Optimizing Boosted Higgs Identification

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Work in progress

R. Alon, E. Duchovn, SL, G. Perez, I. Roth, F. Spano

Work in progress

"Interpreting LHC Discoveries," GGI, 2011, November 2, 2011

Outline

- Introduction (motivation)
- Jet mass and other important jet shapes.
- Template Overlap Method
- LO Template for Higgs and Top
- NLO template (+color flow) for Higgs
- Summary

Looking at boosted massive objects, generic motivations

- New hard dynamics => boosted electroweak+top particles.

  Observing signal => identify collimated $W/Z/h/t$, $\Delta\theta_{ij} \sim m_J/E_J$.

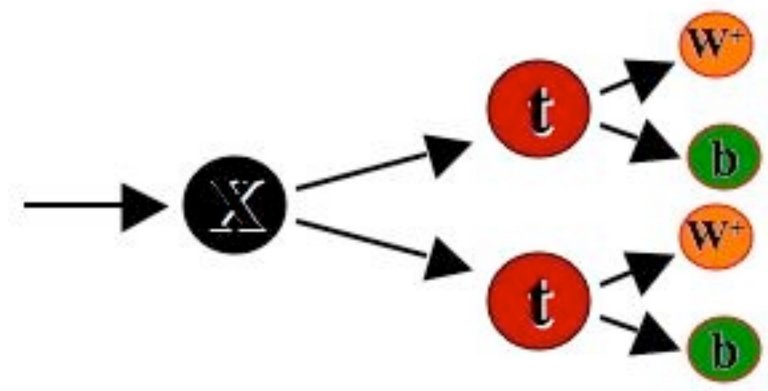
  Seymour (93); Butterworth, Cox, Forshaw (02); Agashe, Belyaev, Krupovnickas, Perez & Virzi (06); Lillie, Randall & Wang (07); Butterworth, Davison, Rubin & Salam (08).

- Massive particles easier to identify when boosted.

  Combinatorial background is removed, less soft junk collected & often backgrounds fall faster than signal with energy.
  For instance $h+V, t, \chi^0$

The challenge of highly boosted Massive Jets

- Fine tuning solution => New states decay quickly to massive SM particles



The challenge of highly boosted Massive Jets

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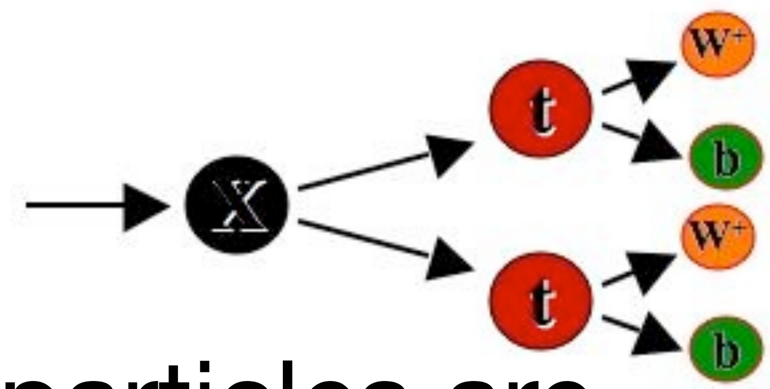
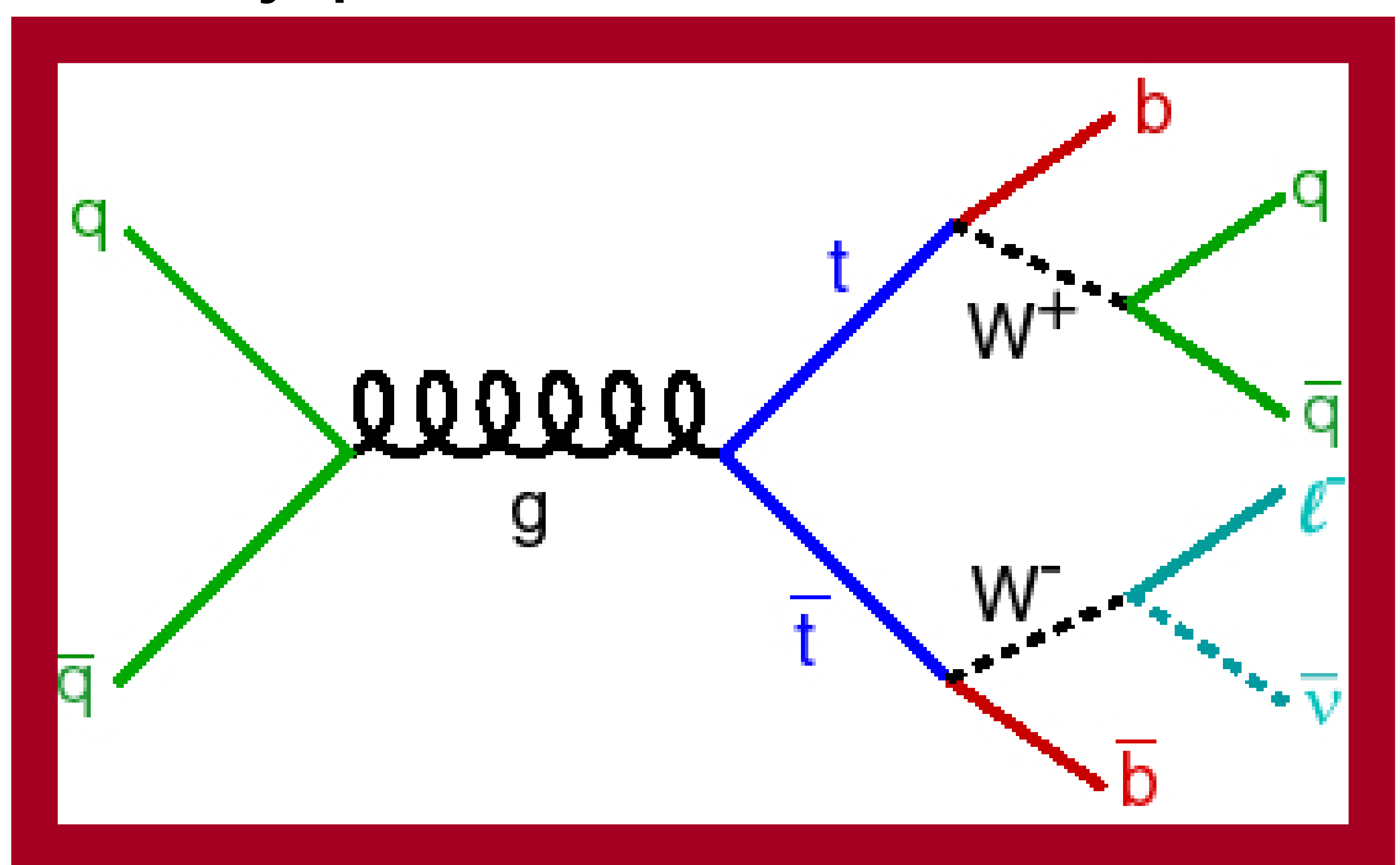


♦ Since $M_{t,h} \ll M_X$ the outgoing SM particles are ultra-relativistic, their decay products are collimated



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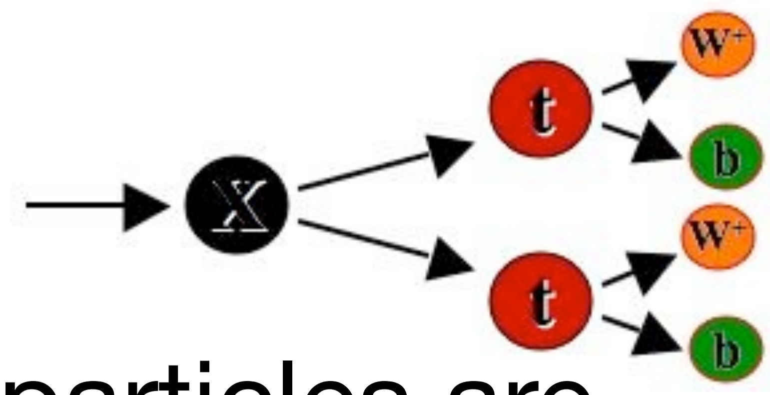
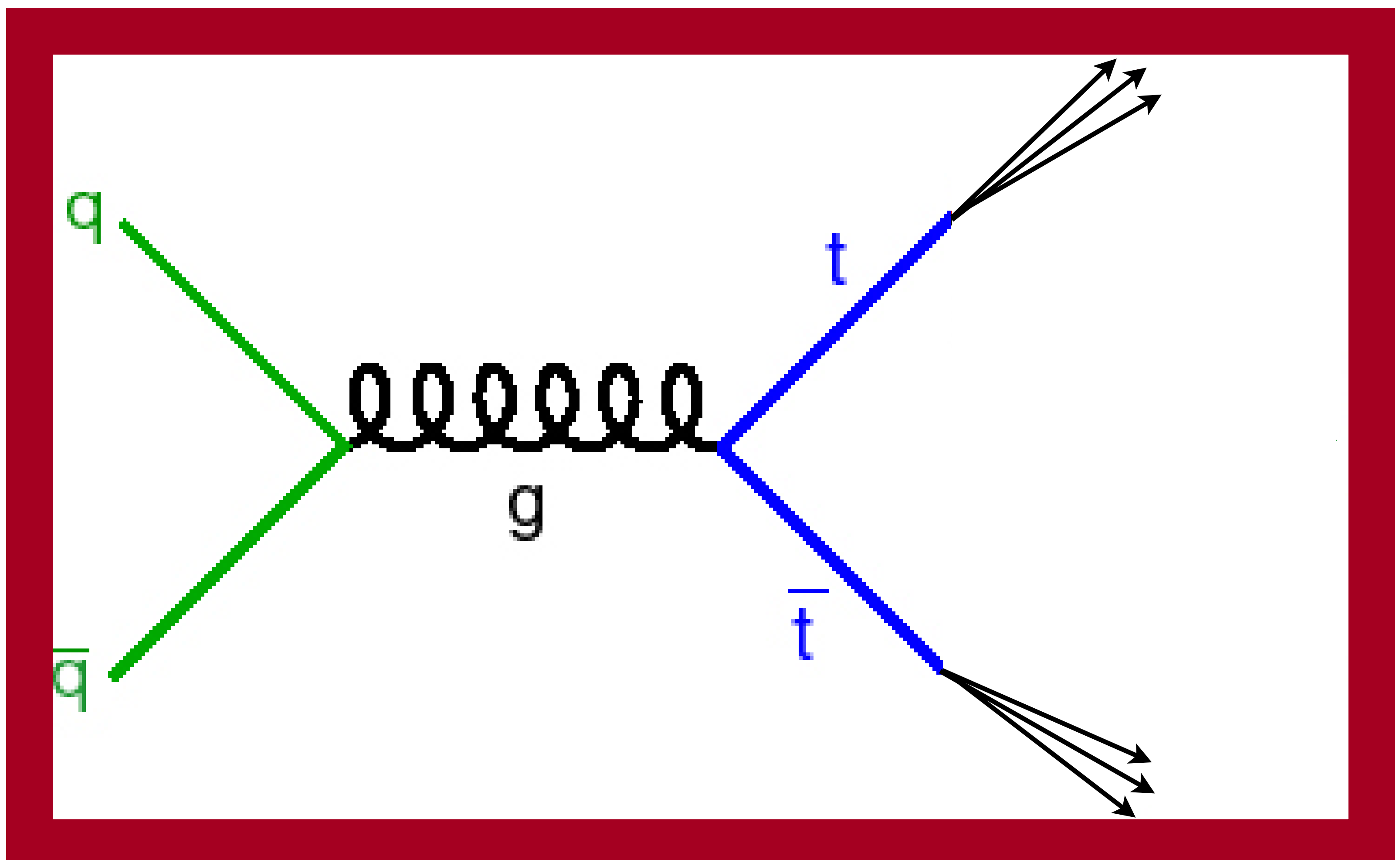
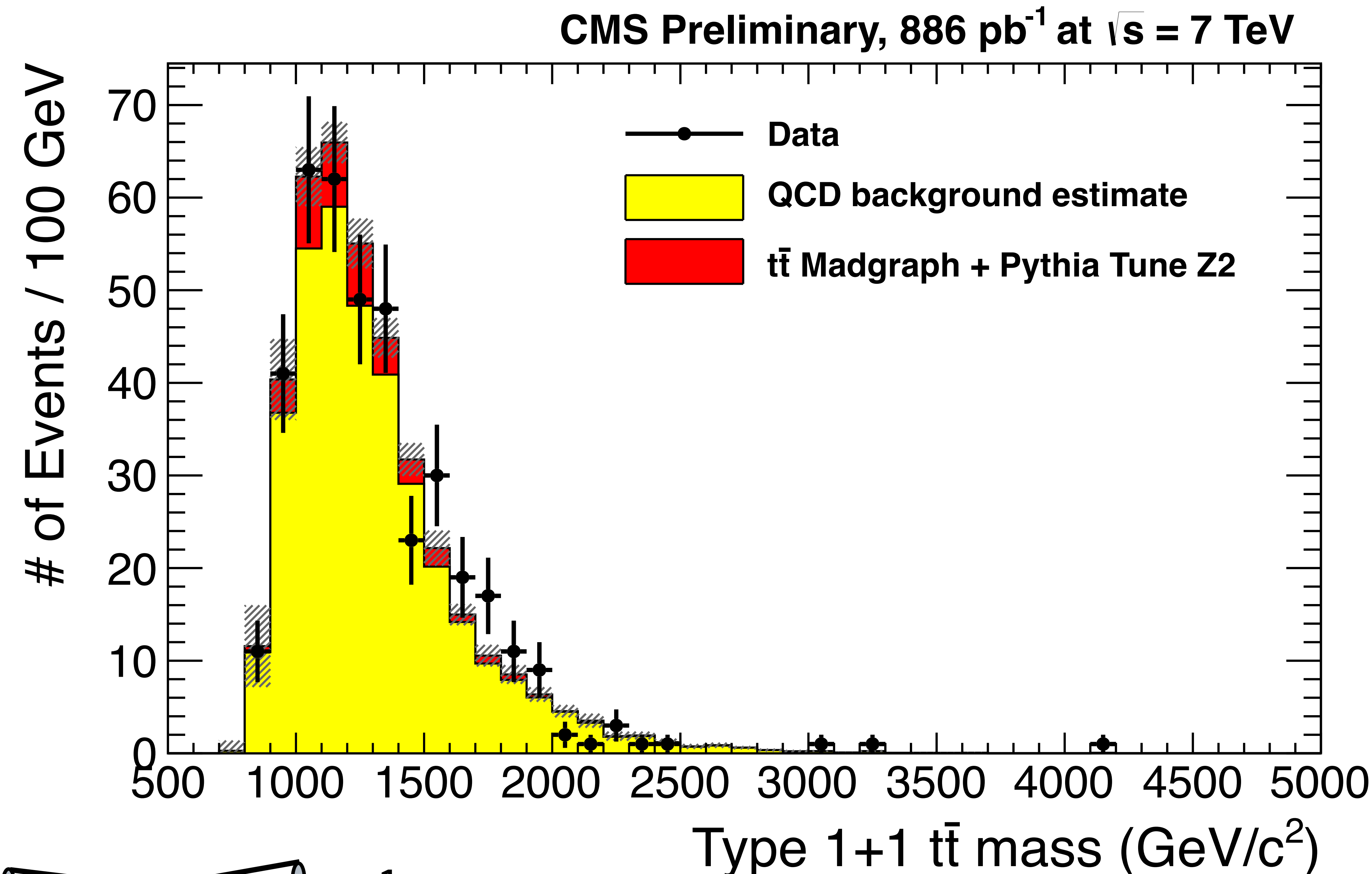


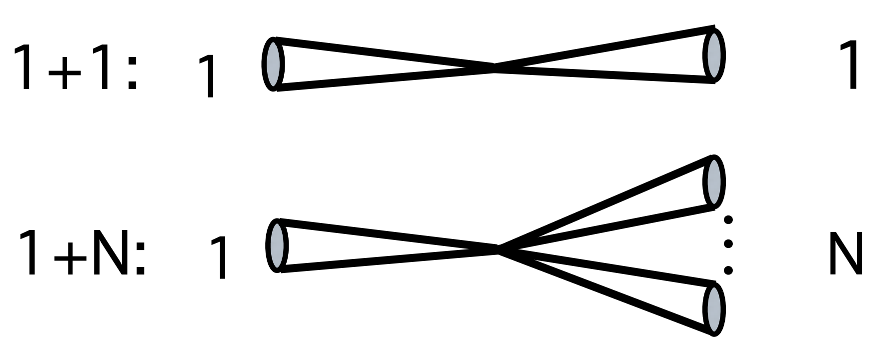
- Since $M_{t,h} \ll M_X$ the outgoing SM particles are ultra-relativistic, their decay products are collimated

- The concept of boosted massive jet emerges



The LHC frontier: hard/boosted tops phys.

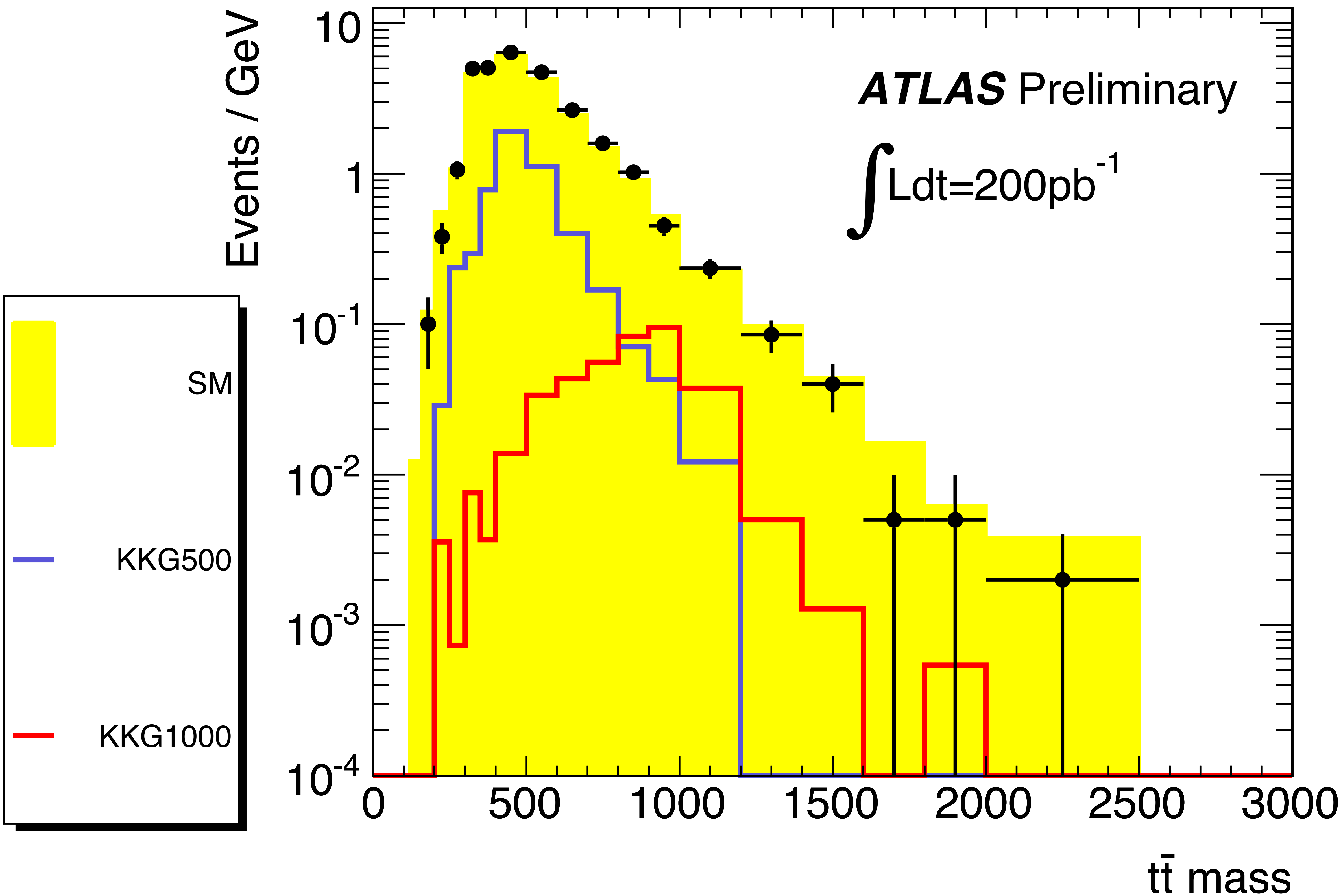




CMS PAS EXO-11-006

(nothing interesting found by CMS in the 2+1 case)

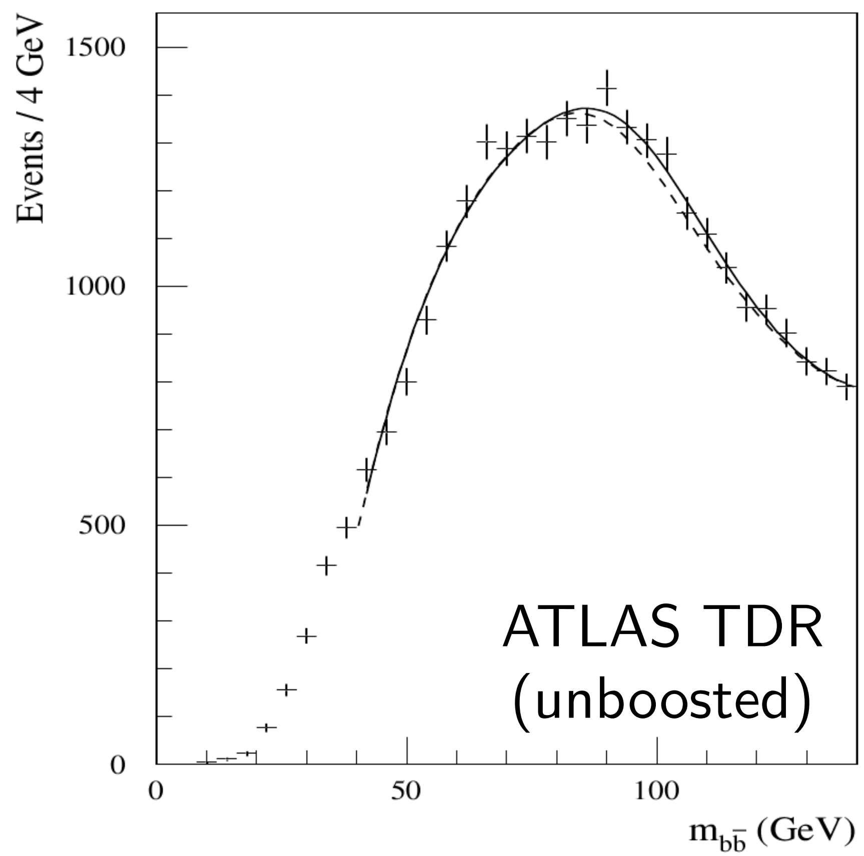
The LHC frontier: hard/boosted tops phys.

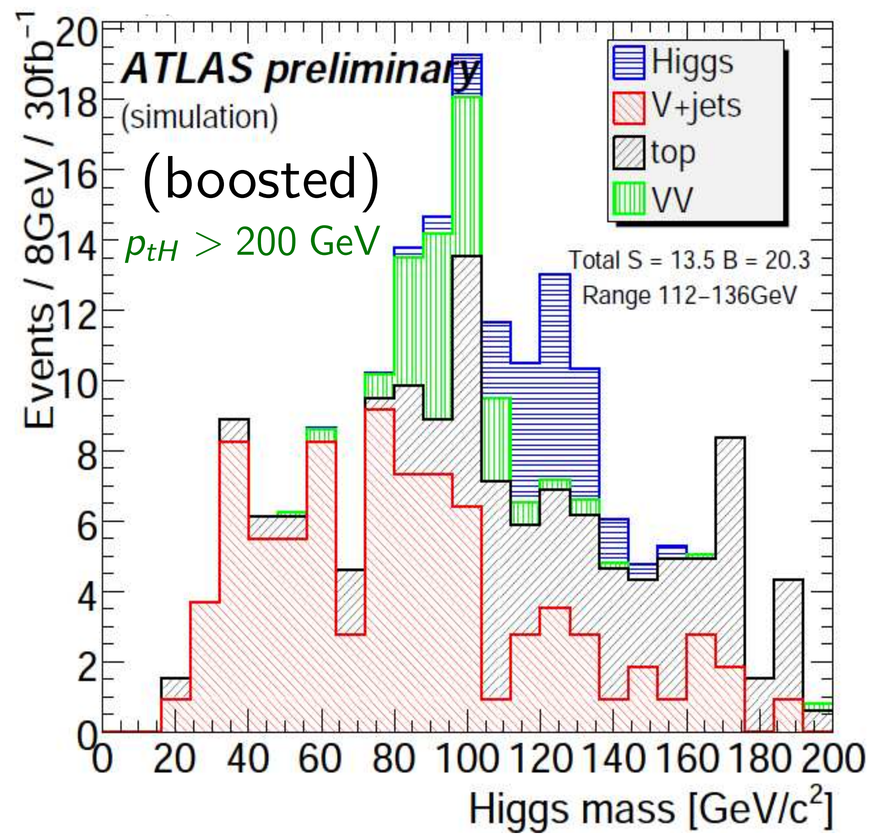


Higgs hunting

✦Search for Higgs boson in $W/Z+H$, $H \to b\bar{b}$.

Butterworth, Davison, Rubin & Salam (08).





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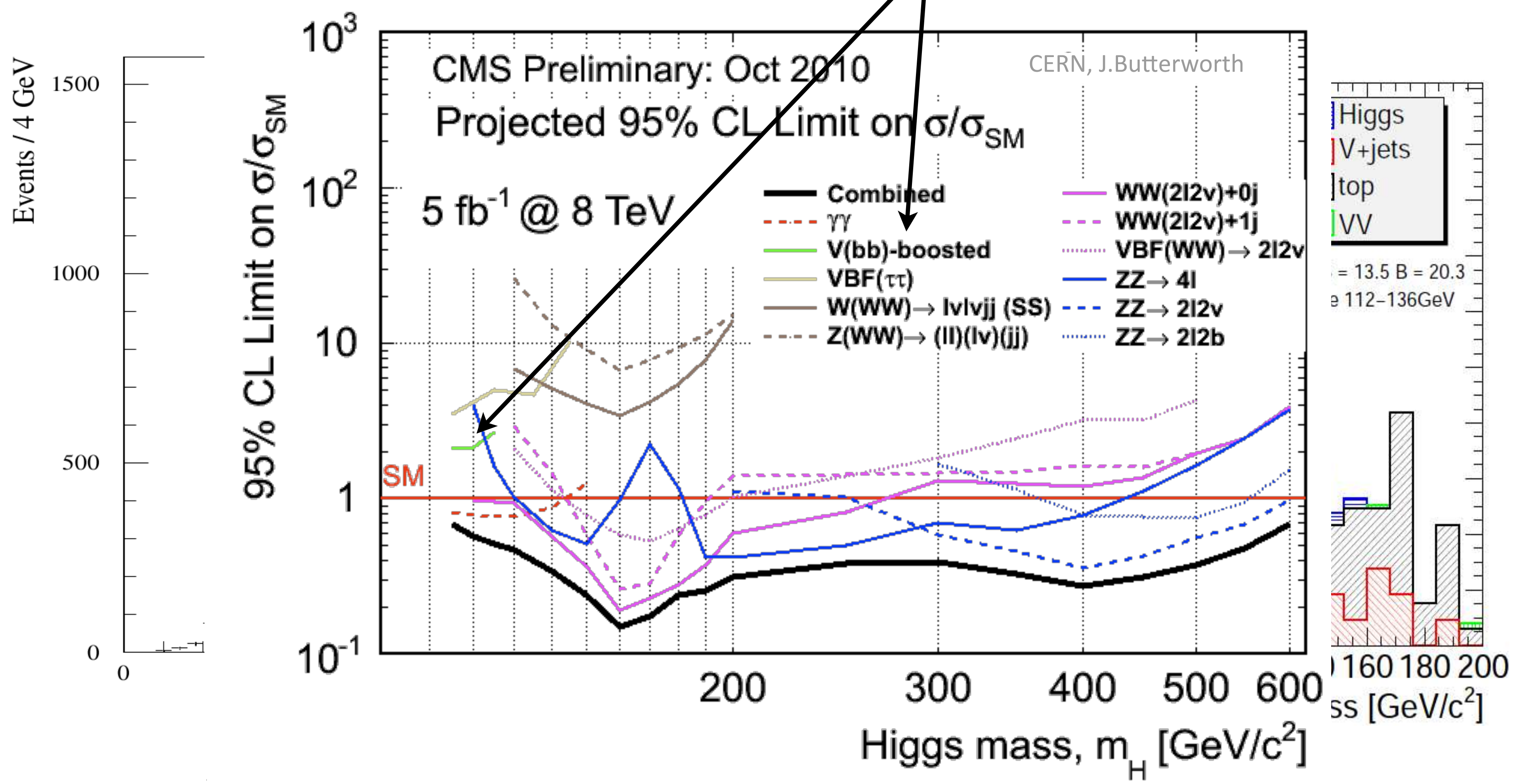
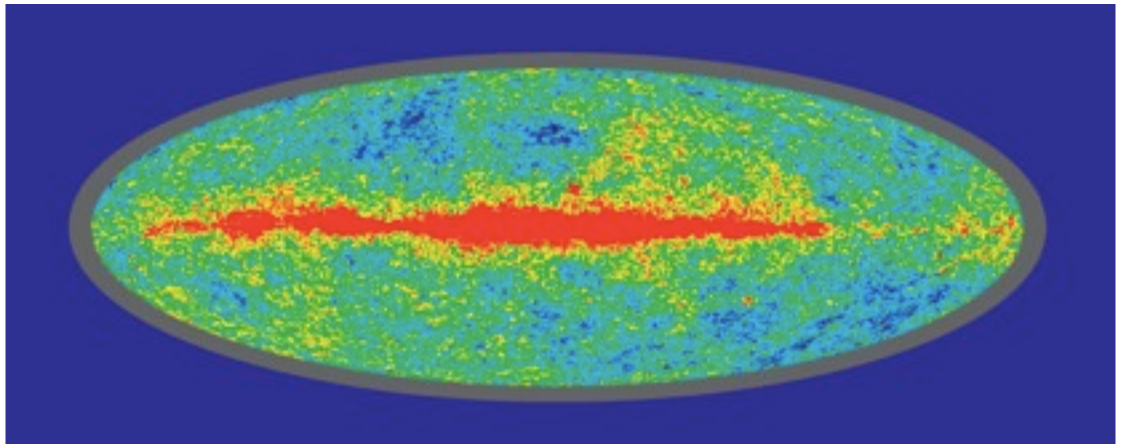
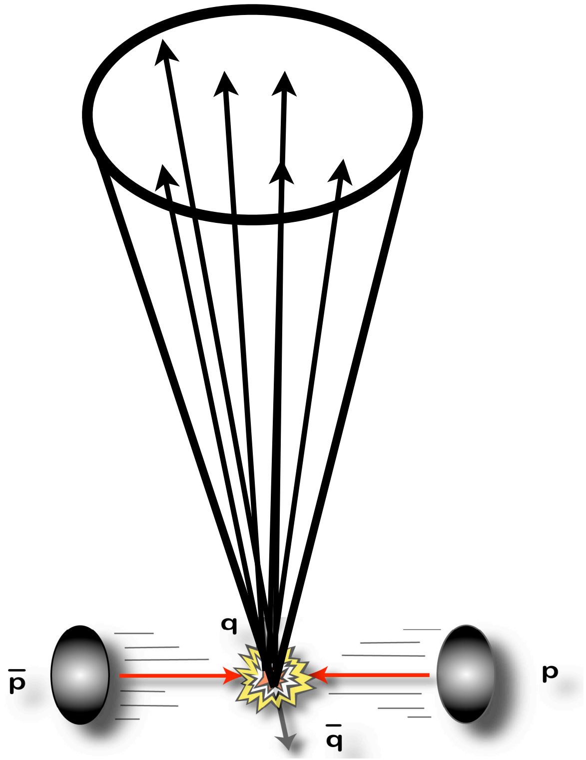


Less competitive than $h \to \gamma\gamma$ but important. (can be improved?)

