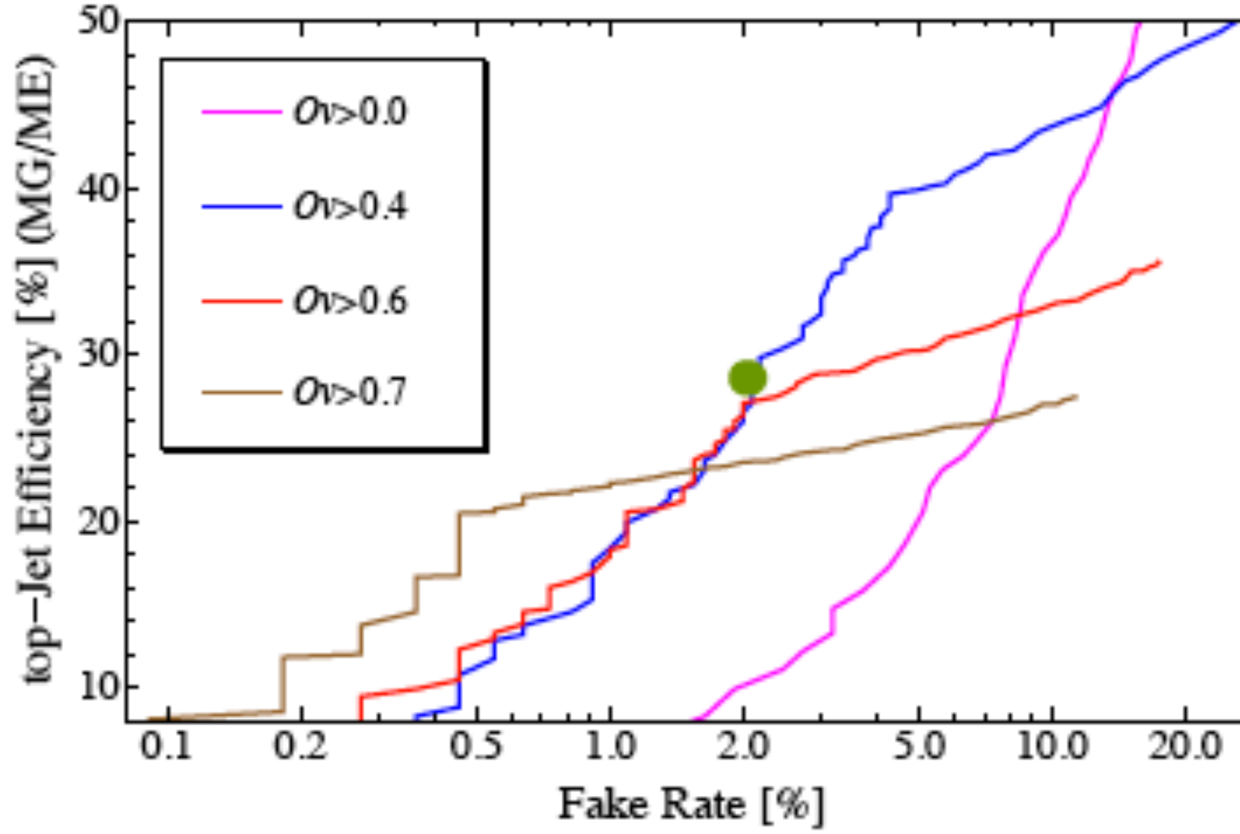
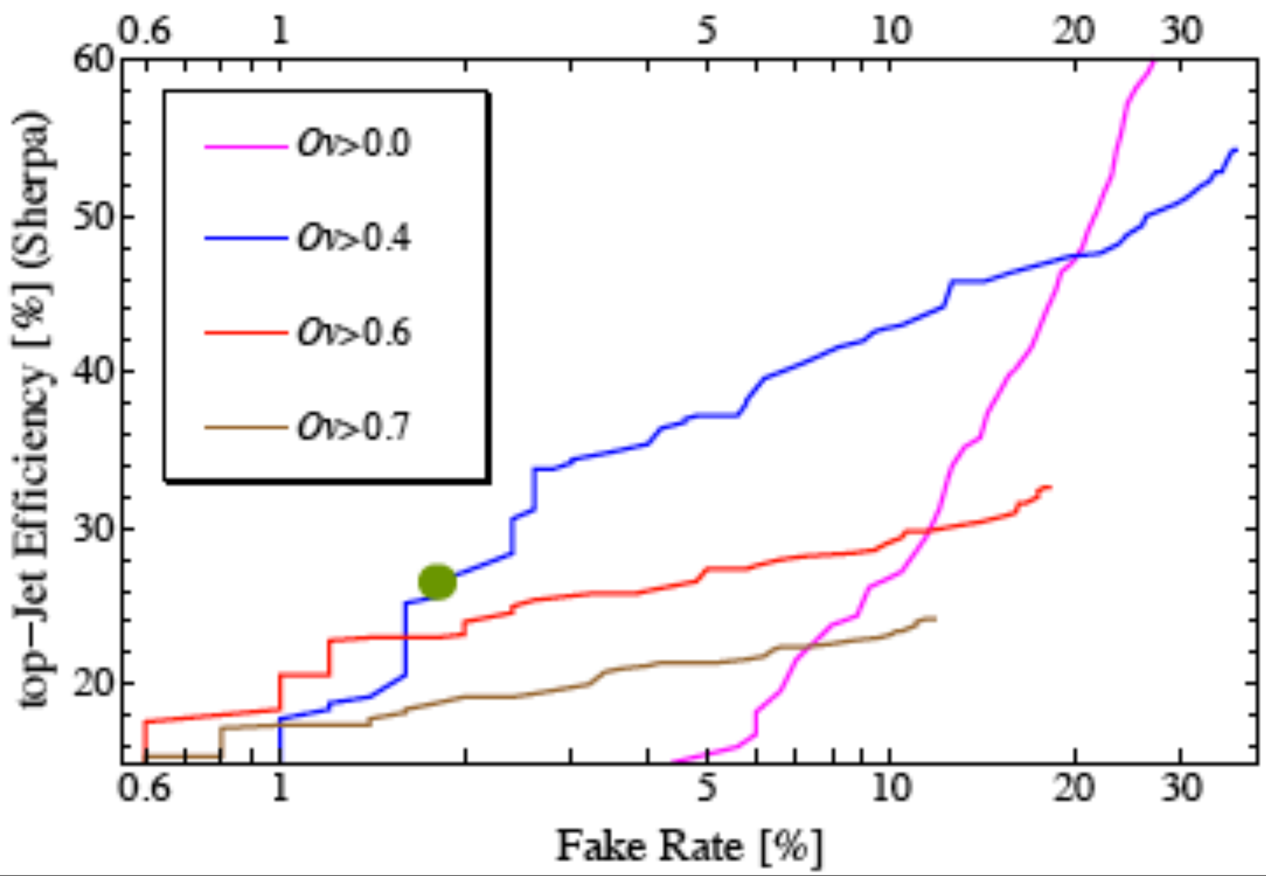




