Template Overlap Method for Higgs and New Physics Searches

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PRD 82, 054034 (2010)

L. Almeida, O. Erdogan, J. Juknevich, SL, G. Perez, & G. Sterman

arXiv:1112.1957 (PRD)

Work in progress...

MC4BSM 2012, Cornell University

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
- NP searches
- Summary

Jets & New Physics

- ”Jets” in cosmic rays described in: Edwards et al., Phil. Mag. (1957)
- Looking for new physics in “energetic” jets has a long tradition:

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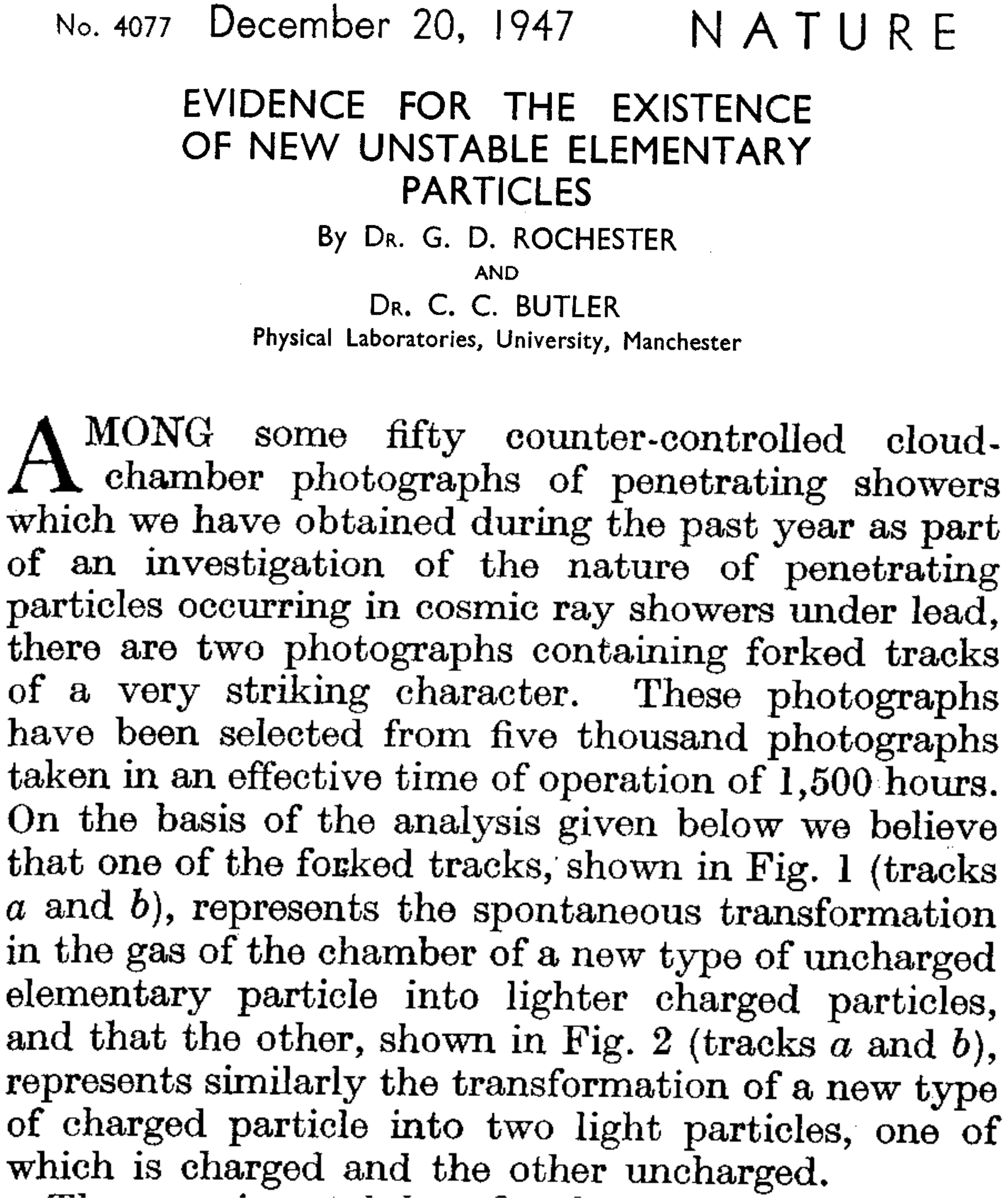

No. 4077 December 20, 1947 NATURE

EVIDENCE FOR THE EXISTENCE OF NEW UNSTABLE ELEMENTARY PARTICLES

By Dr. G. D. ROCHESTER
AND
Dr. C. C. BUTLER
Physical Laboratories, University, Manchester

AMONG some fifty counter-controlled cloud-chamber photographs of penetrating showers which we have obtained during the past year as part of an investigation of the nature of penetrating particles occurring in cosmic ray showers under lead, there are two photographs containing forked tracks of a very striking character. These photographs have been selected from five thousand photographs taken in an effective time of operation of 1,500 hours. On the basis of the analysis given below we believe that one of the forked tracks, shown in Fig. 1 (tracks *a* and *b*), represents the spontaneous transformation in the gas of the chamber of a new type of uncharged elementary particle into lighter charged particles, and that the other, shown in Fig. 2 (tracks *a* and *b*), represents similarly the transformation of a new type of charged particle into two light particles, one of which is charged and the other uncharged.

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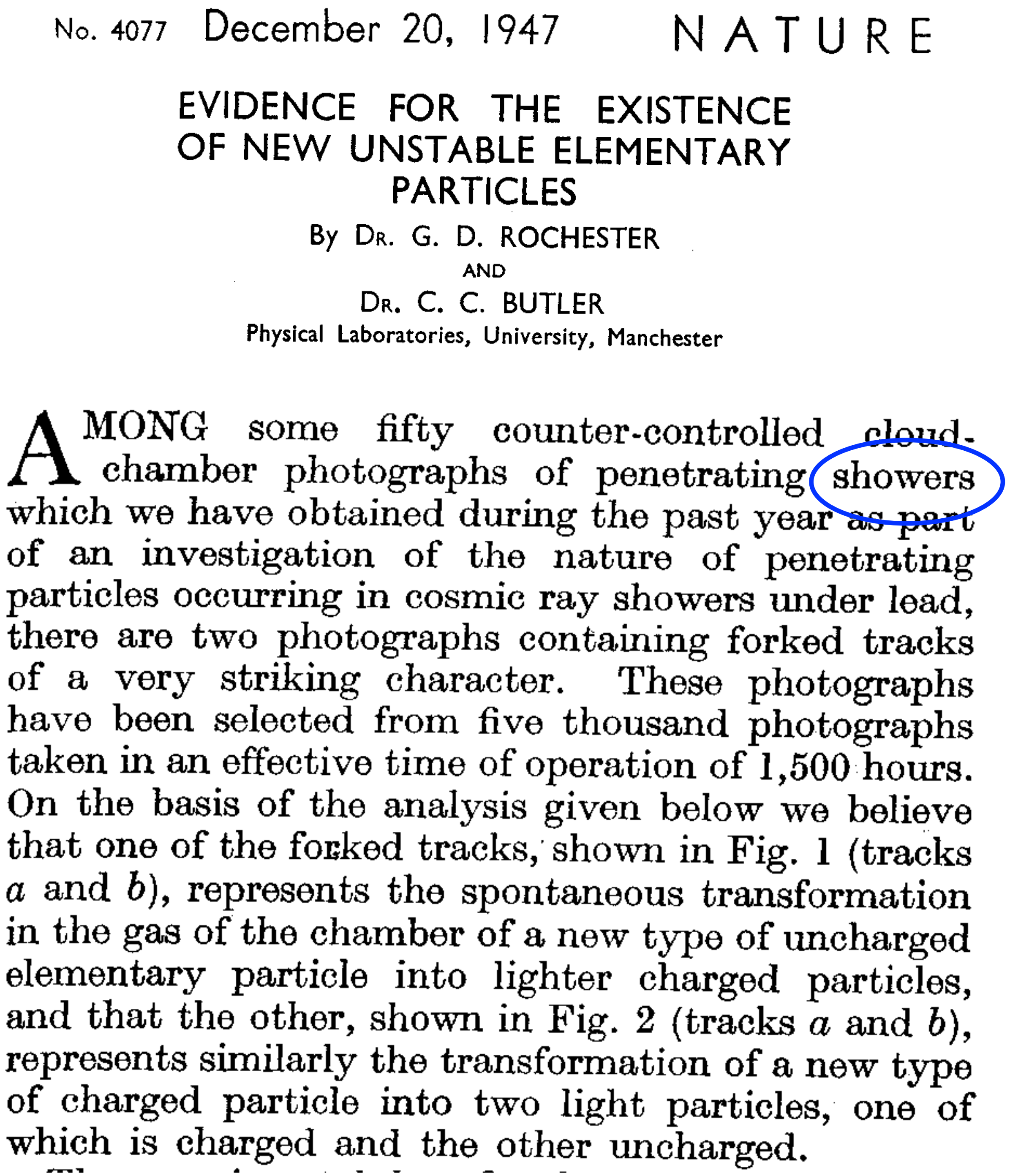

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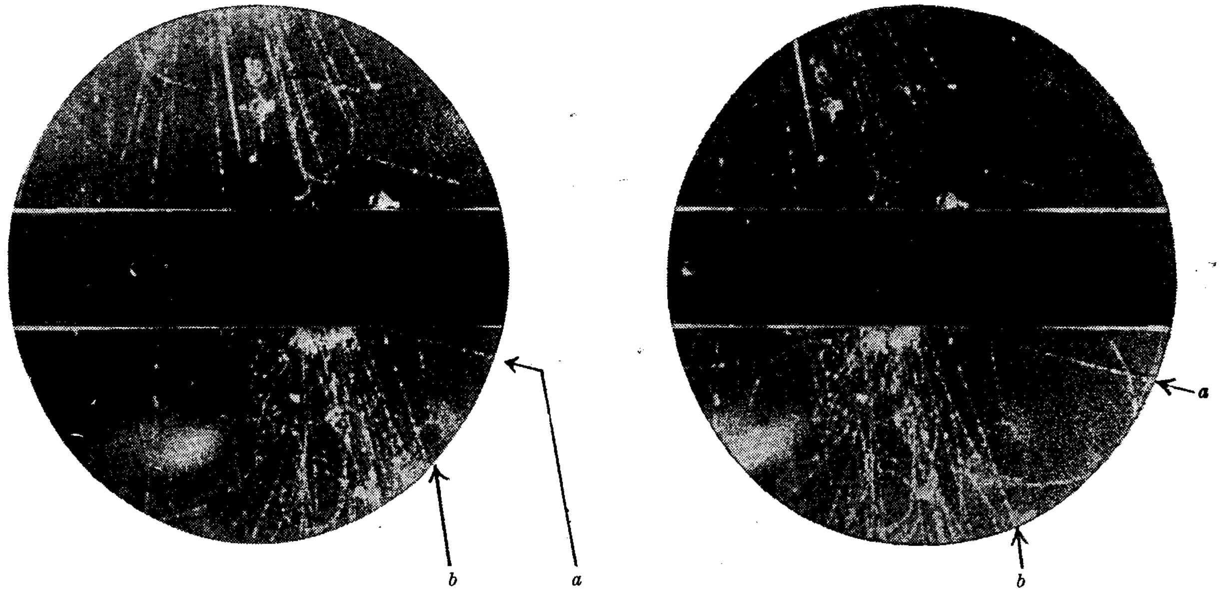

Fig. 1. STEREOSCOPIC PHOTOGRAPHS SHOWING AN UNUSUAL FORK (*a b*) IN THE GAS. THE DIRECTION OF THE MAGNETIC FIELD IS SUCH THAT A POSITIVE PARTICLE COMING DOWNWARDS IS DEVIATED IN AN ANTICLOCKWISE DIRECTION

Jets & New Physics

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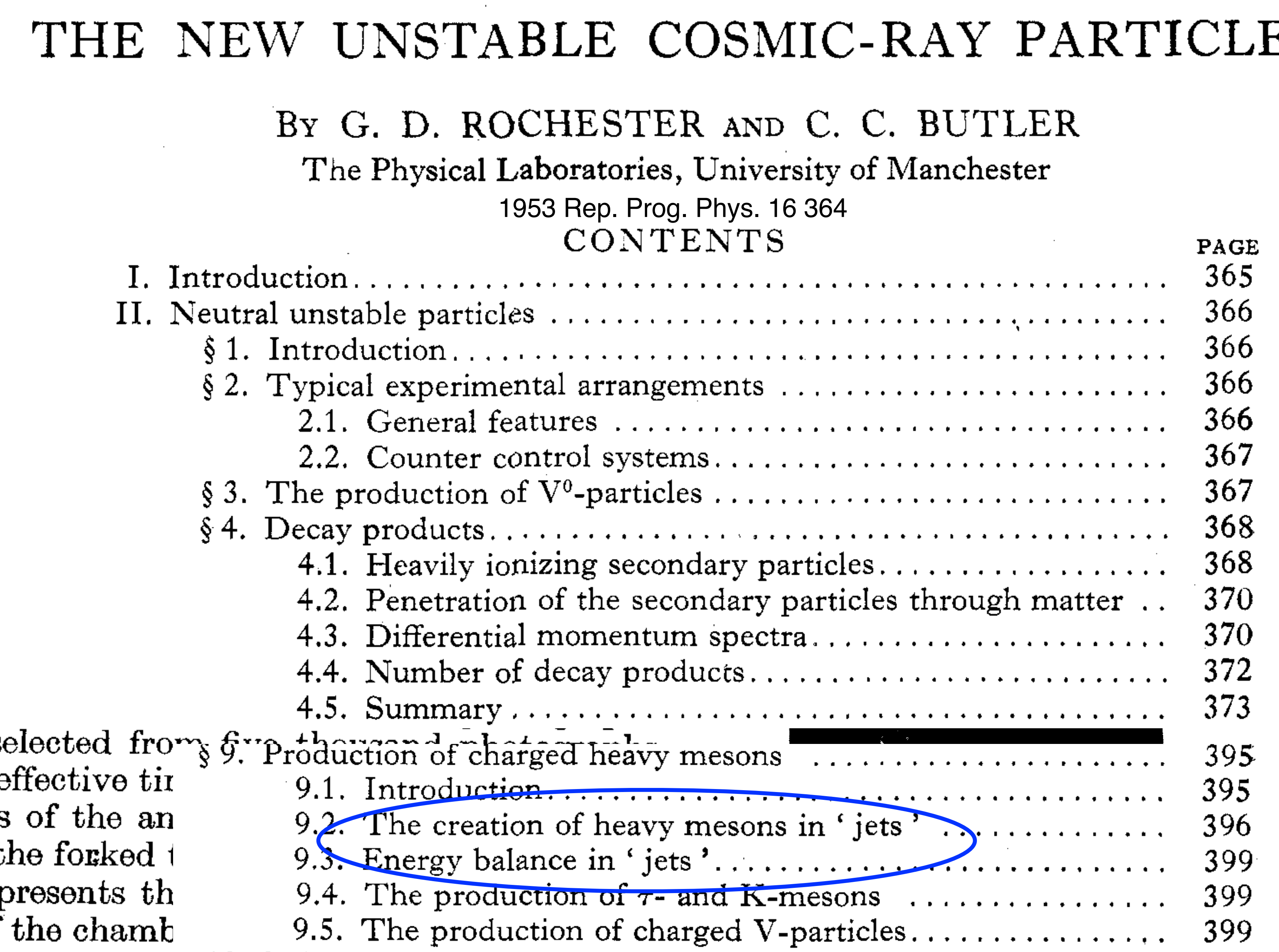

THE NEW UNSTABLE COSMIC-RAY PARTICLES

By G. D. ROCHESTER and C. C. BUTLER

The Physical Laboratories, University of Manchester

1953 Rep. Prog. Phys. 16 364

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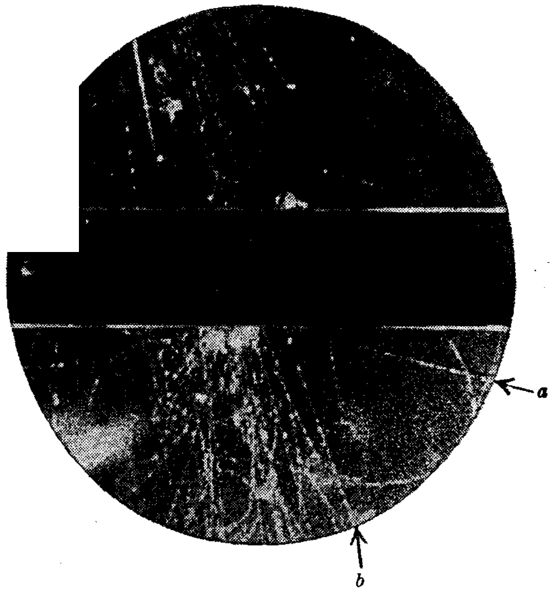
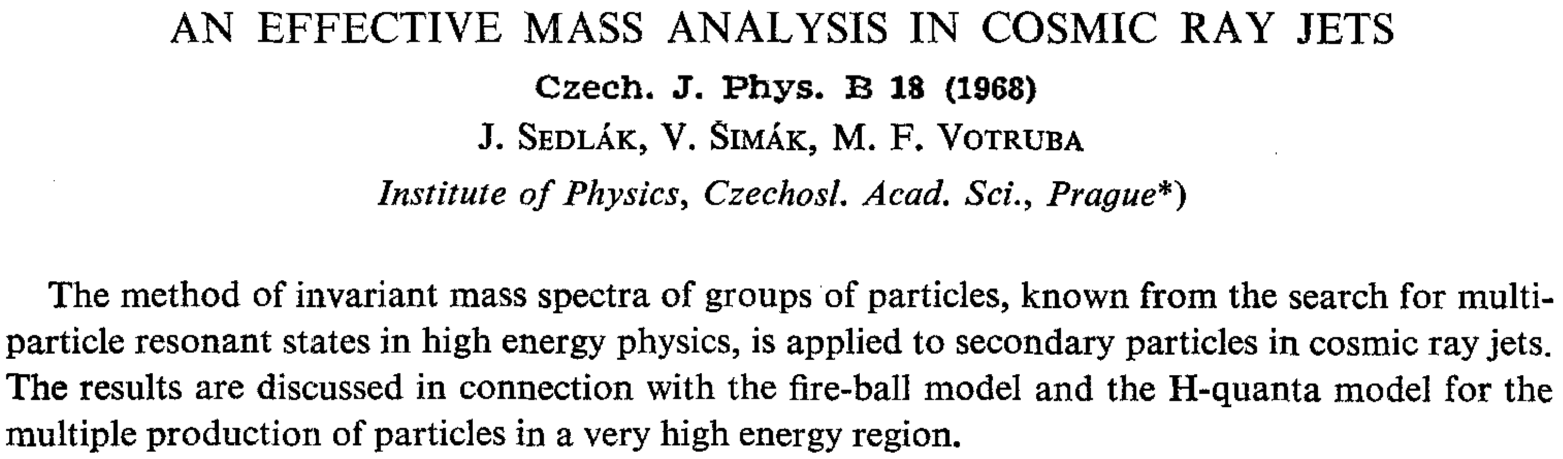


Fig. 1. Stereoscopic photographs showing an unusual fork (*a b*) in the gas. The direction of the magnetic field is such that a positive particle coming downwards is deviated in an anticlockwise direction

Jets Mass

- Jet masses can be an important tool for NP searches.