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





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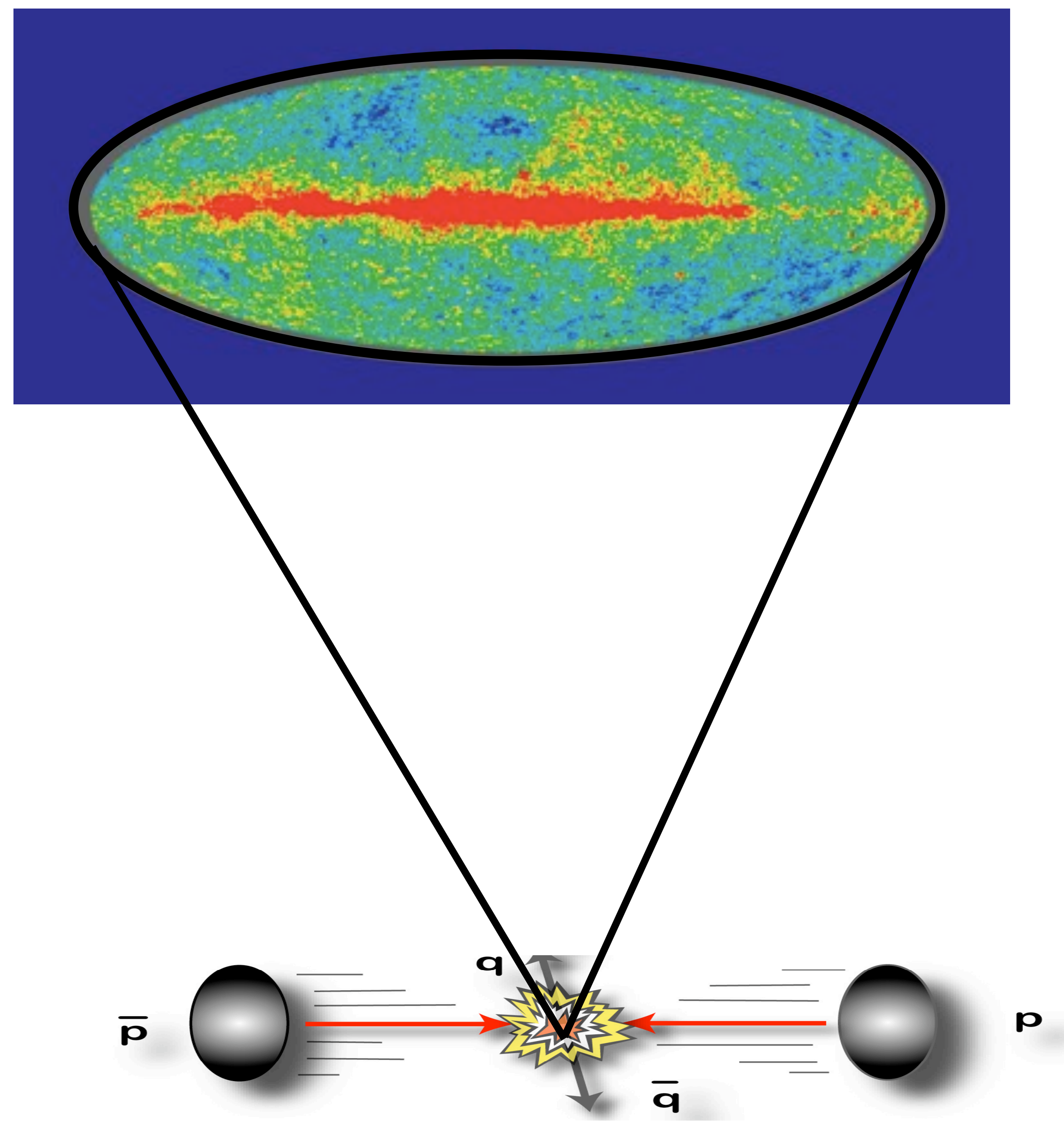

i)Jet Mass

ii)Jet Shapes

iii)Template Overlap Method

1) LO for Higgs and Top

2) NLO Higgs(+color flow)

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 & real data.
- 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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+ detector smearing.

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 $m^t_J \sim m_t + \delta m_{QCD} + \delta m_{EW}$

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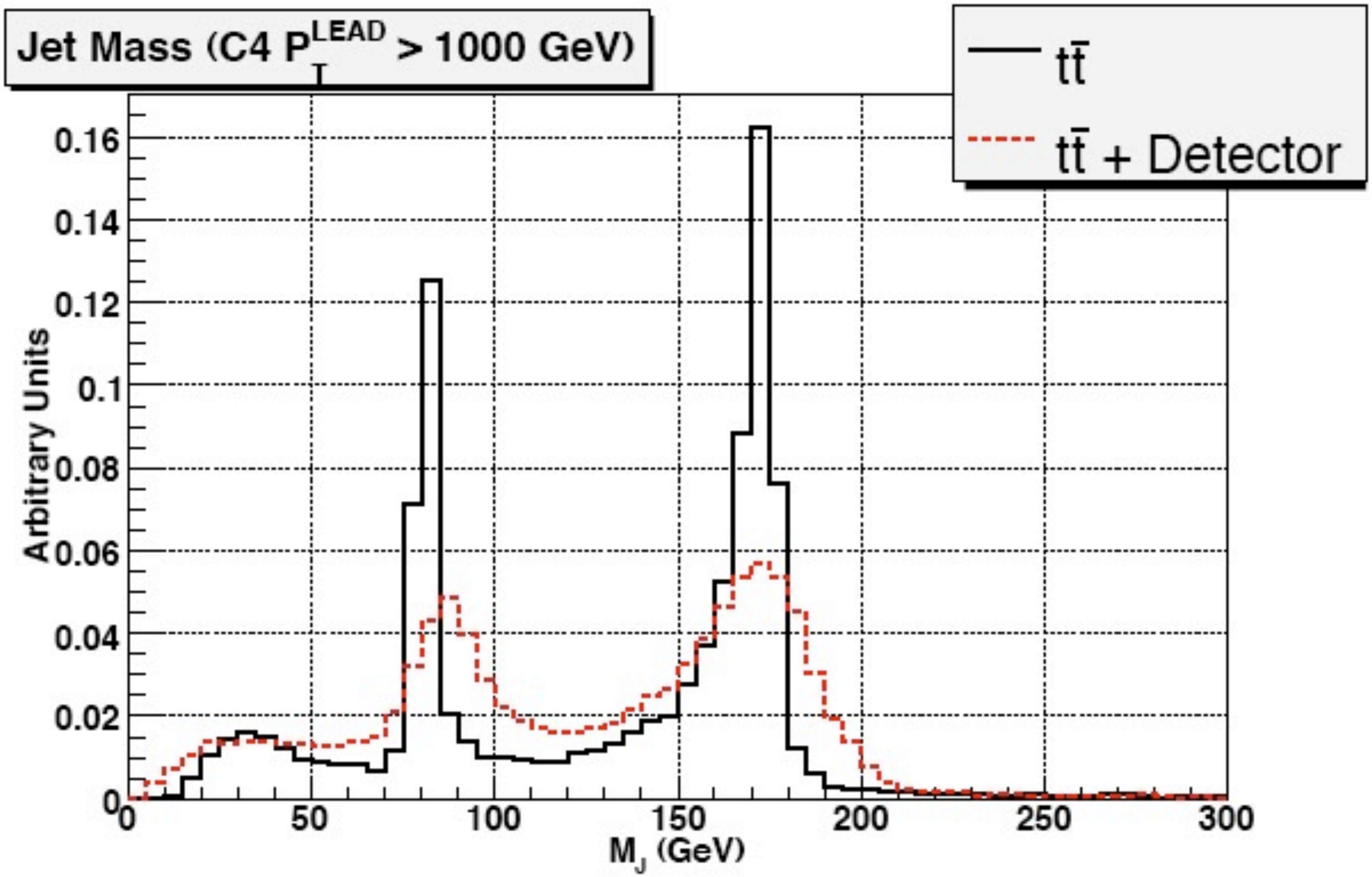
(Fleming, Hoang, Jain, Mantry, Scimemi, Stewart) Almeida, SL, Perez Sung, & Virzi.

Sherpa => (CKKW) Transfer functions, JES



QCD jet mass distribution

✦Boosted QCD Jet via factorization:

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

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

- 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:

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

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$$\int dm_J \qquad\qquad i = Q, G$$

- can interpret the jet fu… …iven p_T to acquire a mass betwee…

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

Full expression:

$$\frac{d\sigma_{H_A H_B \to J_1 J_2}}{dm^2_{J_1} dm^2_{J_2} d\eta} = \sum_{abcd} \int dx_a\, dx_b\, \phi_a(x_a, p_T)\, \phi_b(x_b, p_T) \frac{\ldots}{dp_T d\eta}(x_a, x_b, \eta, p_T)$$

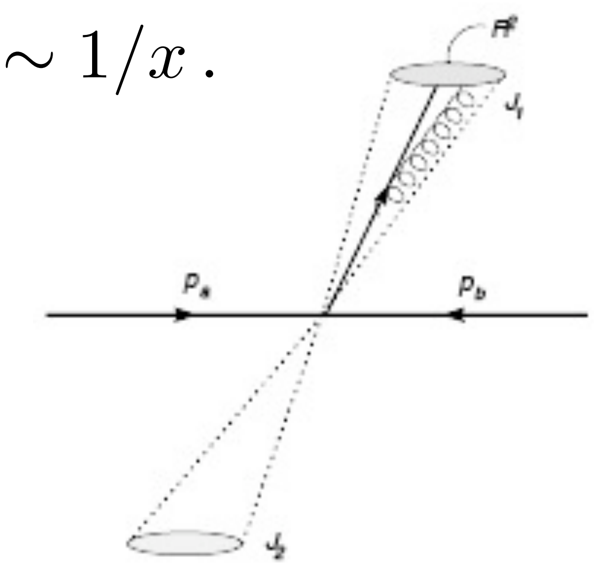
$$S\left(m^2_{J_1}, m^2_{J_2}, \eta, p_T, R^2\right)\ J_1^{(c)}(m^2_{J_1}, \eta, p_T, R^2) J_2^{(d)}(m^2_{J_2}, \eta, p_T, R^2)$$

Energy dist' massive jets, splitting function

In QCD the probability for a parton j to emit a parton i with energy fraction x at angle θ is

$$d\sigma \propto \alpha_s P_{ij}(x) dx \frac{d\theta}{\theta}$$

$P_{ij}(x)$ is the Altarelli-Parisi matrix $\quad P_{ij} \sim 1/x$.

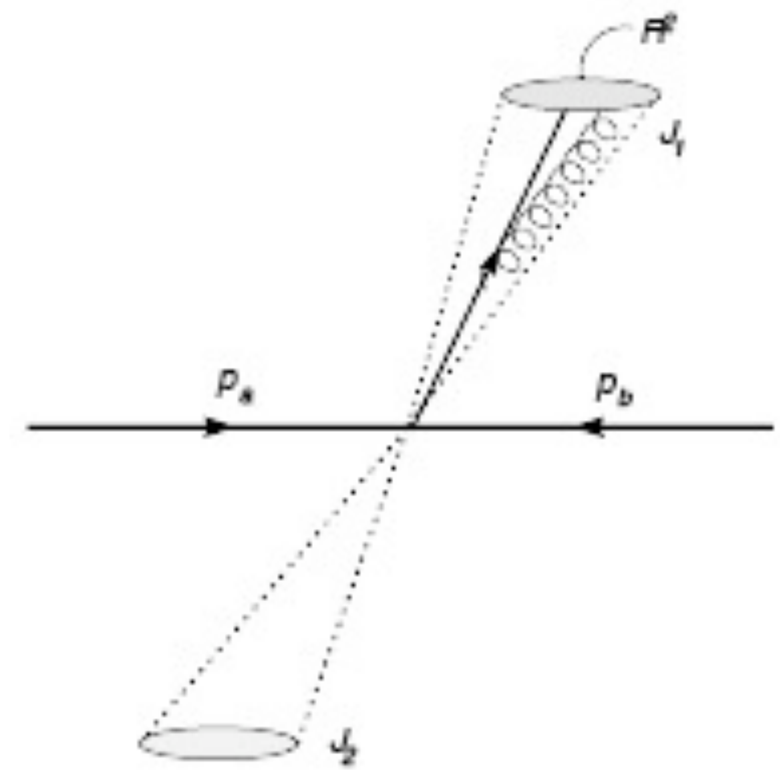


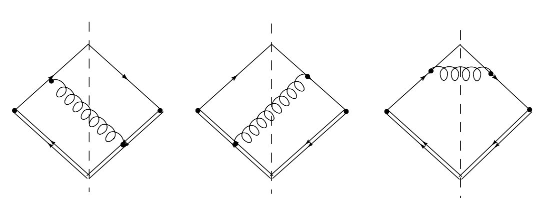
$$\text{Given } m_J^2 \approx x E_J^2 \theta^2 \Rightarrow \frac{d\sigma}{dm_J^2} \propto \alpha_s \frac{C_F}{m_J^2} \int_{\frac{m_J}{E_J}}^{R} \frac{d\theta}{\theta} \propto \alpha_s \frac{C_F}{m_J^2} \log\left(\frac{E^2 R^2}{m_J^2}\right)$$

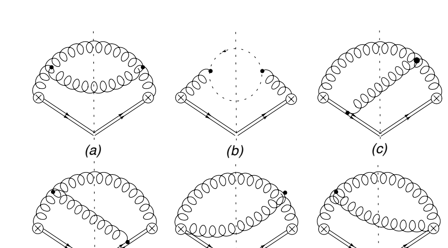
$C_F = 4/3$ for quarks, $C_A = 3$ for gluons.

QCD jet mass distribution, Q+G

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







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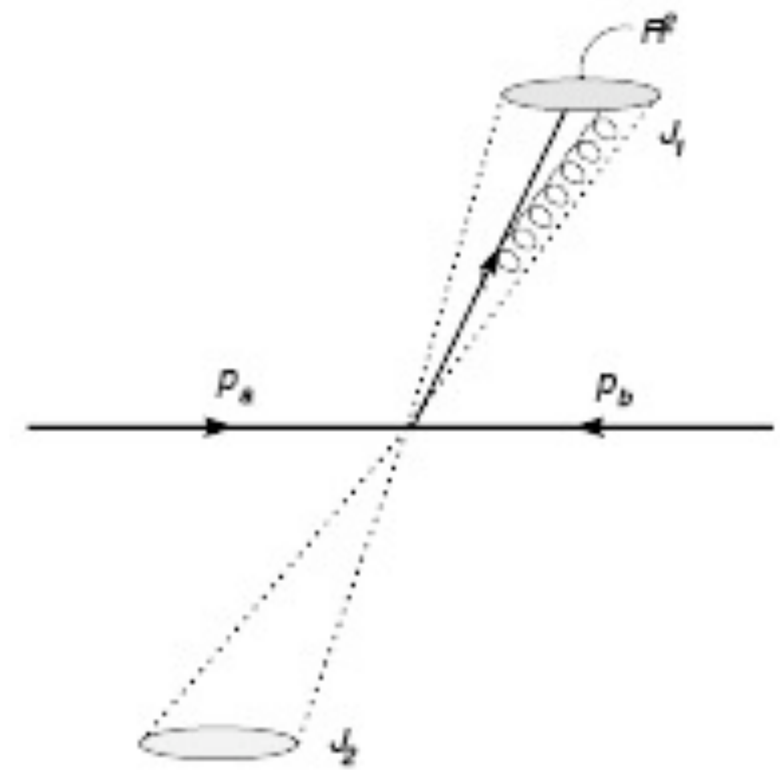

$$J^{(eik),c}(m_J, p_T, R) \simeq \alpha_S(p_T)\frac{4\,C_c}{\pi m_J}\log\left(\frac{R\,p_T}{m_J}\right)$$

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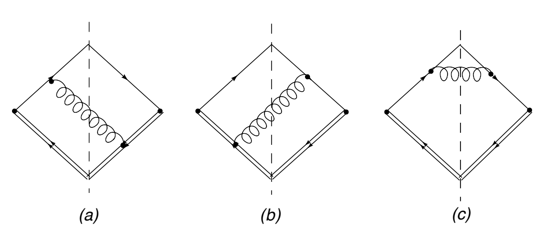
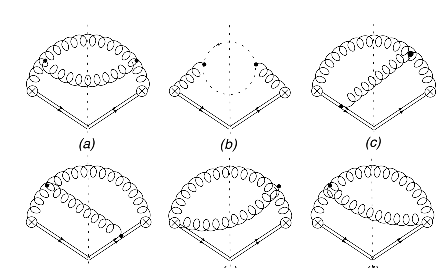


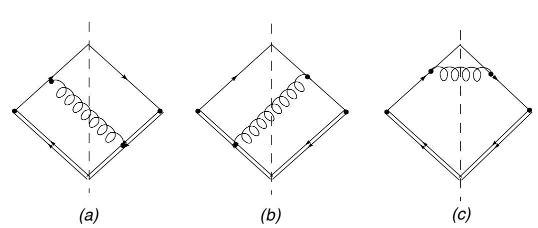


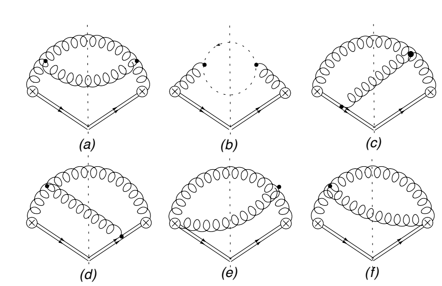
QCD jet mass distribution, Q+G

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

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

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





QCD jet mass distribution, Q+G

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

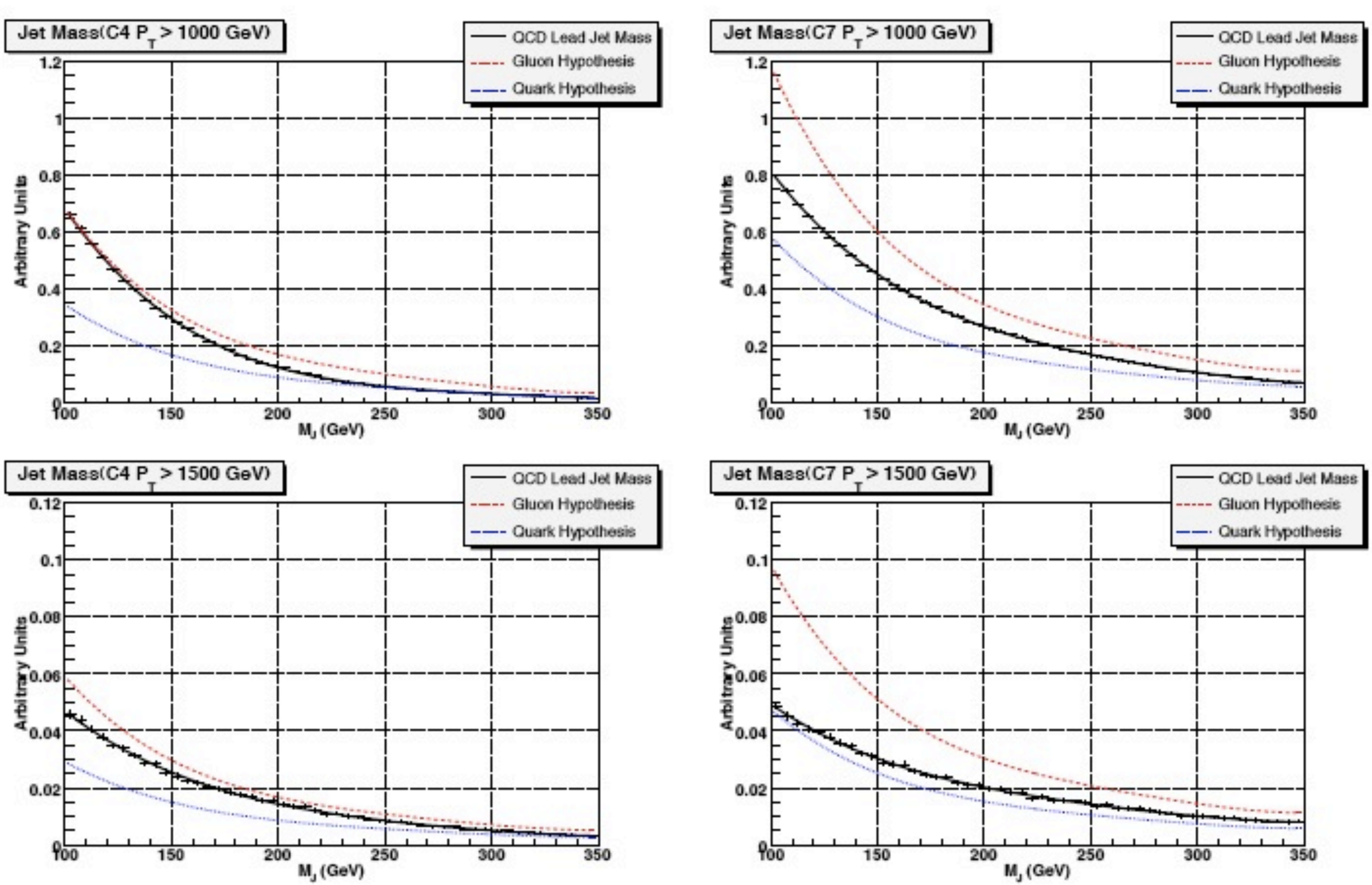
$C_F = 4/3$ for quarks, $C_A = 3$ for gluons.

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

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

Jet mass distribution theory vs. MC

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



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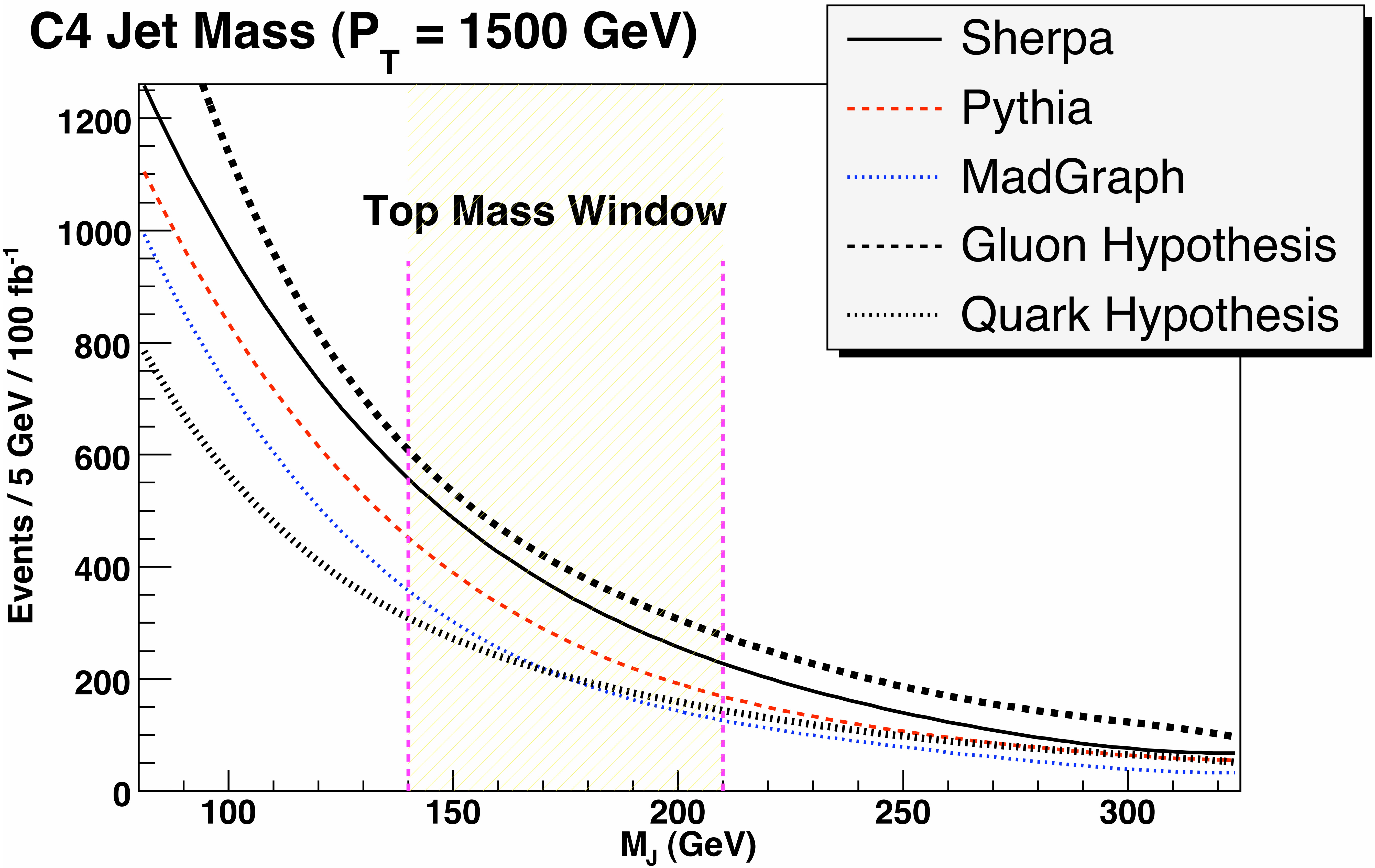