$Pf > 0.6$ and $Ov > 0.4$



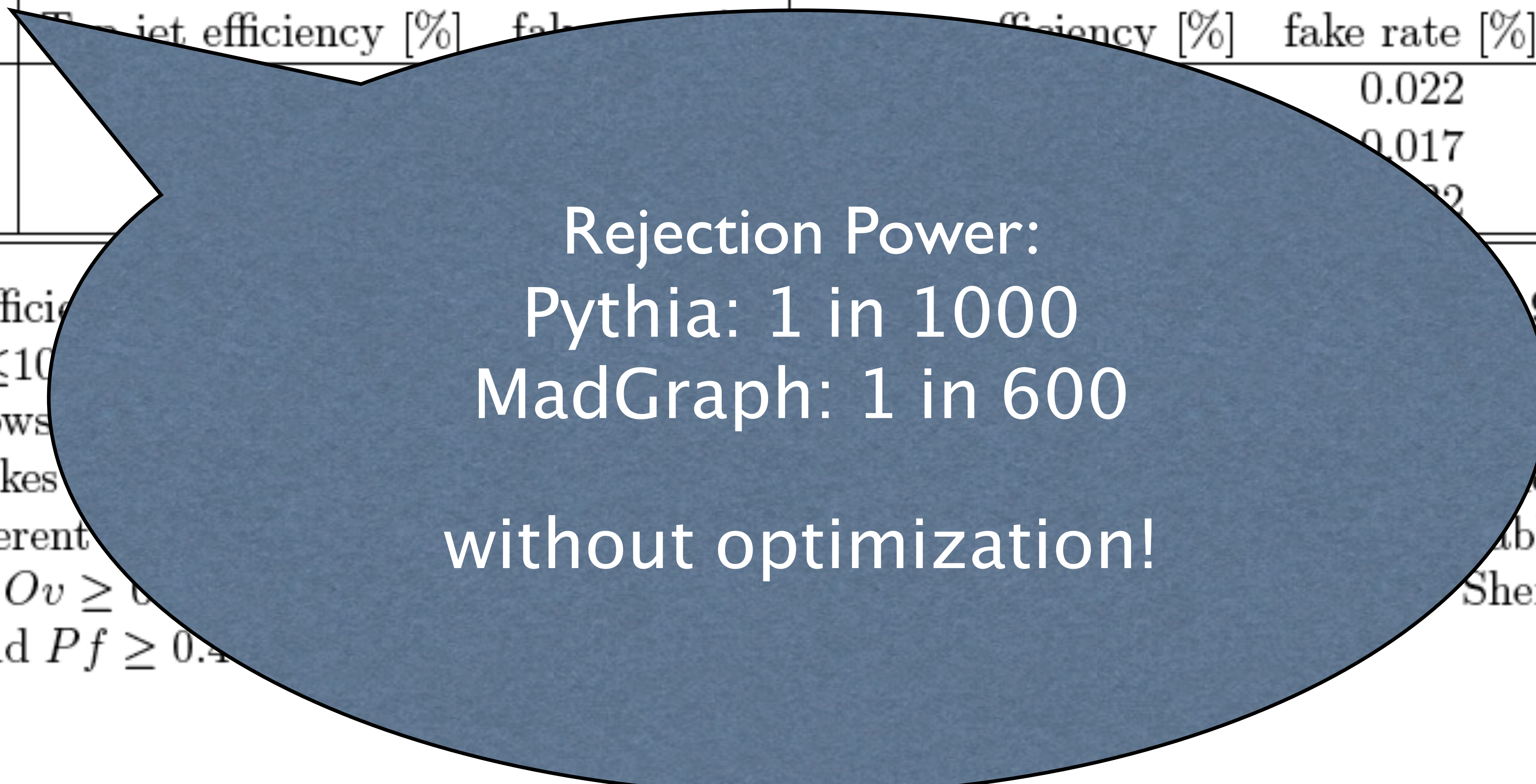
Three-particle Templates and Top Decay

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: $D = 0.5$), 95 GeV$\leq P_0 \leq$1050 GeV, 160 GeV$\leq m_J \leq$190 GeV and $m_{top} = 174$ GeV. The left pair o columns shows efficiencies and fake rates found by imposing the jet mass window only. Th 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 variable 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 Sherp $Ov \geq 0.6$ and $Pf \geq 0.48$.

Fake Rate [%]

Three-particle Templates and Top Decay



MC	Jet mass cut only		Mass cut + Ov + Pf	
	T... jet efficiency [%]	fa...	...fficiency [%]	fake rate [%]
Pythia8				0.022
MG/ME				0.017
Sherpa				...2

Table 1: Effici... 95
GeV≤ P_0 ≤10...
columns shows...
right pair takes...
For the different...
for Pythia8 $Ov \geq$ ... Sherp...
$Ov \geq 0.6$ and $Pf \geq 0.4$...

Fake Rate [%]

Three-particle Templates and Top Decay

- Template method provide a favorable rejection power compared to other methods (algorithm based jet-substructure)

Three-particle Templates and Top Decay

- ♦ Template method provide a favorable rejection power compared to other methods (algorithm based jet-substructure)

- ♦ Template method is under theory control, while other methods depends on jet-reconstruction algorithm by removing soft jets (loosing theoretical handle)

Three-particle Templates and Top Decay

- Template method allows for systematic improvement: (our template is a simple example)
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: (our template is a simple example) 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 Higgs 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