AN EFFECTIVE MASS ANALYSIS IN COSMIC RAY JETS

Czech. J. Phys. B 18 (1968)

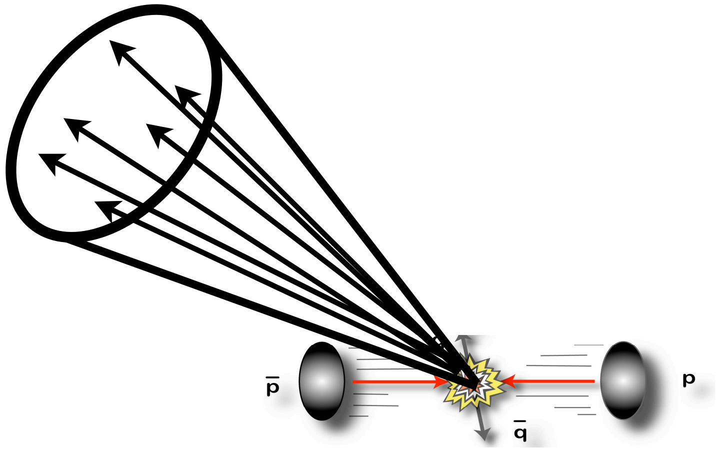
J. SEDLÁK, V. ŠIMÁK, M. F. VOTRUBA

*Institute of Physics, Czechosl. Acad. Sci., Prague**)

The method of invariant mass spectra of groups of particles, known from the search for multiparticle resonant states in high energy physics, is applied to secondary particles in cosmic ray jets. The results are discussed in connection with the fire-ball model and the H-quanta model for the multiple production of particles in a very high energy region.

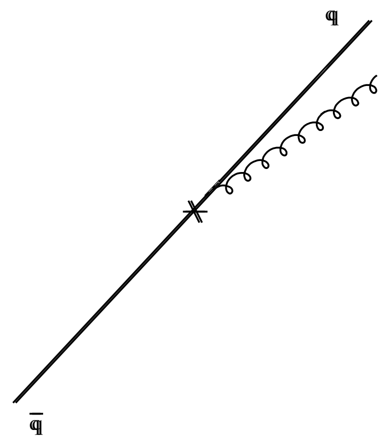
- Modern (relevant) jet mass definition:

$$m_J^2 = \left(\sum\nolimits_{i\in R} P_i\right)^2 , \quad Pi^2 = 0 \, , \ \text{for} \quad E_J \gg m_J \gg \Lambda_{\text{QCD}} \, .$$



Importance of jet mass, QCD story

- QCD: soft collinear singularities => narrow jets are “light”.



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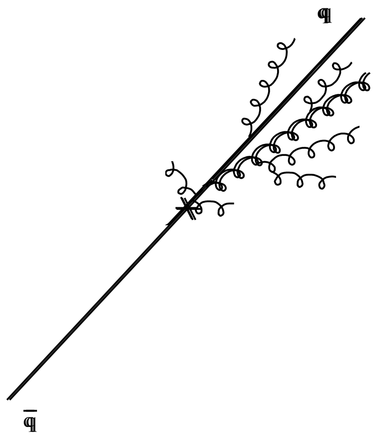

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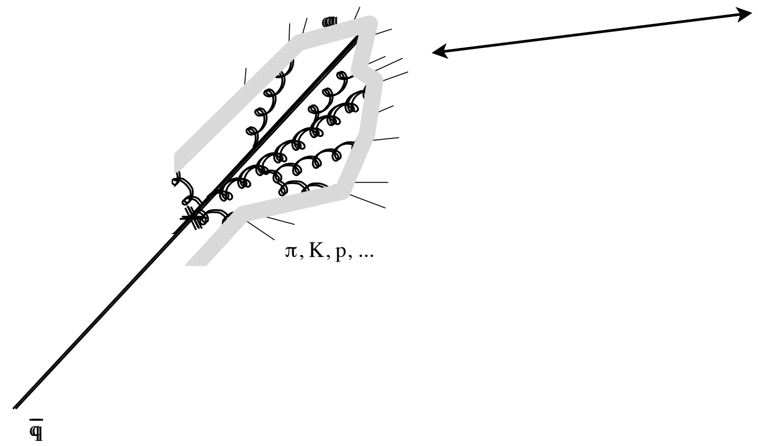

$$m_J^2 \ll E_J^2 R^2$$

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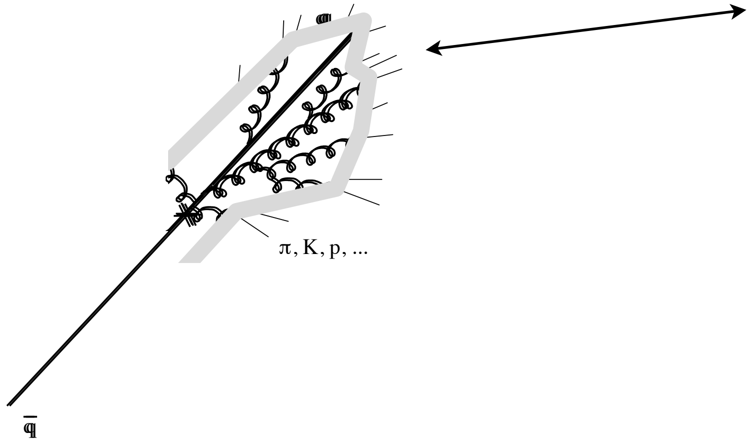

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- Data ? (high P_T , large m_j)

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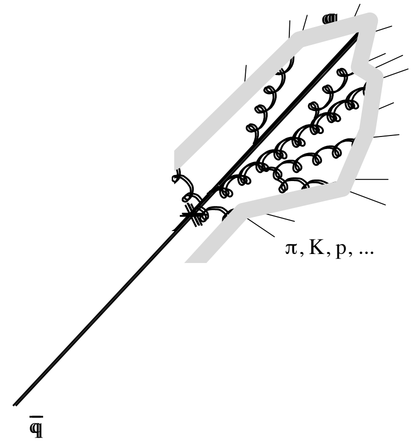
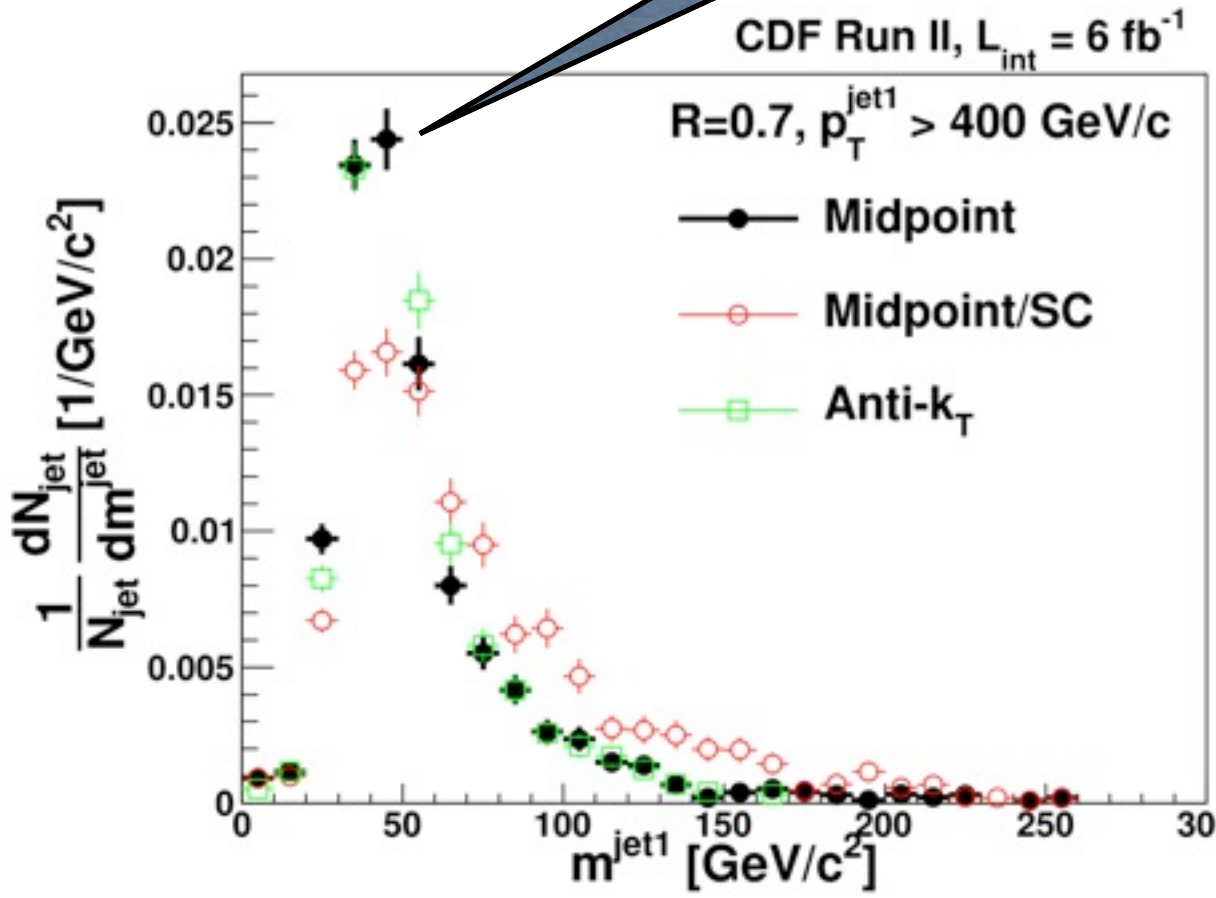


most QCD jets are of low mass

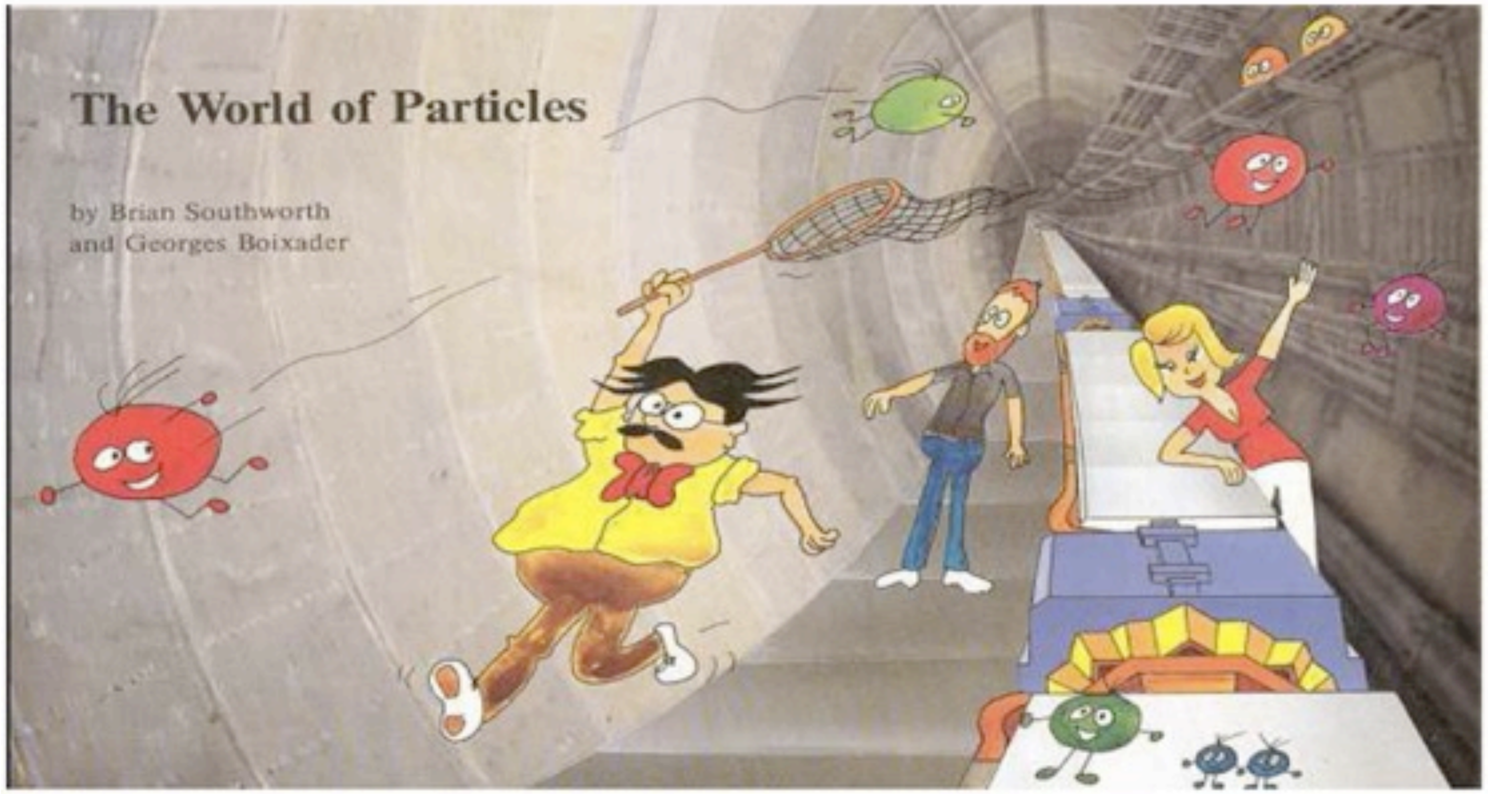
- Data ? (high P_T , large m_j)



(ignore non-IR safe red dots)

CDF/ANAL/TOP/PUBLIC/10234; 1106.5952 [hep-ex]

How is this related to new physics or Higgs searches?


The World of Particles

by Brian Southworth
and Georges Boixader

Looking at boosted massive objects, generic motivations

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

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

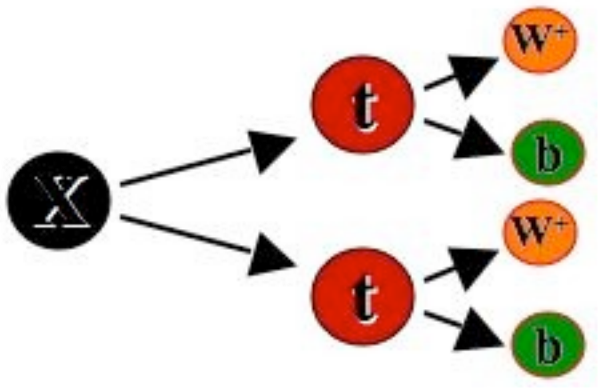
  Seymour (93); Butterworth, Cox, Forshaw (02);
  Agashe, Belyaev, Krupovnickas, Perez & Virzi (06);
  Lillie, Randall & Wang (07); Butterworth, Davison,
  Rubin & Salam (08).

- 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 →



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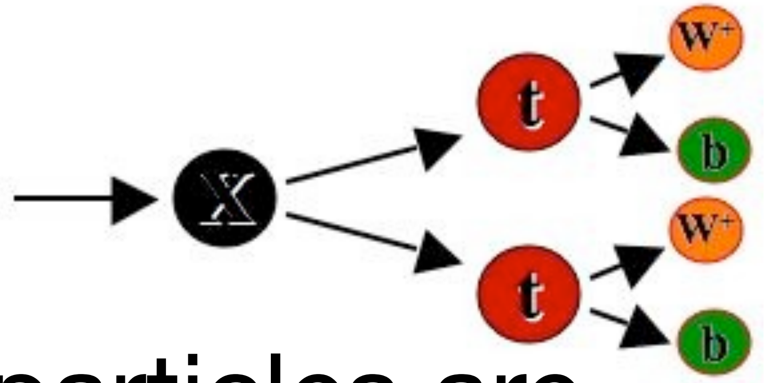
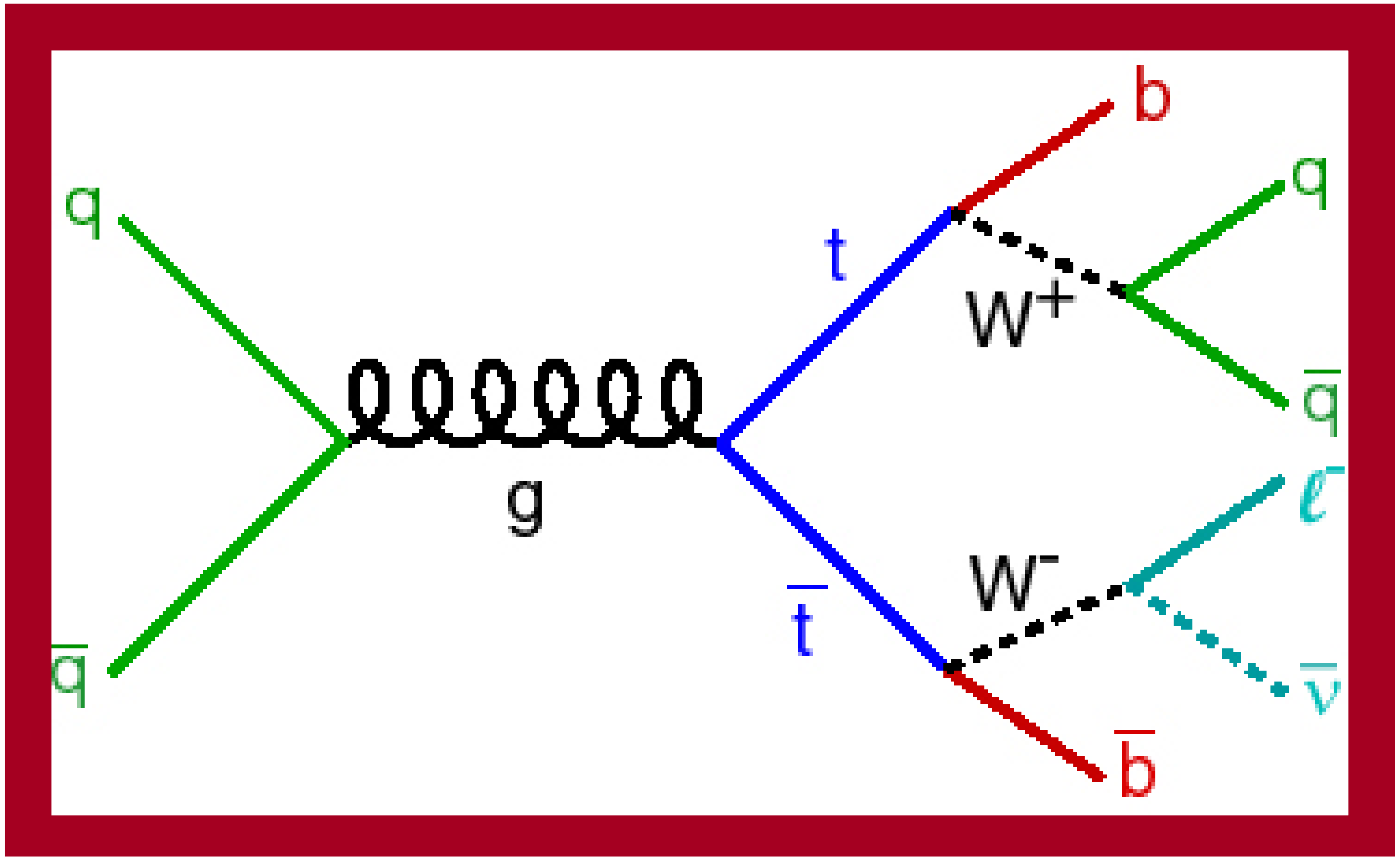