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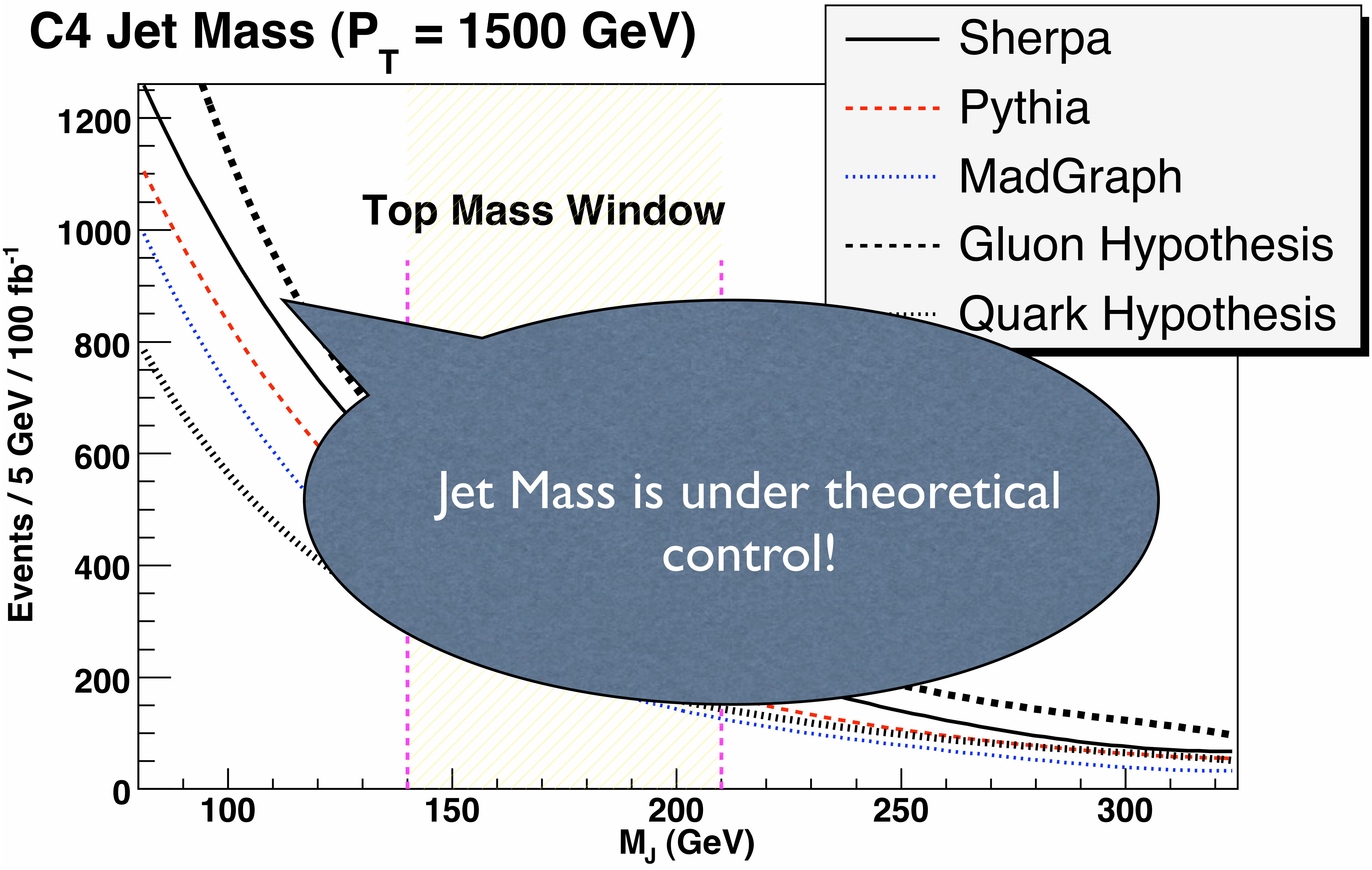
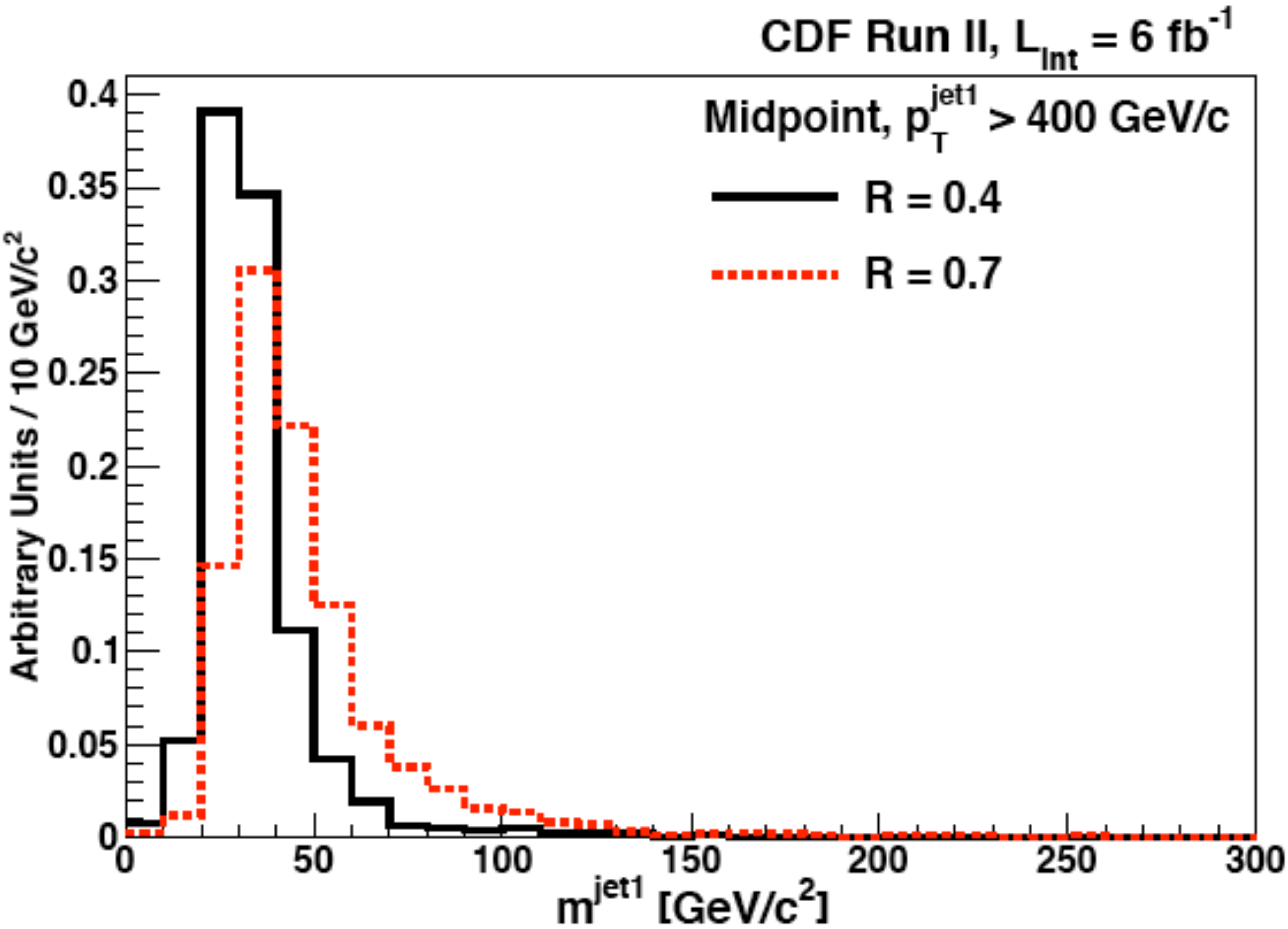


Jet mass distribution @ CDF



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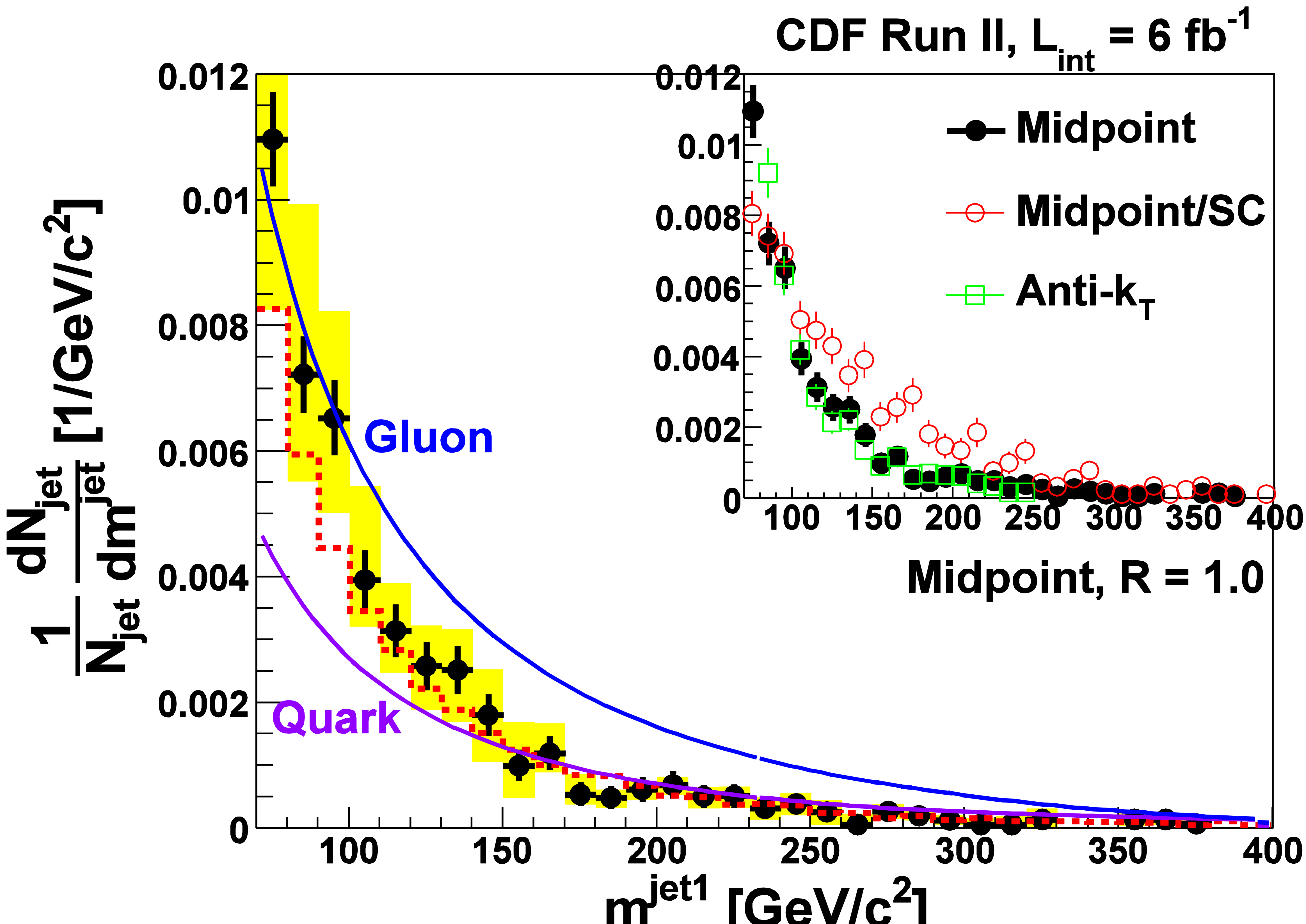

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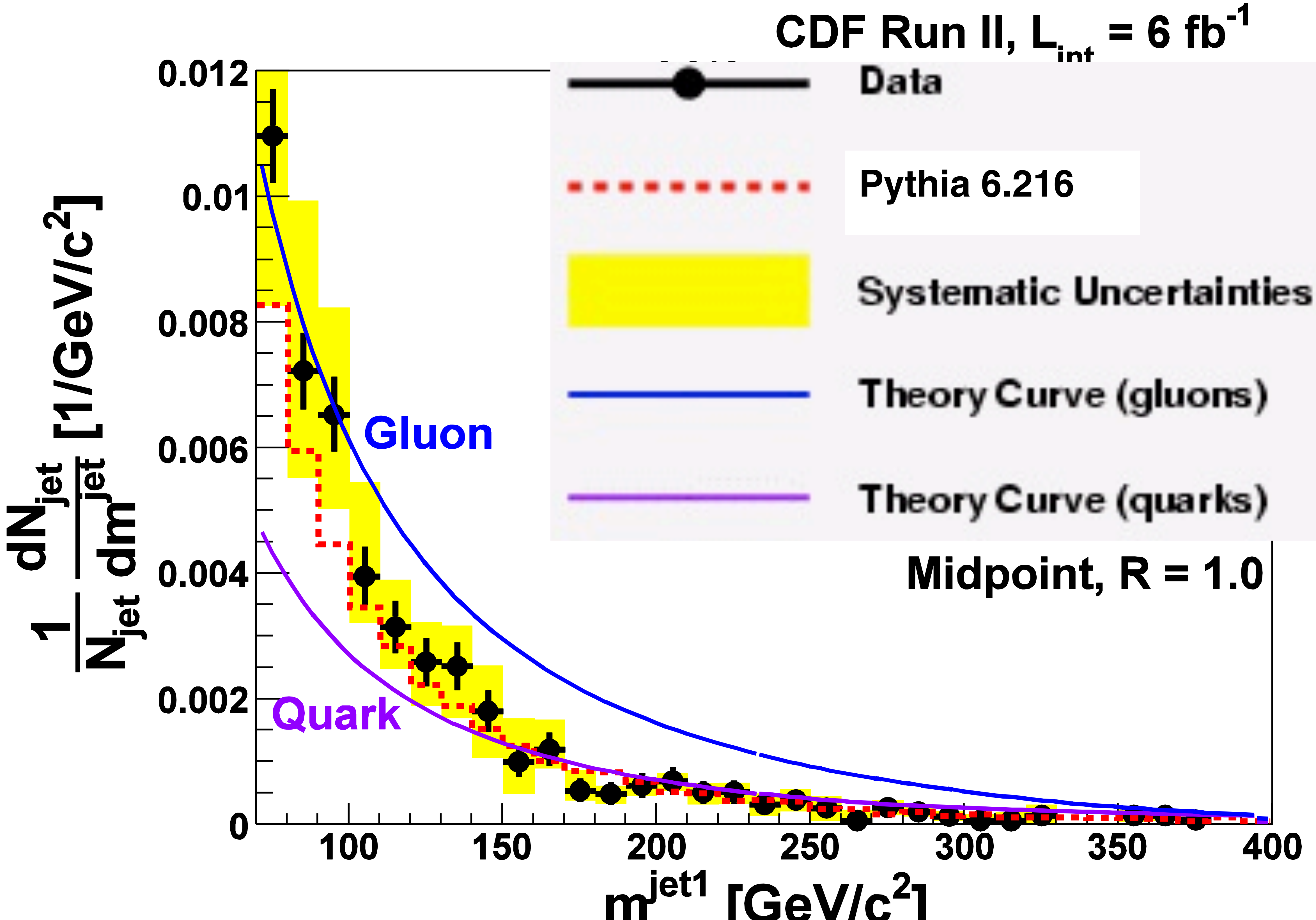

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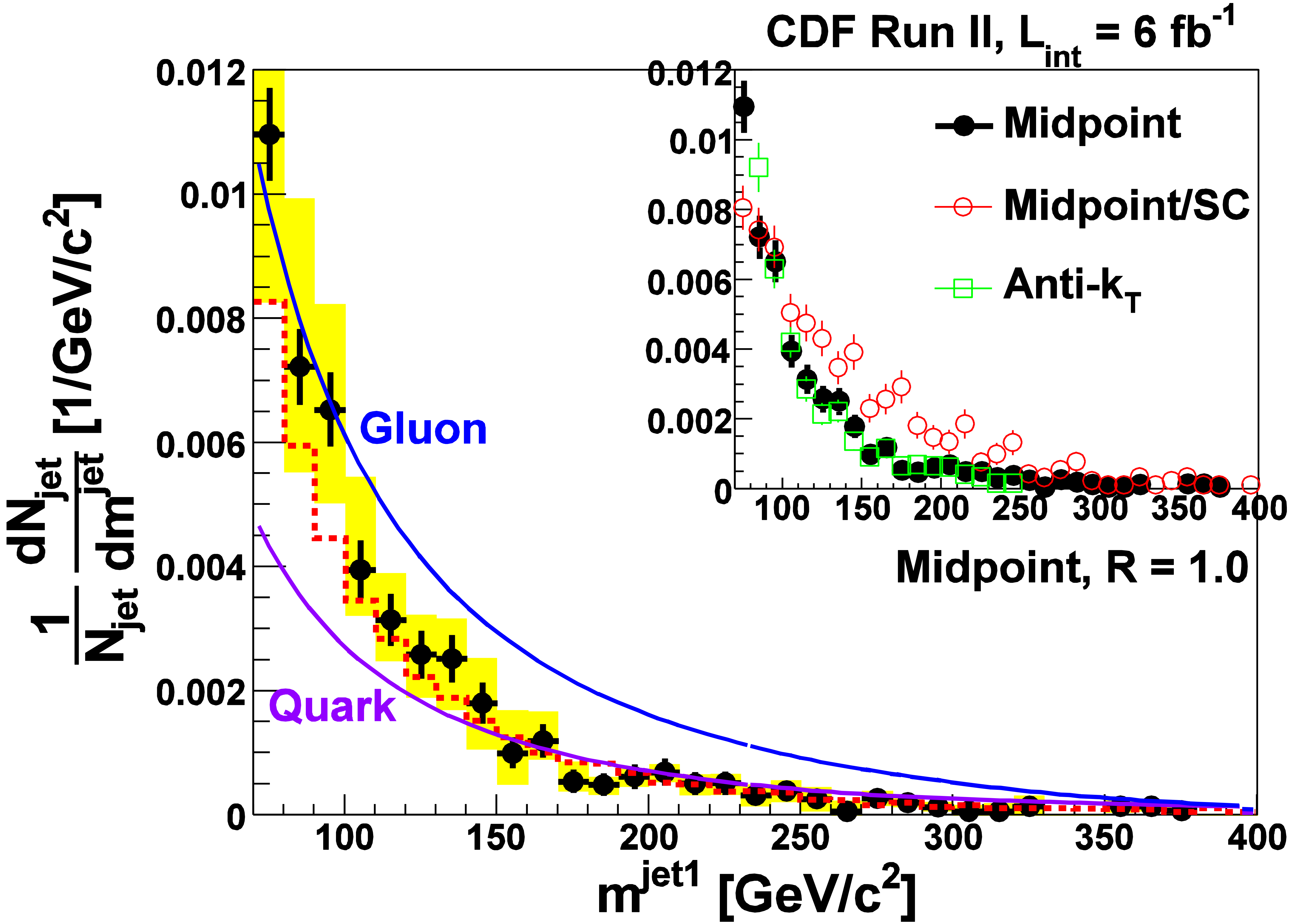

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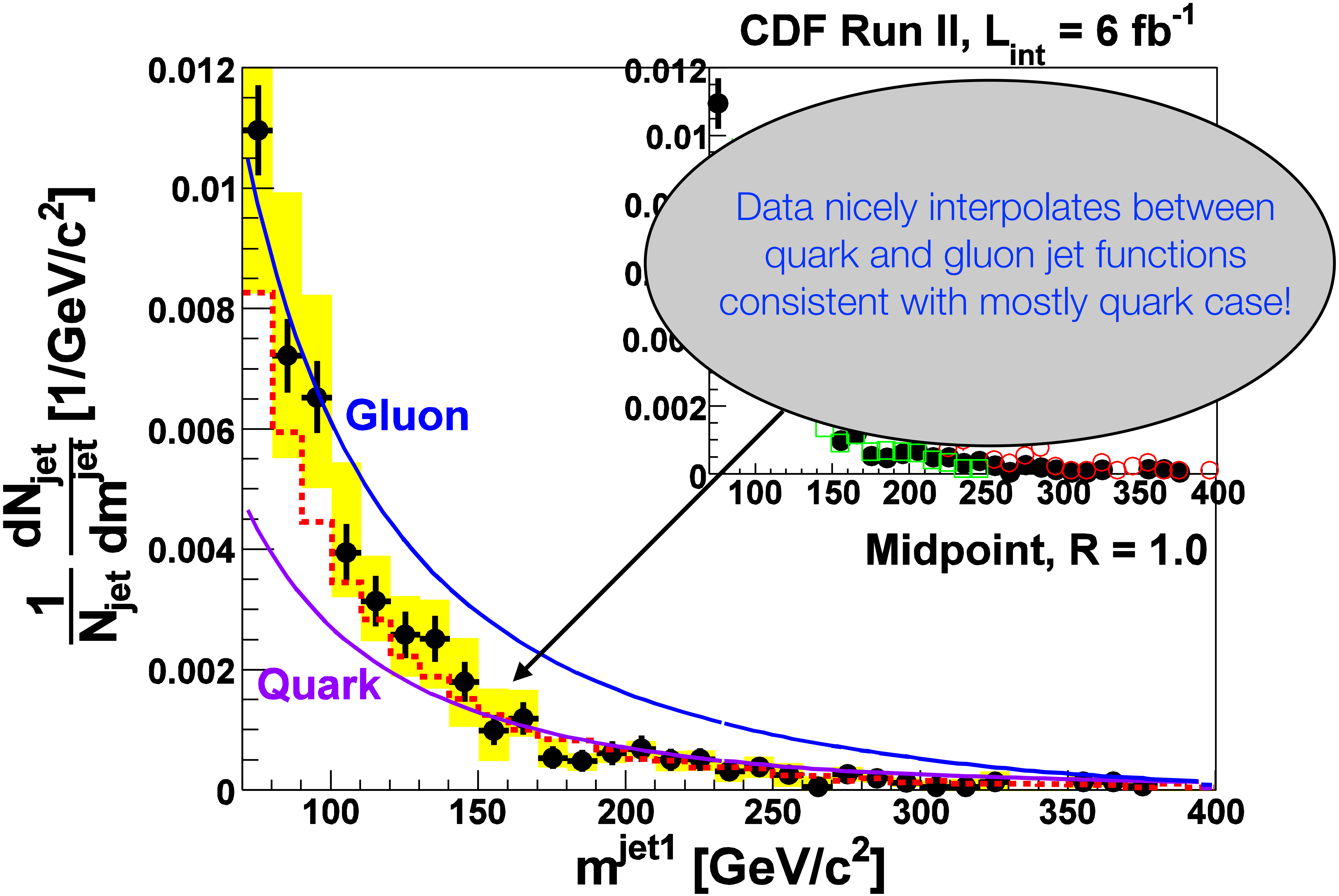

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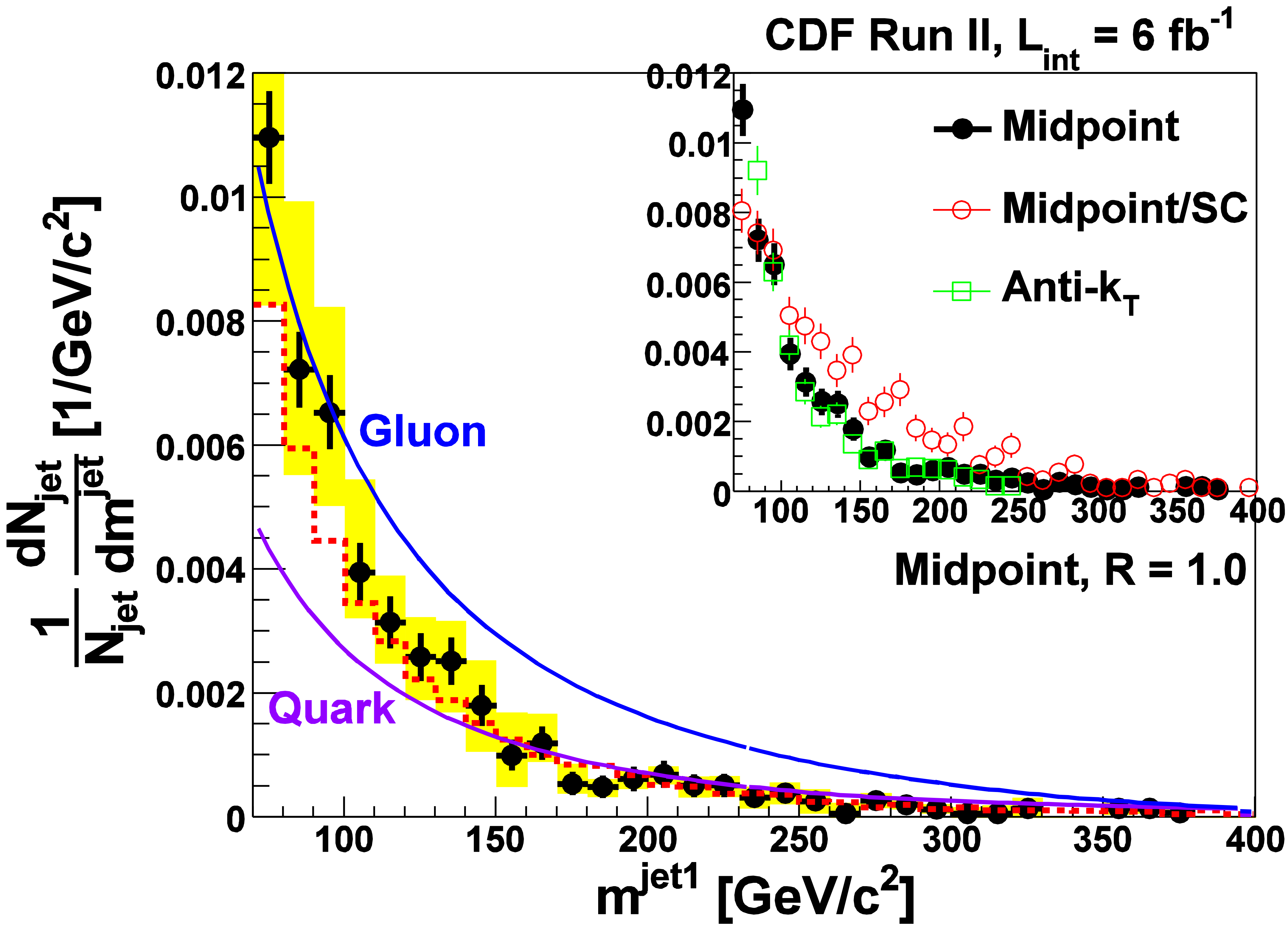

ATLAS-CONF-2011-073 & CMS PAS EXO-11-006.

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

Beyond mass, higher moments, angularity (2 body)

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

Berger, Kucs, Sterman, PRD (03);
Almeida, SL, Perez, Stermam, Sung & Virzi, PRD (09).

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

$$\text{QCD: } \propto \frac{1}{\tau_{-2}}$$

$$h\text{: } \propto \frac{1}{\tau_{-2}^2}$$

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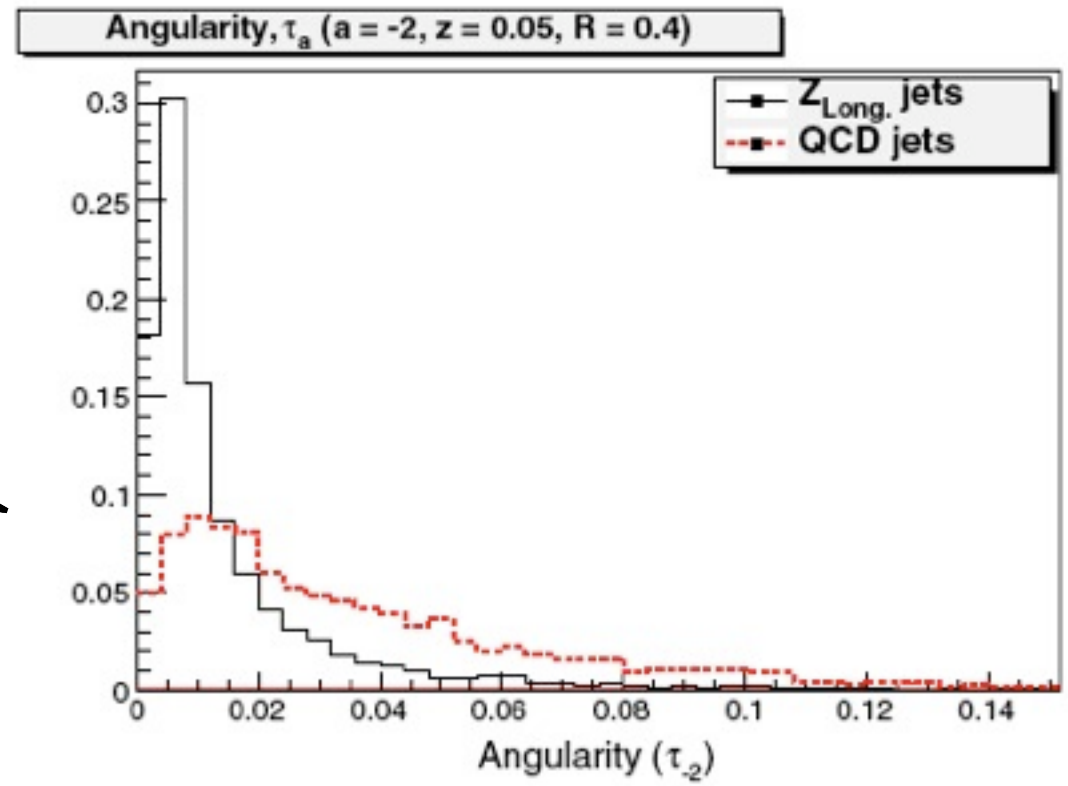
after fixing mass - signal & backgroun dist' are similar in shape !

θ_i^4



$\frac{1}{-2}$

Almeida, SL, Perez, Sterman & Sung.

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.