$$\frac{dJ^{\mathrm{QCD}}}{d\theta_s} \propto \frac{1}{\theta_s}$$

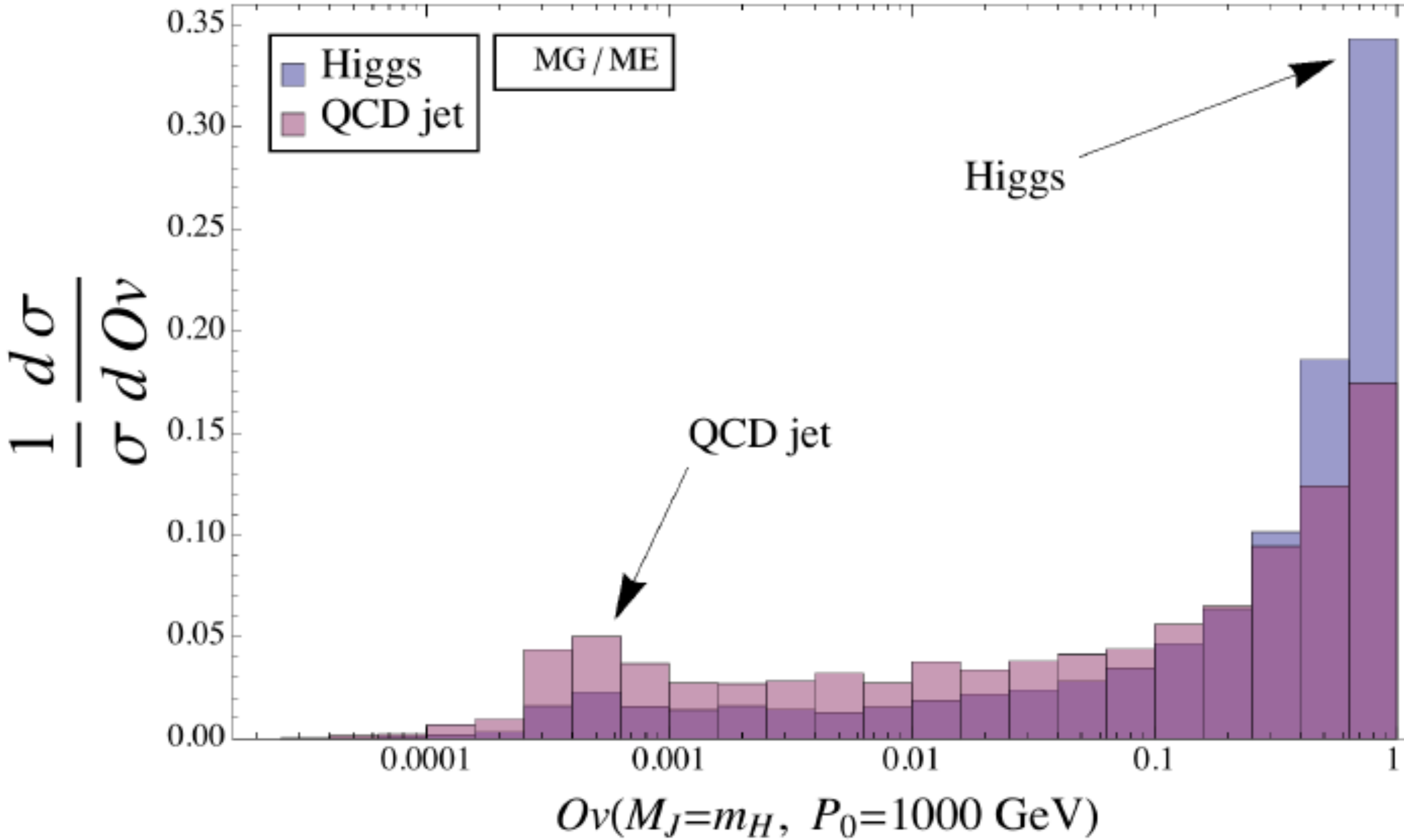
Two-particle Templates and Higgs Decay