- Since $M_{t,h} \ll M_X$ the outgoing SM particles are ultra-relativistic, their decay products are collimated



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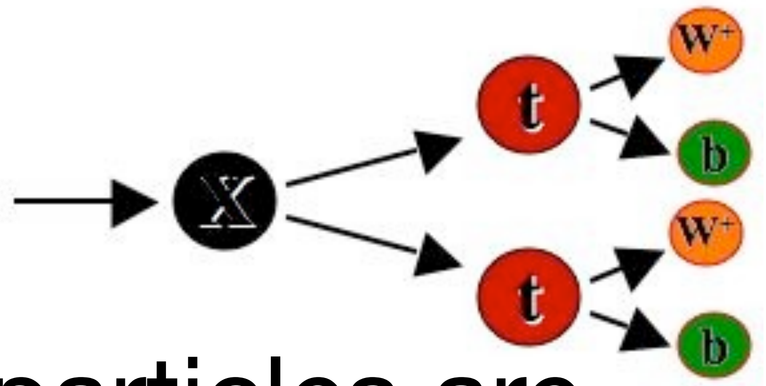
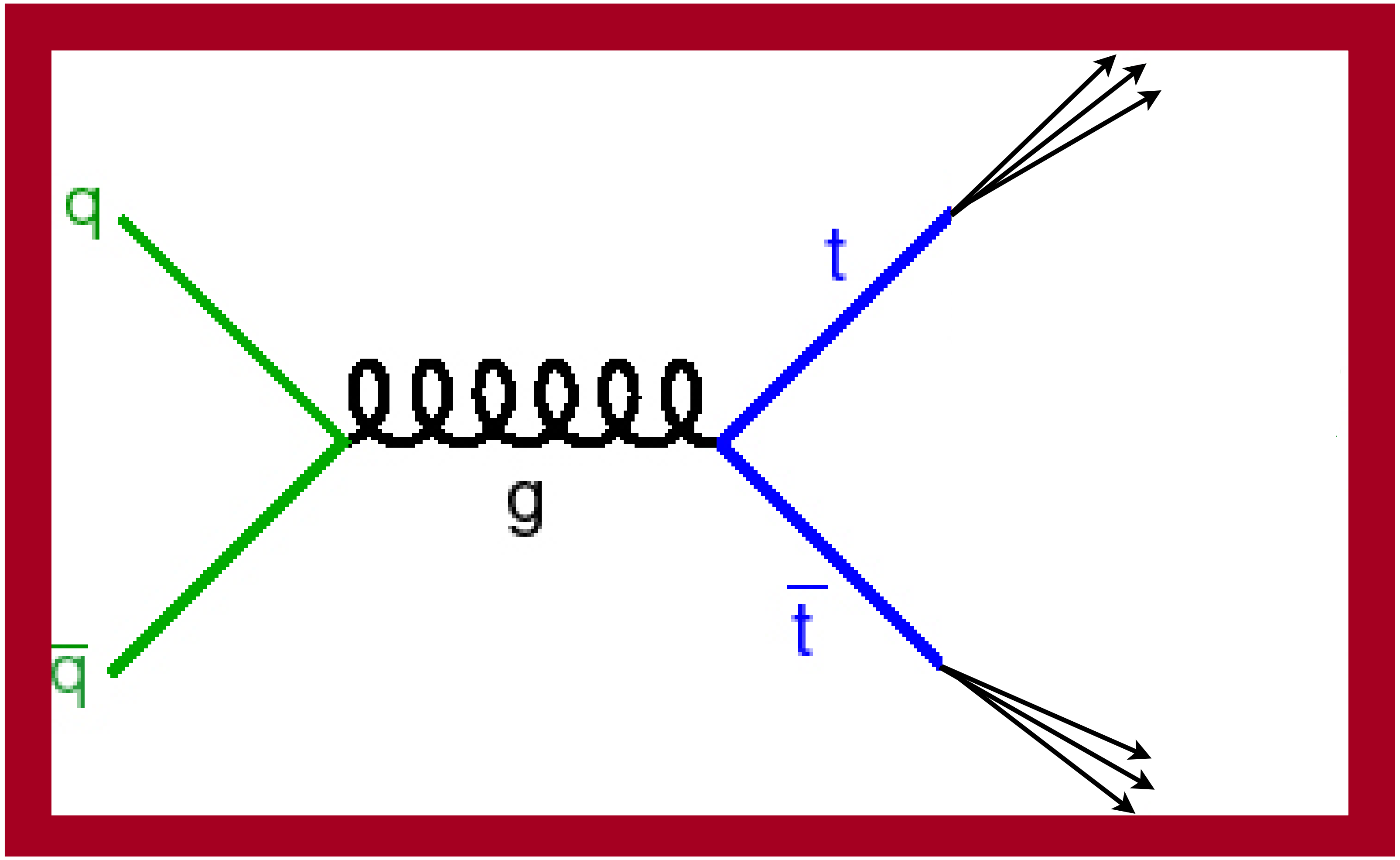
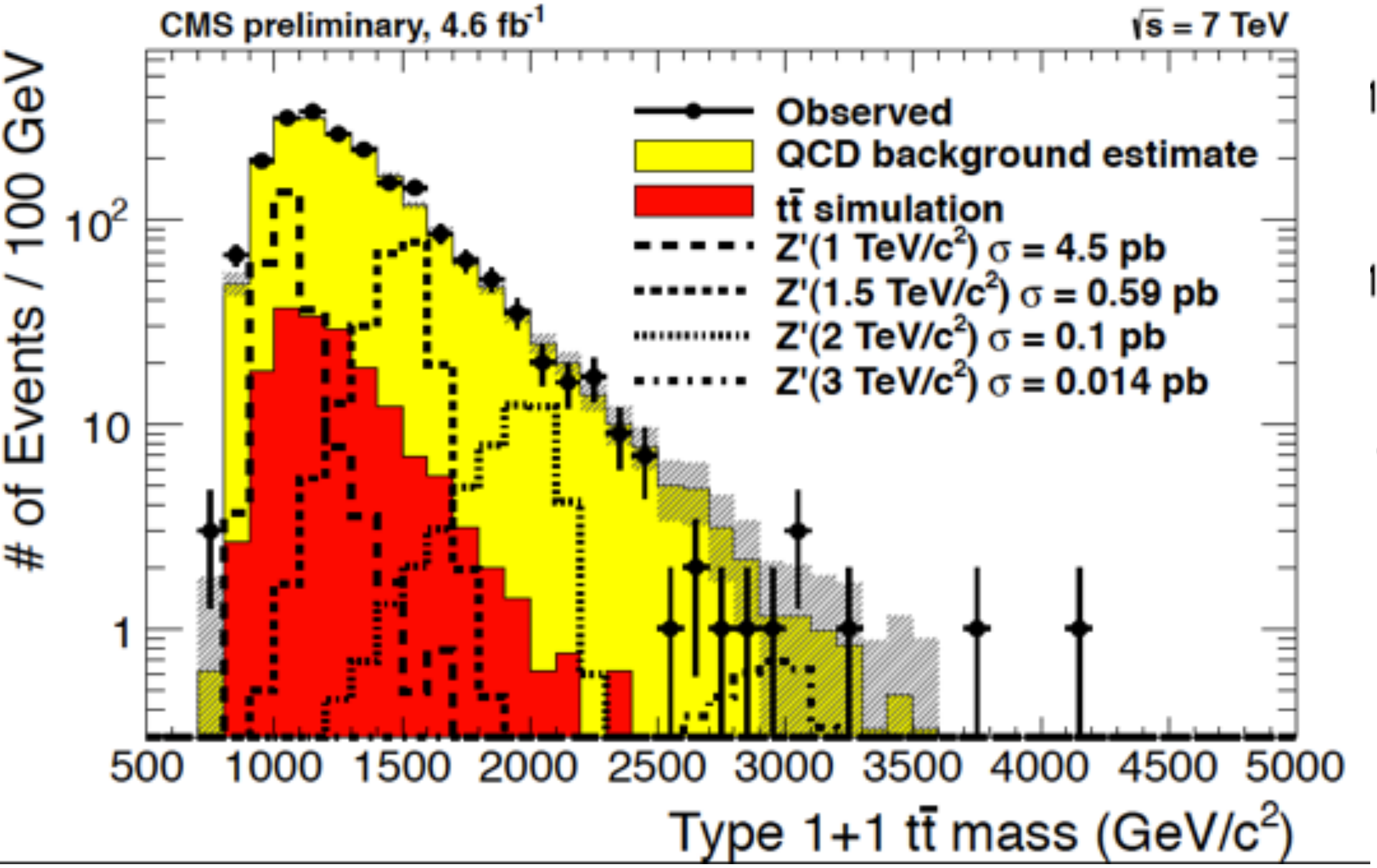


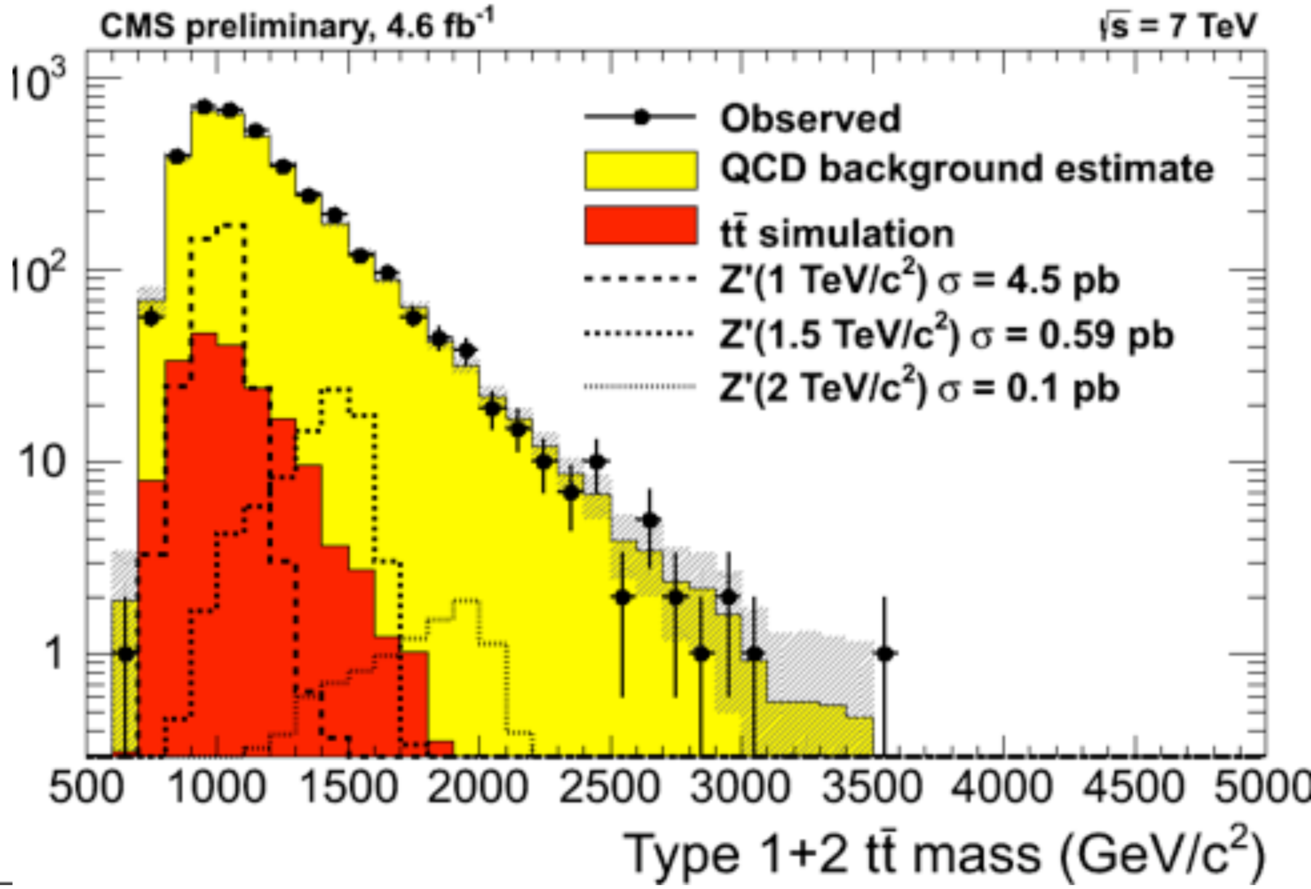
- Since $M_{t,h} \ll M_X$ the outgoing SM particles are ultra-relativistic, their decay products are collimated

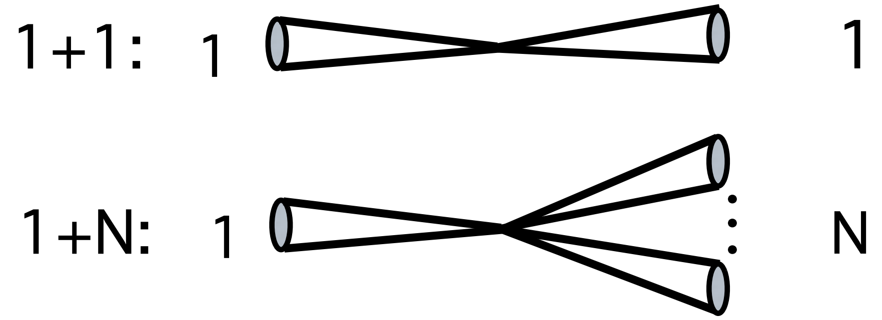
- The concept of boosted massive jet emerges



The LHC frontier: hard/boosted tops phys.