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$$h\text{:} \propto \frac{1}{\tau_{-2}^2}$$

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

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

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

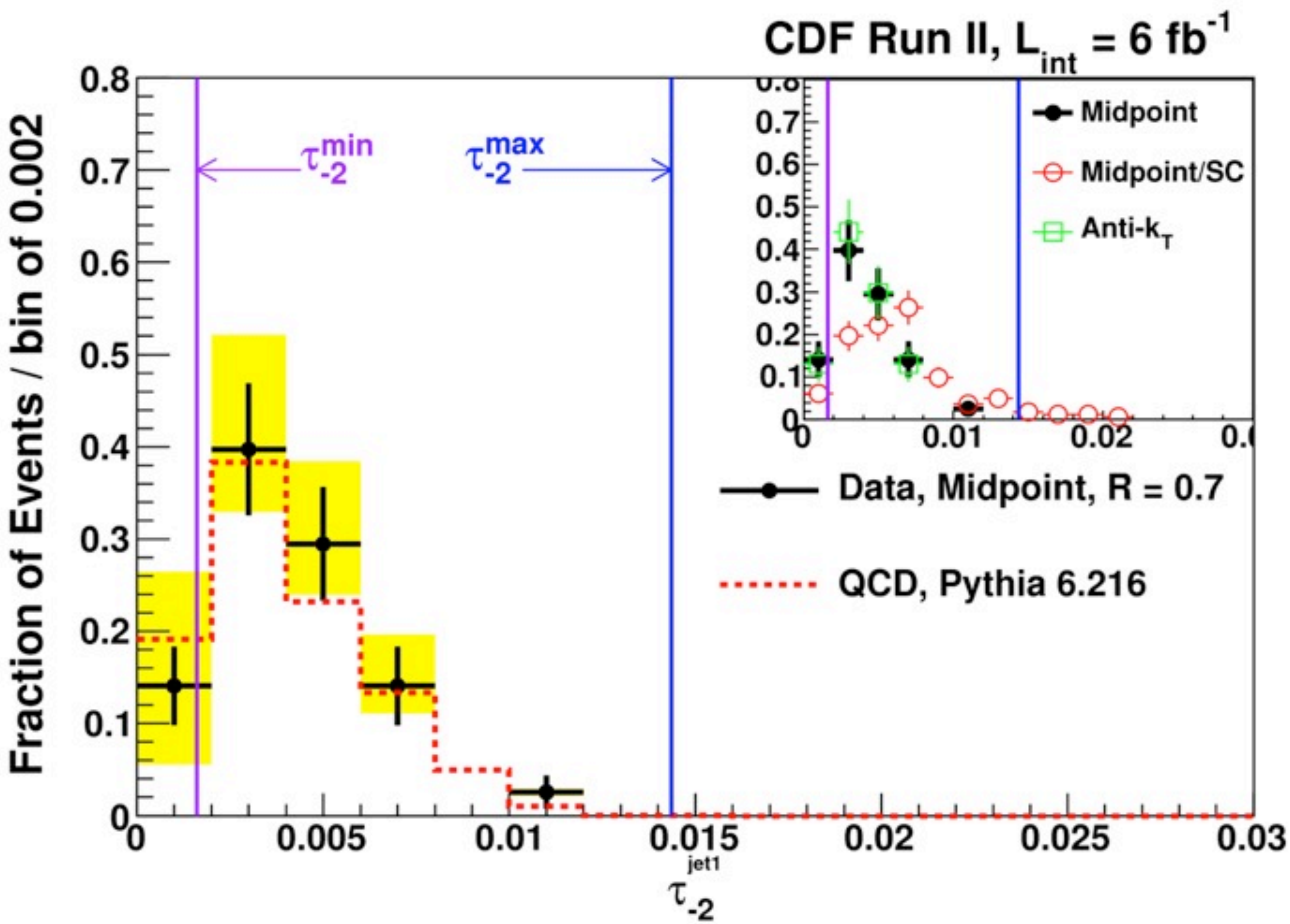
Almeida, SL, Perez, Stermam & Sung, PRD (10).

Beyond mass, higher moments, angularity (2 body)

♦ Given jet mass & momenta, only one additional independent,

varia

RD (09).



τ_{-}

♦ If

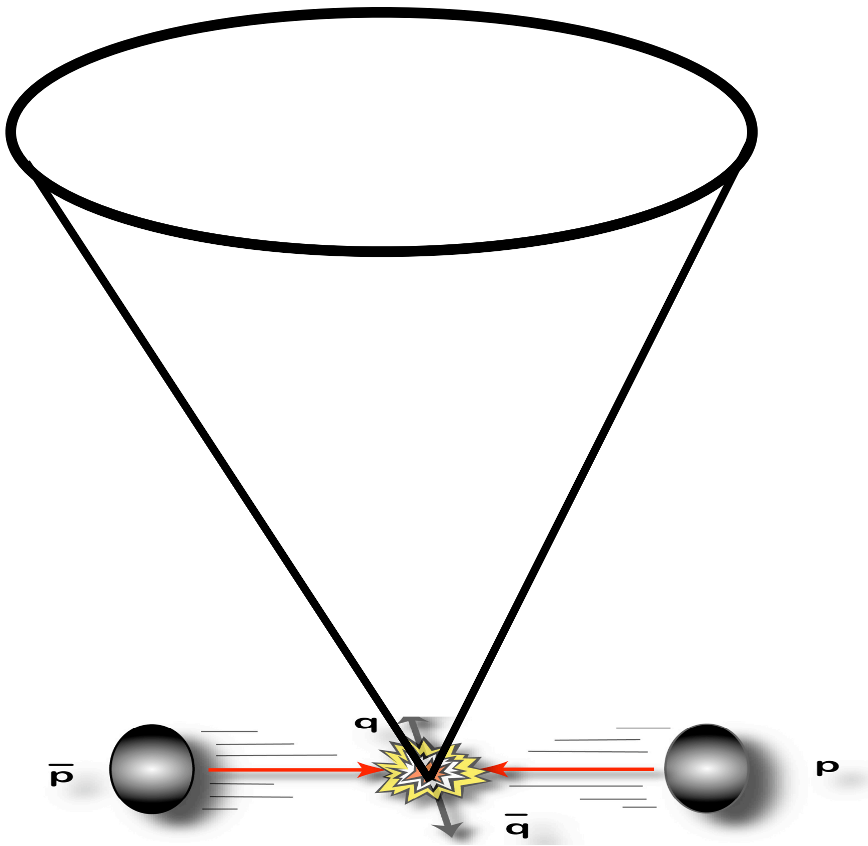
:

Angularity for jets with mass ∈ (90, 120) GeV/c², p_T > 400 GeV/c, 0.1 < |η| < 0.7, cone R=0.7.
Black crosses are the data, red dashed is QCD MC, τ^{min} and τ^{max} predictions are also shown.
The inset plot compares the results with Midpoint/SC and Anti-k_T

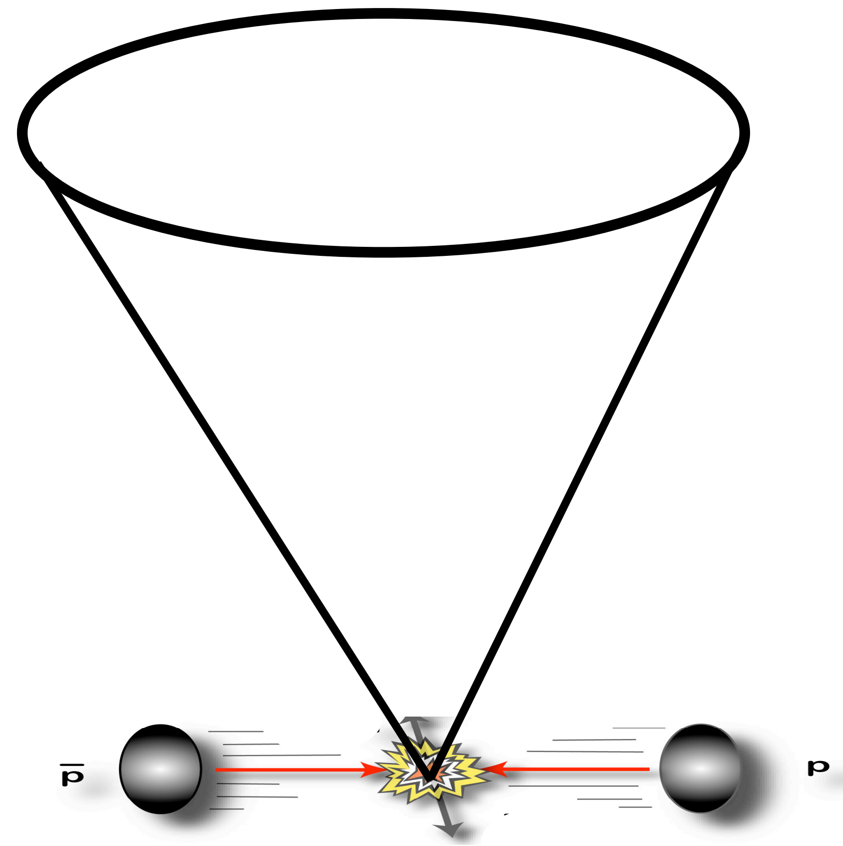
10).

Planar Flow

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



QCD massive jet



top jet

Planar Flow

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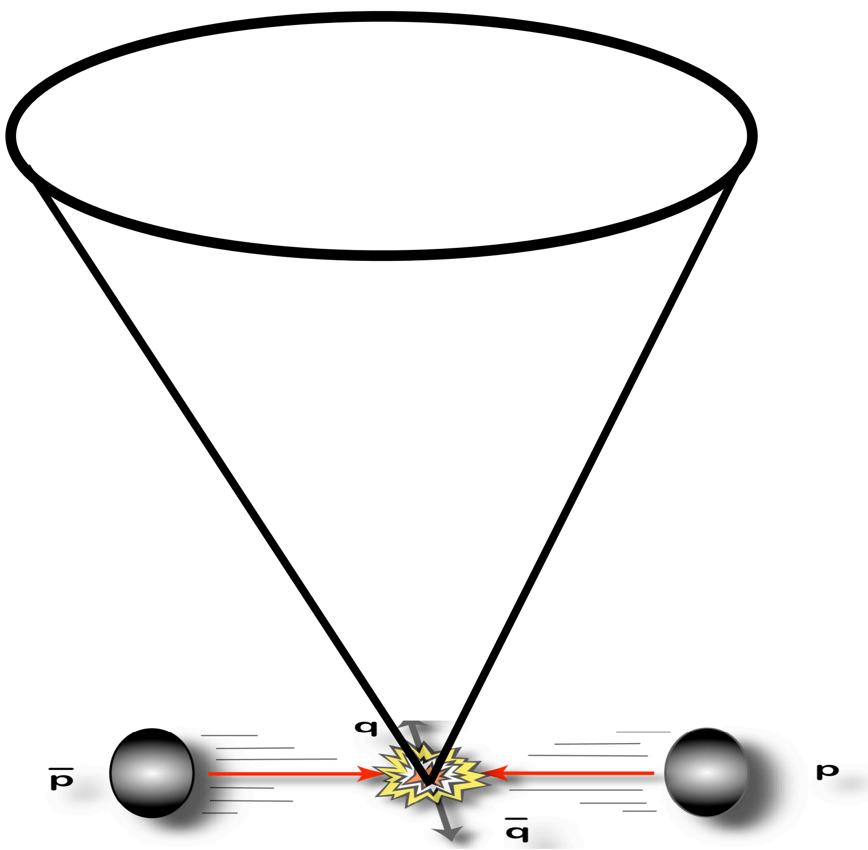
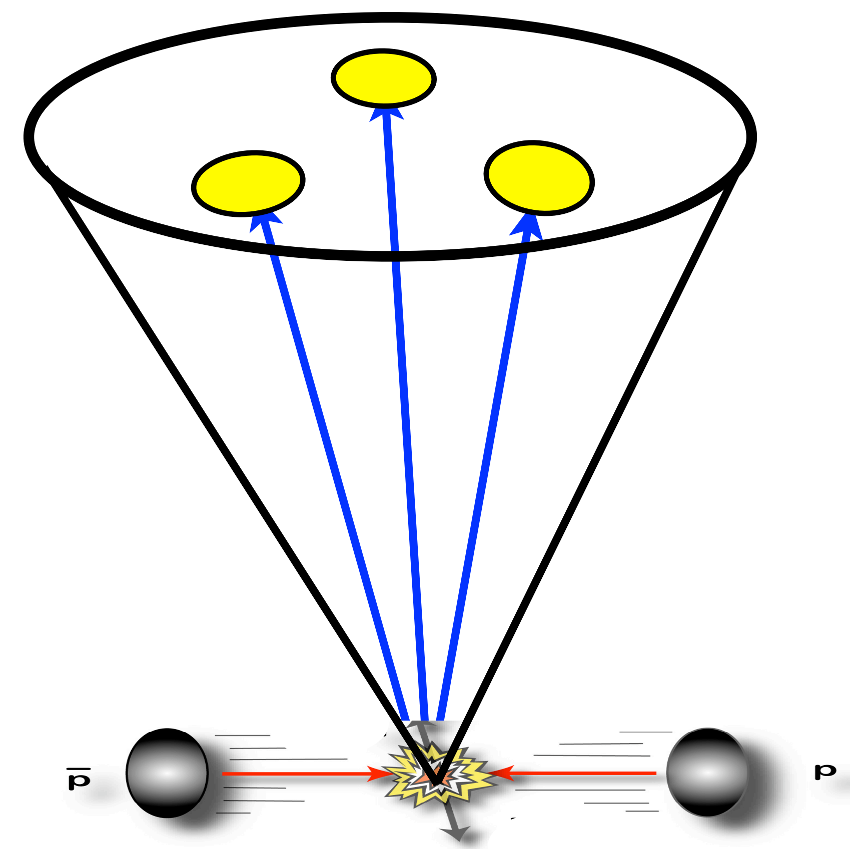


QCD massive jet



top jet

Planar Flow

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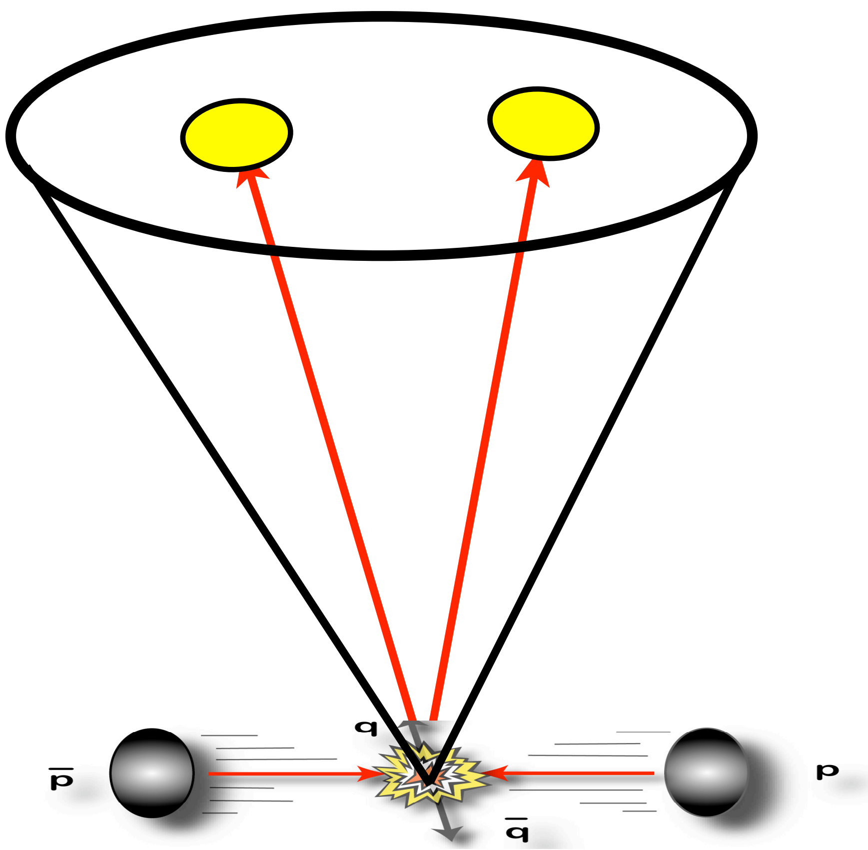
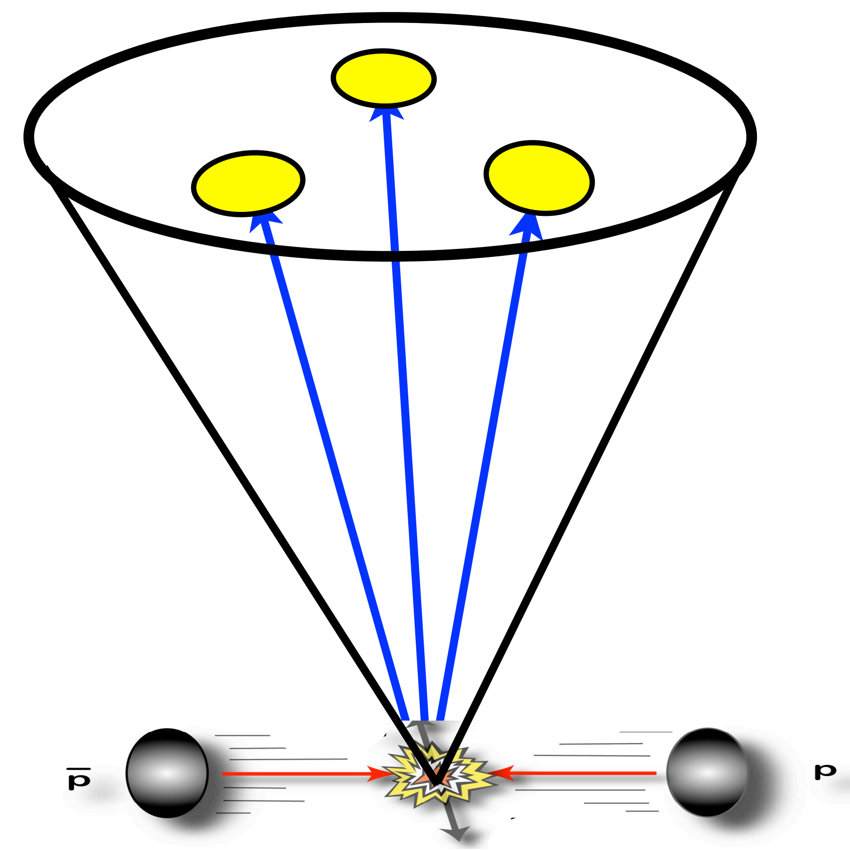


QCD massive jet



top jet

Planar flow

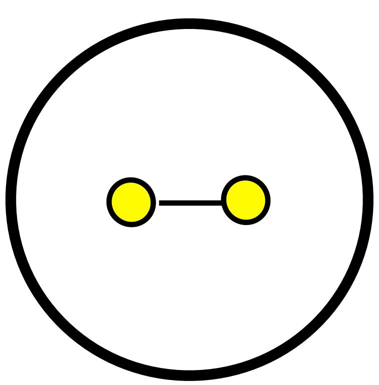
- Top-jet is 3 body vs. massive QCD jet <=> 2-body (our result)

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

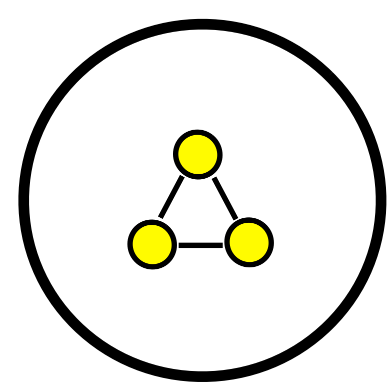
- Planar flow, *Pf*, measures the energy ratio between two primary axes of cone surface:

(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*



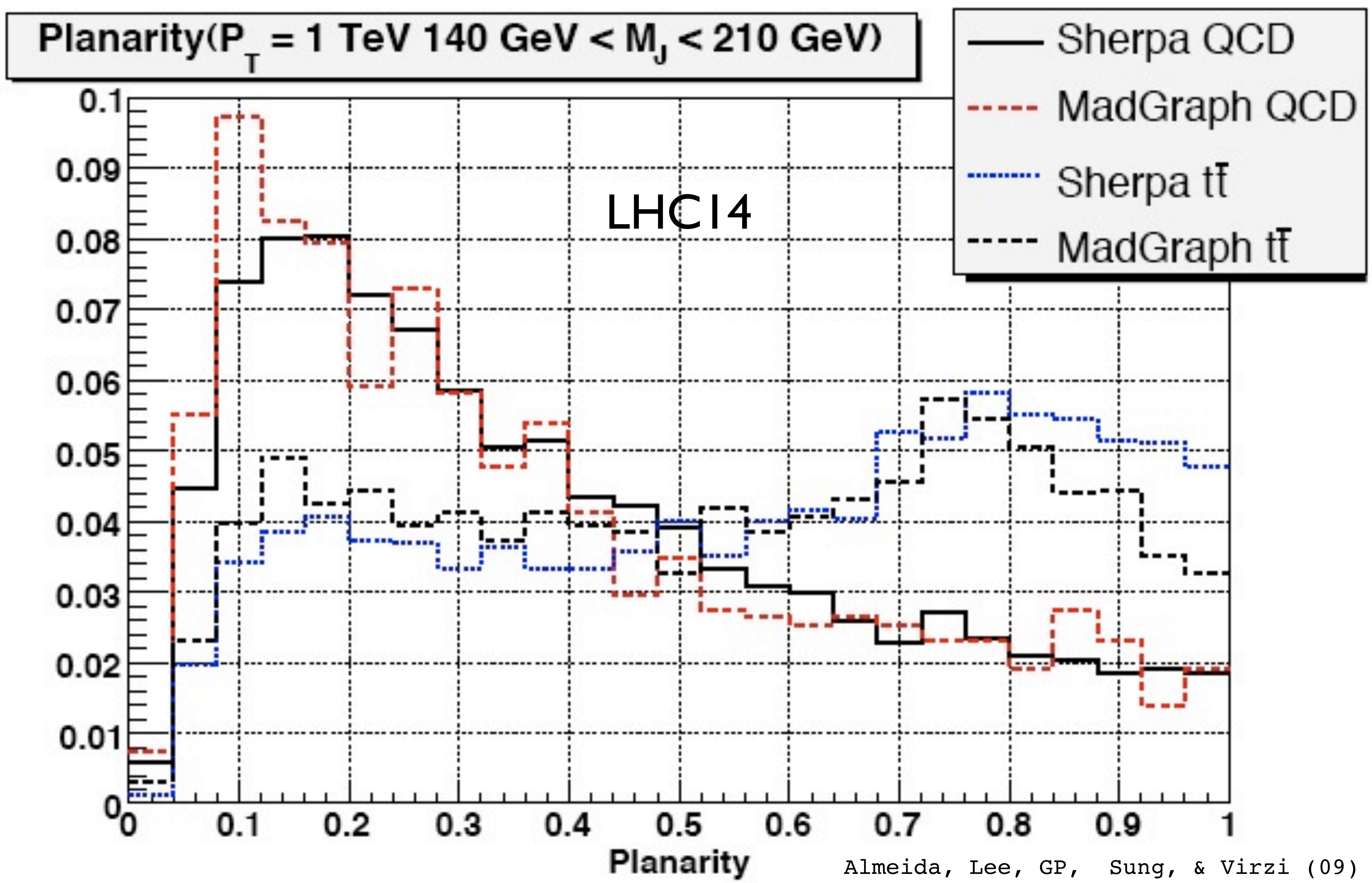
top jet, *Pf=1*

Planar flow

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

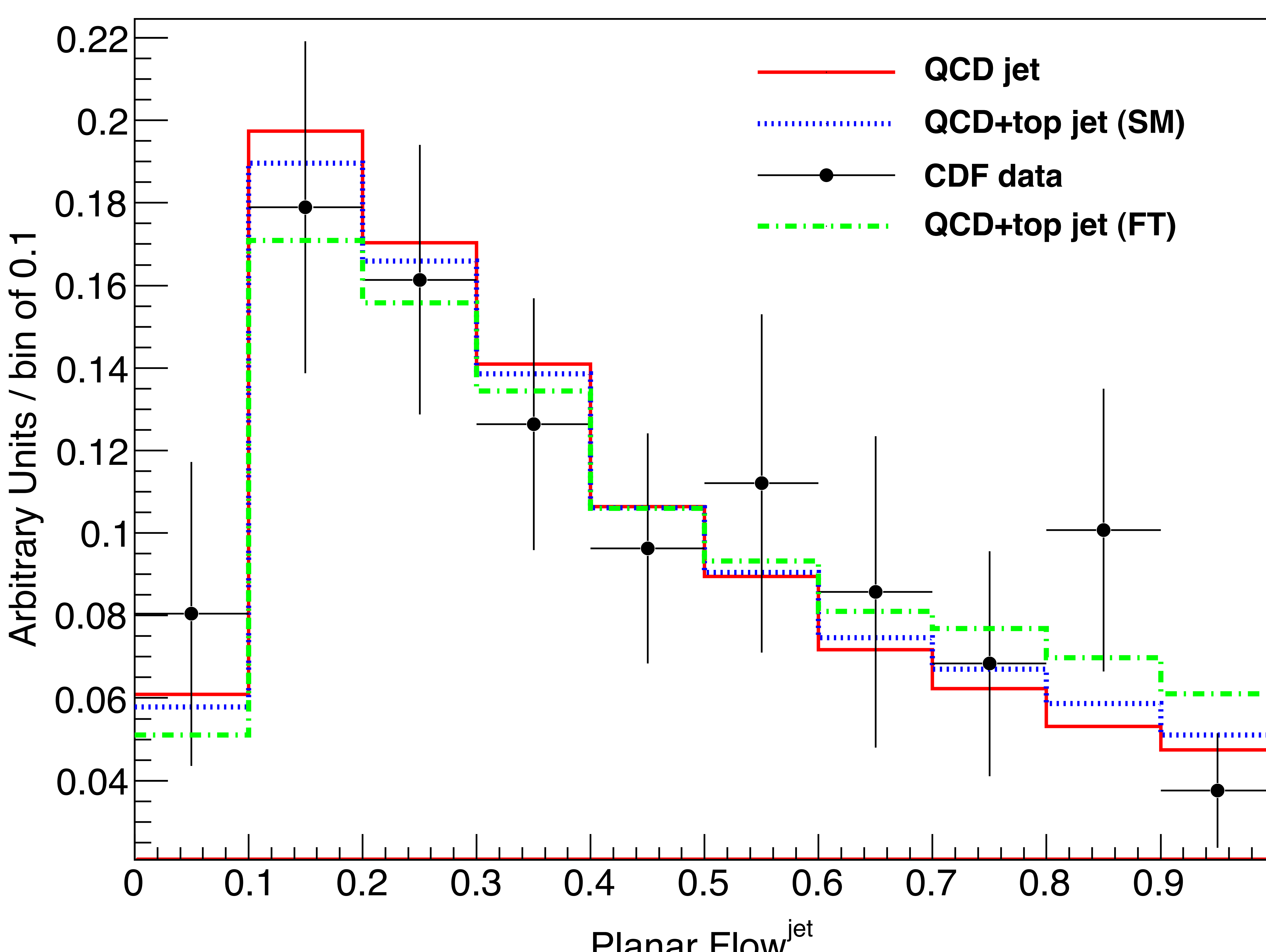
Thaler & Wang, JHEP (08);
Almeida, Lee, GP, Stermam, Sung & Virzi, PRD (09).

- Pla… vo



Almeida, Lee, GP, Sung, & Virzi (09)

Planar flow



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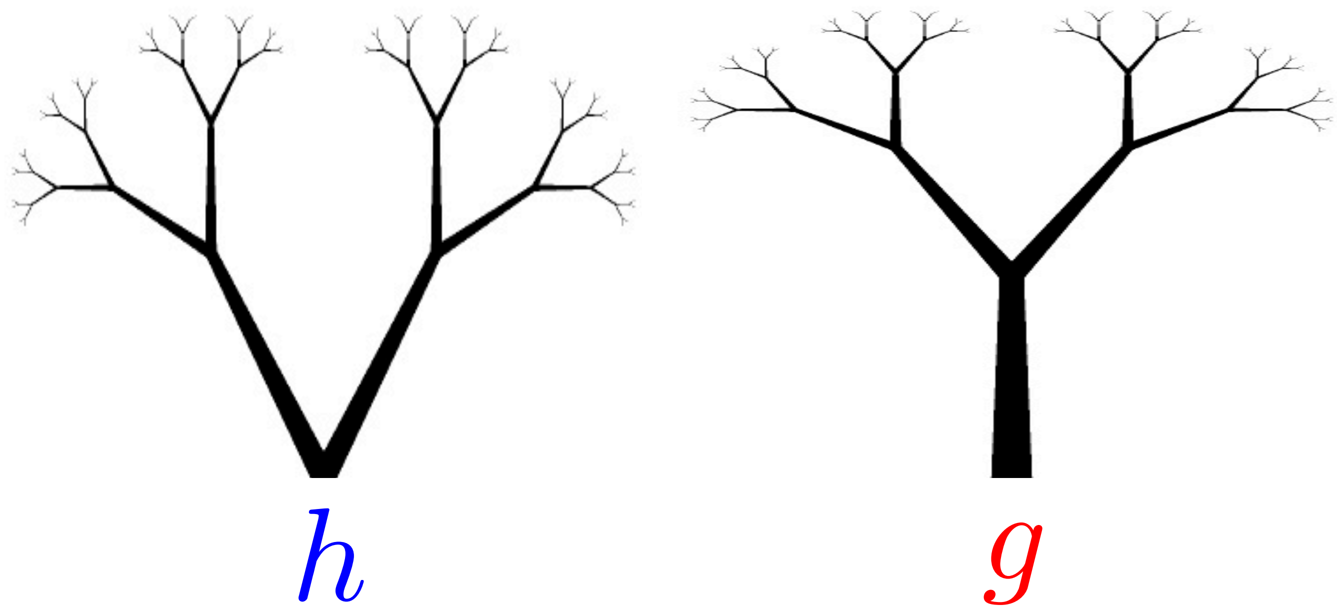
9).