♦ 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.

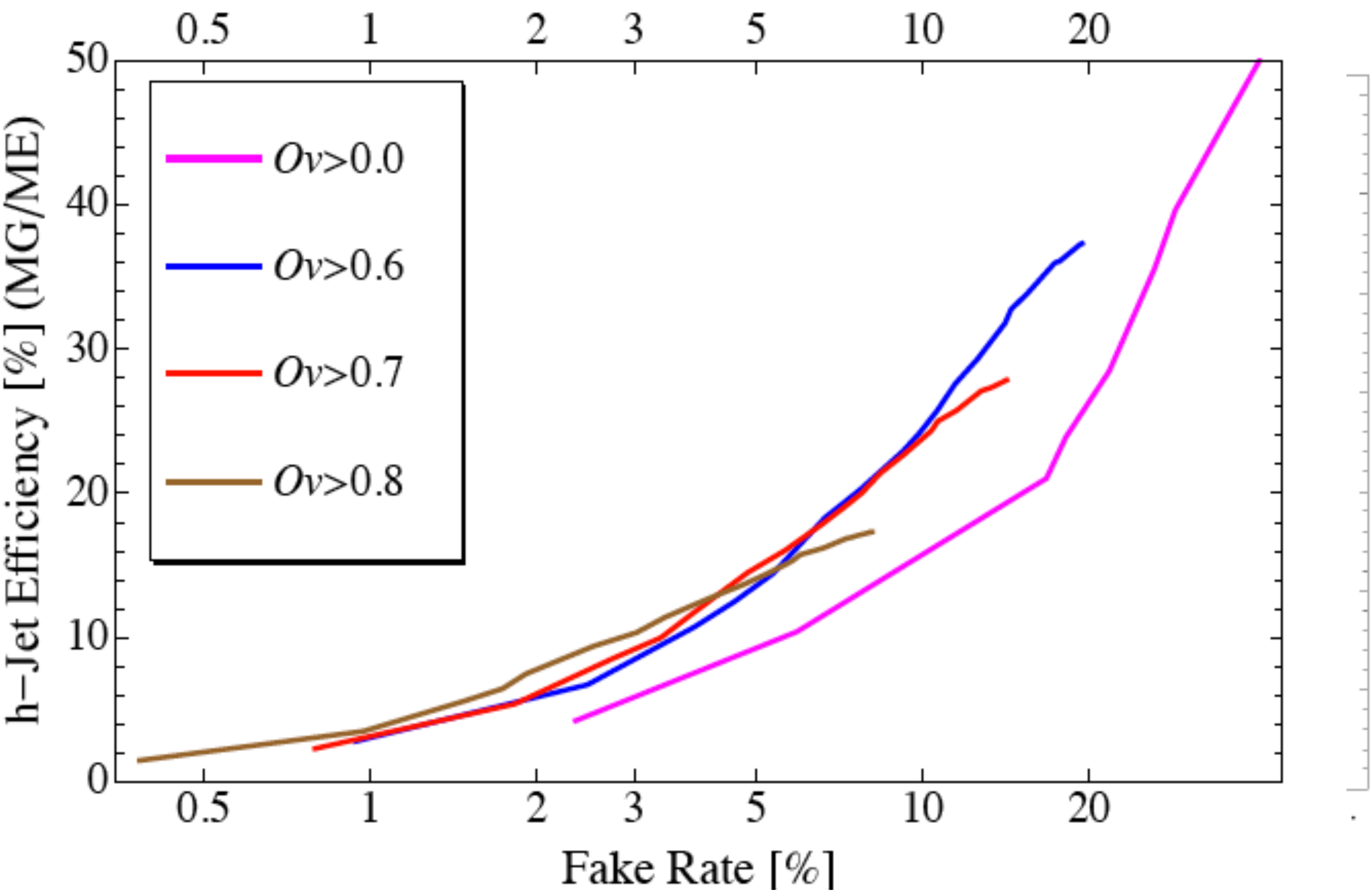
♦ Template Overlap with data discretization