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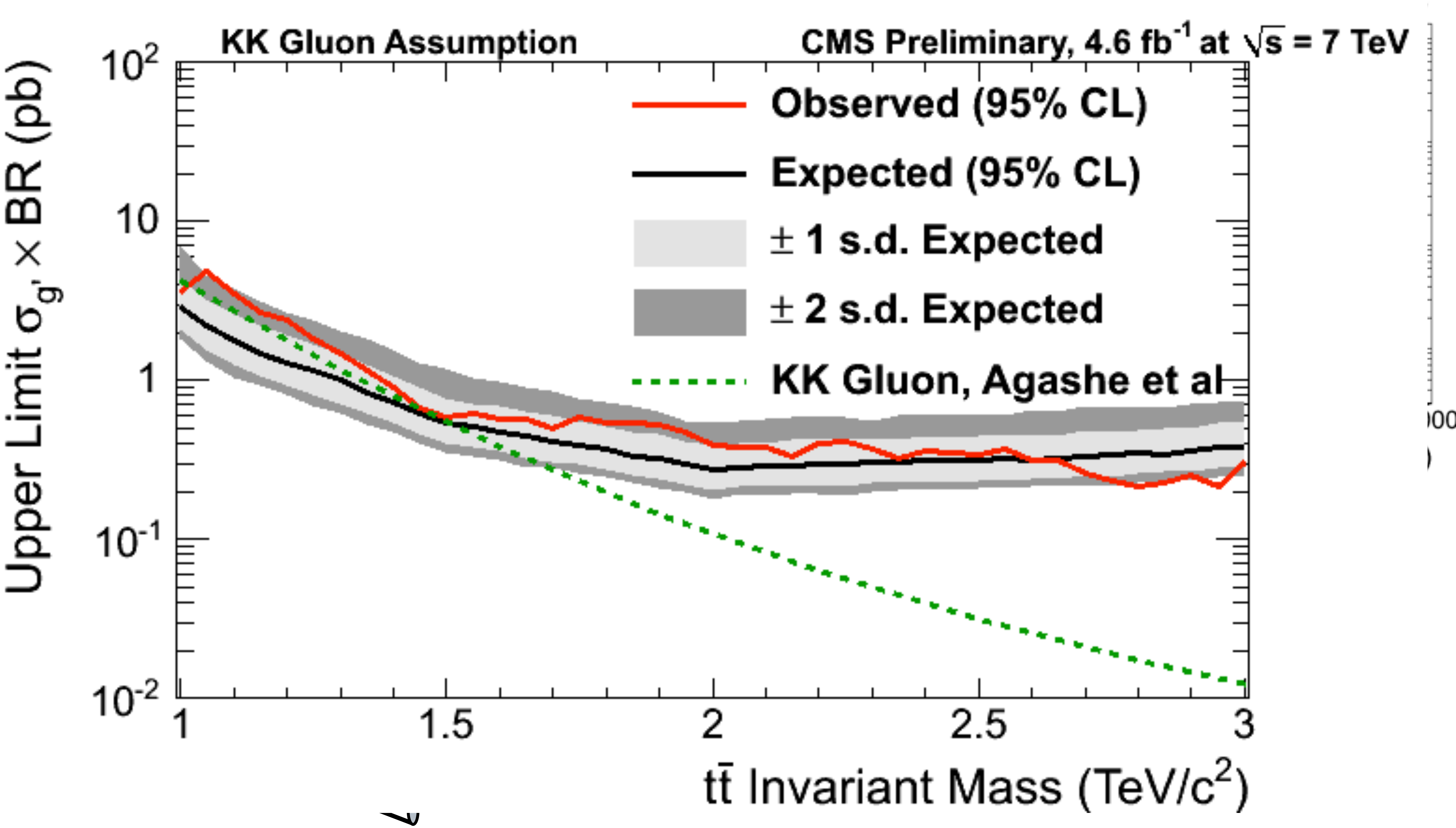
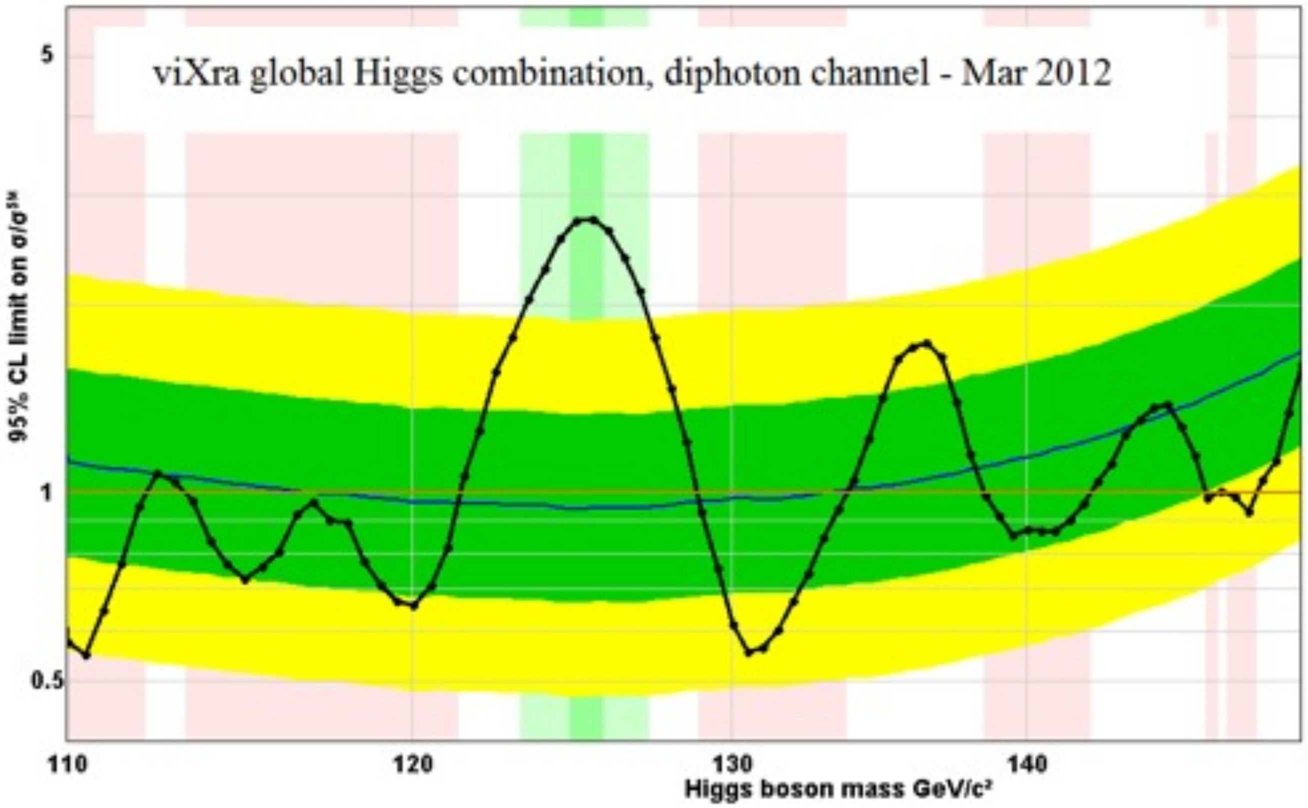
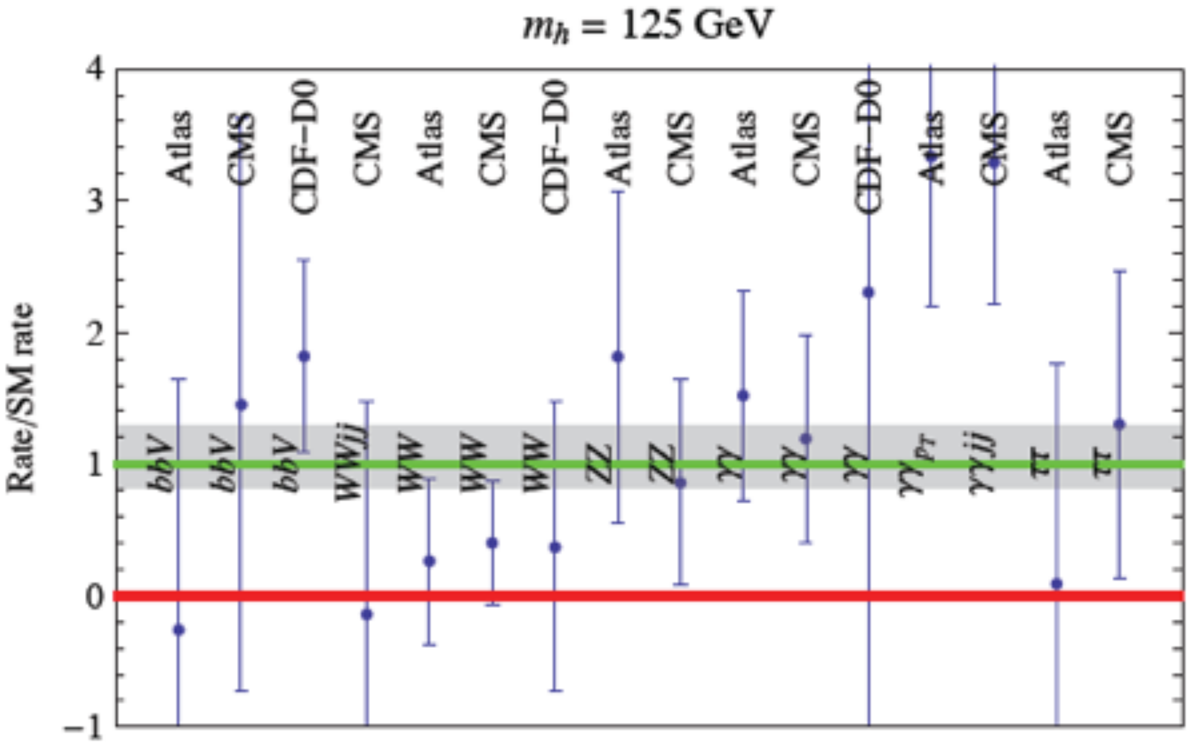
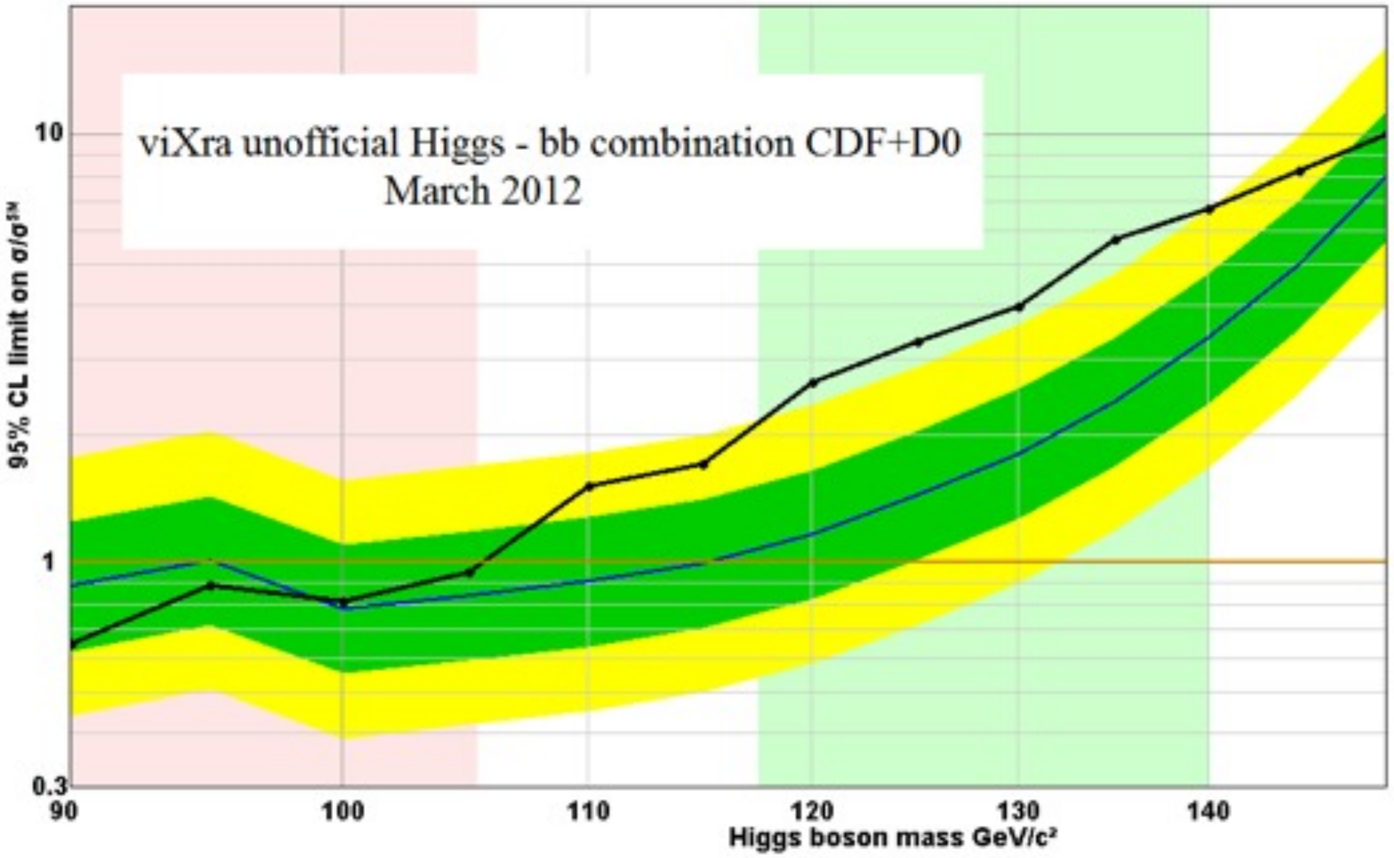


Higgs hunting:current state







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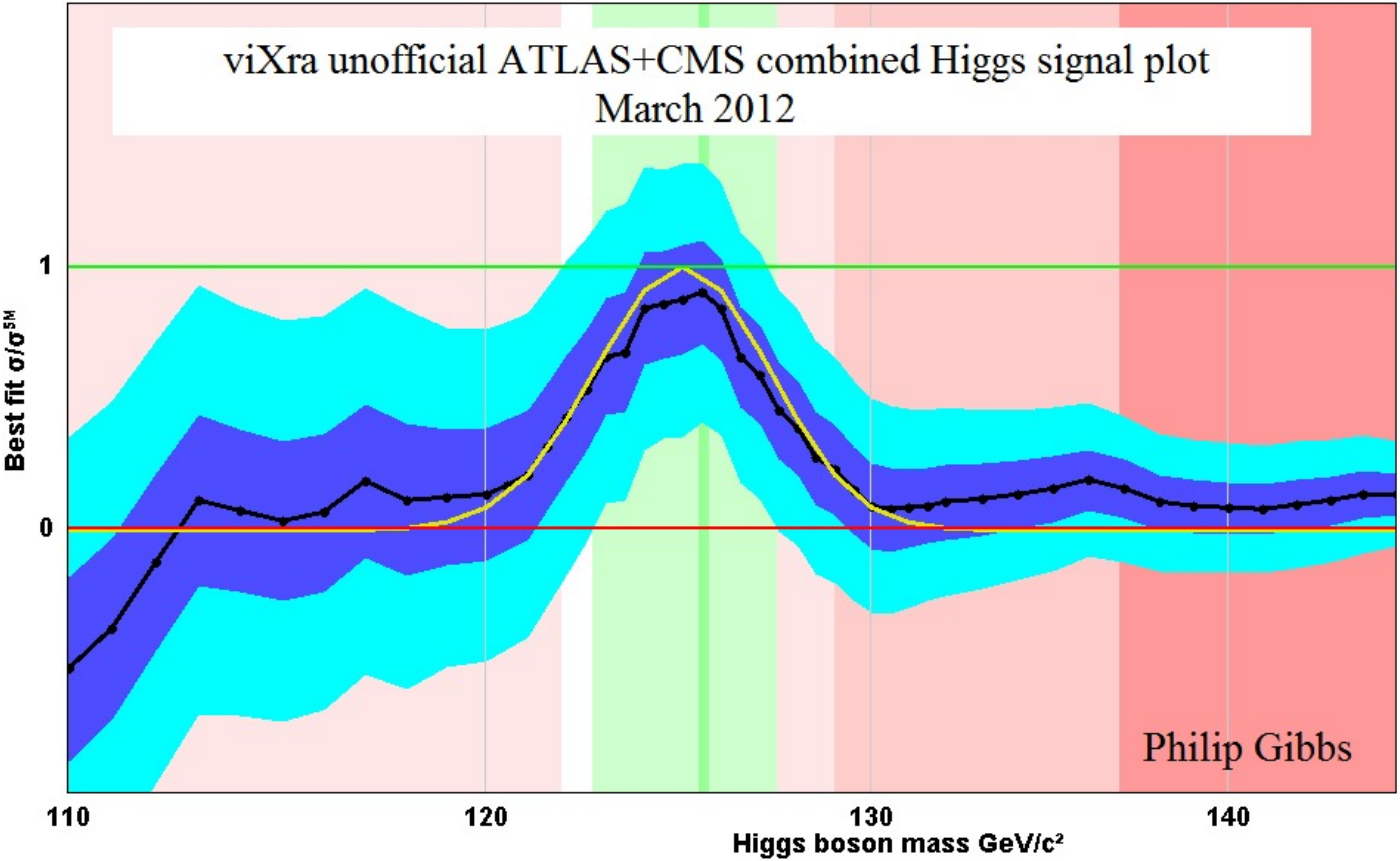

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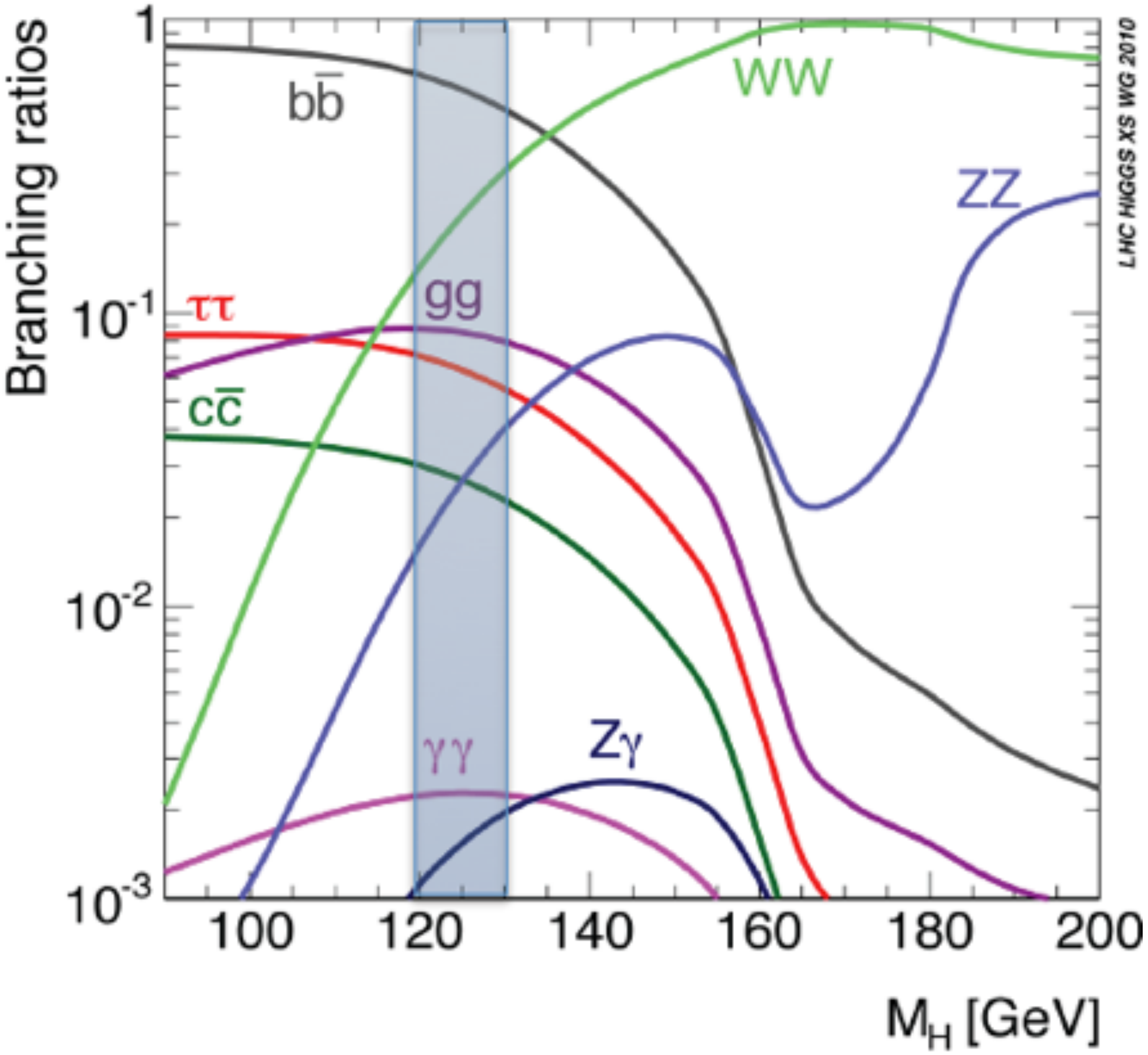
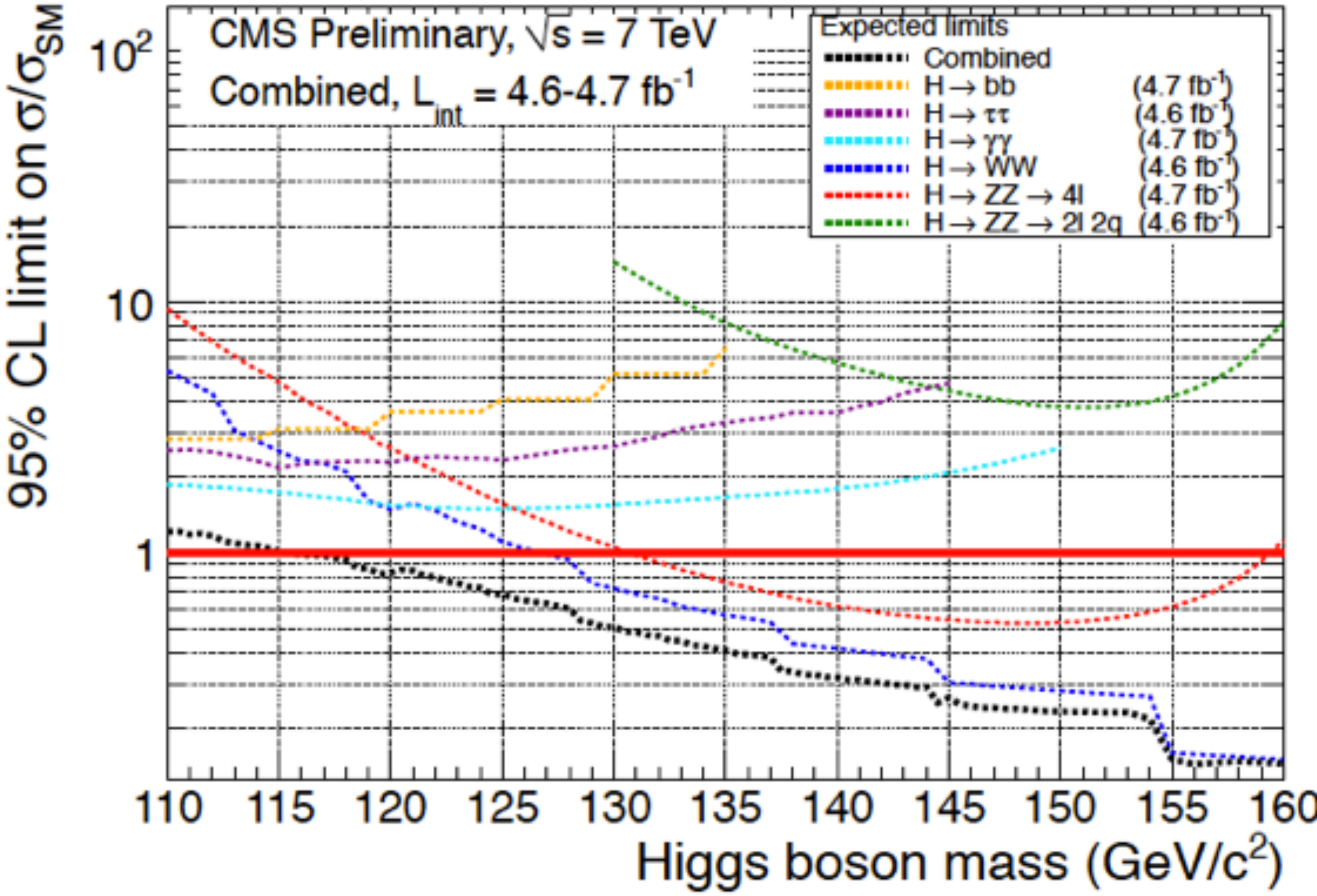
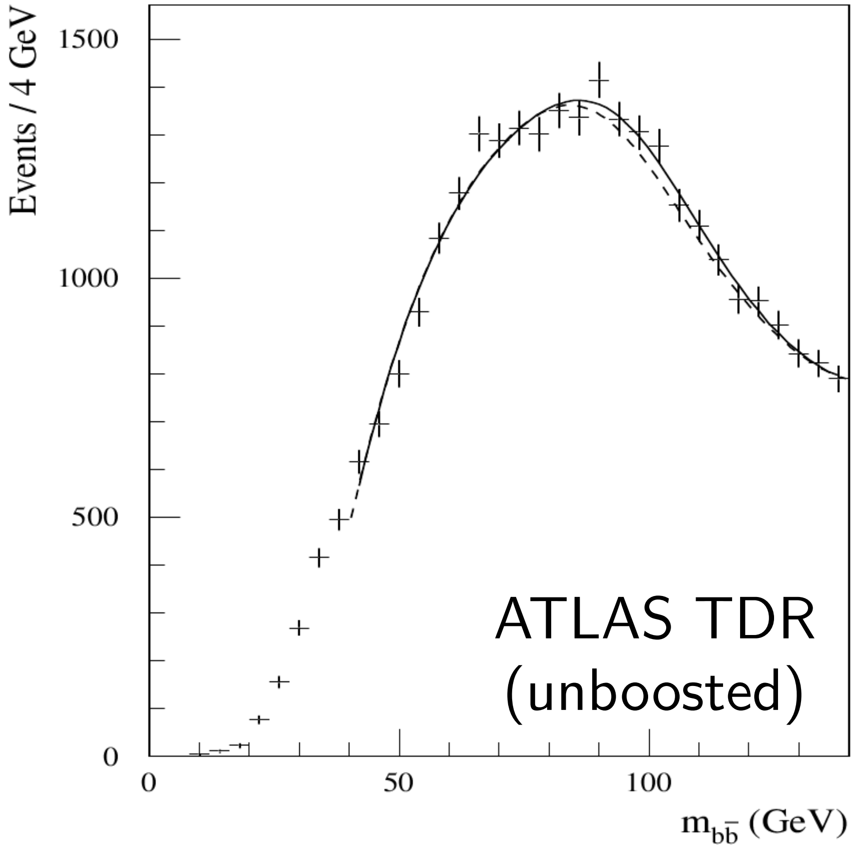