Background rejection, basic approaches



- **Filtering, pruning, trimming.** (simple to implement, very successful)

  Seymour (93); Butterworth, Cox, Forshaw (02); Butterworth, Davison, Rubin & Salam (08); Krohn, Thaler & Wang (10); Ellis, Vermilion & Walsh (09).

- **Moments.** (easy to get LO PQCD, weak jet finder dependence, etc)

  Recently: Almeida, SL, Perez, Sterman, Sung & Virzi; Thaler & Wang (08), etc.

- **Template Overlap.** (easy to get LO PQCD, weak jet finder dep'& beyond, fits the spiky nature of signals)

  Almeida, SL, Perez, Sterman & Sung (10);
  Almeida, Erdogan, Juknevich, SL, Perez, Sterman, in preparation;

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:

$$
\begin{aligned}
|t> &= \text{top distribution} \\
|g> &= \text{massless QCD distribution}
\end{aligned}
$$

Lunch table discussion with Juan Maldacena

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

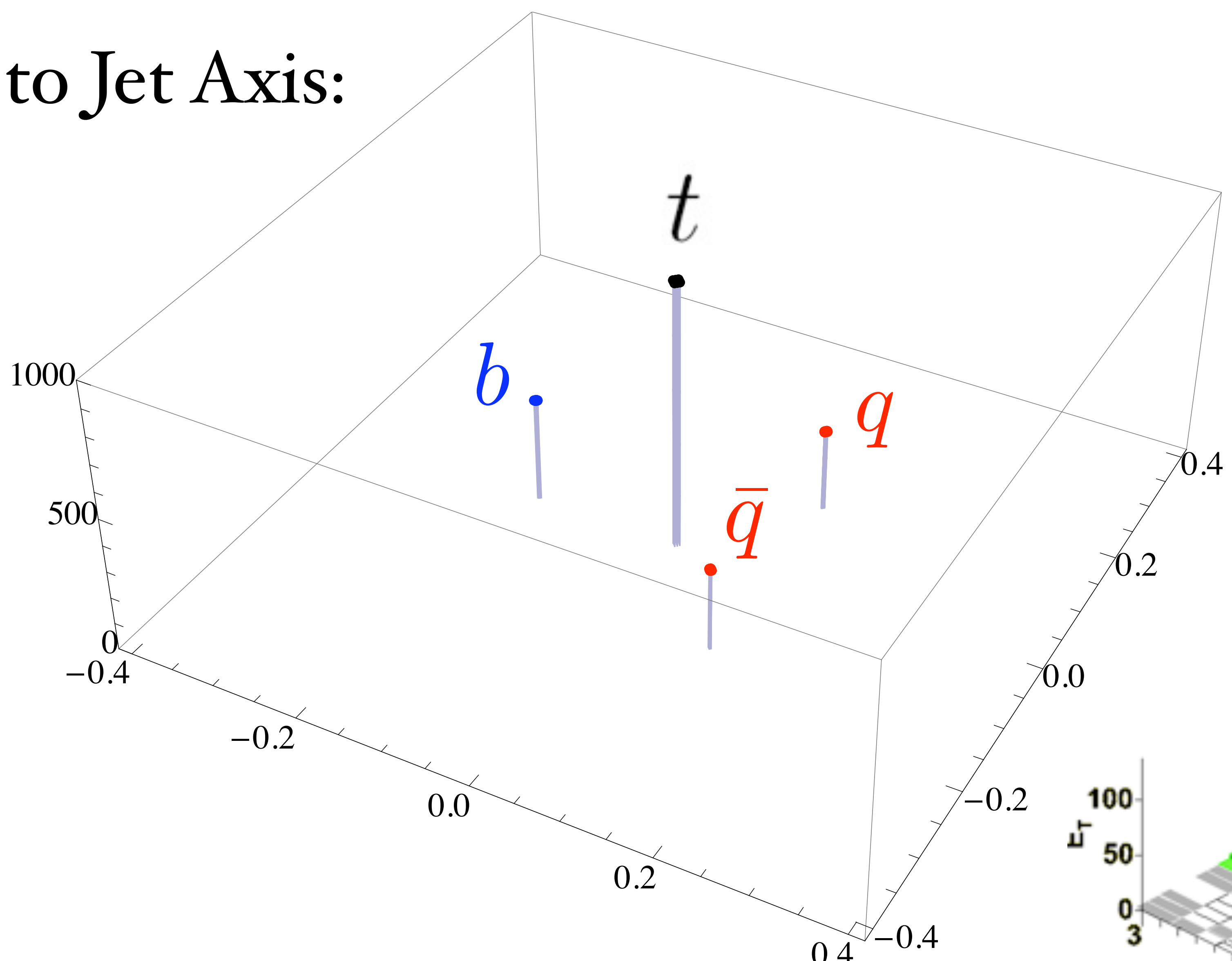
"template"

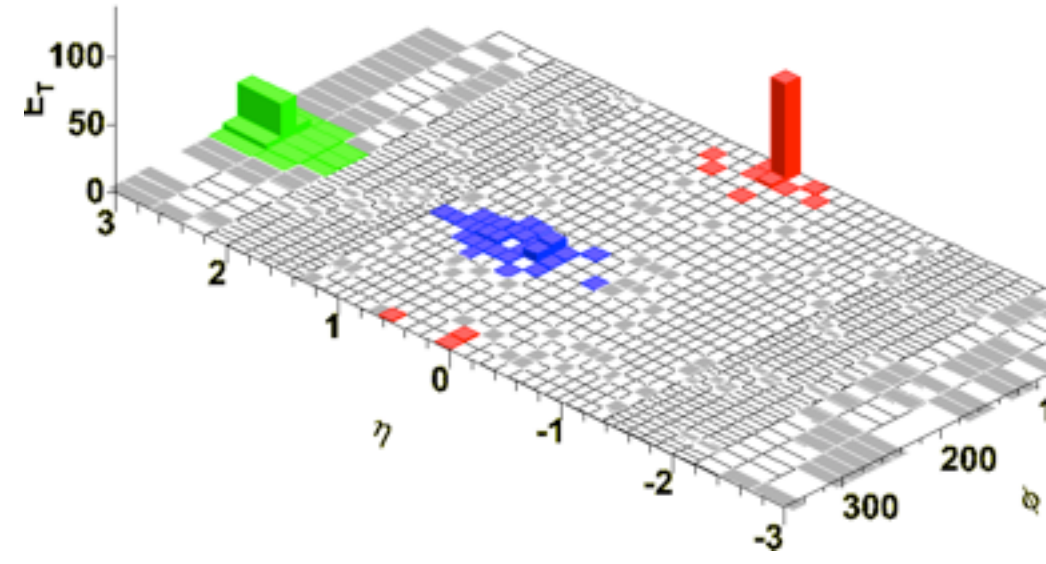
$$R = \left(\frac{< f|t >}{< f|g >}\right) \text{ is maximized.}$$

Example: The Golden Triangle

$$E(\hat{p}_x, \hat{p}_y)$$

Plane $\perp$ to Jet Axis:





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

Template Overlap Method

- General overlap functional:

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

- 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.

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-particle phase space:

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

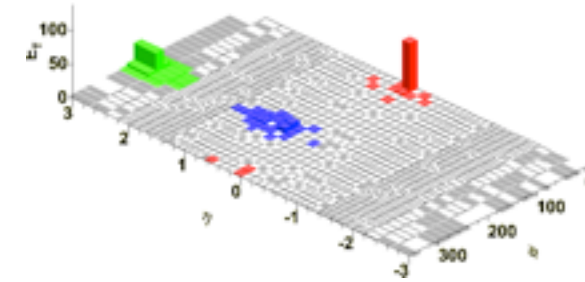
-we may choose F to be a normalized step function around the directions of the template momenta p_i

- For a given template, with direction of particle a, n_a and its energy $E_a^{(f)}$:

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

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.

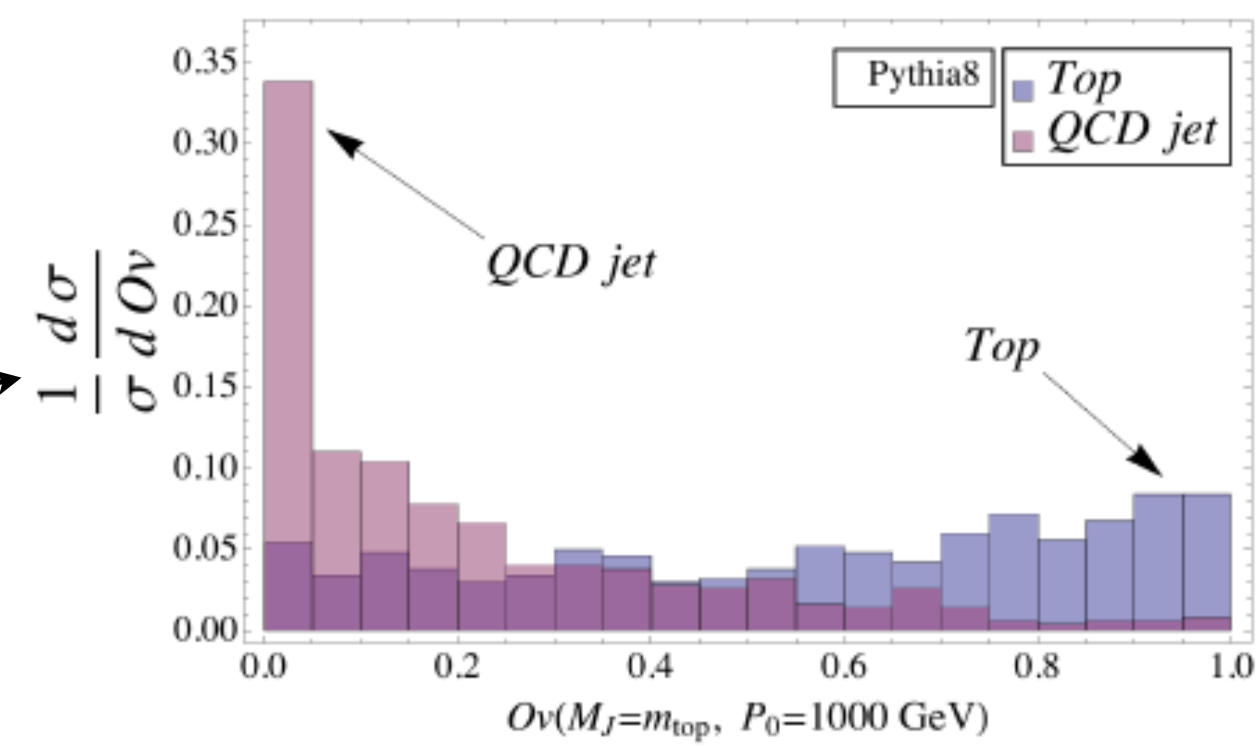


- Template Overlap with data discretization

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

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

after mass cut

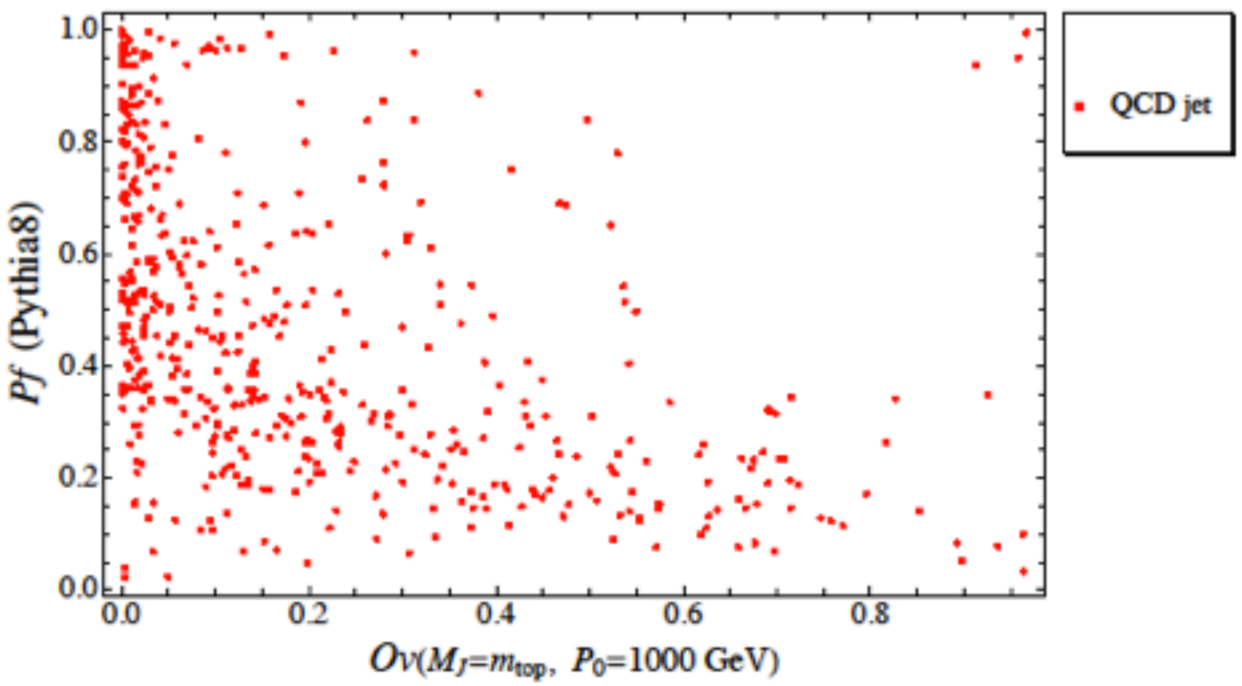


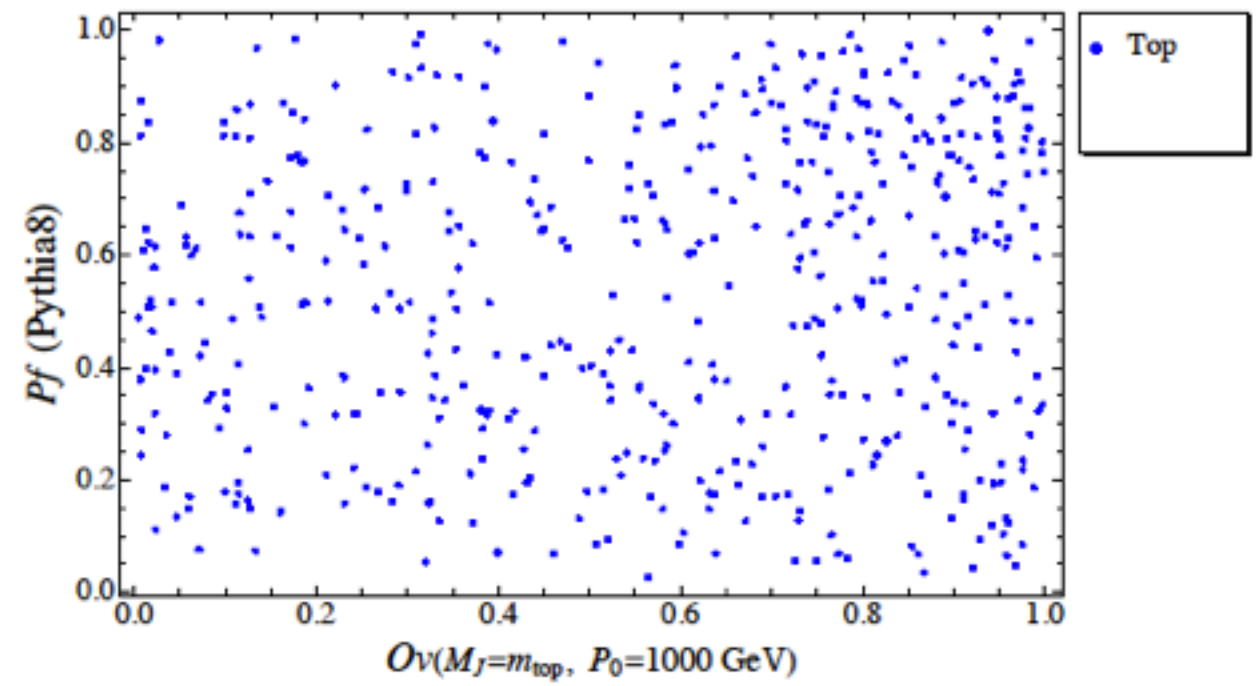
Three-particle Templates and Top Decay

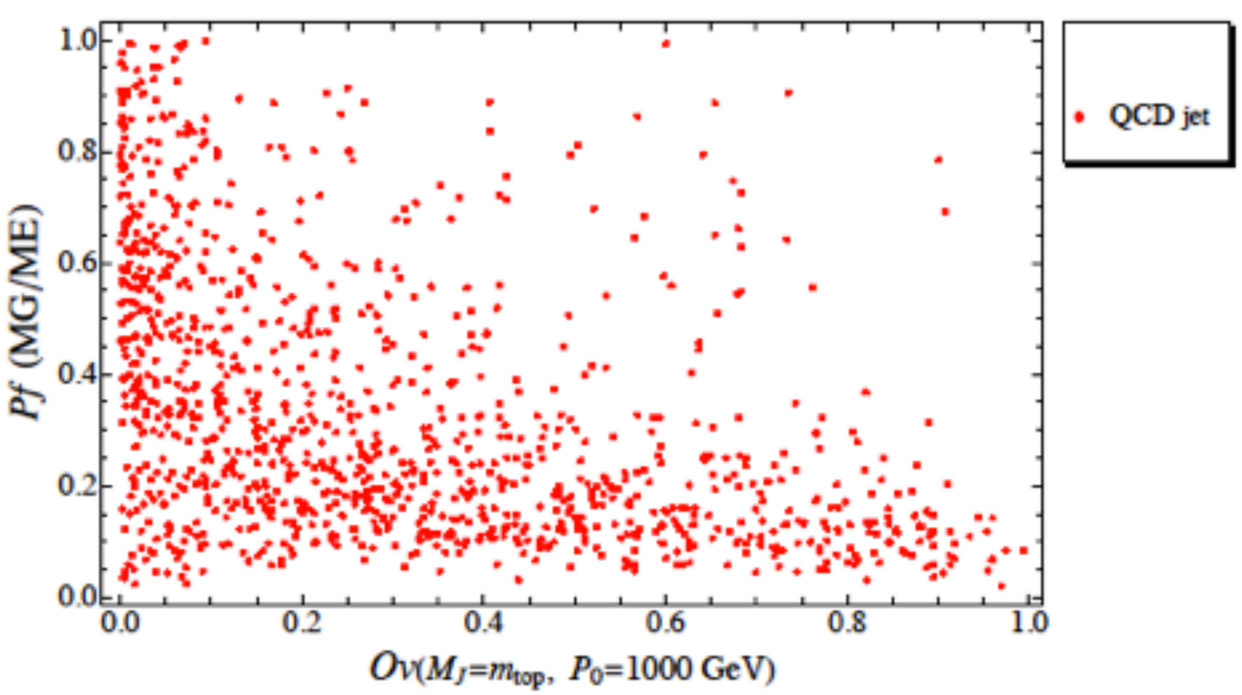
- Combined with "Planar flow"-distinguishes between many three-jet events with large template overlaps.

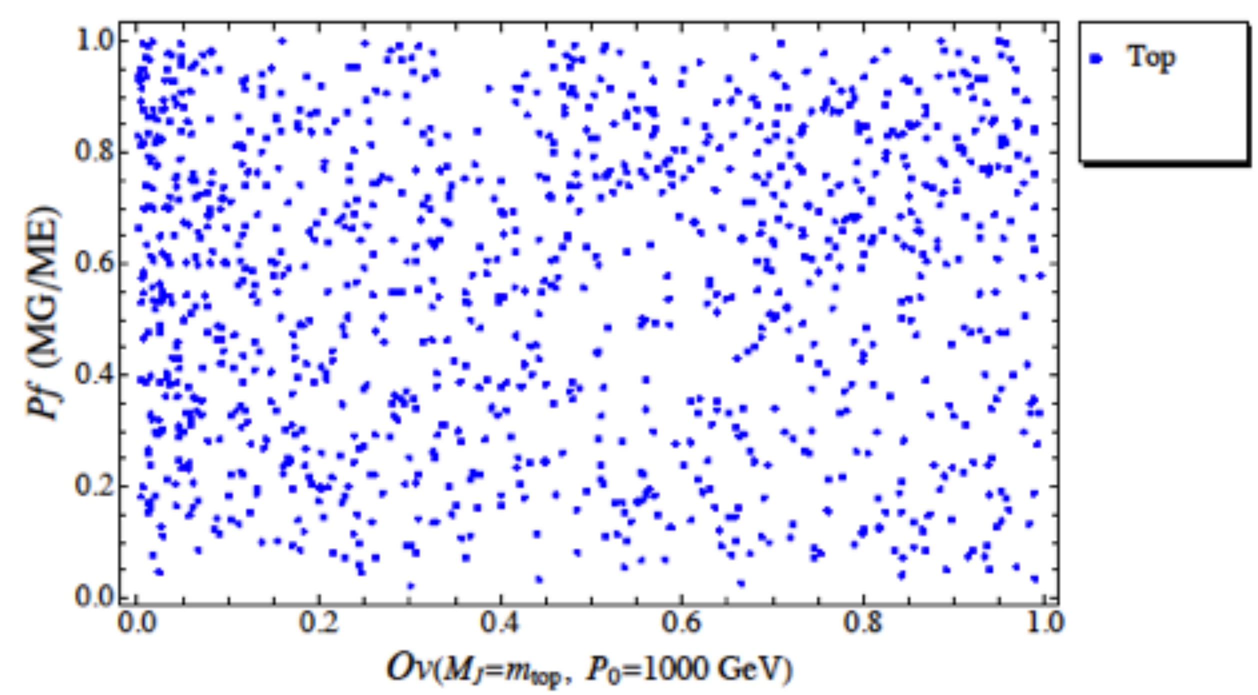
- In general, QCD events with large *Ov* will have significantly smaller planar flow than top decay events; for the QCD jets a large overlap would be a result of a kinematic "accident".