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

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

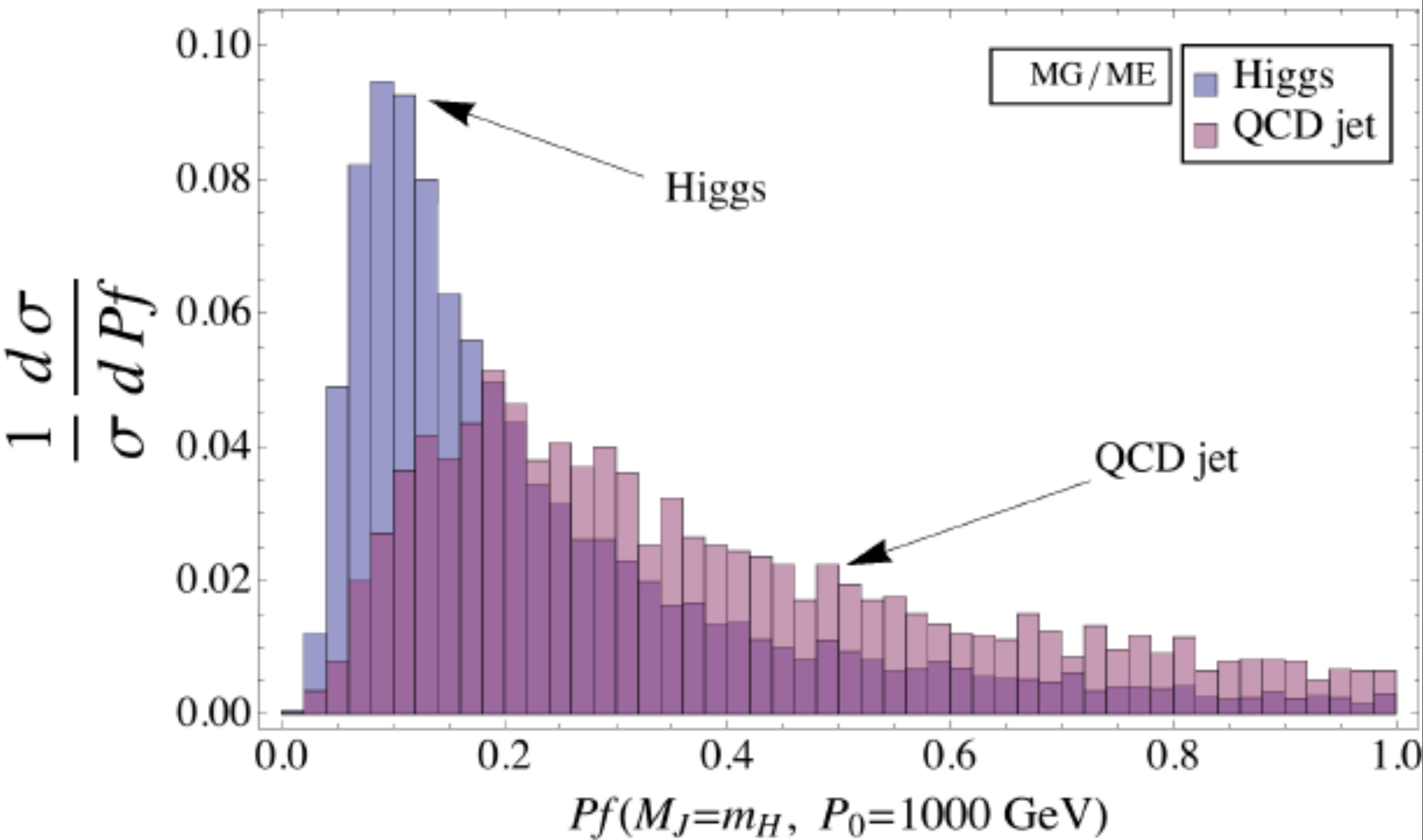
Two-particle Templates and Higgs Decay

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

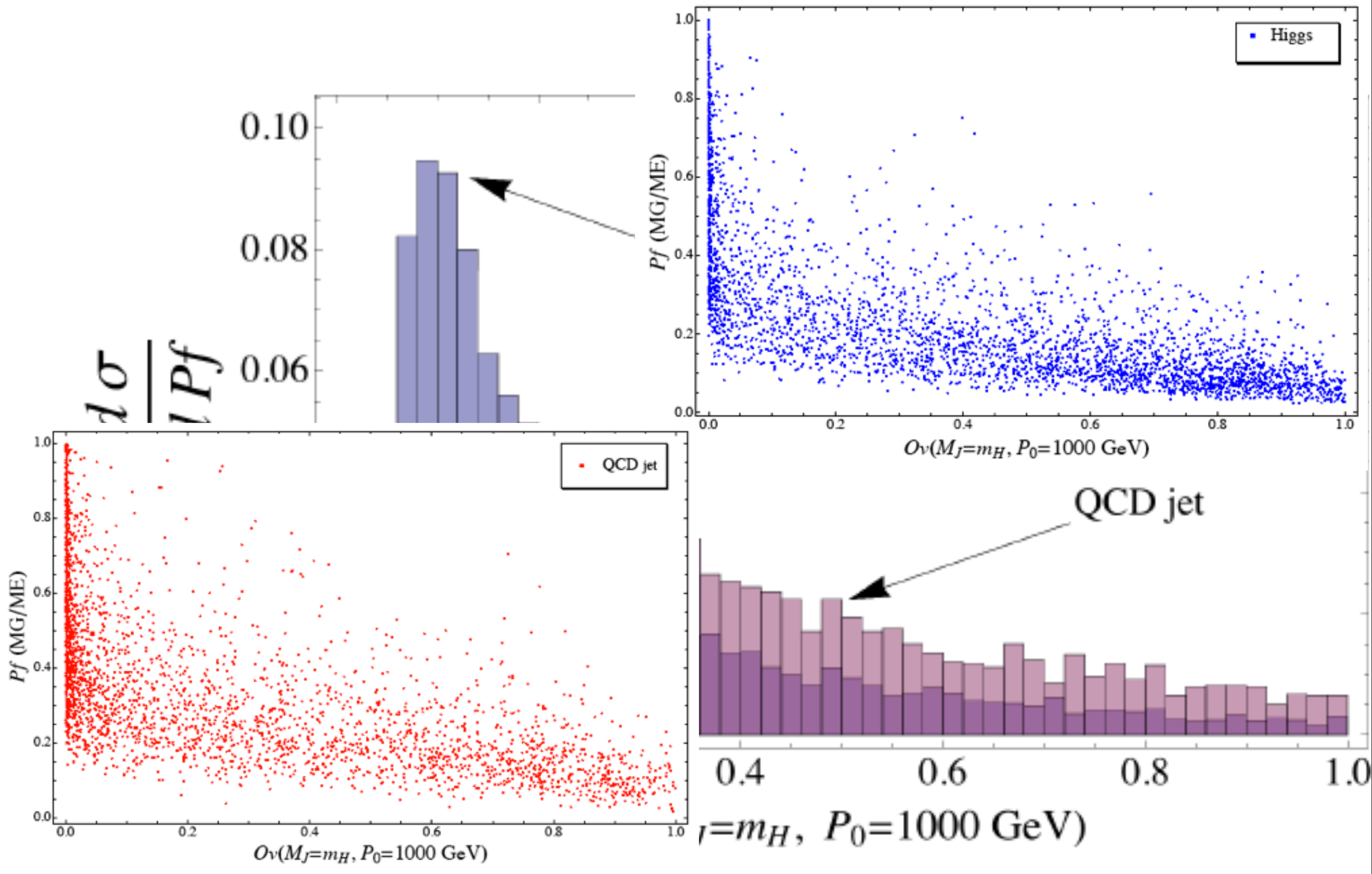