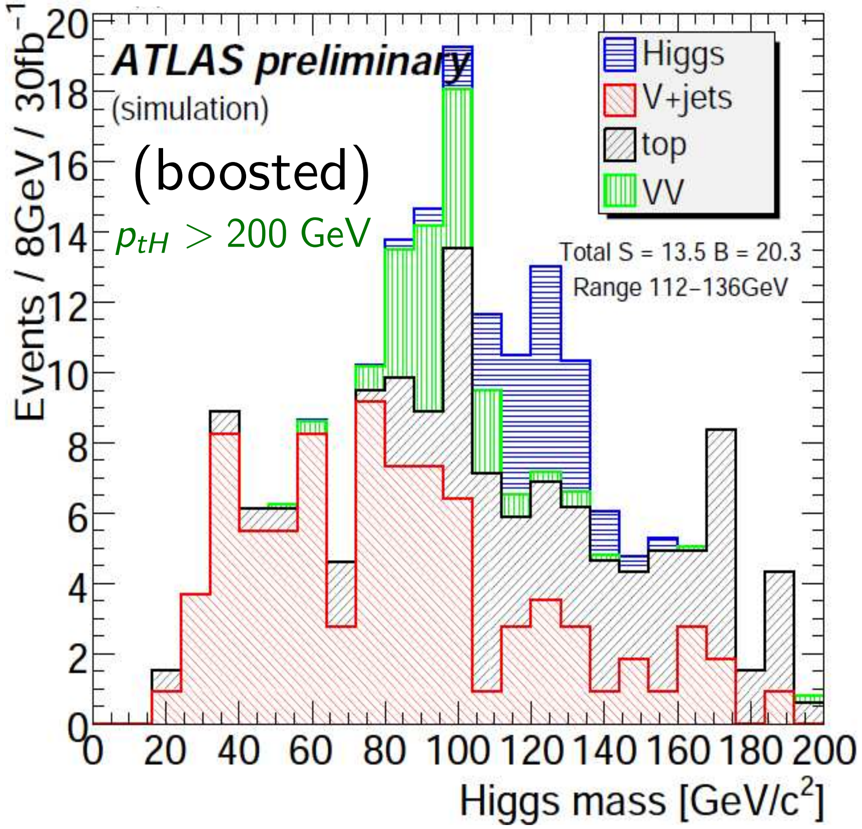


Higgs hunting

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

Butterworth, Davison, Rubin & Salam (08).





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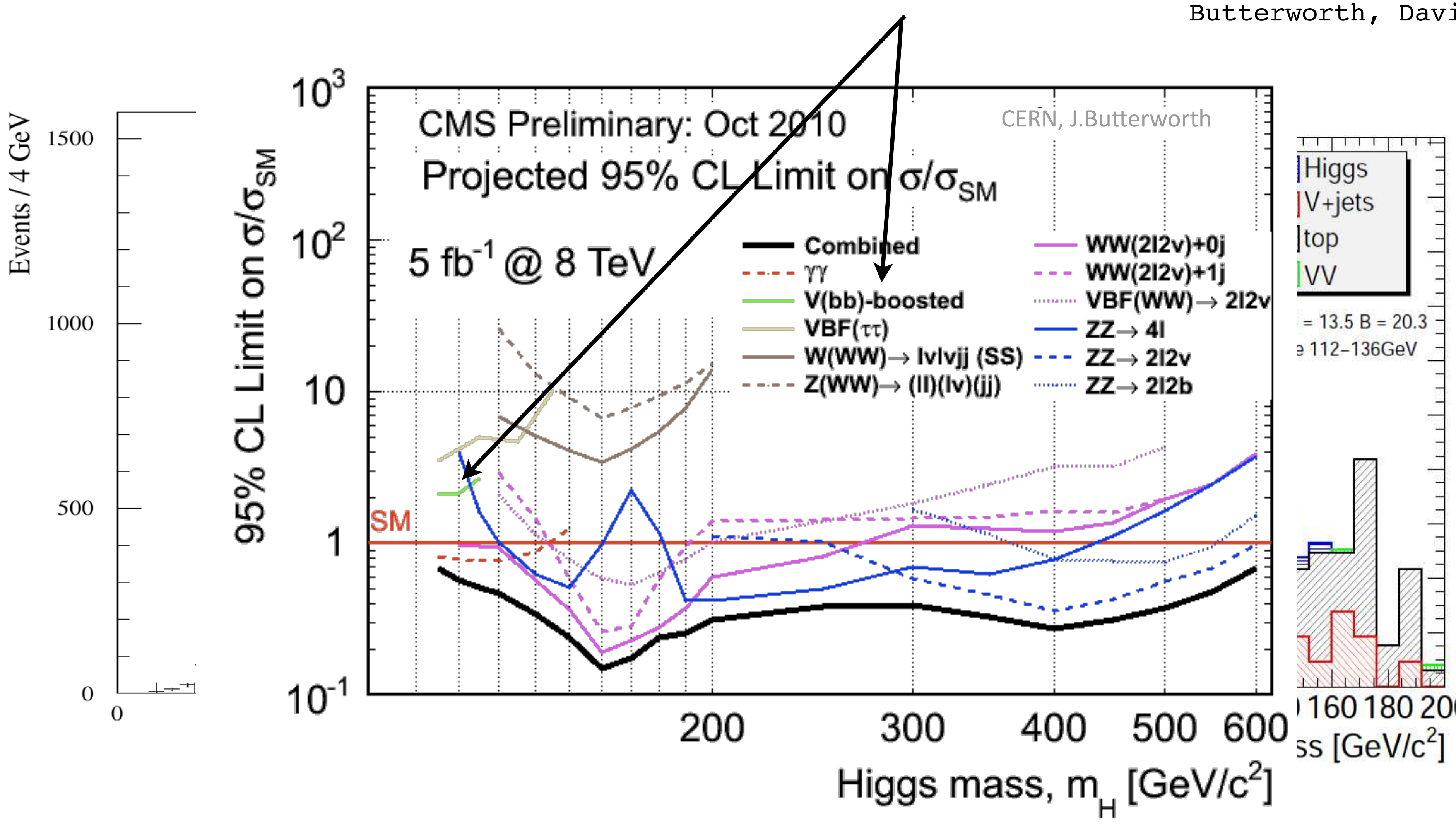
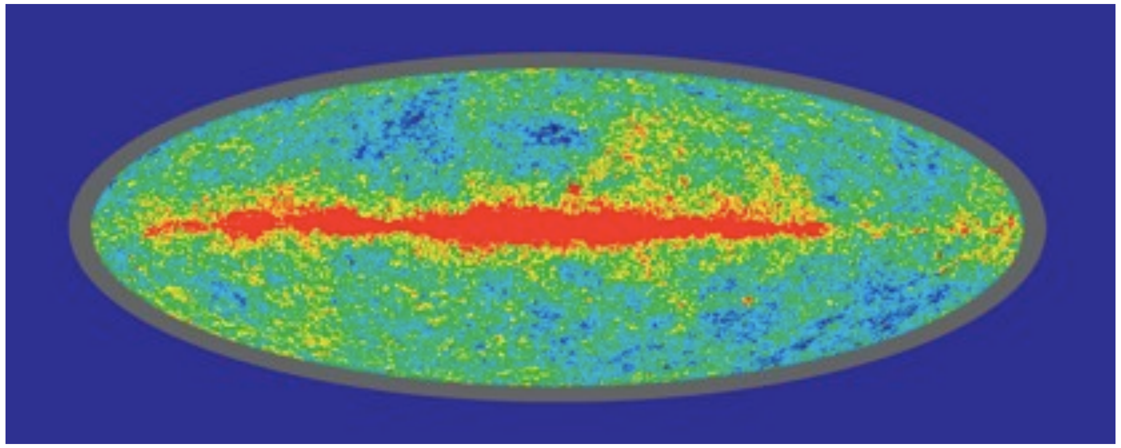
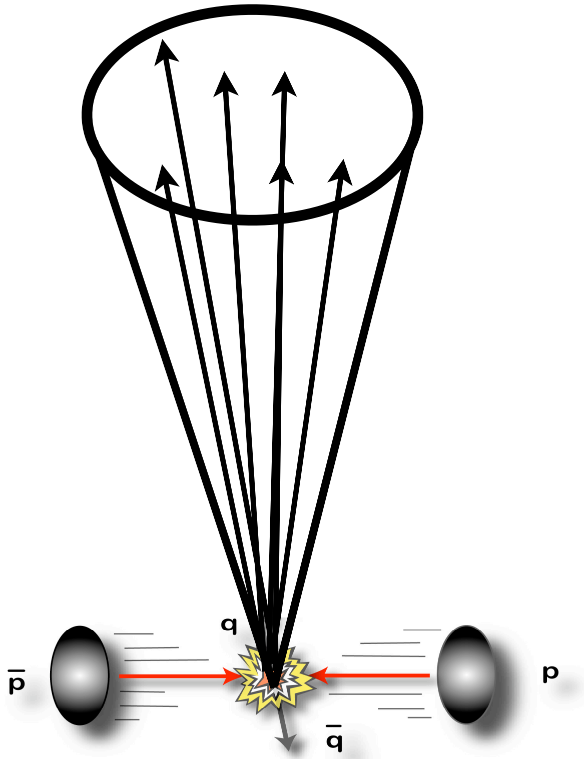


Less competitive than $h \to \gamma\gamma$ but important. (can be improved?)

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





Need to understand the energy flow inside jet
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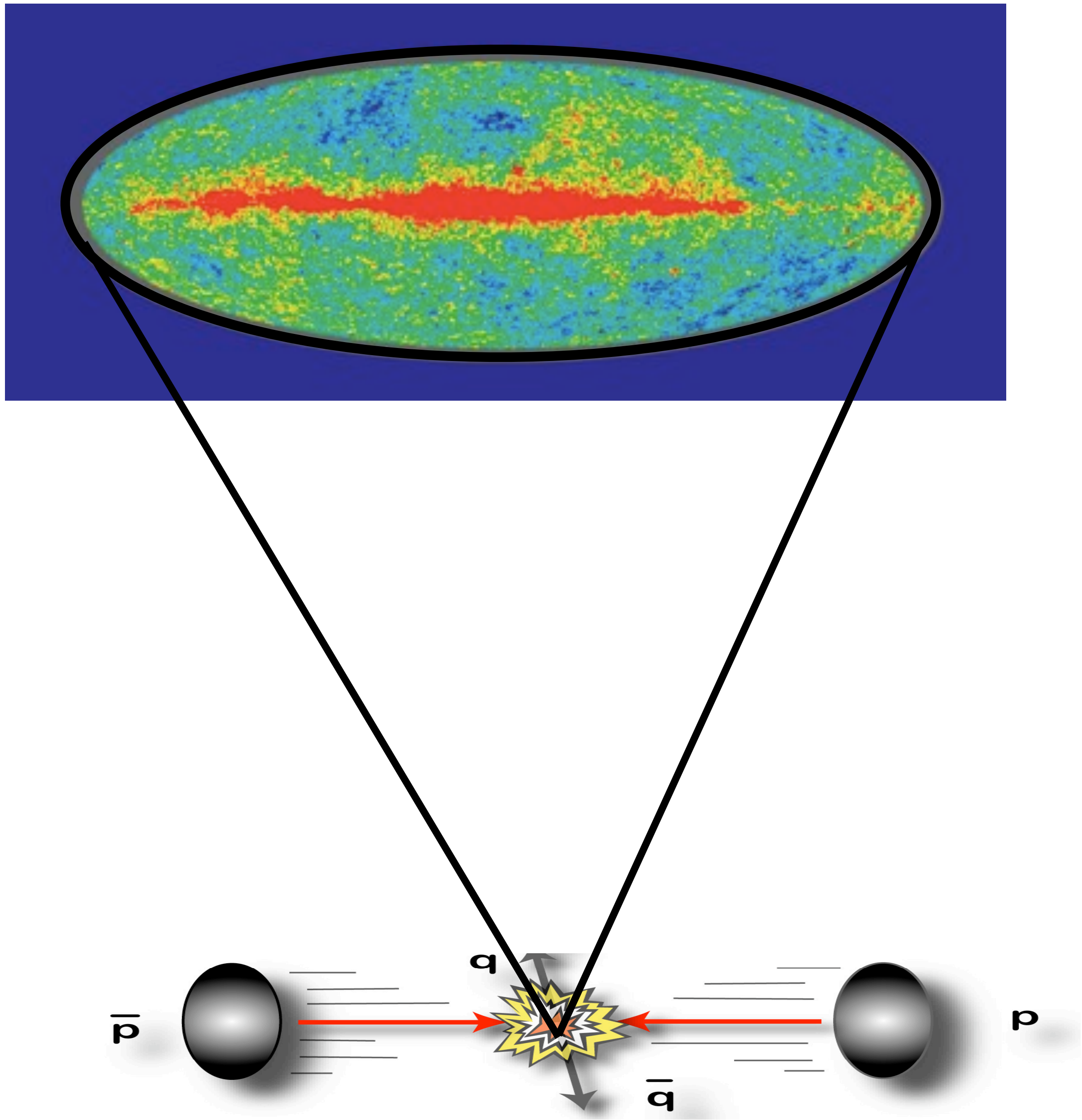
i)Jet Mass

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: $m_J^2 = (\sum_{i \in R} P_i)^2, \; Pi^2 = 0$
- Jet mass is non-trivial both for S & B

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

Jet Mass-Overview

- Jet mass-sum of “massless” momenta in h-cal inside the cone: $m_J^2 = (\sum_{i\in R} P_i)^2, \quad Pi^2 = 0$
- 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 $m^t_J \sim m_t + \delta m_{QCD} + \delta m_{EW}$

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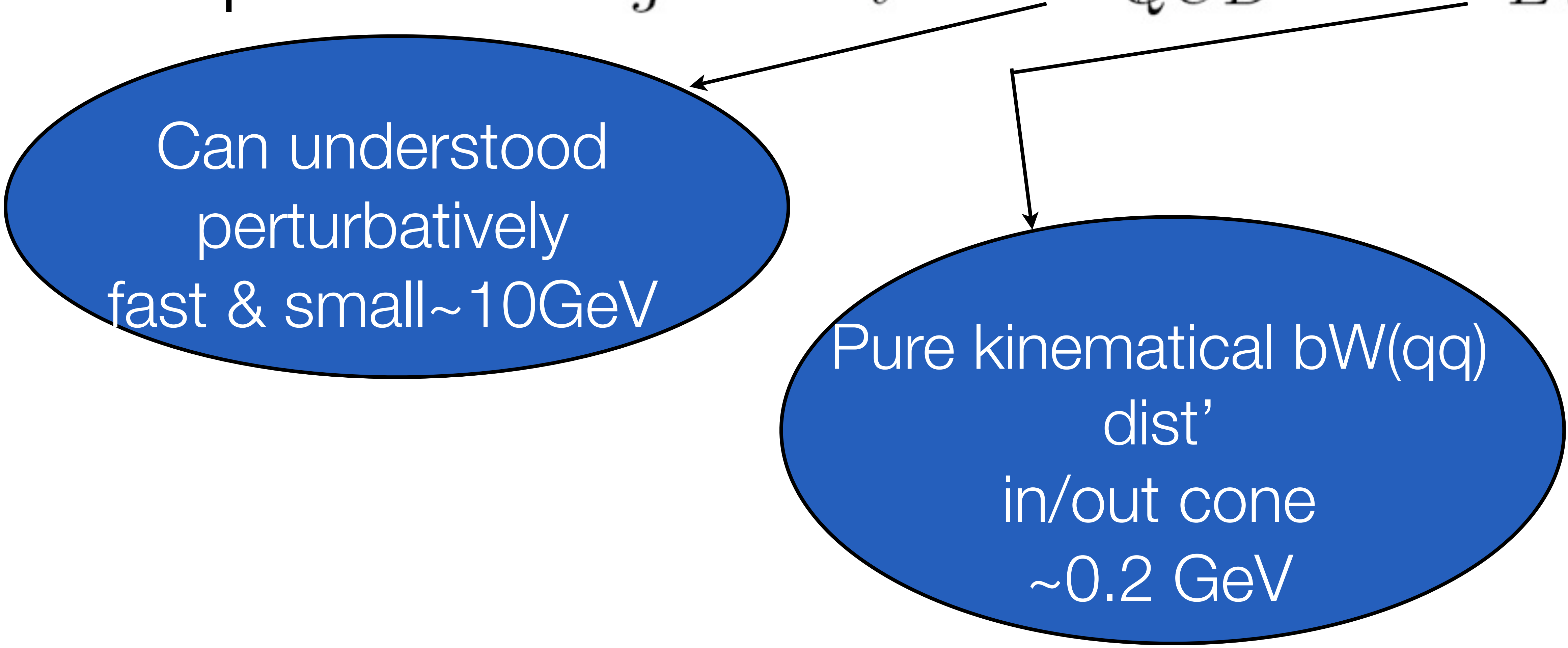

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Pure kinematical bW(qq) dist' in/out cone ~0.2 GeV

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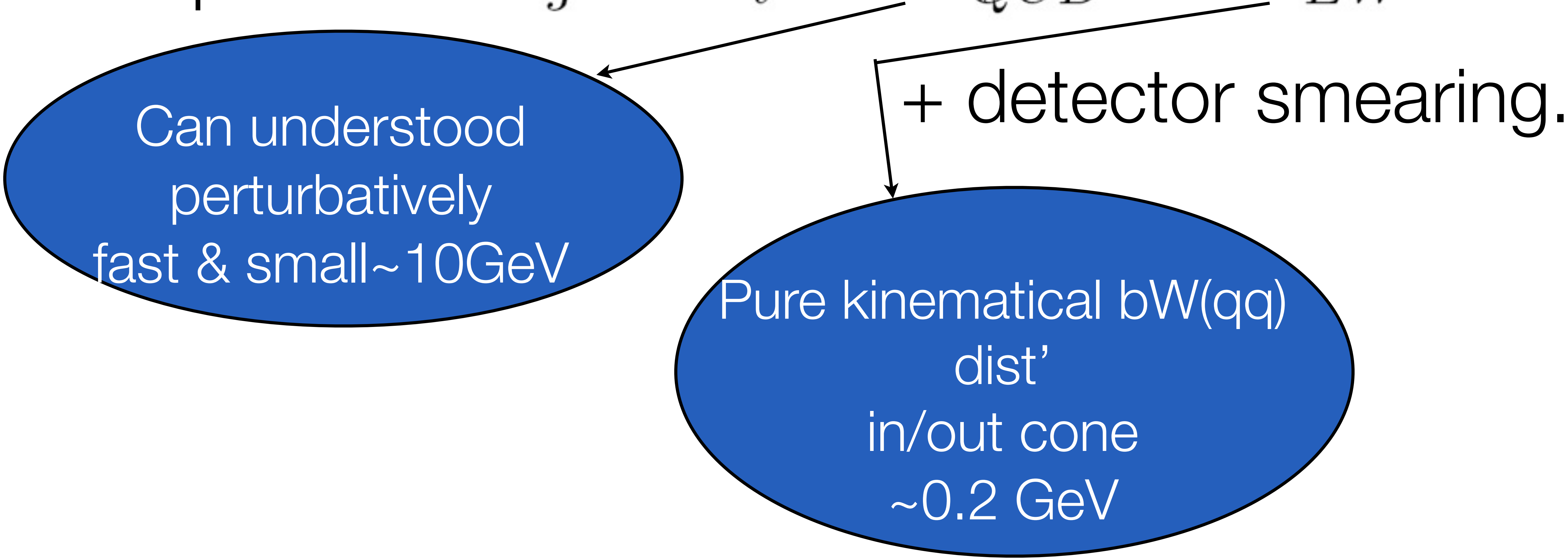

+ detector smearing.