Three-particle Templates and Top Decay

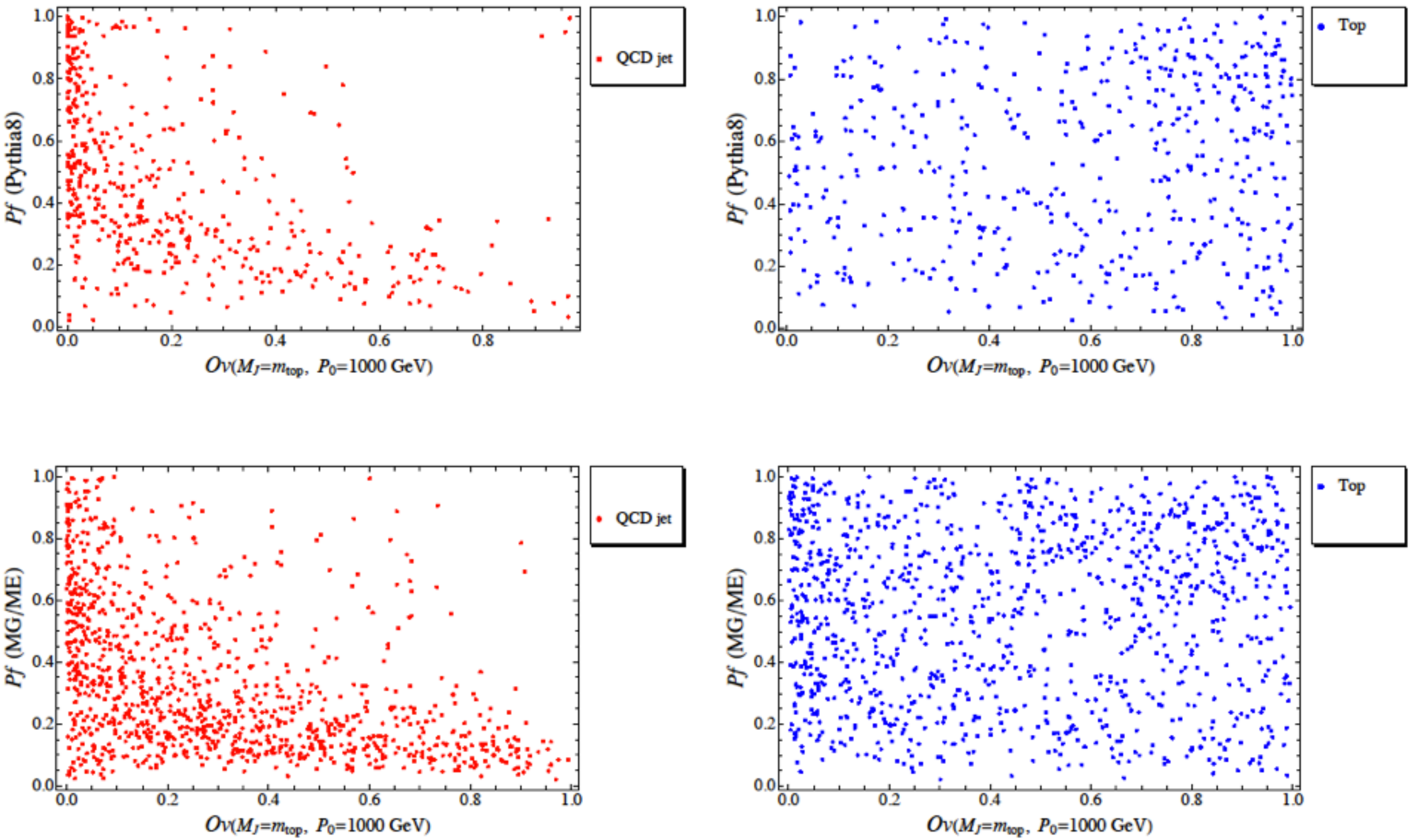




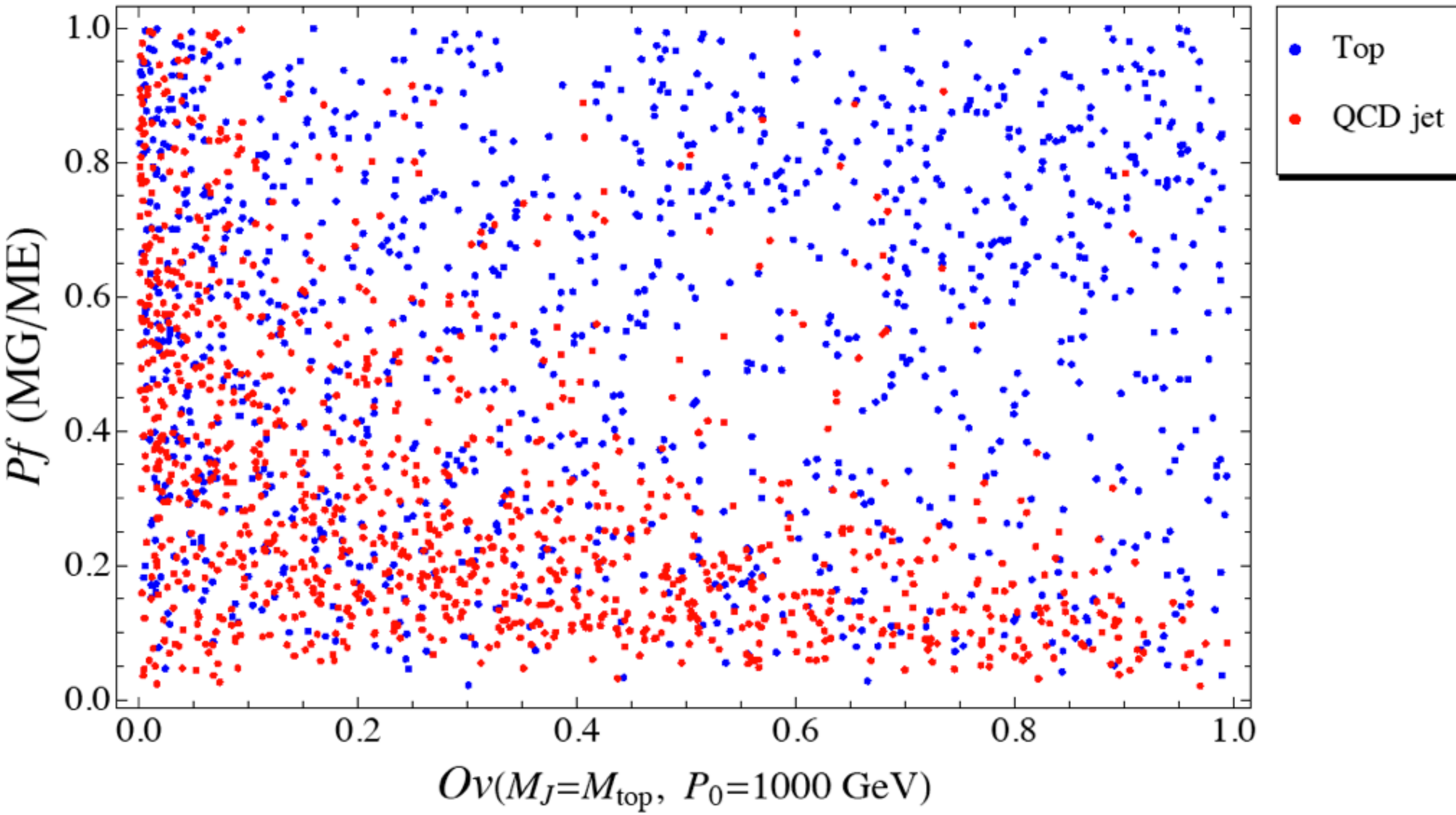




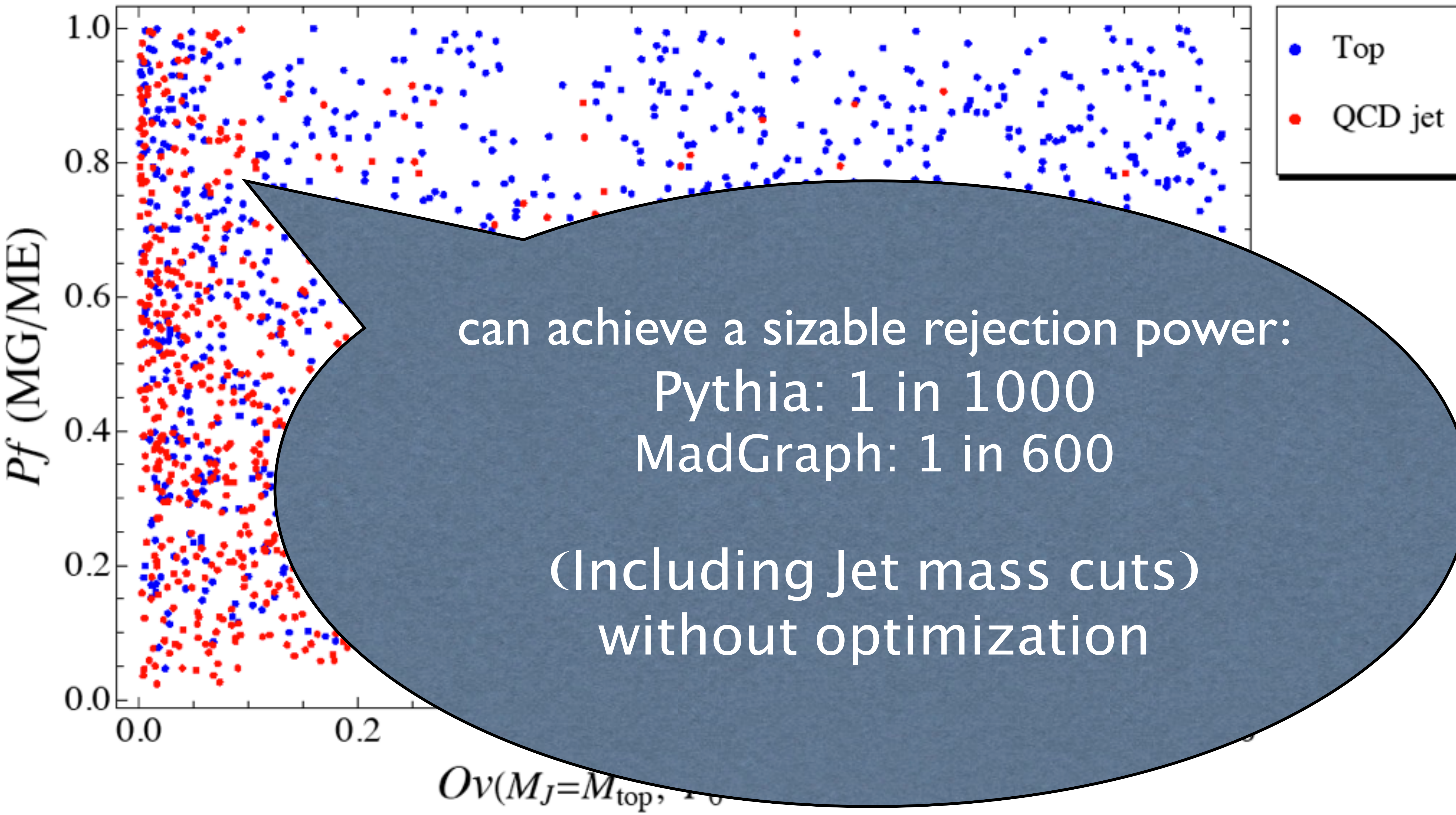
Three-particle Templates and Top Decay



Three-particle Templates and Top Decay



Three-particle Templates and Top Decay



Two-particle Templates and Higgs Decay

- Construct template: two particle phase space for Higgs decay (easy) $|f\rangle = |h\rangle^{(\mathrm{LO})} = |p_1, p_2\rangle$

- Higgs: at fixed $z = m_J/P_0 \ll 1$, 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

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

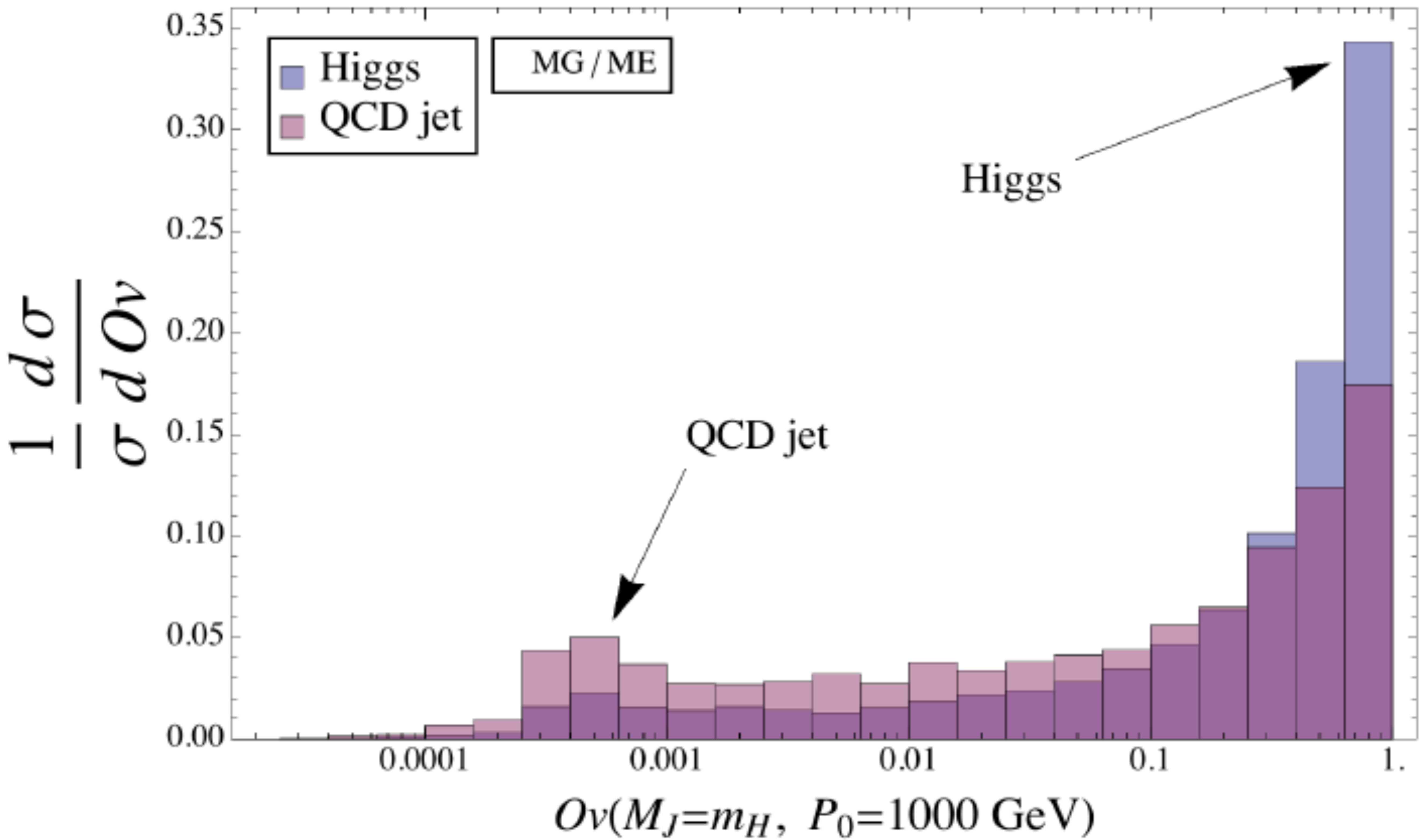
Two-particle Templates and Higgs Decay

- 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.

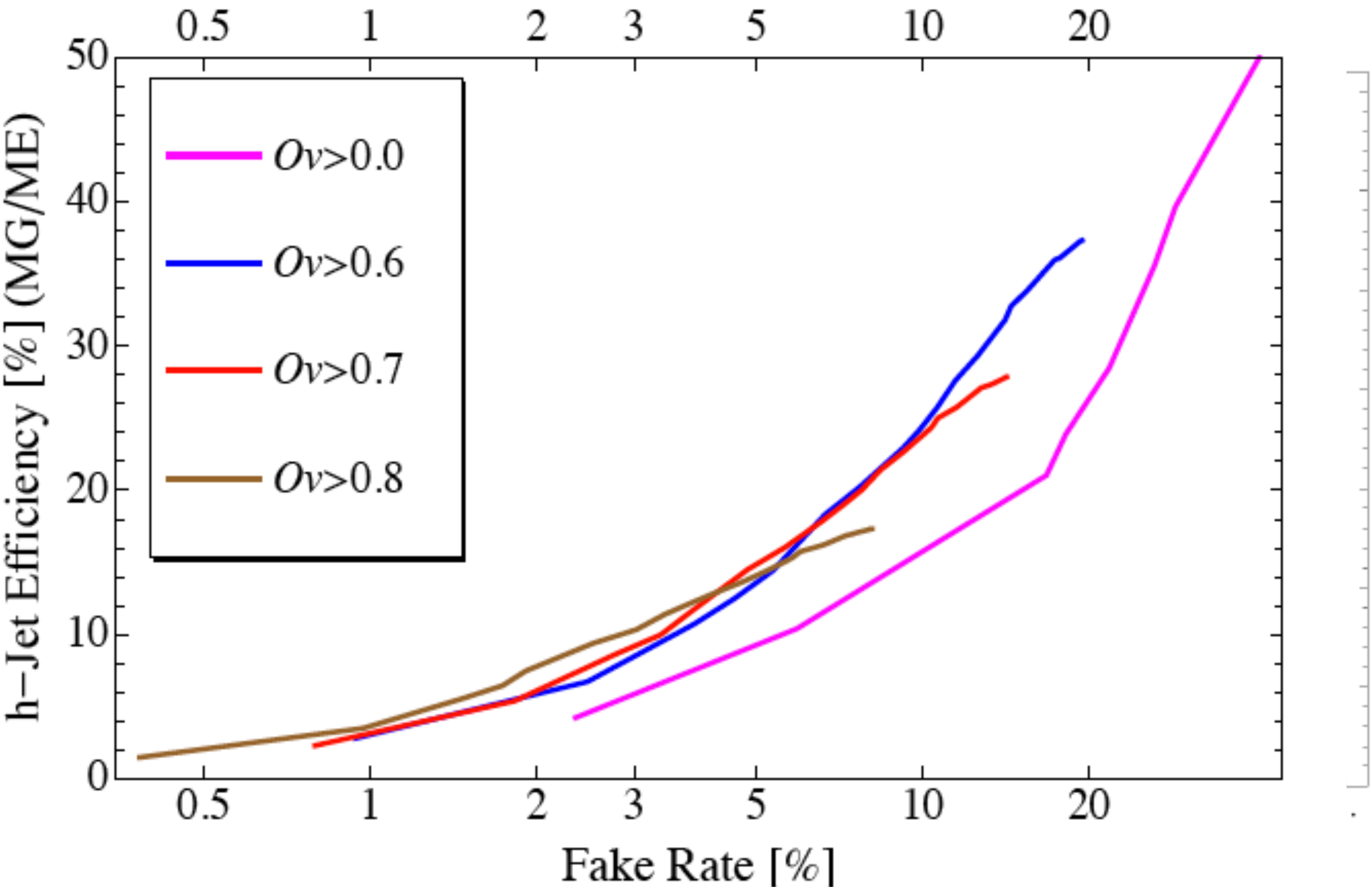
- Template Overlap with data discretization

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

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

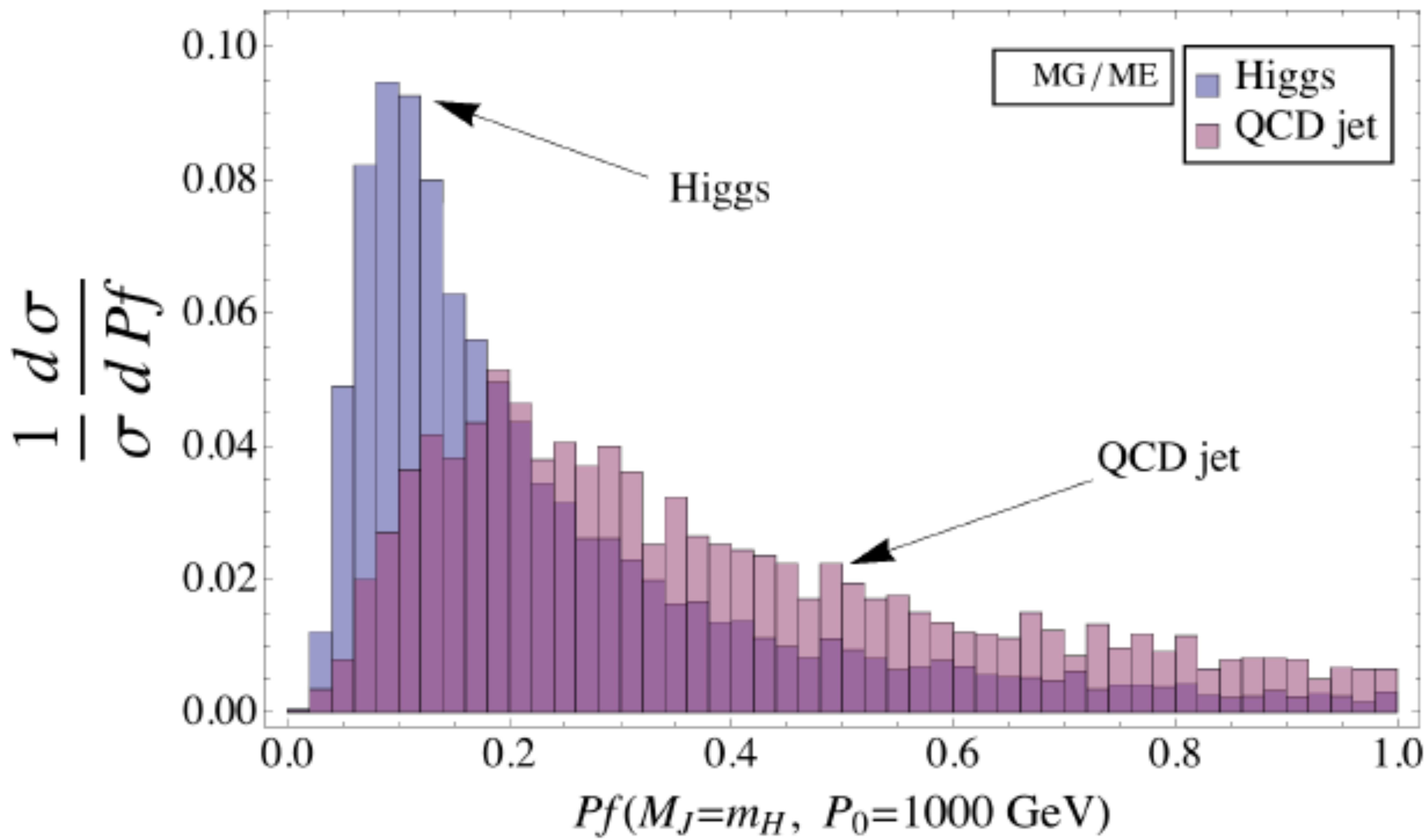
Two-particle Templates and Higgs Decay

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

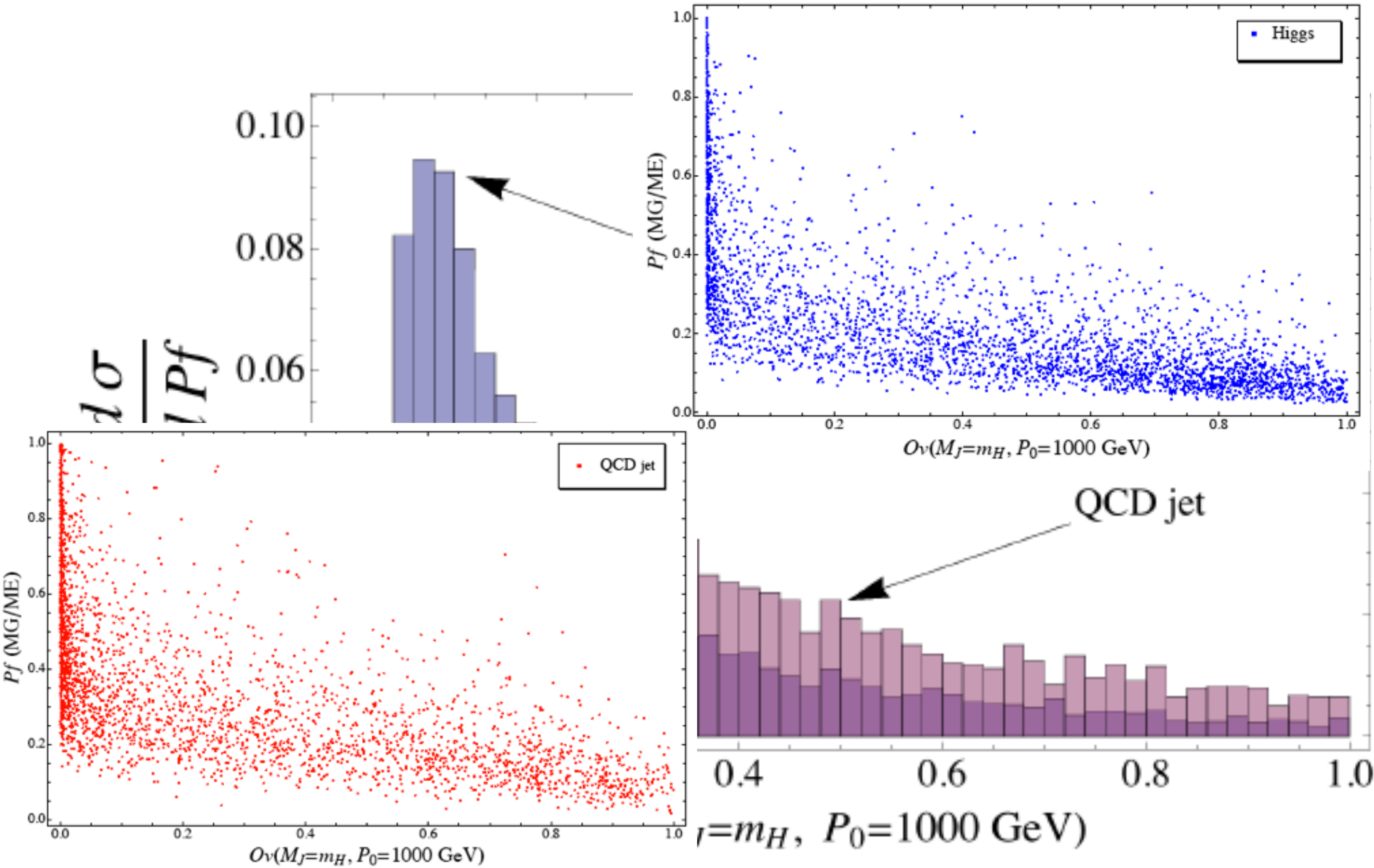
- The effects of higher-order effects can be partly captured by using Planar flow

(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

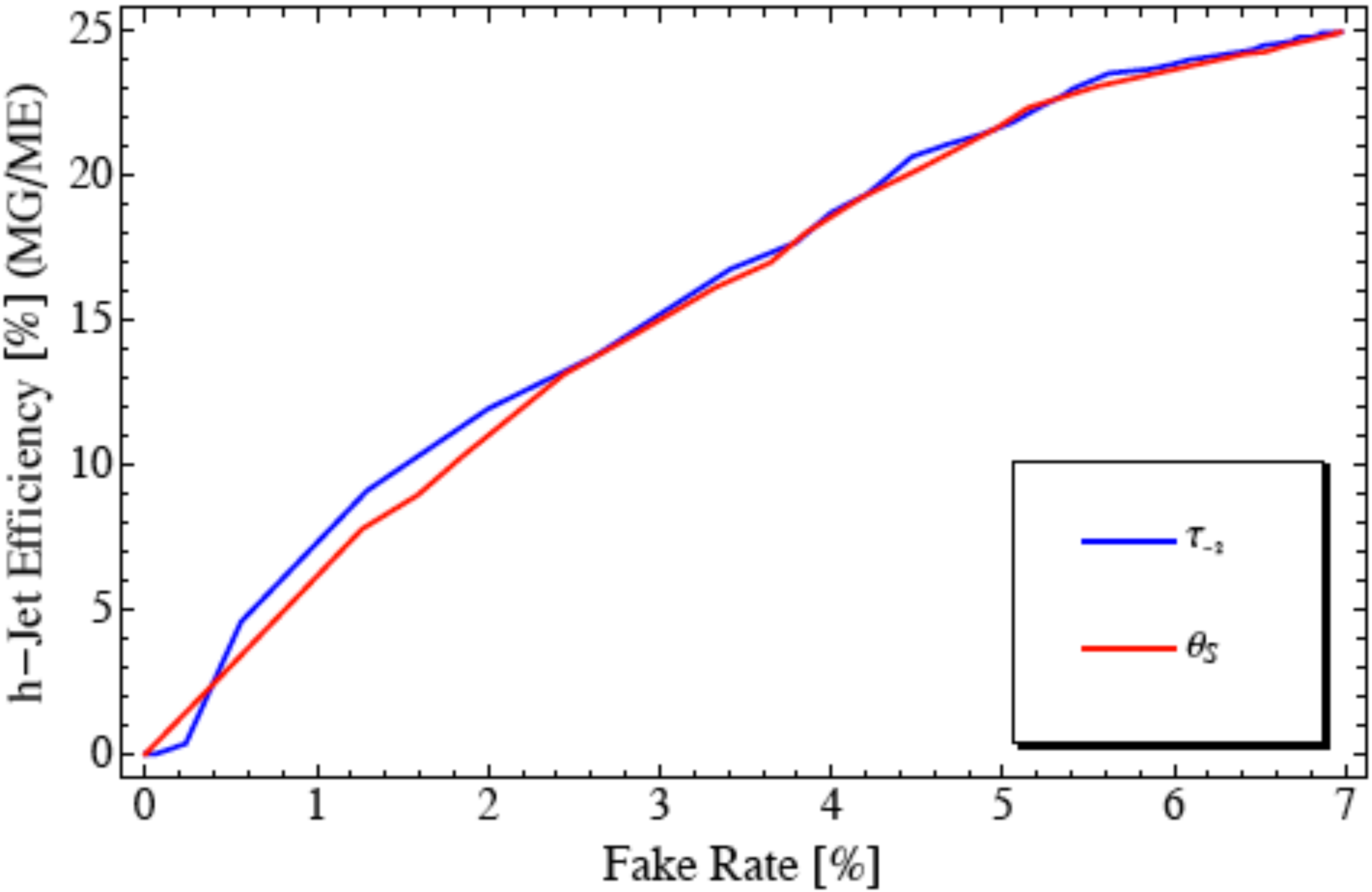
- Combined with angularity or Θ_s : can improved rejection power (Θ_s and angularities are related)

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



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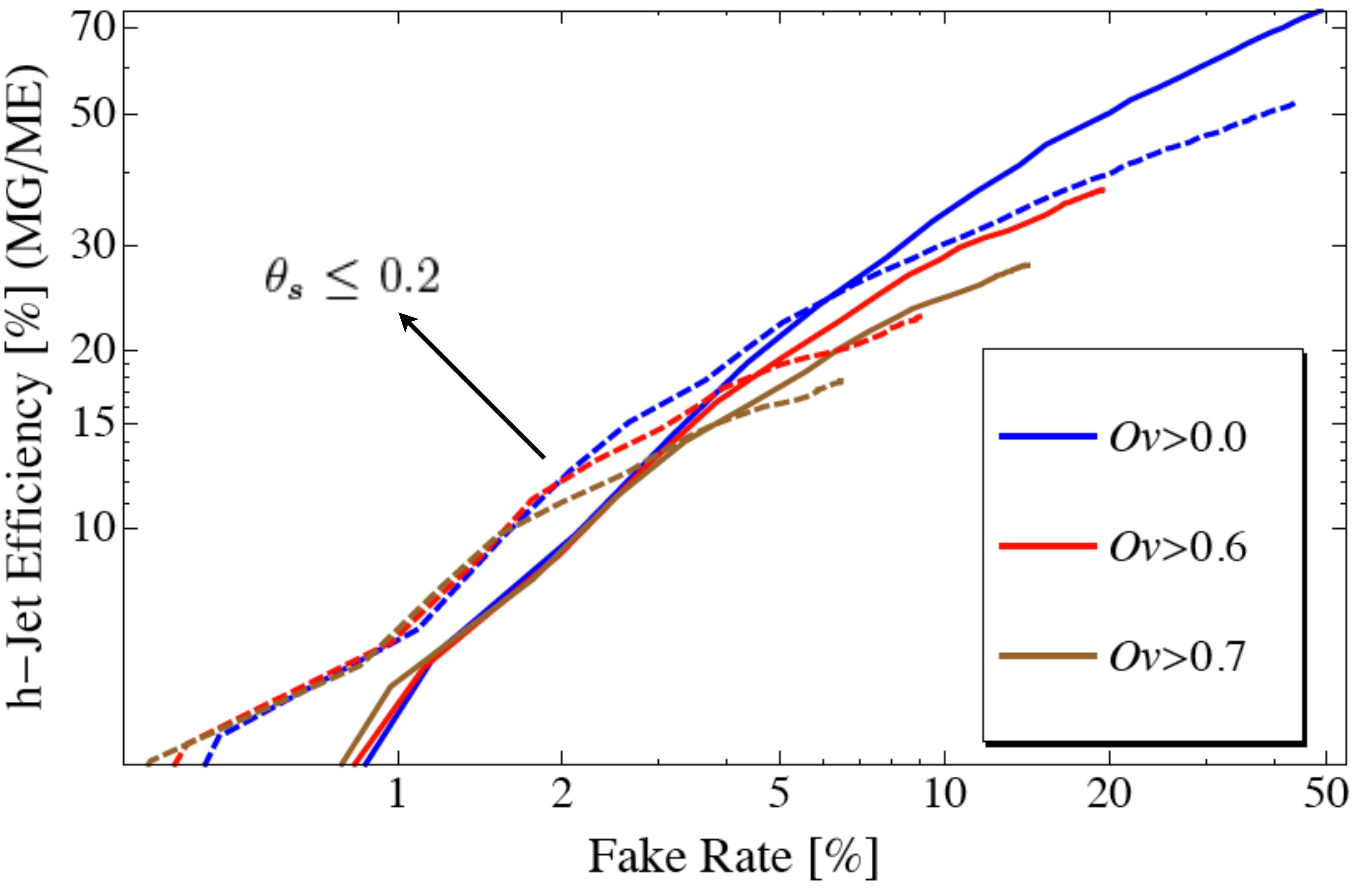
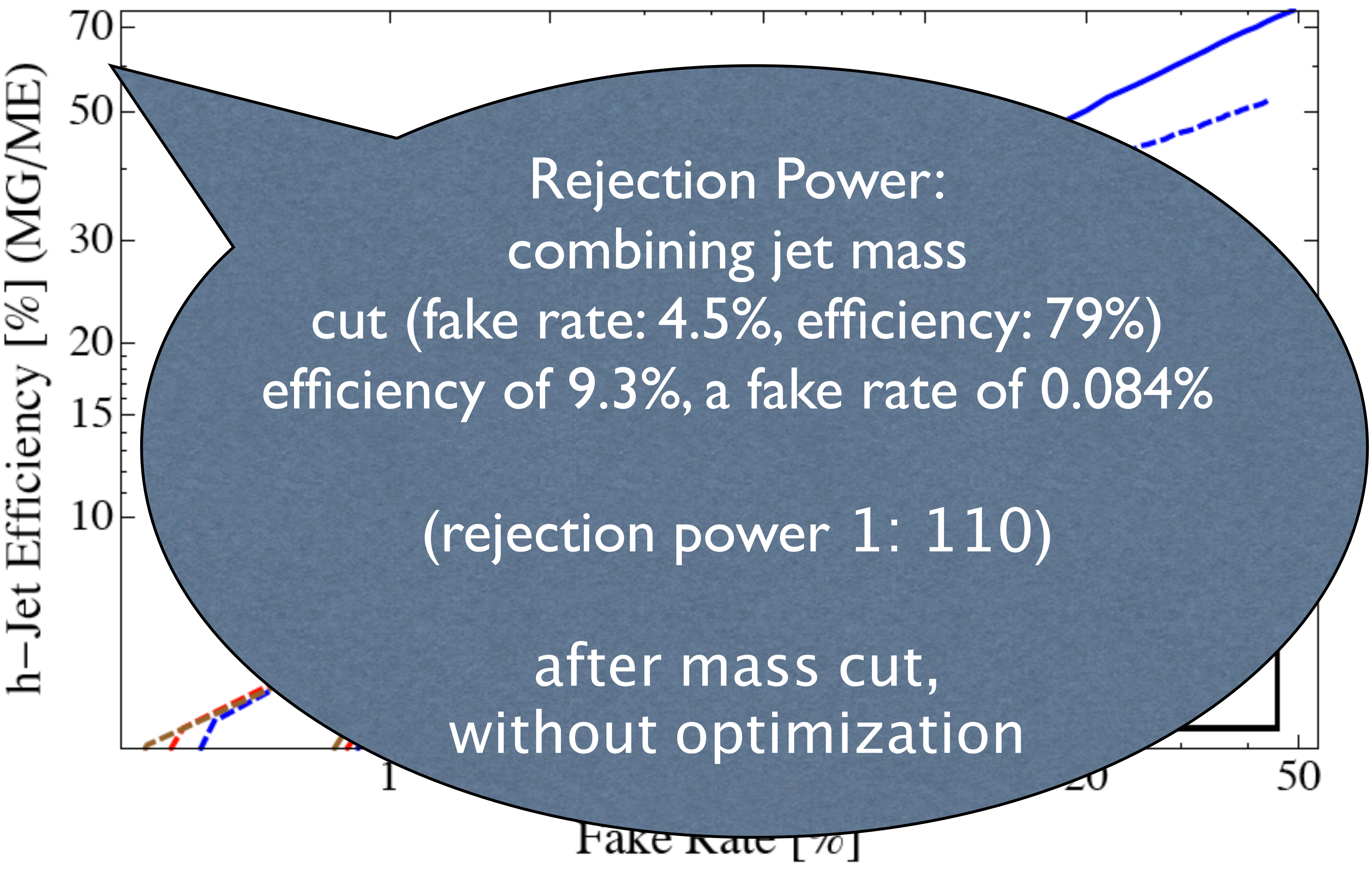


Two-particle Templates and Higgs Decay



NLO Templates and Higgs Decay

L. Almeida, O. Erdogan, J. Juknevich, SL, G. Perez, & G. Sterman (in preparation)

- NLO => Soft radiation (+color flow???)