♦ The effects of higher-order effects can be partly captured by using Planar flow

(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

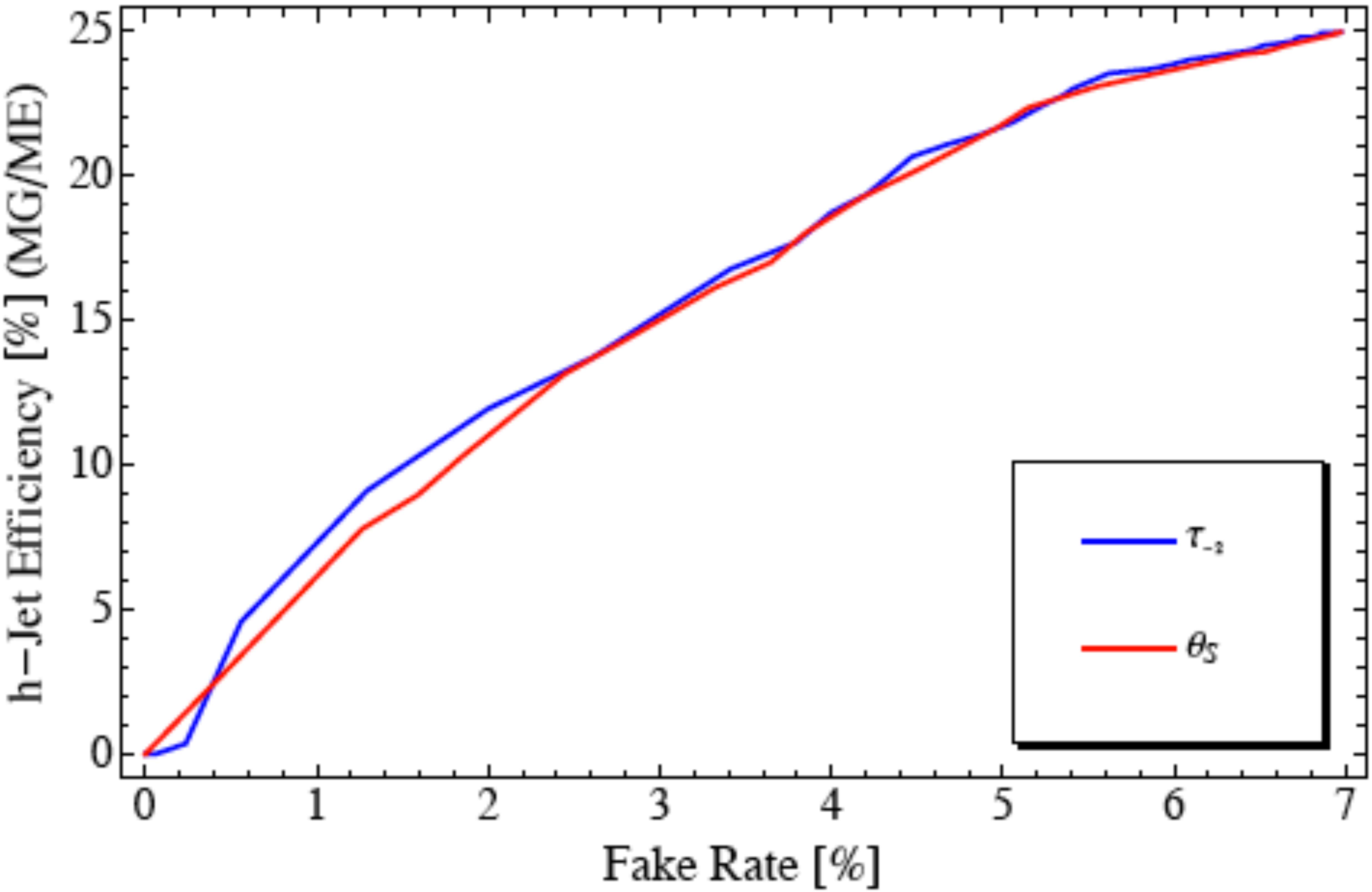
♦ Combined with angularity or Θ_s : can improved rejection power (Θ_s and angularities are related)