Can understood perturbatively fast & small~10GeV

Pure kinematical bW(qq) dist' in/out cone ~0.2 GeV

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)
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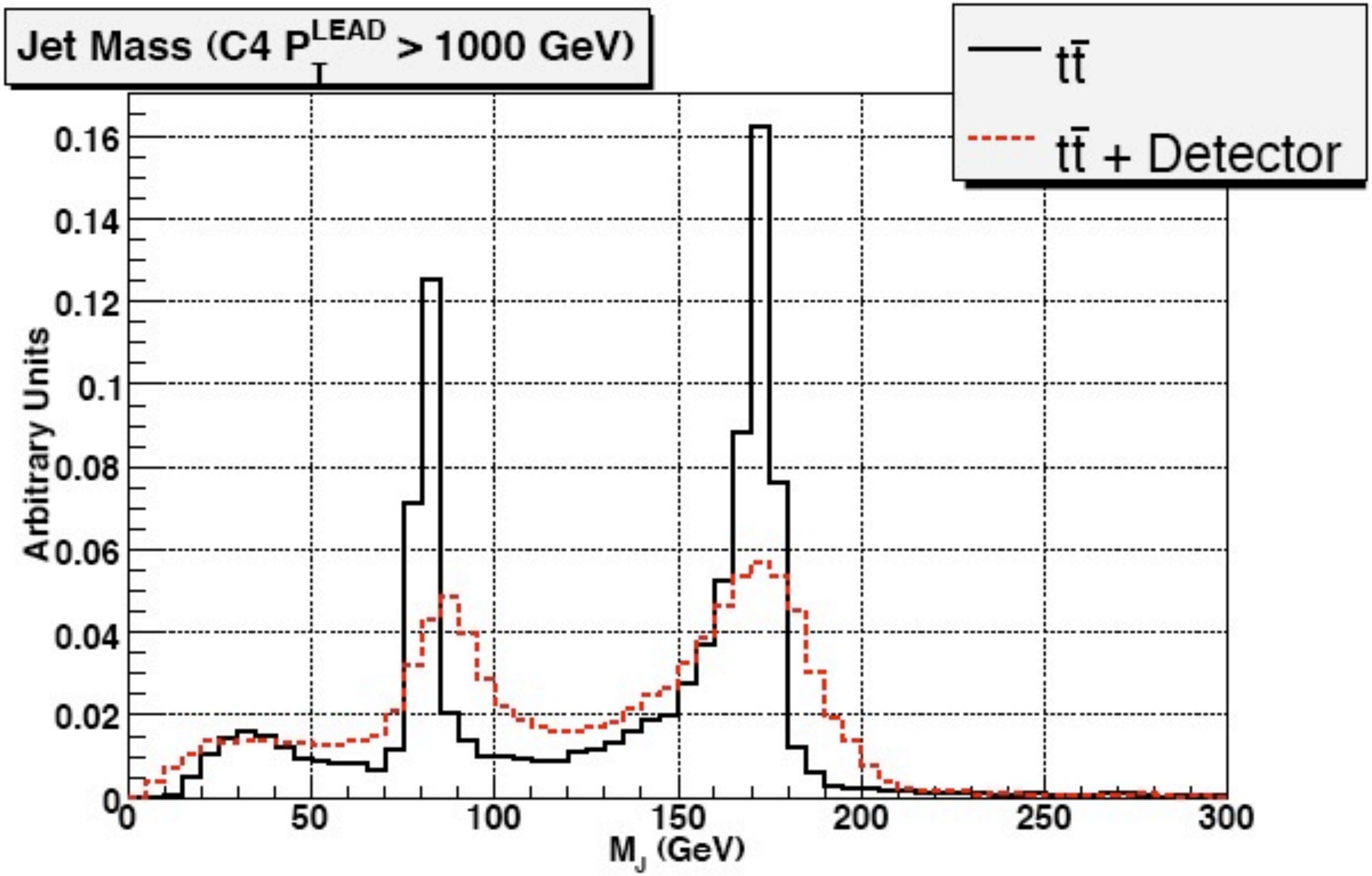
(Fleming, Hoang, Jain, Mantry, Scimemi, Stewart) Almeida, SL, Perez Sung, & Virzi.

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 p_T to acquire a mass between m_J and $m_J + \delta m_J$

Full expression:

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

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

QCD jet mass distribution

✦Boosted QCD Jet via factorization:

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

$$\int dm_J$$

$$i = Q, G$$

- 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:

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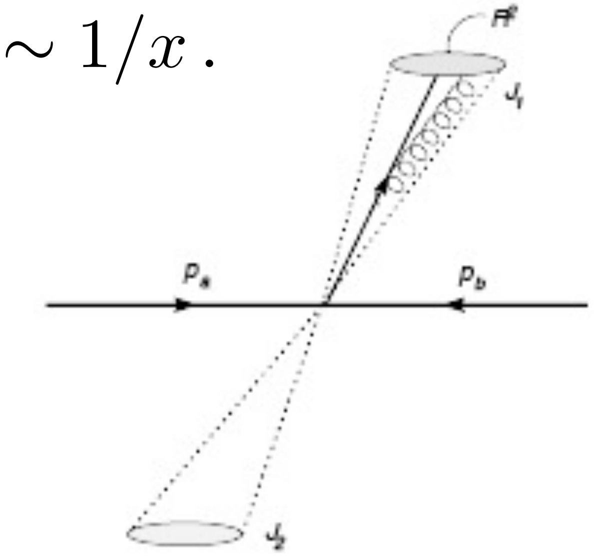
Energy dist' massive jets, splitting function

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 $P_{ij} \sim 1/x\,.$



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

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

QCD jet mass distribution, Q+G

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

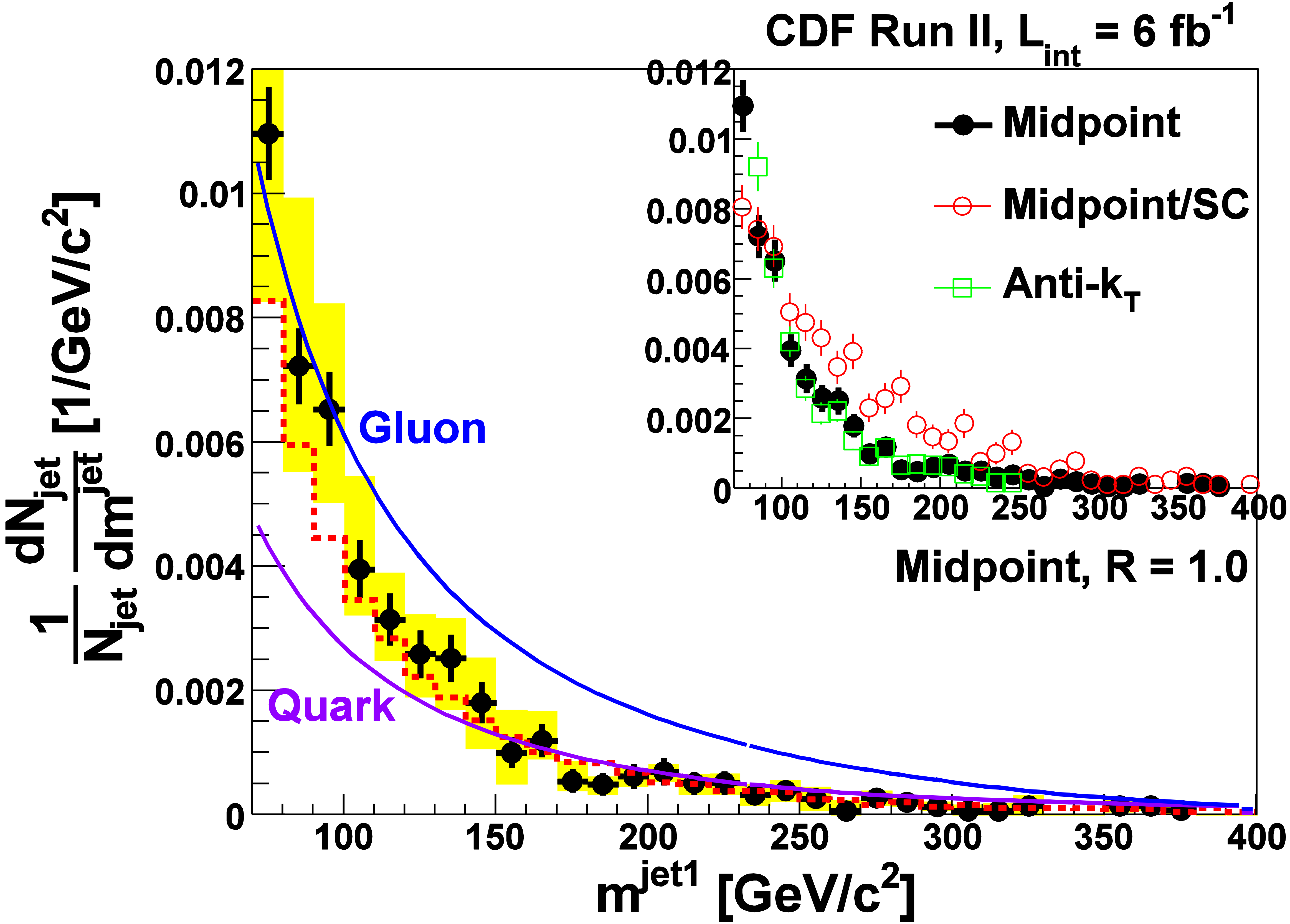
$C_F = 4/3$ for quarks, $C_A = 3$ for gluons.

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

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

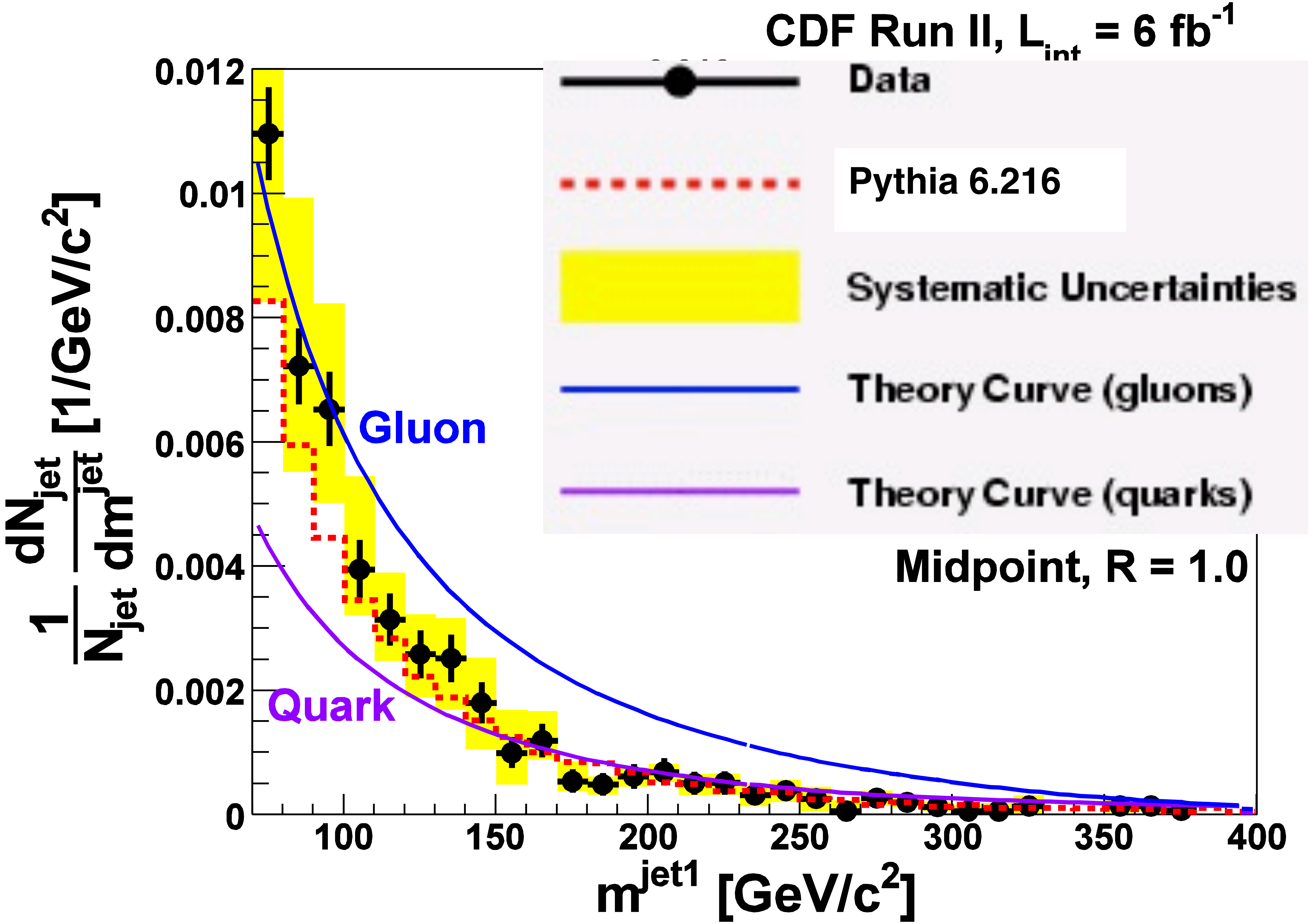
$$\left.\frac{d\sigma_{pred}(R)}{dp_T dm_J}\right._{lower\ bound} = J^q\left(m_J, p_T, R\right) \sum_c \left(\frac{d\sigma^c\left(R\right)}{dp_T}\right)_{\mathrm{MC}},$$

Jet mass distribution @ CDF



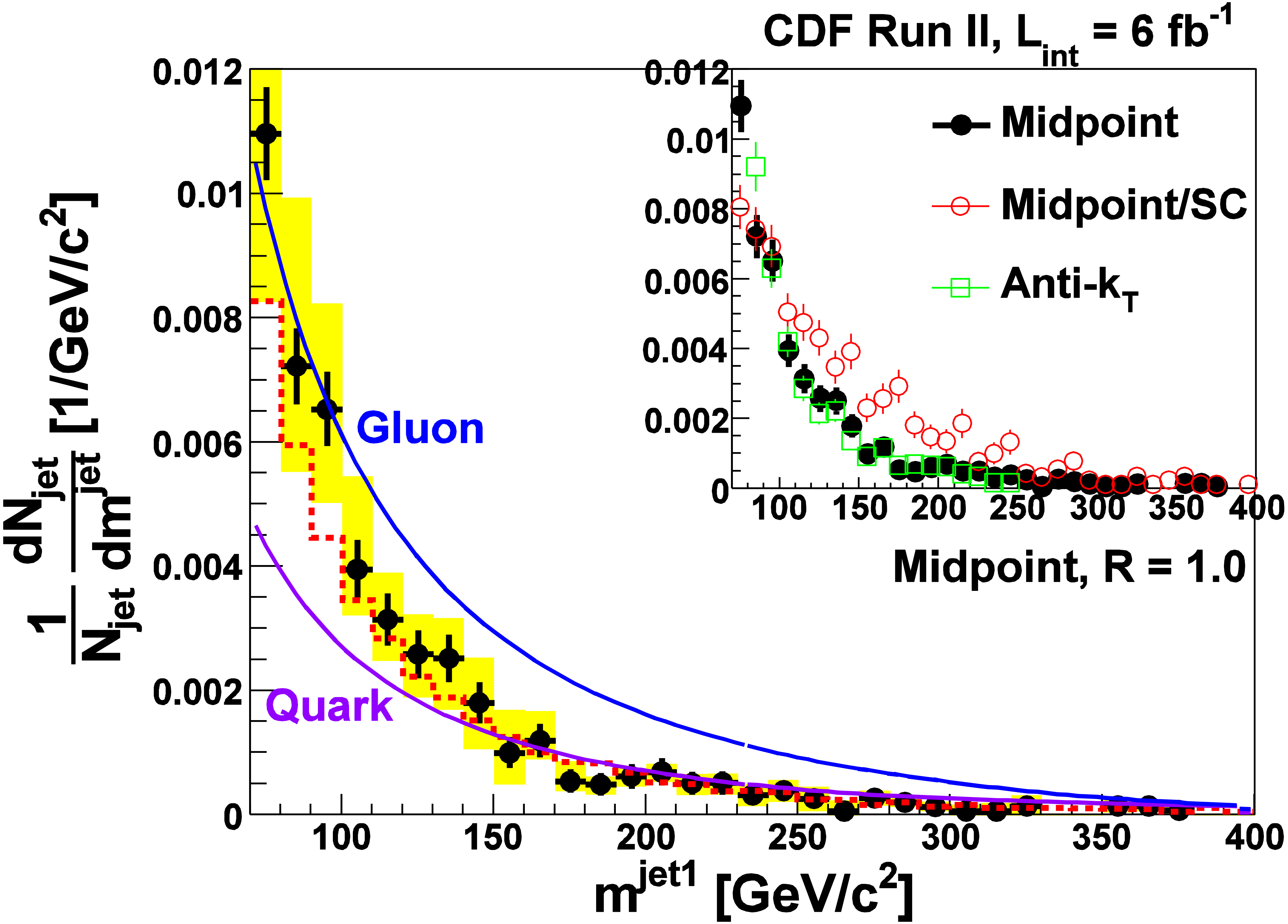
ATLAS-CONF-2011-073 & CMS PAS EXO-11-006.