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I. Sung (09)
J. Gallicchio and M. Schwartz (10),
K. Black, J. Gallicchio, J. Huith, M. Kagan, M. Schwartz, B. Tweedie (10)
A. Hook, M. Jankowiak, J. Wacker (11)
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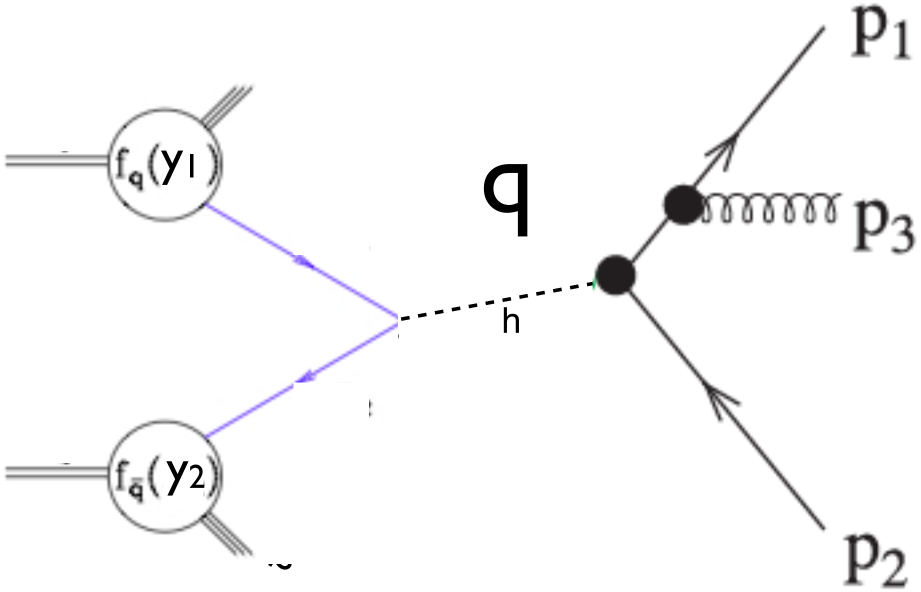
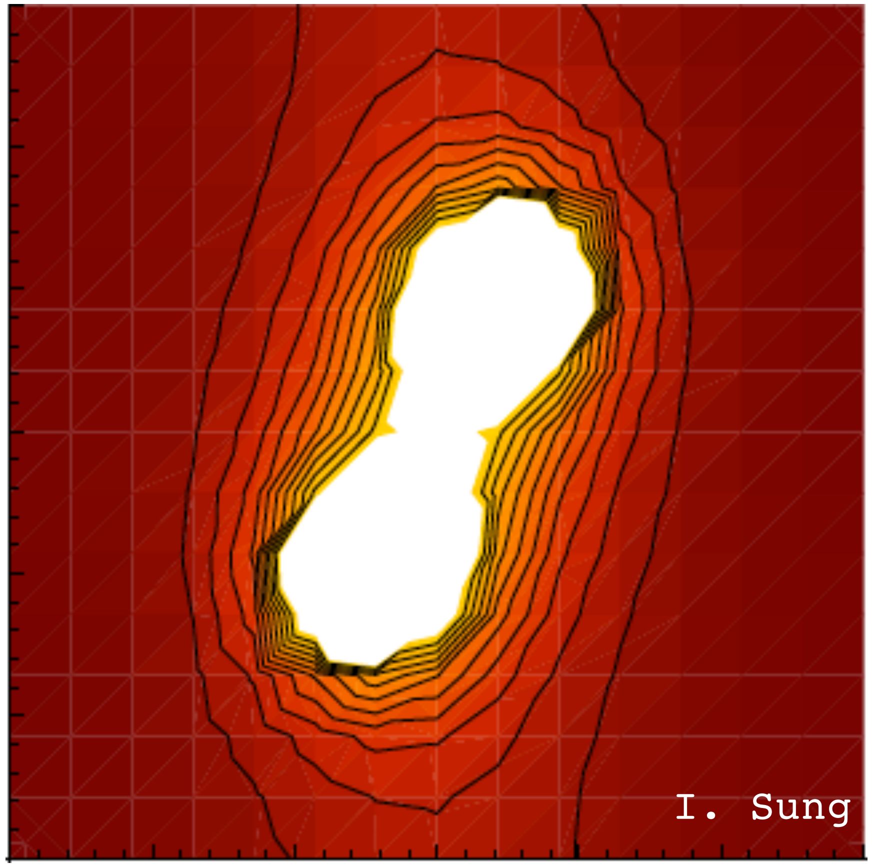
- NLO template:



$$x_i = \frac{E_i}{\sqrt{s}/2} = \frac{2p_i \cdot q}{s}$$

$$0 < x_i < 1.$$



- Construct template from the rest frame: three Euler angles + x_1 & x_2

$$p_a^\mu(x_1, x_2, \psi, \theta, \phi) = L_z(\gamma) R_z(\psi) R_x(\theta) R_z(\phi)\, p_a^\mu|_{P_J^z=0}(x_1, x_2)$$

NLO Templates and Higgs Decay

L. Almeida, O. Erdogan, J. Juknevich, SL, G. Perez, & G. Sterman (in preparation)

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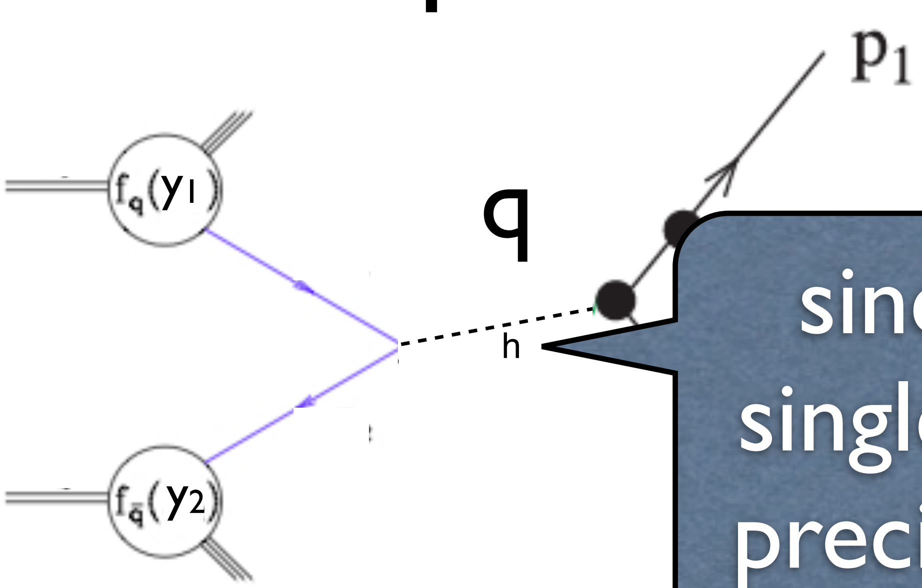
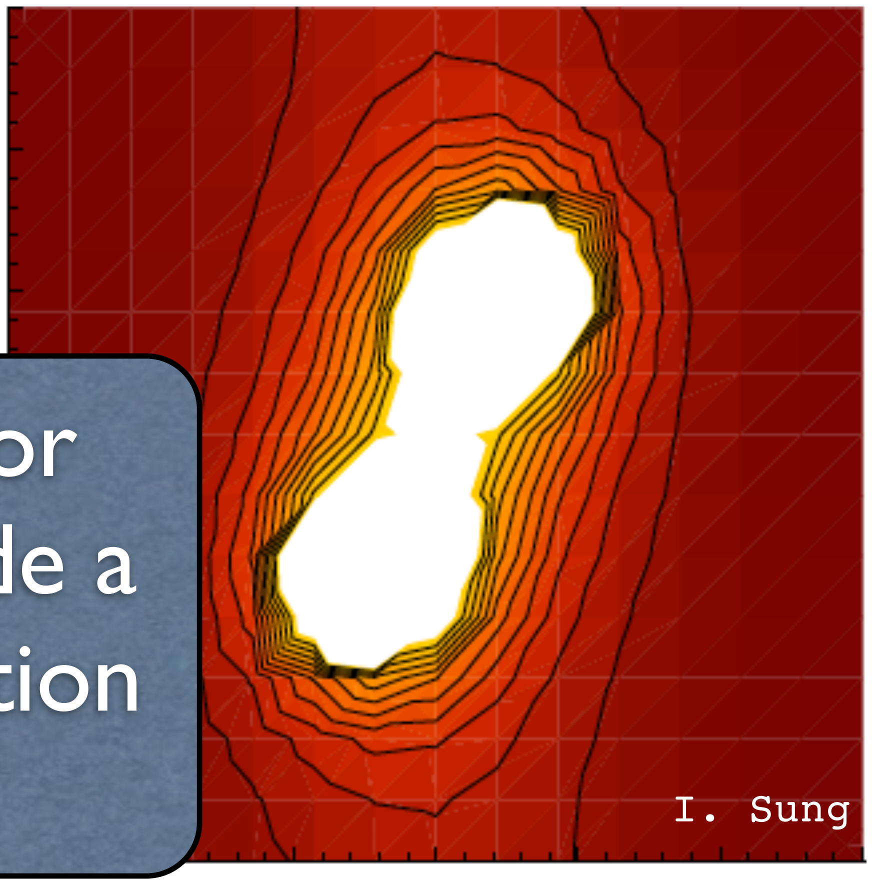
- NLO template:



since Higgs is a color singlet we can provide a precise NLO calculation in the rest frame.



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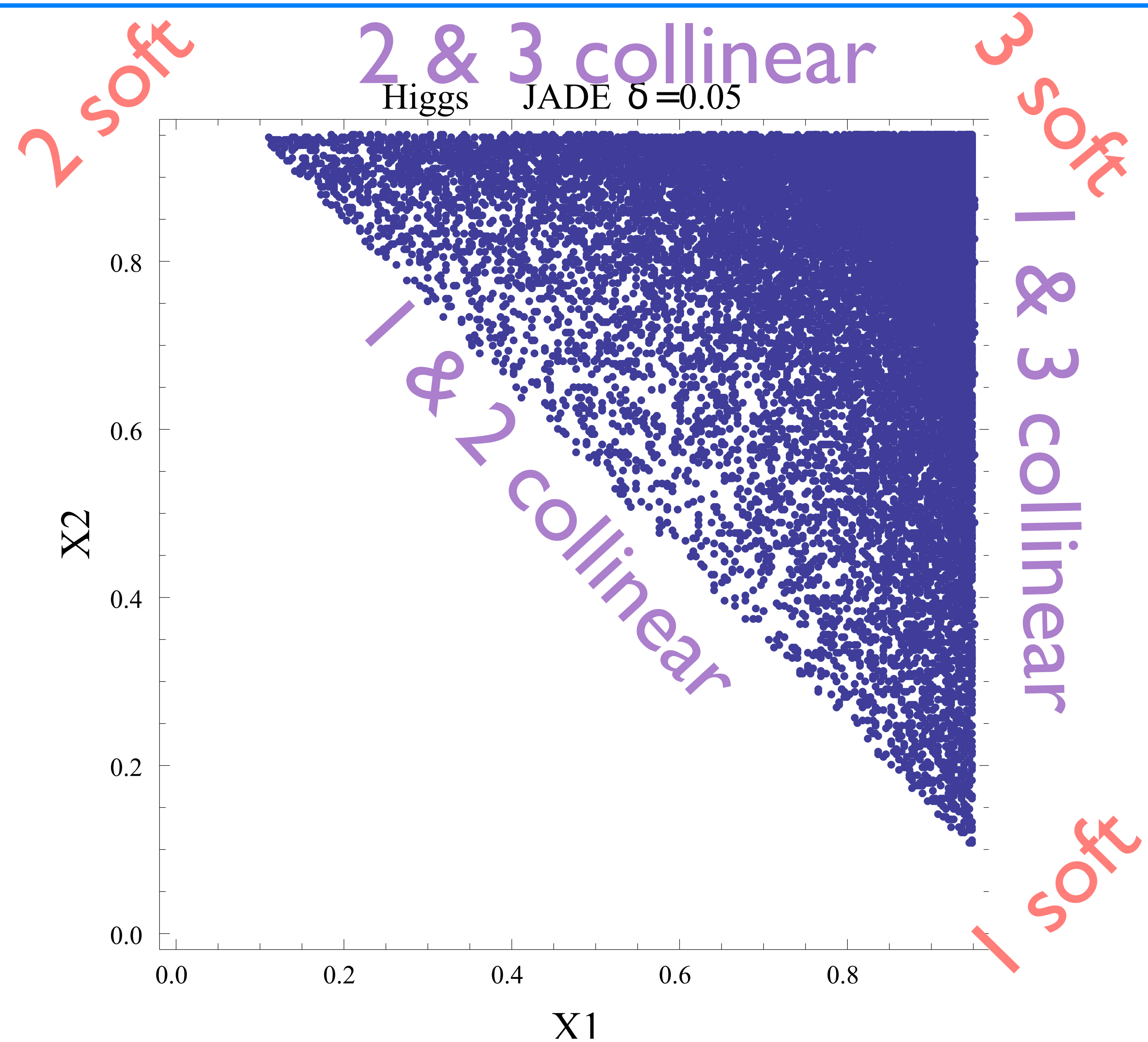
$$p_a^\mu(x_1, x_2, \psi, \theta, \phi) = L_z(\gamma) R_z(\psi) R_x(\theta) R_z(\phi)\, p_a^\mu|_{P_J^z=0}(x_1, x_2)$$

NLO Templates and Higgs Decay

- Differential cross section at NLO:

$$\frac{d\Gamma(H \to q\bar{q}g)}{\Gamma_0} = \frac{1}{8\pi^2} C_F \alpha_s \frac{(1-x_1-x_2)^2+1}{(1-x_1)(1-x_2)} dx_1 dx_2\, d(\cos\theta) d\phi$$



Drees & Hikasa, PLB (90)

$$\begin{aligned} x_1 x_2 (1-\cos\theta_{12}) &= 2(1-x_3), \\ x_2 x_3 (1-\cos\theta_{23}) &= 2(1-x_1), \\ x_3 x_1 (1-\cos\theta_{31}) &= 2(1-x_2). \end{aligned}$$

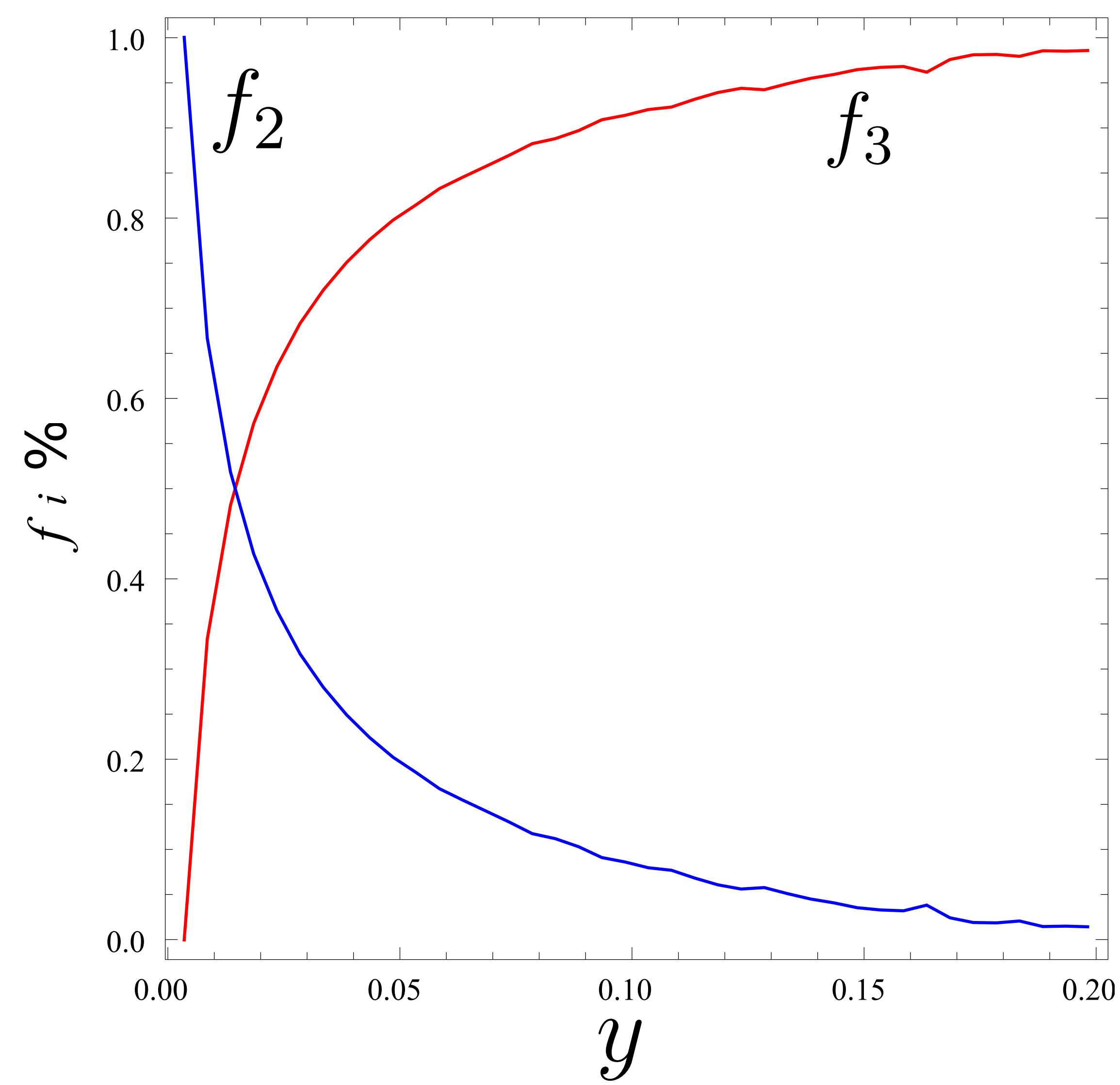
Jade with δ=0.05 separate 2 vs 3-jet case

$$y_{\rm cut} = \frac{m_{ij}^2}{m_H^2} = 0.05$$

Higgs NLO template, cont'

$$\sigma^{NLO} = \sigma(2\,\mathrm{jet}) + \sigma(3\,\mathrm{jet}) \qquad \sigma(n\,\mathrm{jet}) = f_n\,\sigma$$

$$f_2 = 1 - f_3.$$



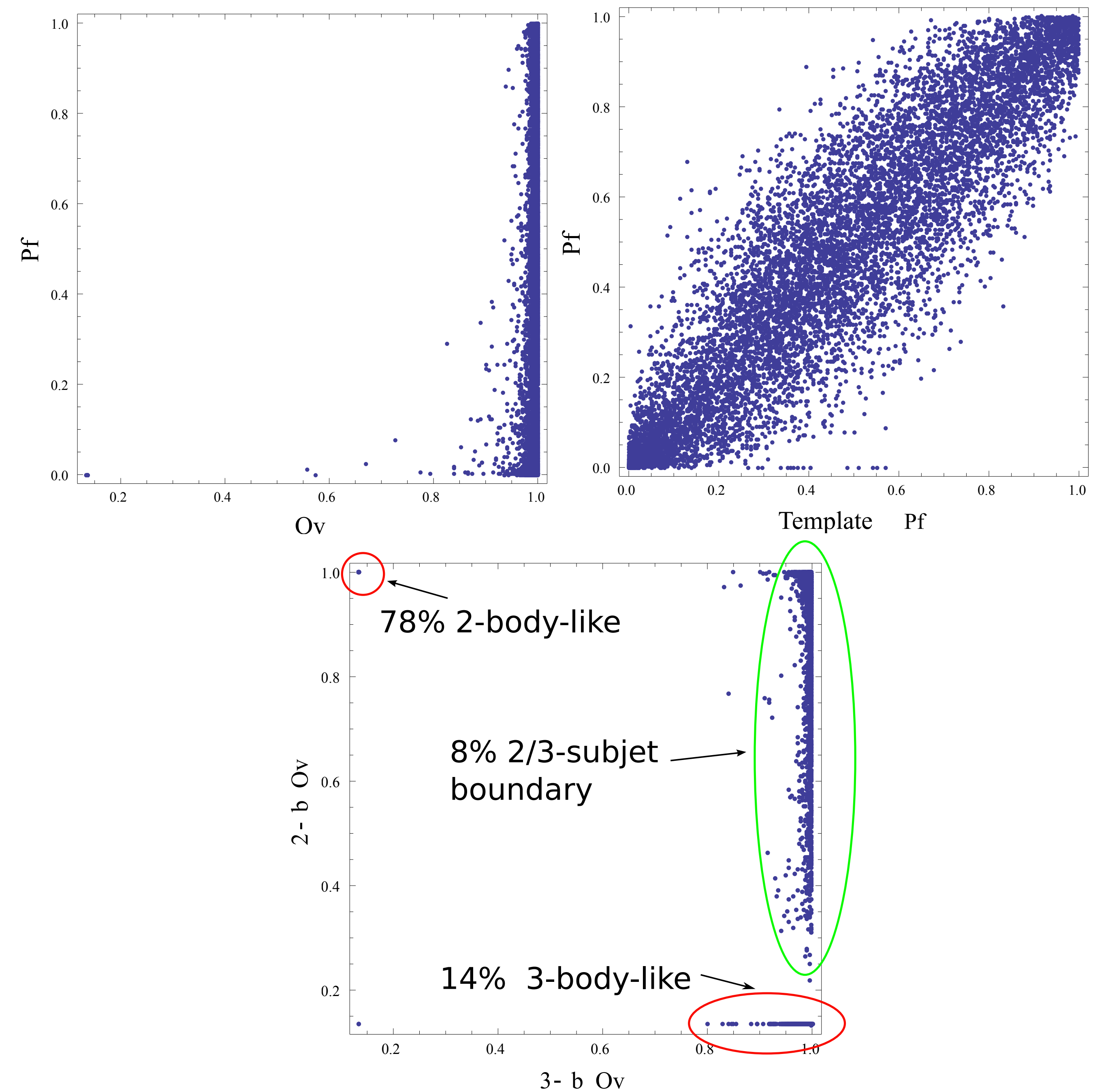
$$y_{ij} = \frac{2E_iE_j(1-\cos\theta_{ij})}{s}$$

$$y_{ij} < y$$

- Finally: Boost it to the lab frame (now depends on all 5 variables).

Results

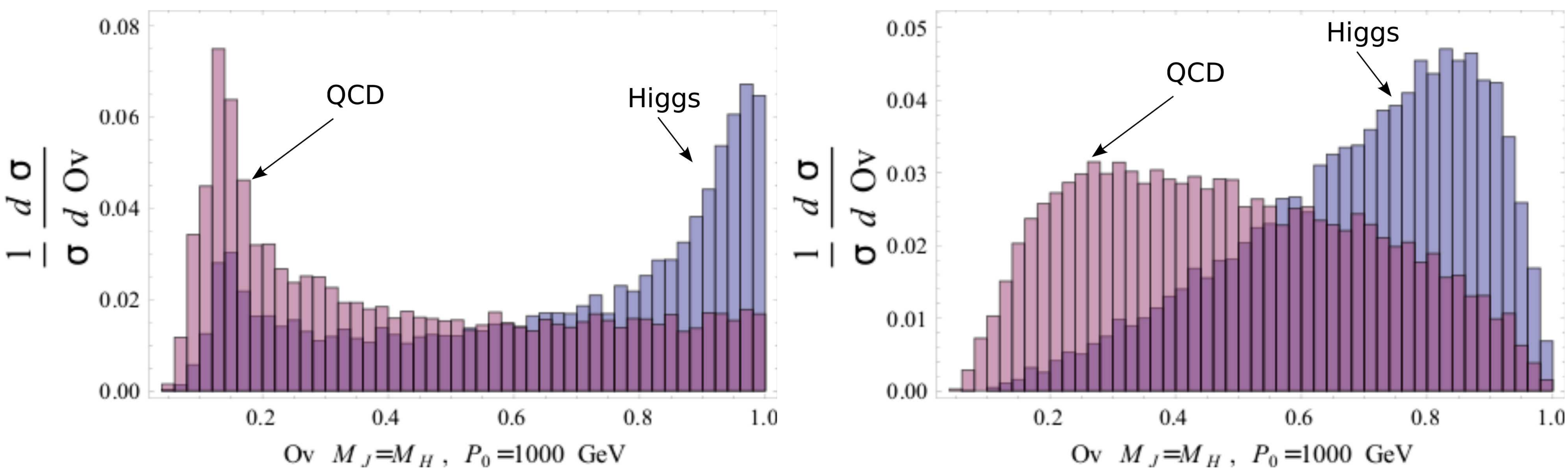
Few sanity
partonic checks:



A scatter plot of template overlap and Pf for LO parton-level MC output for higgs decay, with $P_0 = 1$ TeV, $m_{higgs} = 120$ GeV.

♦ Can now calculate semi-analytically various shapes: Pf, x_1-x_2 etc...; focus on rejection.

2body & 3body S vs. B max(Ov) dist'



Histograms of template overlap Ov with Higgs jets and QCD jets from Pythia 8, for $R = 0.5$, 950 GeV$\leq P_0 \leq$1050 GeV, 110 GeV$\leq m_J \leq$130 GeV and $m_{higgs} = 120$ GeV using 2-body templates (Left) and 3-body templates (Right).

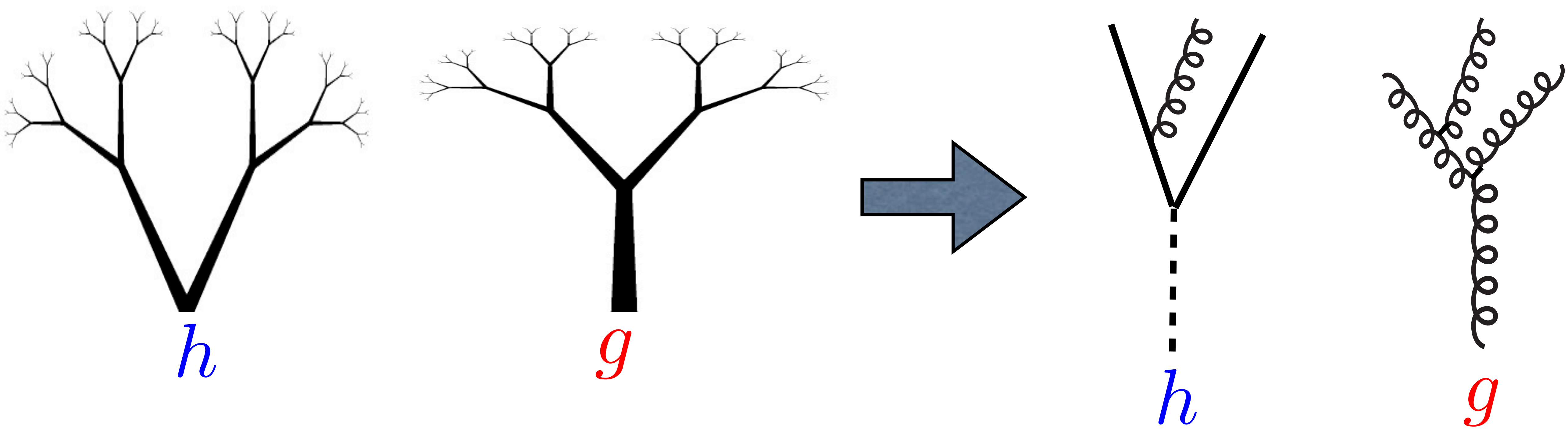
Can do better than that ...