Two-particle Templates and Higgs Decay

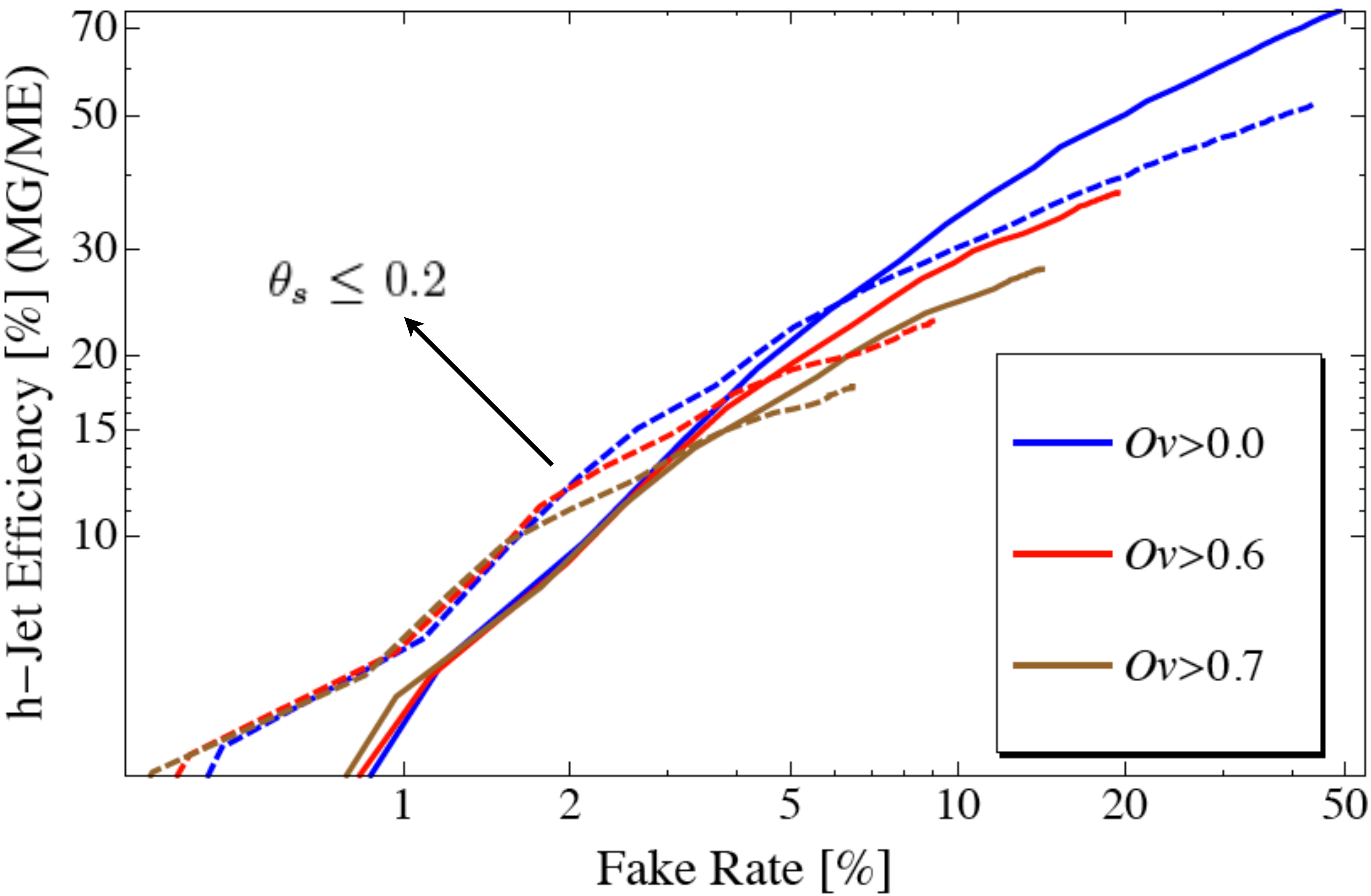
♦ Combined with angularity or Θ_s : can improved rejection power (Θ_s and angularities are related)

♦ 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.