Jet mass distribution @ CDF



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

Jet mass distribution @ CDF



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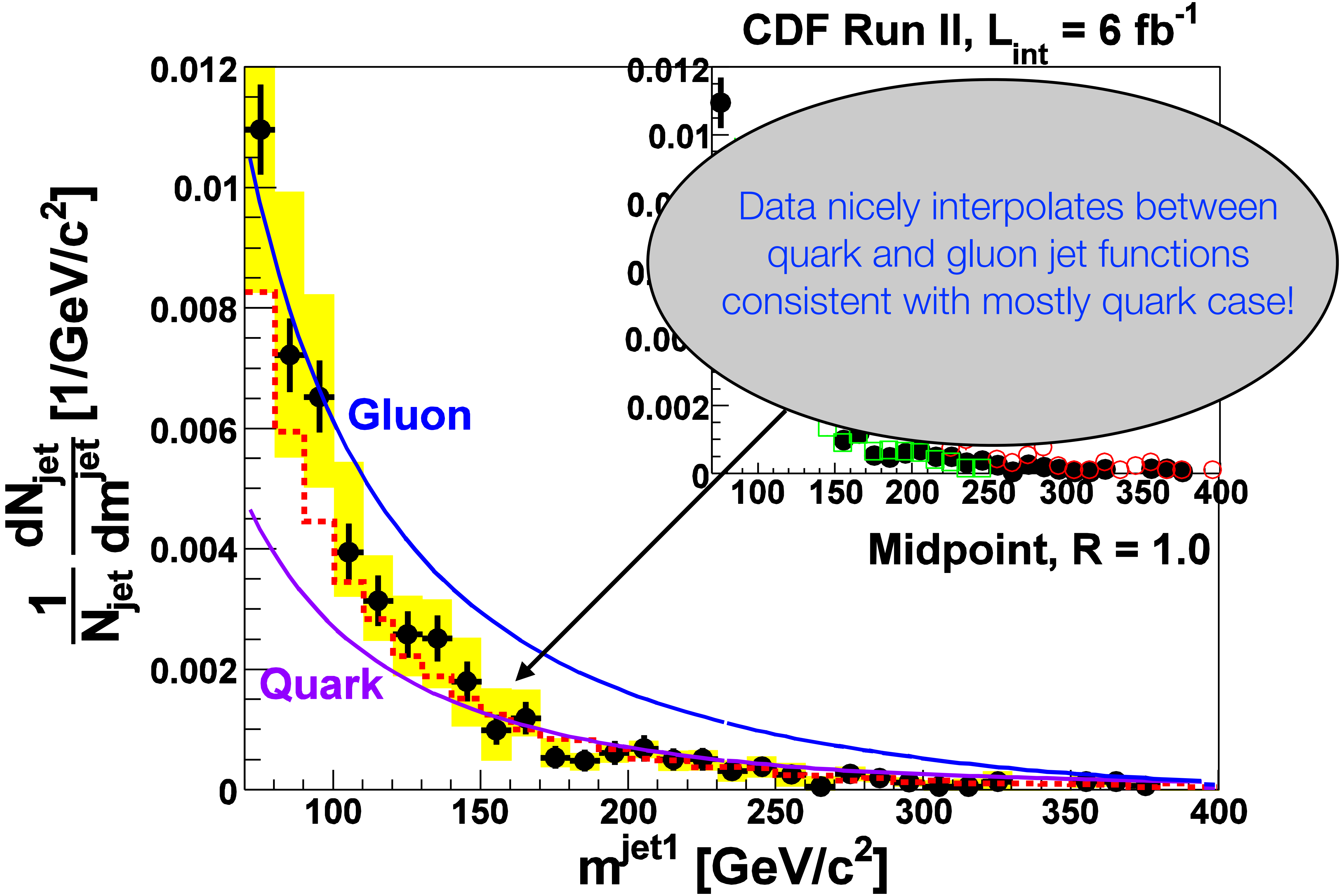
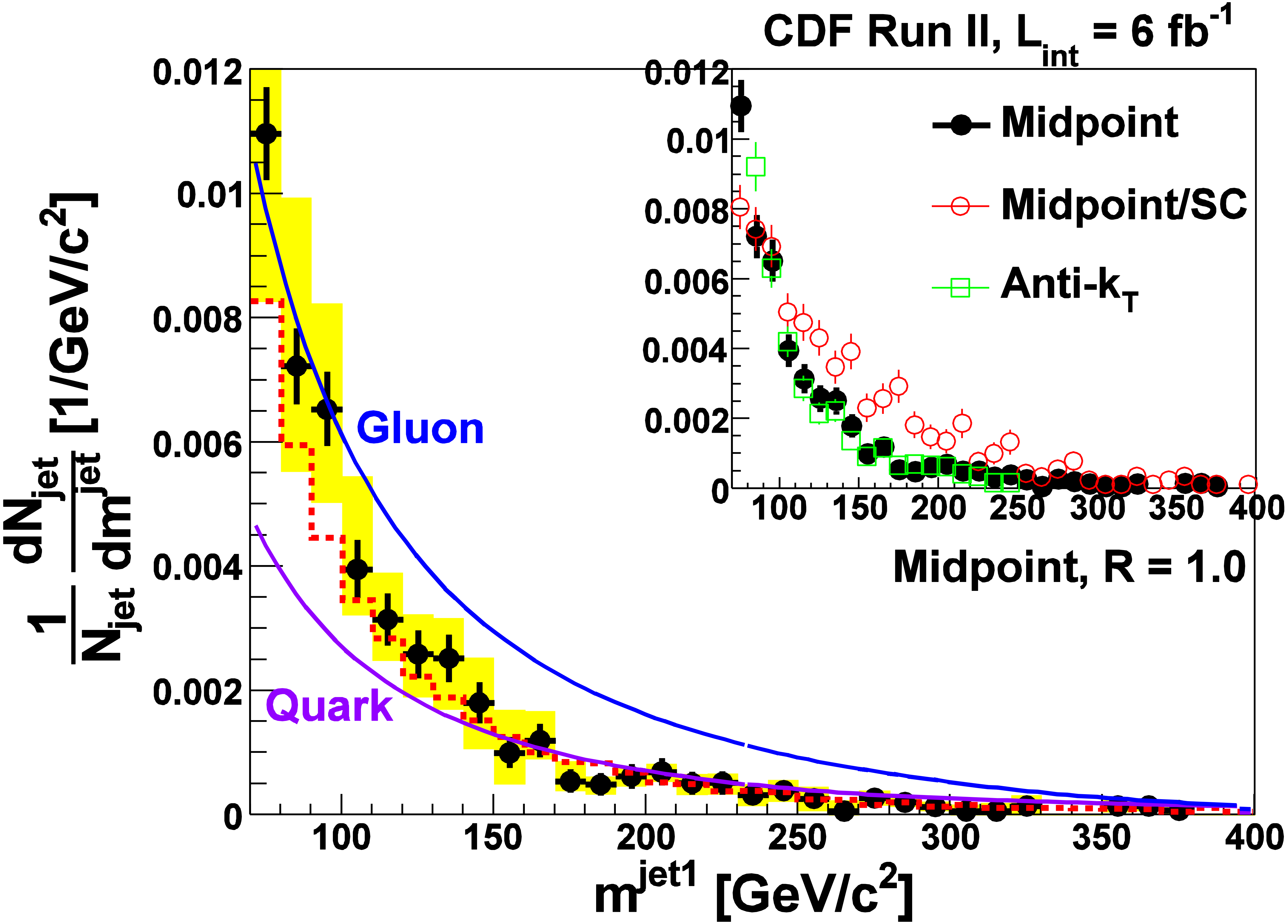


Data nicely interpolates between quark and gluon jet functions consistent with mostly quark case!

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

Jet mass distribution @ CDF



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).

$$\tau_{-2} \sim \frac{1}{m}\sum_{i\in J} E_i\theta_i^4 \qquad \Longrightarrow \qquad \begin{array}{l} \text{QCD:} \propto \frac{1}{\tau_{-2}} \\ h\text{:} \ \propto \frac{1}{\tau_{-2}^2} \end{array}$$

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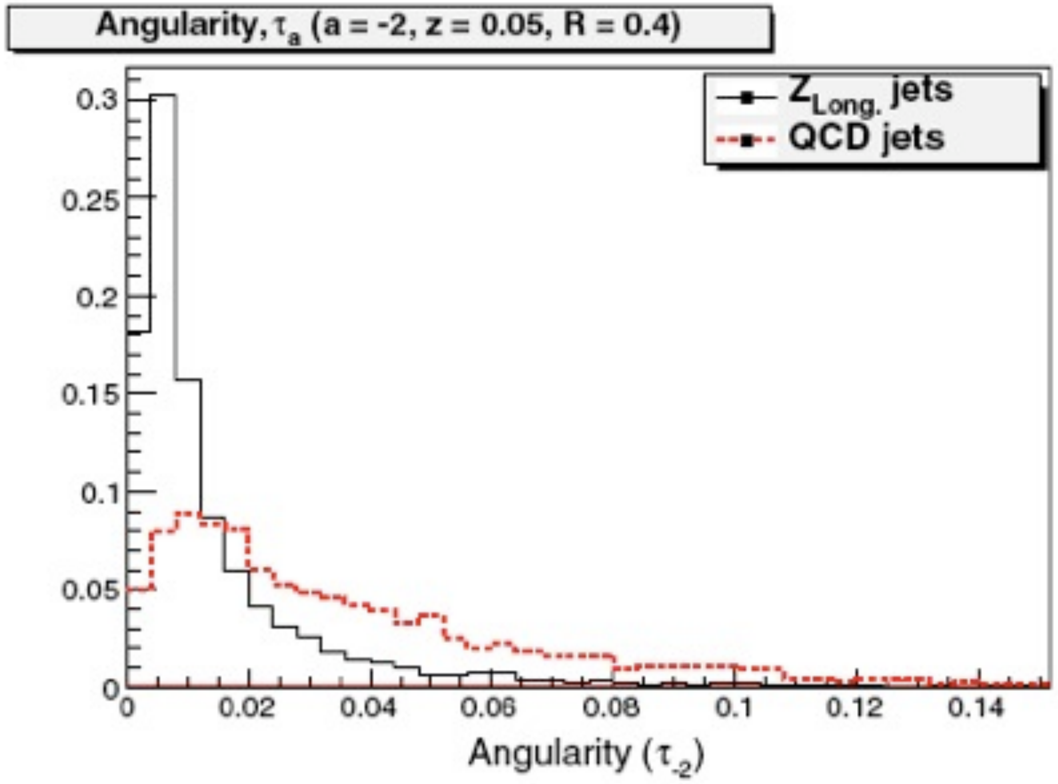
after fixing mass - signal & backgroun dist' are similar in shape !

θ_i^4



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.

$\frac{1}{-2}$

Almeida, SL, Perez, Sterman & Sung.

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➡

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

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

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

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

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

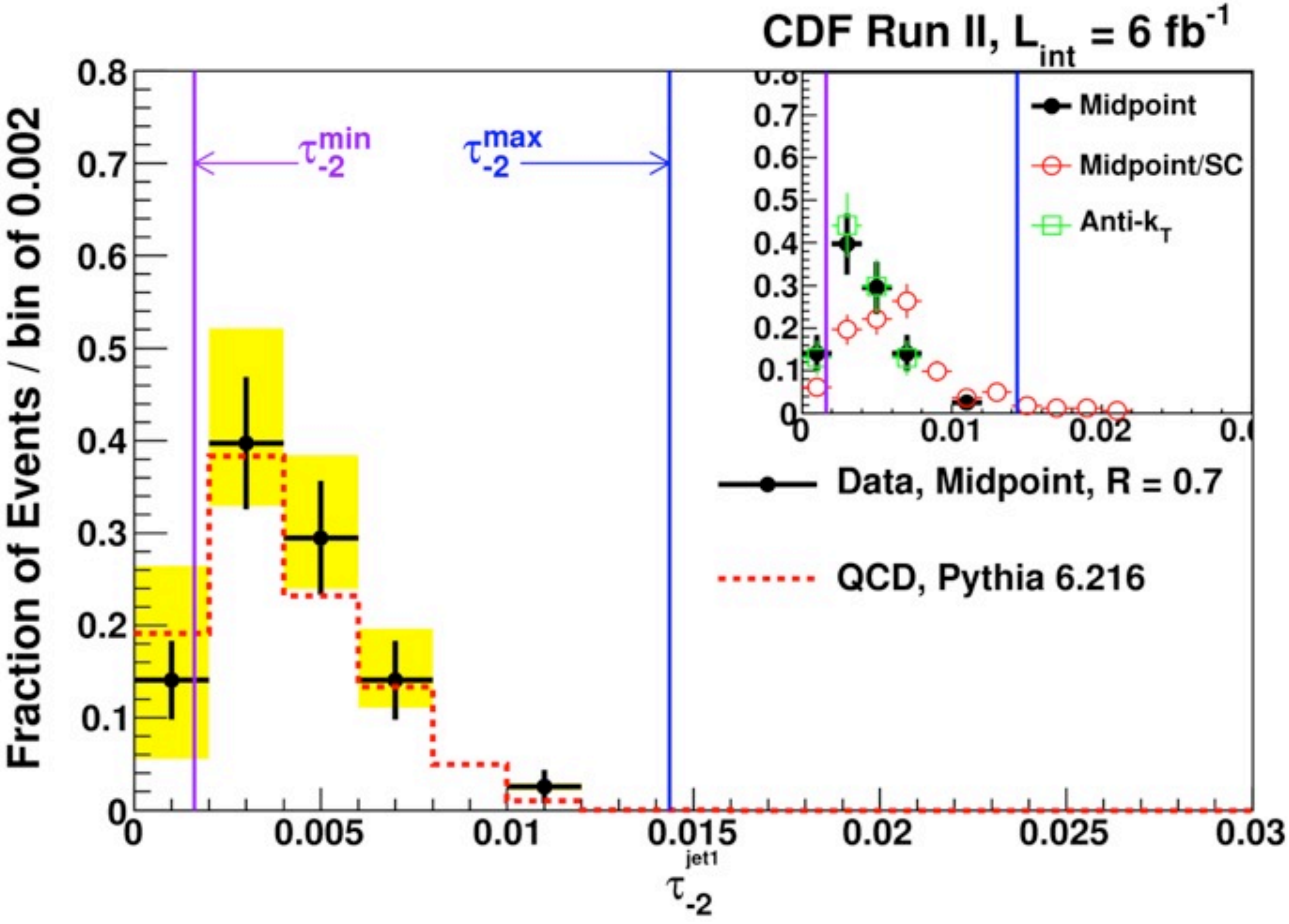
`Almeida, SL, Perez, Stermam & Sung, PRD (10).`

Beyond mass, higher moments, angularity (2 body)

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

varia

RD (09).



Angularity for jets with mass ∈ (90, 120) GeV/c^2, 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

τ_-

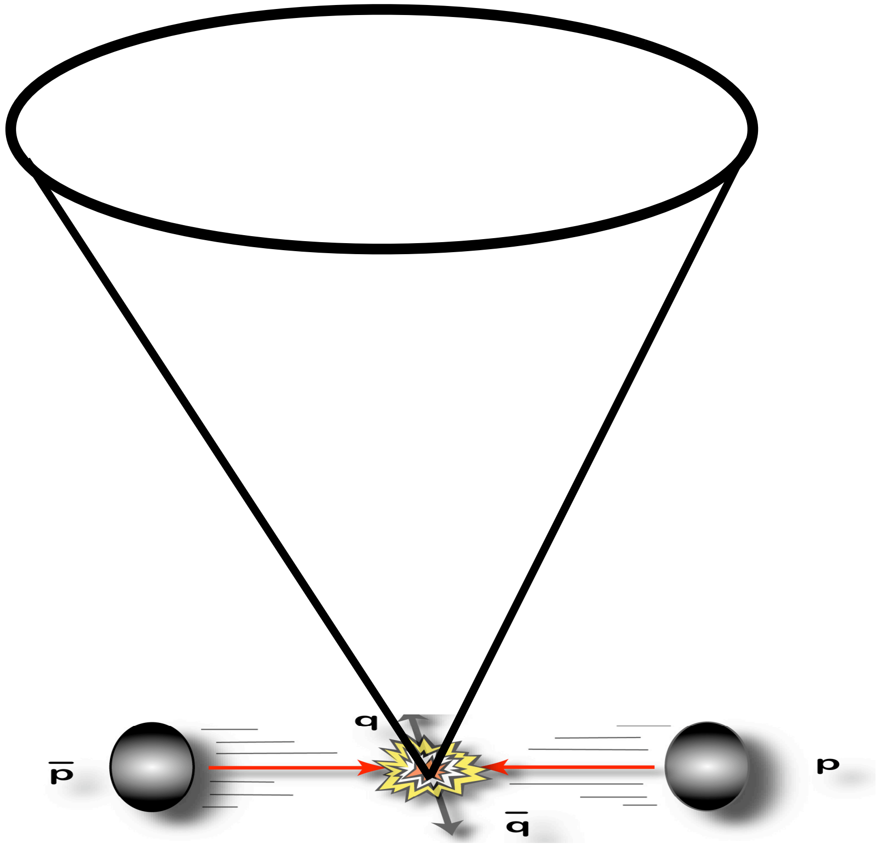
- If

:

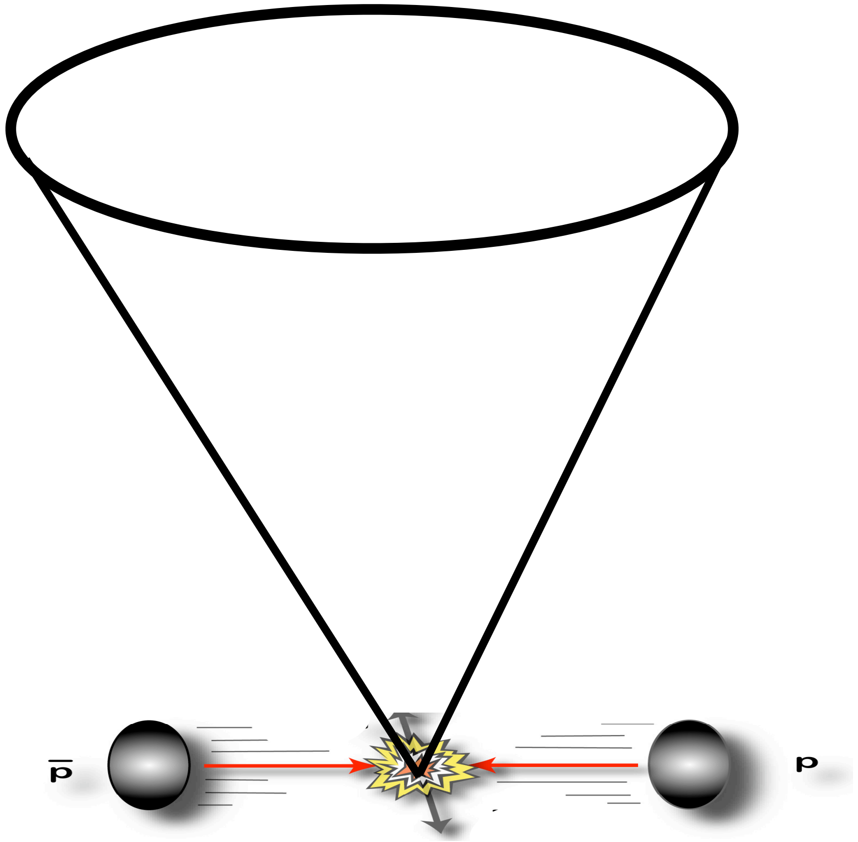
(10).