- Max template $O\nu$ => access to partonic information.

Can do better than that ...

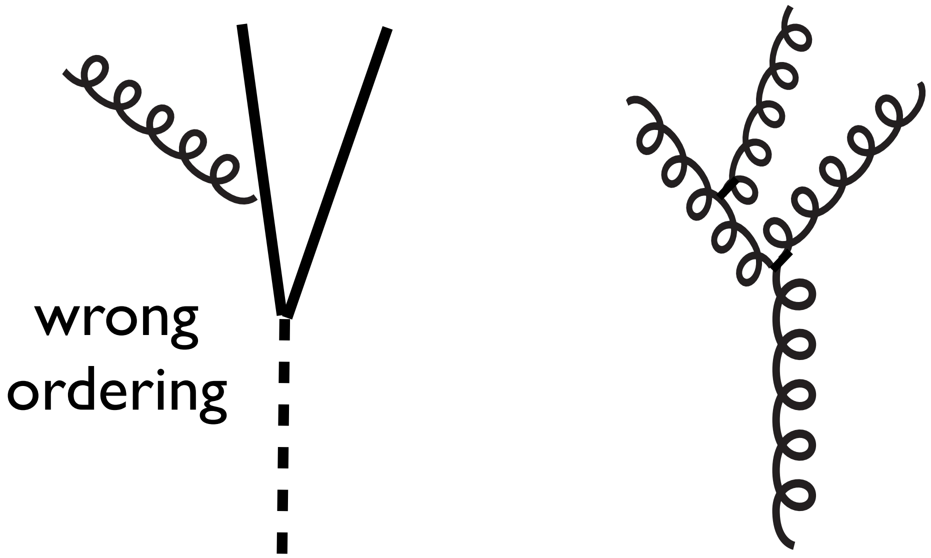
- Max template *Ov* => access to partonic information.

However, templates are purely 3-prong kinematics
=> If S & B were genuinely only 3body then both would always yield large overlaps => no separation.



Distributions of some of 5 variables differ!

- Can use angular ordering:



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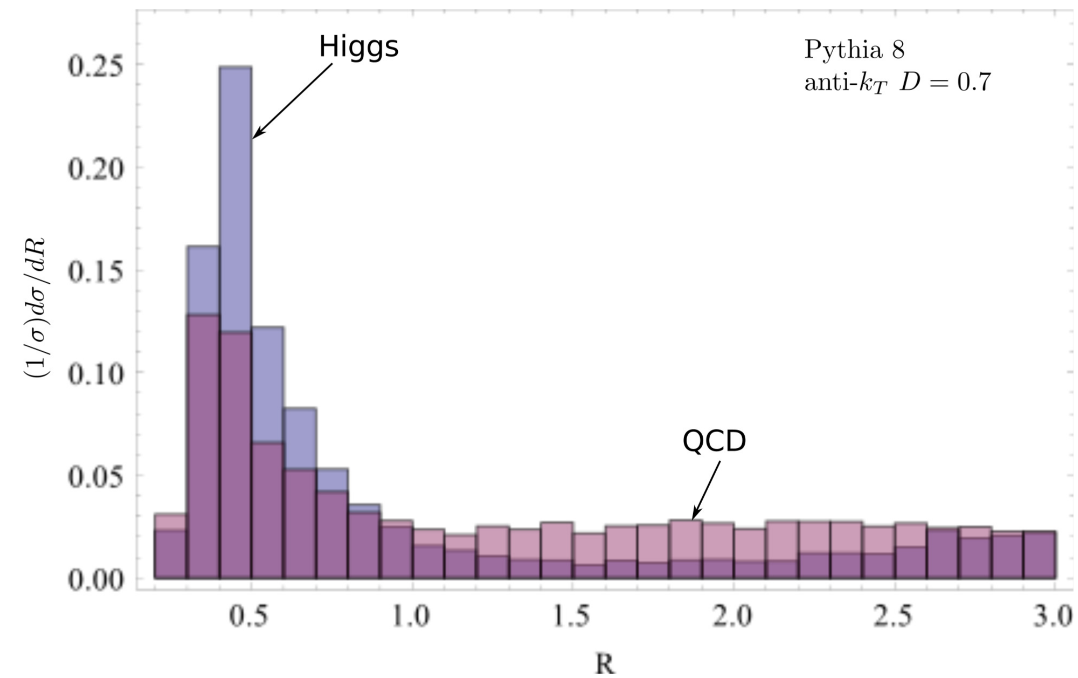


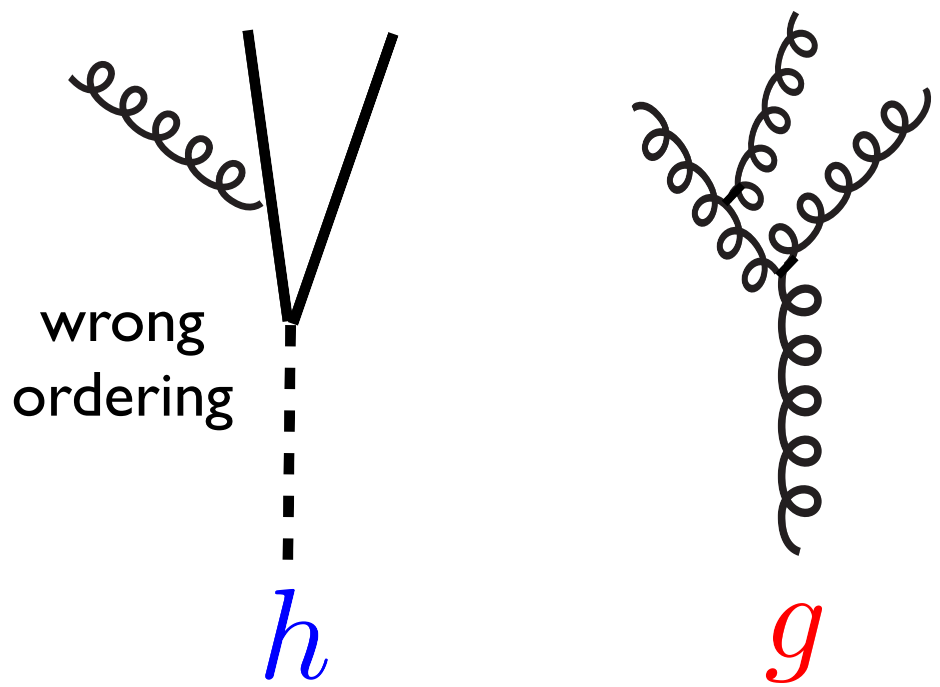
$$R = \min\{\theta_{13}/\theta_{12}, \theta_{23}/\theta_{12}\},$$

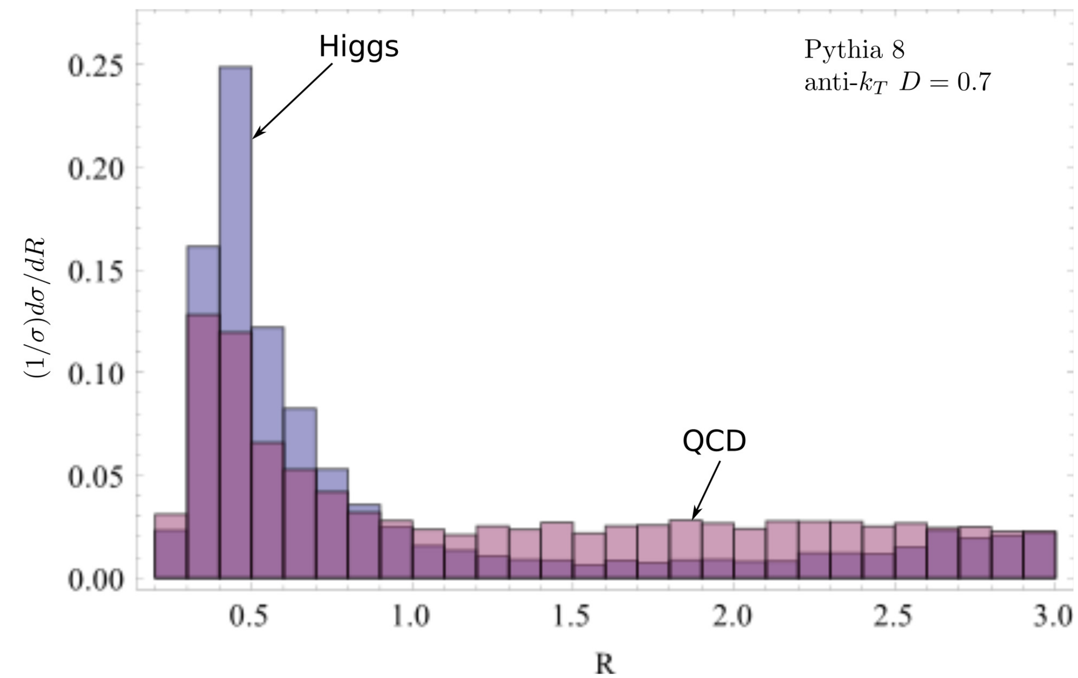
$$b = \sum_i \theta_i$$

$$V_{dip} \approx R/r^2$$

Distributions of some of 5 variables differ!

- Can use angular ordering:

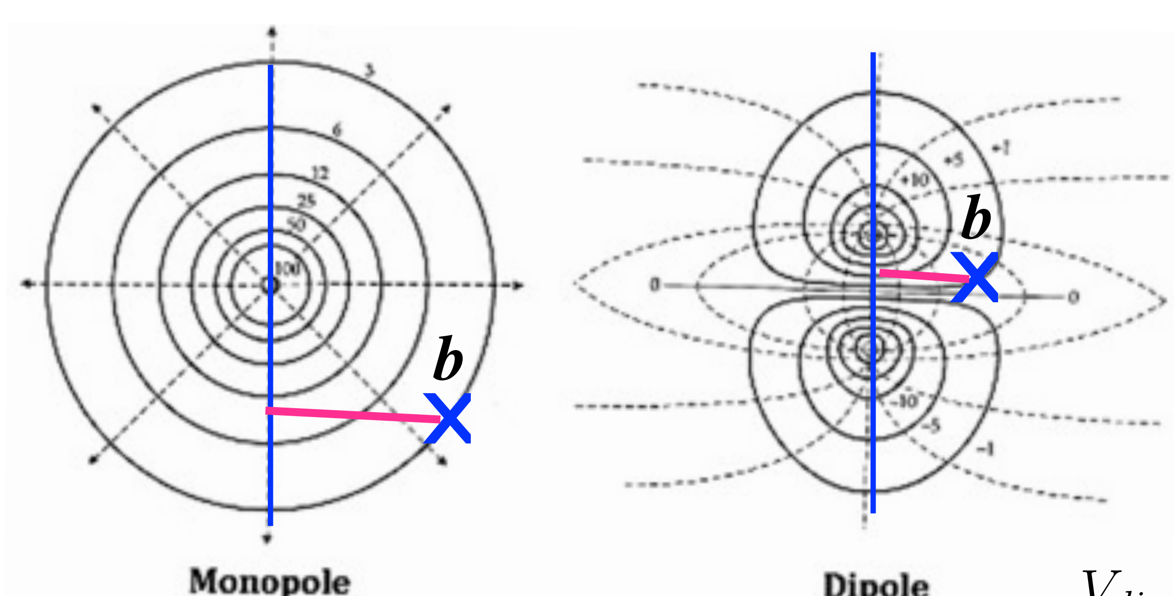




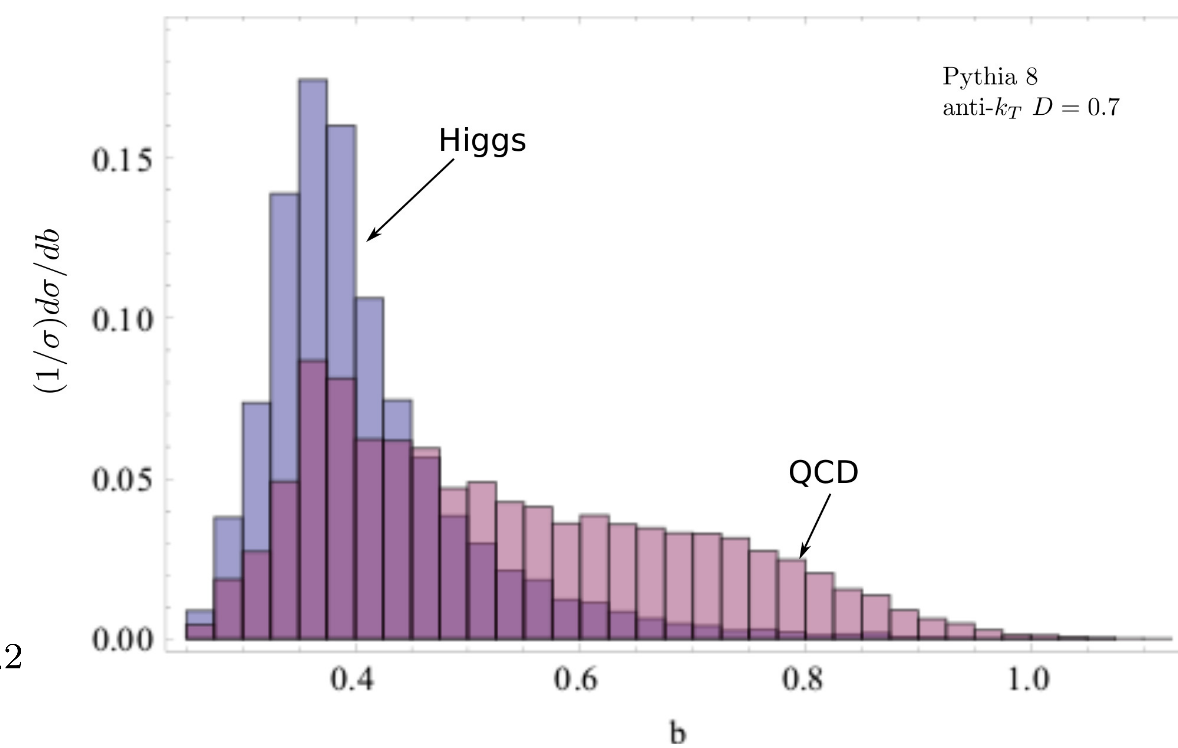
$$R = \min\{\theta_{13}/\theta_{12}, \theta_{23}/\theta_{12}\},$$

- Can use monopole vs. dipole (soft gluon):

$$b = \sum_i \theta_i$$

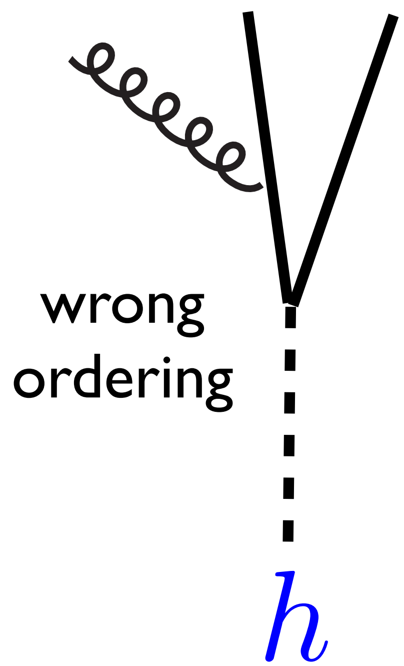


$$V_{dip} \approx R/r^2$$



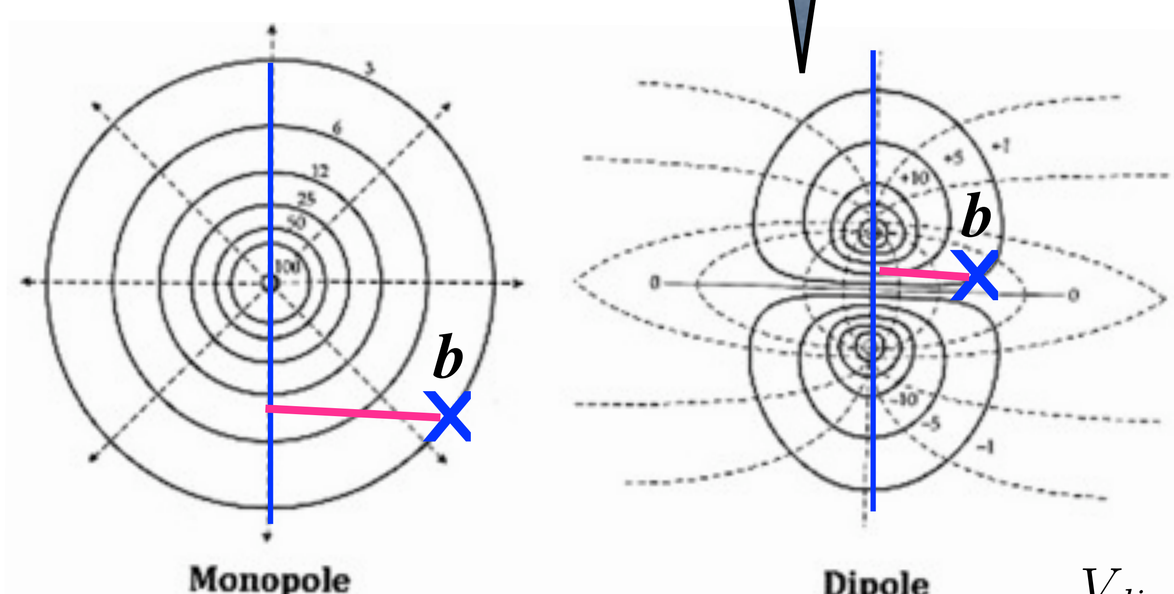
Distributions of some of 5 variables differ!

♦ Can use a

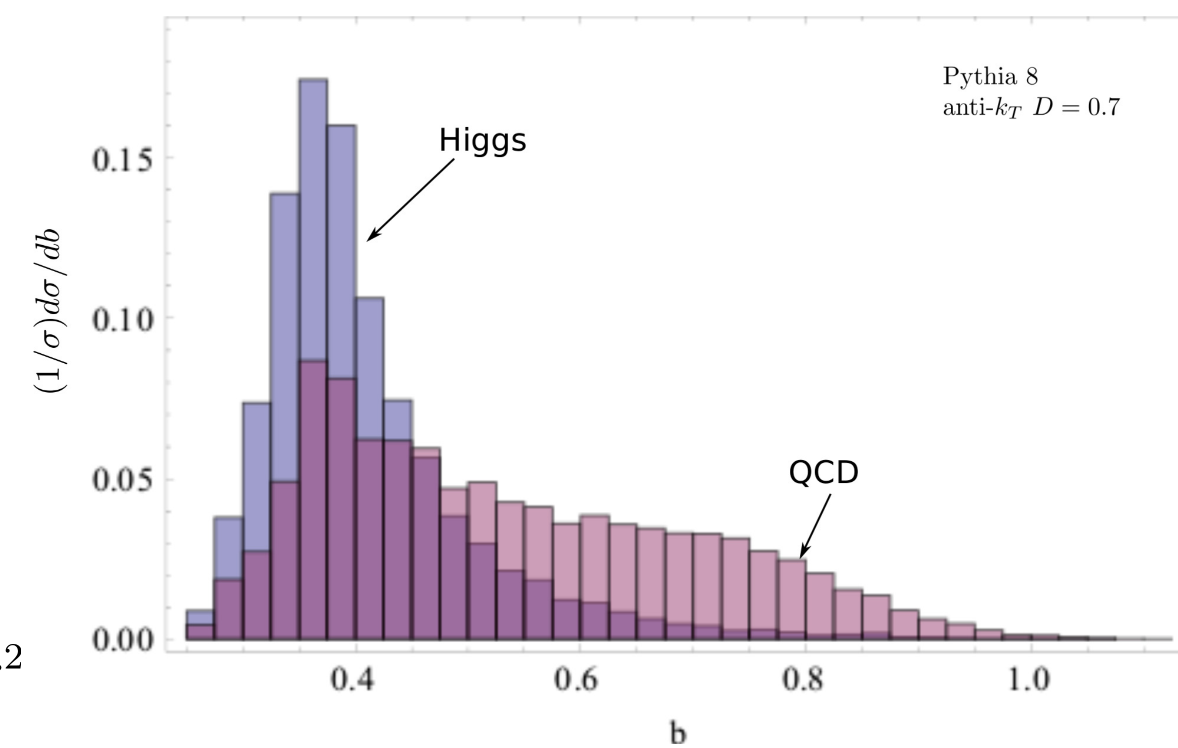


Color Flow: Radiation from a colour dipole prefers to radiate among the color connected partners. Therefore a singlet state decaying into coloured objects will tend to have more radiation closer to the dipole created by its initial decay into a $q\bar{q}$ pair. On the other hand, radiation from a coloured object will be color connected to other parts of the event leading to additional radiation in-between jets or a jet and beam.

♦ Can use m

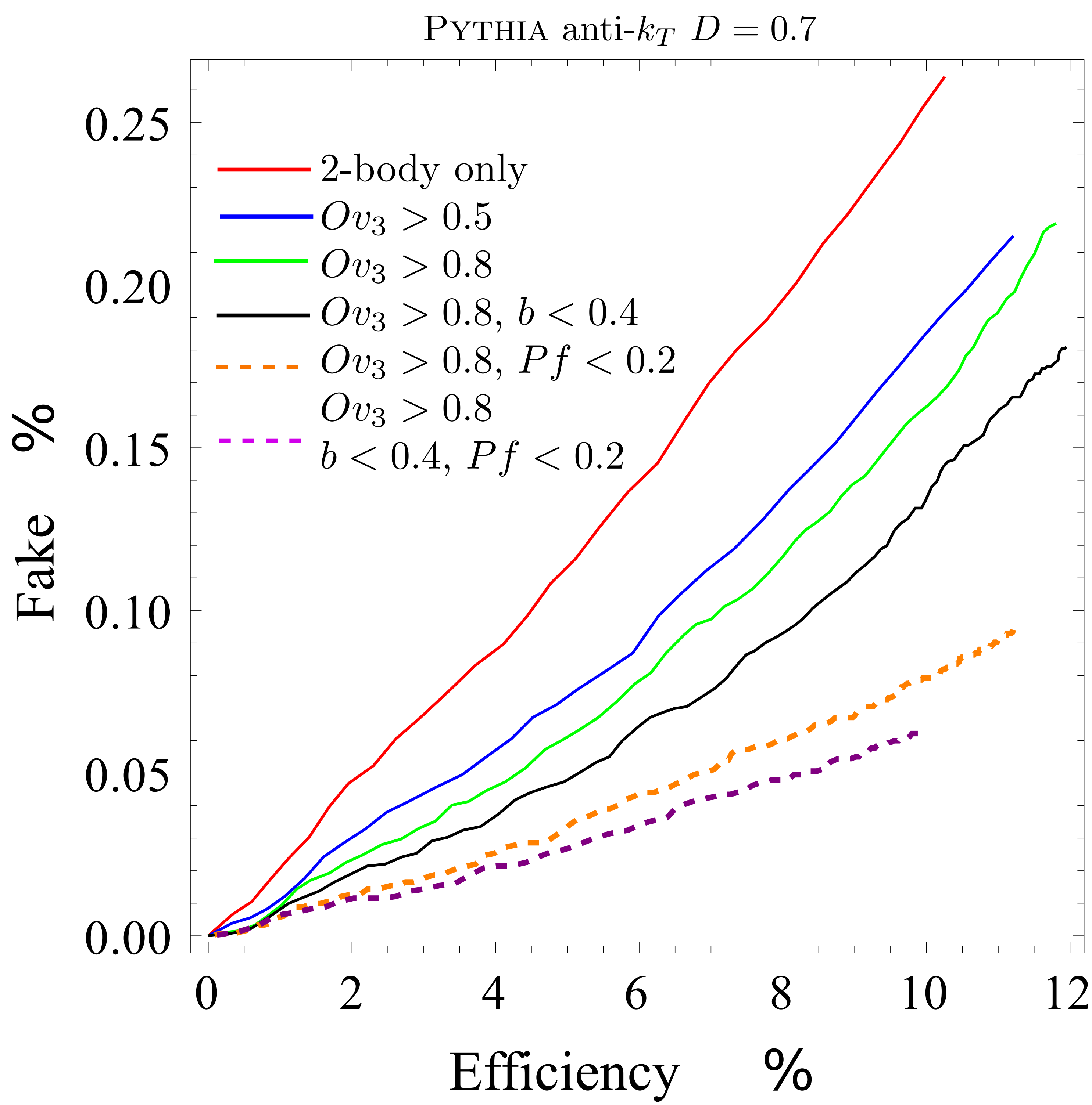


$V_{dip} \approx R/r^2$



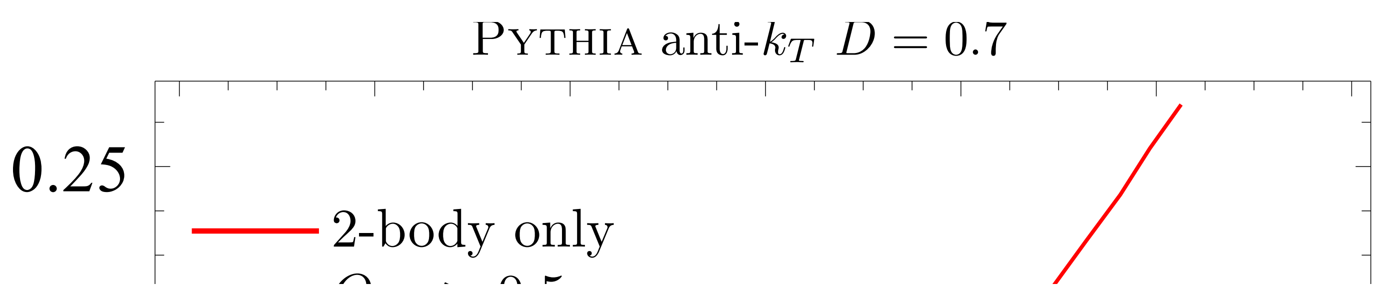
Fake vs. efficiency 2-body vs. 3-body

Varying 2-body max(Ov) value (including mass cut)



Fake vs. efficiency 2-body vs. 3-body

Varying 2-body max(Ov) value (including mass cut)

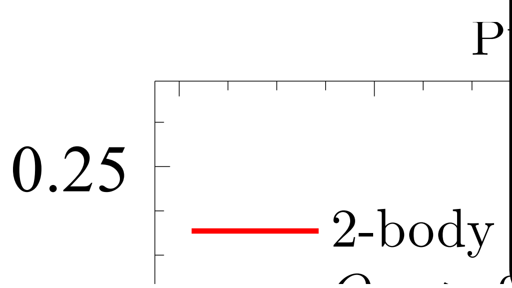


MC	Jet mass cut only		Mass cut + Ov +b+ Pf	
	Higgs-jet efficiency [%]	fake rate [%]	Higgs-jet efficiency [%]	fake rate [%]
PYTHIA 8	60	10	10	0.05
MG/ME	60	10	10	0.05
SHERPA	40	10	10	0.07

Efficiencies and fake rates for jets with $R = 0.7$ (using anti-k_T: $D = 0.7$), 950 GeV$\leq P_0 \leq$1050 GeV, 110 GeV$\leq m_J \leq$130 GeV and $m_{higgs} = 120$ 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 both Ov's, b and Pf in addition to the mass window. For the different MC simulations, we have imposed various cuts on Ov, b and Pf variables: for PYTHIA $Ov_2 \geq 0.8$, $Ov_3 \geq 0.8$, $b < 0.4$ and $Pf < 0.2$, for MG/ME $Ov_2 \geq 0.8$, $Ov_3 > 0.8$, $b < 0.4$ and $Pf < 0.2$ and for SHERPA $Ov_2 \geq 0.7$, $Ov_3 > 0.7$, $b < 0.45$ and $Pf < 0.3$.

Fake vs. efficiency 2-body vs. 3-body

Varying 2-body max(O



Naive rejection power (eff'/fake rate) -

`Pythia8 & MG/ME:`

`better than`

`1 in 200`

MC	Jet mass cut only		Mass cut + Ov +b+ Pf	
	Higgs-jet efficiency [%]	fake rate [%]	Higgs-jet efficiency [%]	fake rate [%]
PYTHIA 8	60	10	10	0.05
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Summary

- Fixed order LO prediction => adequate for boosted massive narrow jets.
- LHC+CDF: Qualitative agreement with data.
- Can calculate jet shapes => smooth moments.
- Other extreme: describe jet energy flow as spikes => template function.
- Higgs: calculated NLO energy flow + template function => expected to yield very strong rejection power.
- Many applications for NP searches.