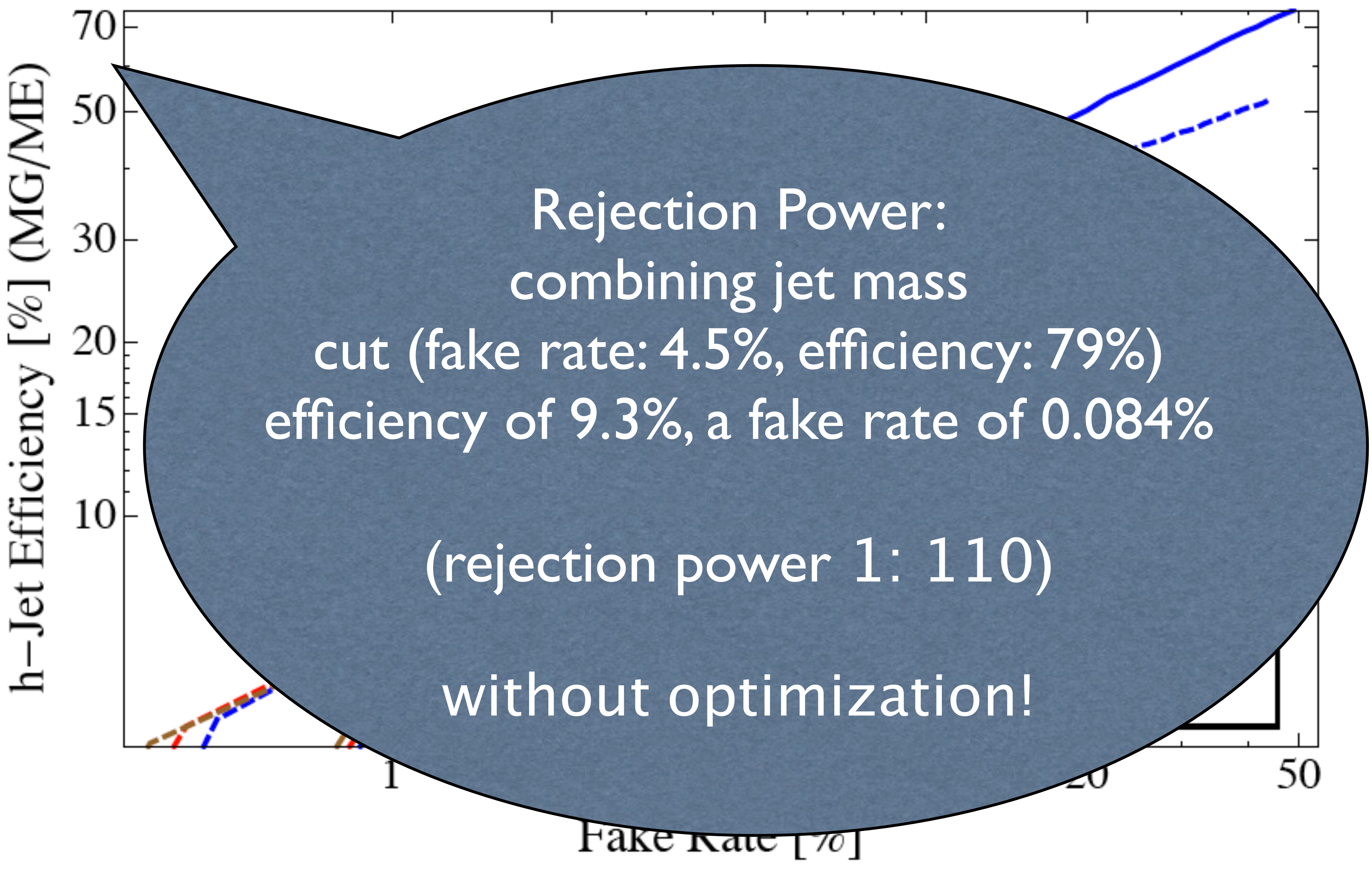
Two-particle Templates and Higgs Decay



Two-particle Templates and Higgs Decay



Two-particle Templates and Higgs Decay



Summary

- LHC => new era, boosted massive jets may be important for NP discovery
- Jet function provides a systematic approach to describe the jet mass background
- Substructures- jet shapes provide a global feature of the Jets (useful for highly collimated jets)
- Template Overlap method - provides a theoretical handle with good rejection power (systematically improvable): showed top and Higgs case, but can be more imaginative (can be used to NP particle decay)