Planar Flow

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



QCD massive jet



top jet

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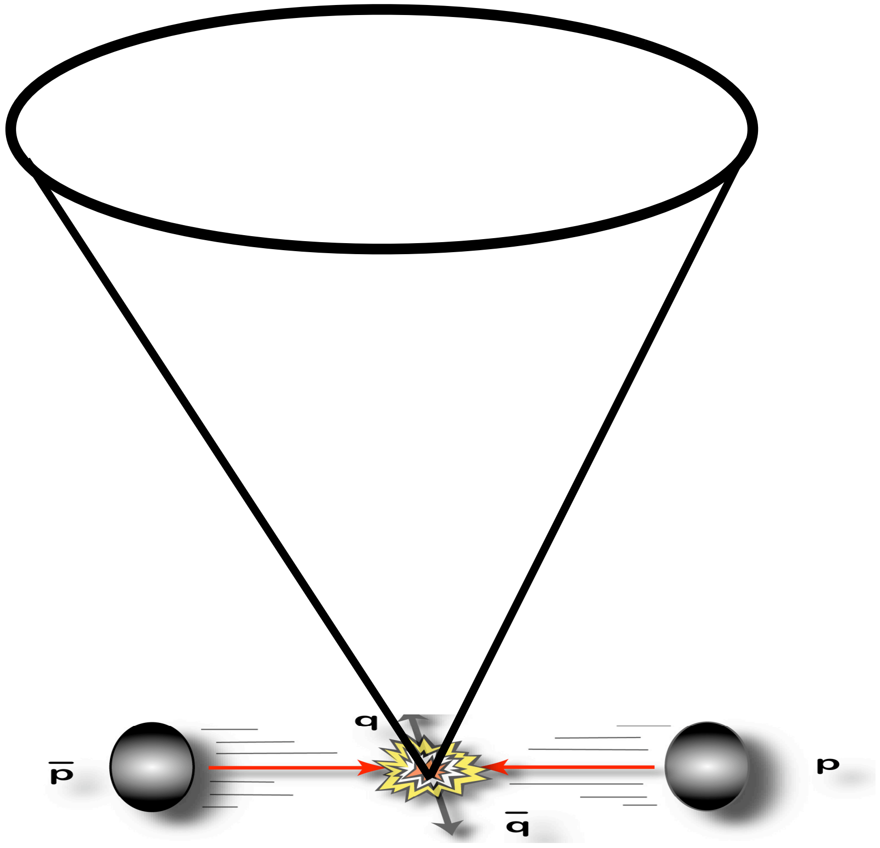

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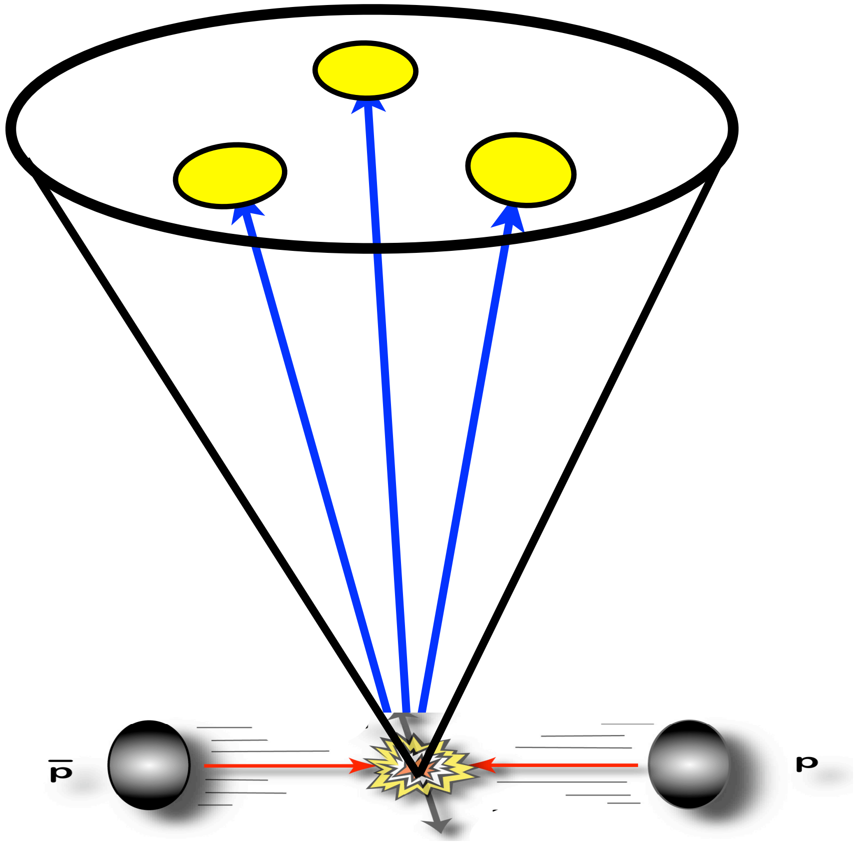

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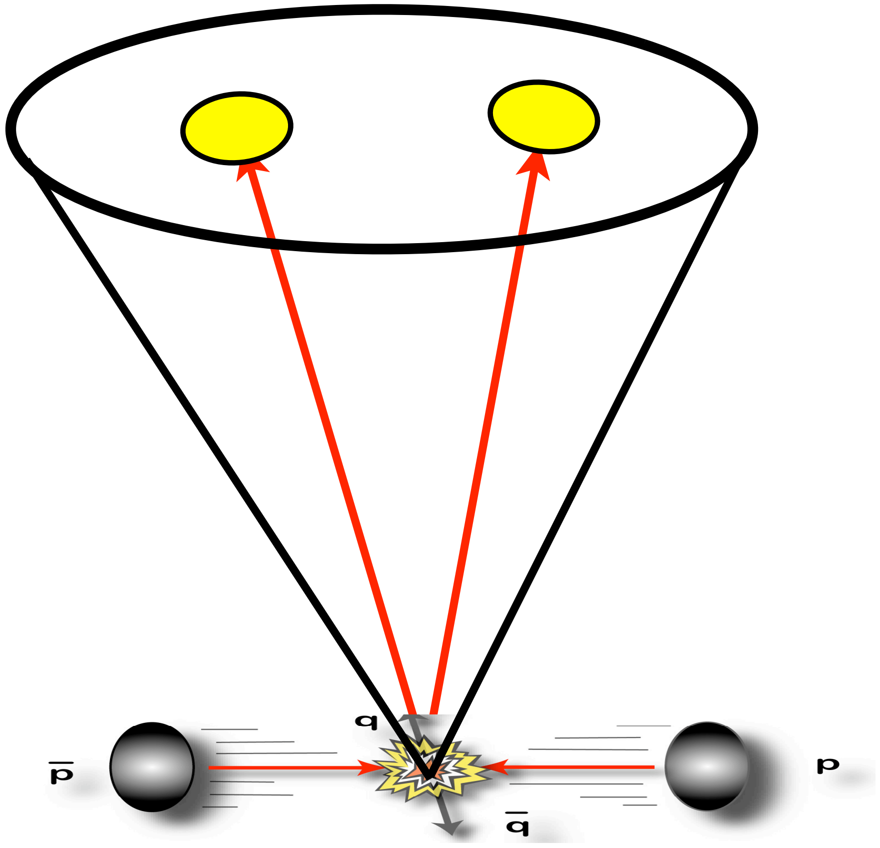

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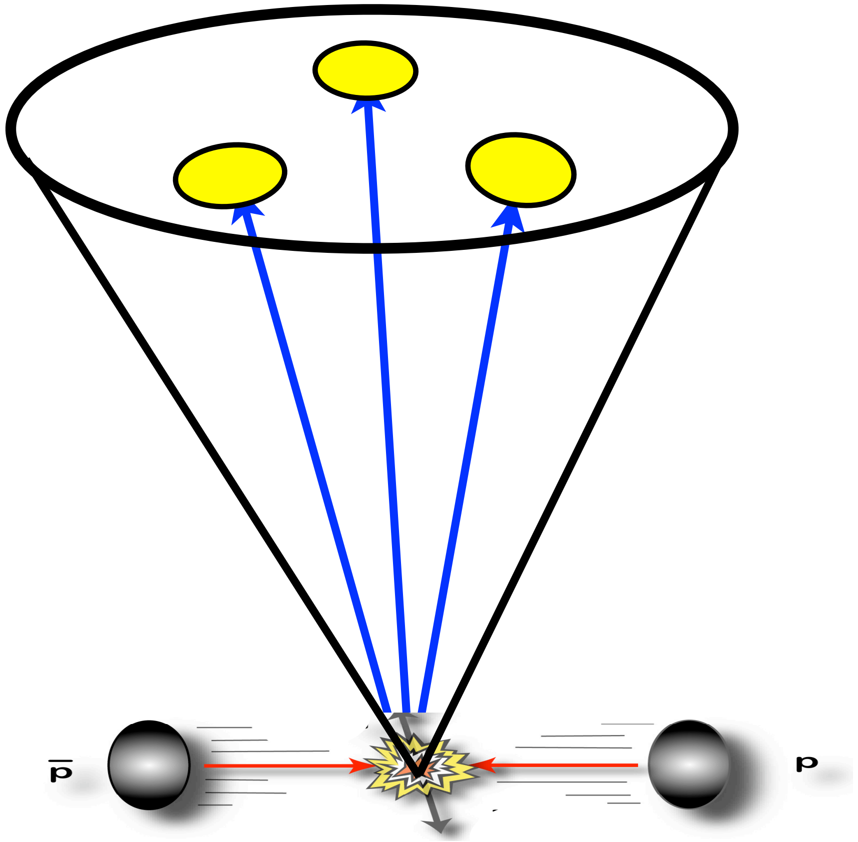


top jet

Planar flow

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

`Thaler & Wang, JHEP (08);`
`Almeida, SL, Perez, Stermam, Sung & Virzi, PRD (09).`

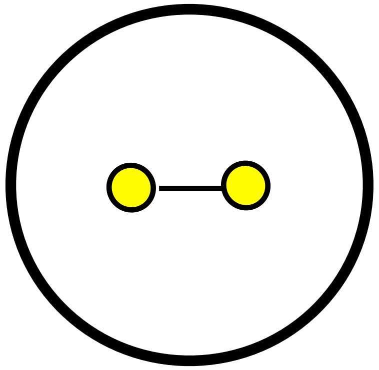
- Planar flow, *Pf*, measures the energy ratio between two primary axes of cone surface:

(i) "moment of inertia":

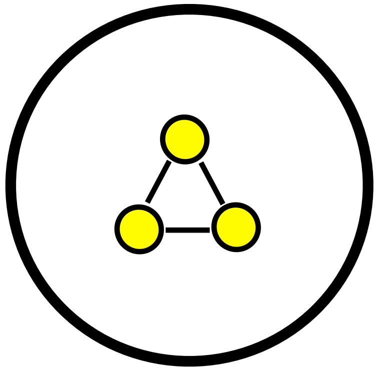
$$I_E^{kl} = \frac{1}{m_J} \sum_{i \in R} E_i \frac{p_{i,k}}{E_i} \frac{p_{i,l}}{E_i} \,,$$

(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*

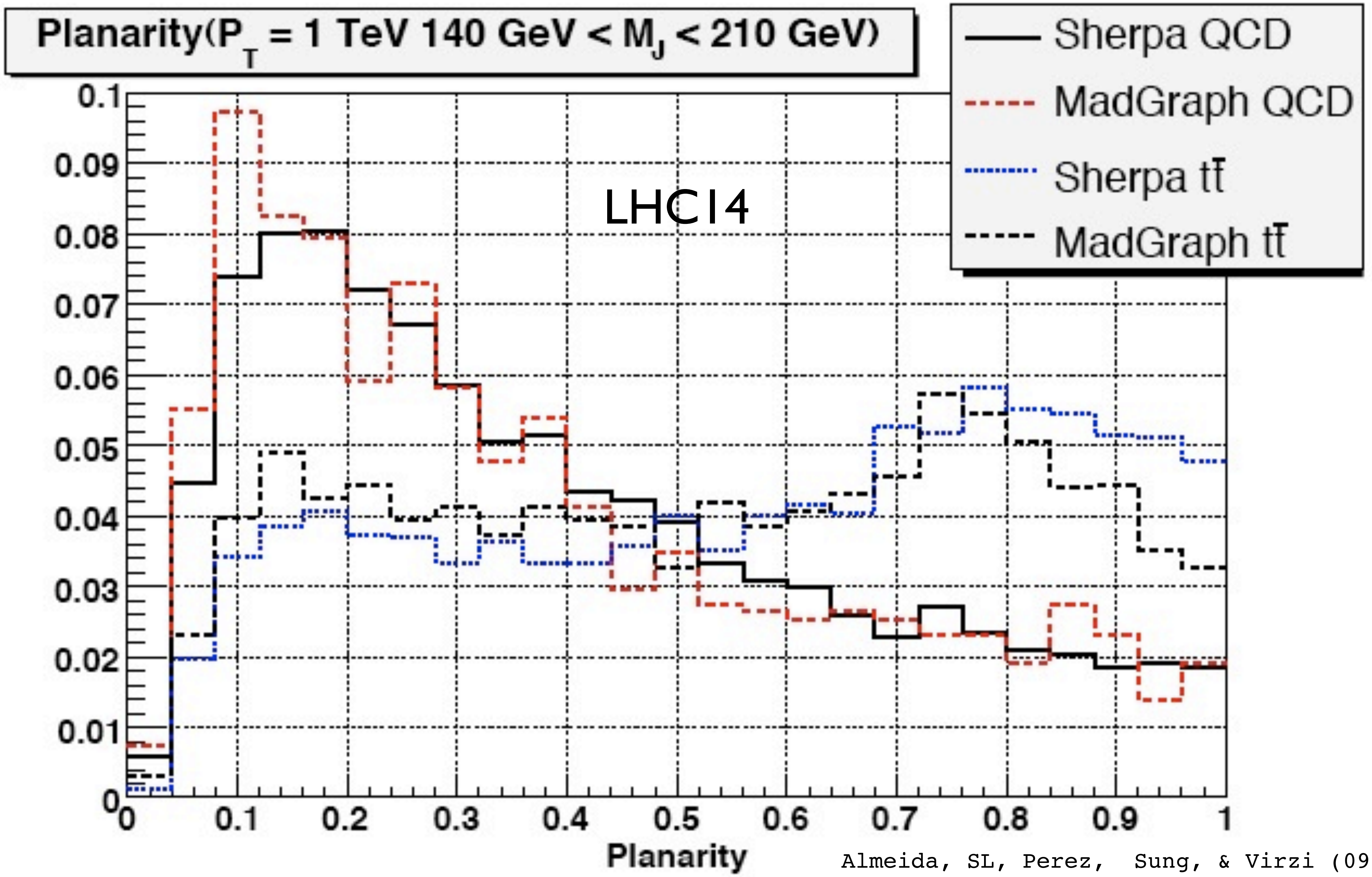
Planar flow

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

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

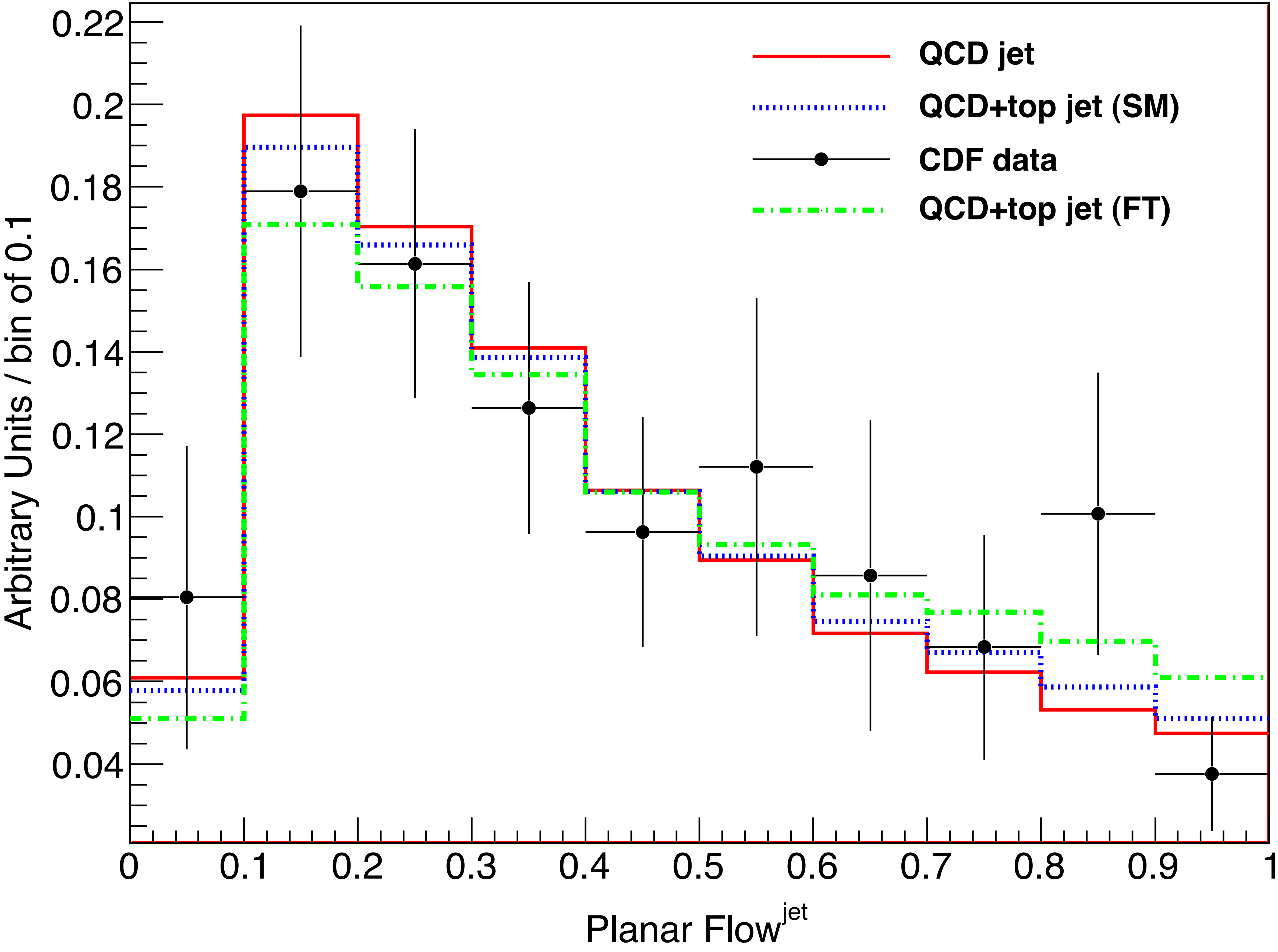
- Pla

wo



Almeida, SL, Perez, Sung, & Virzi (09)

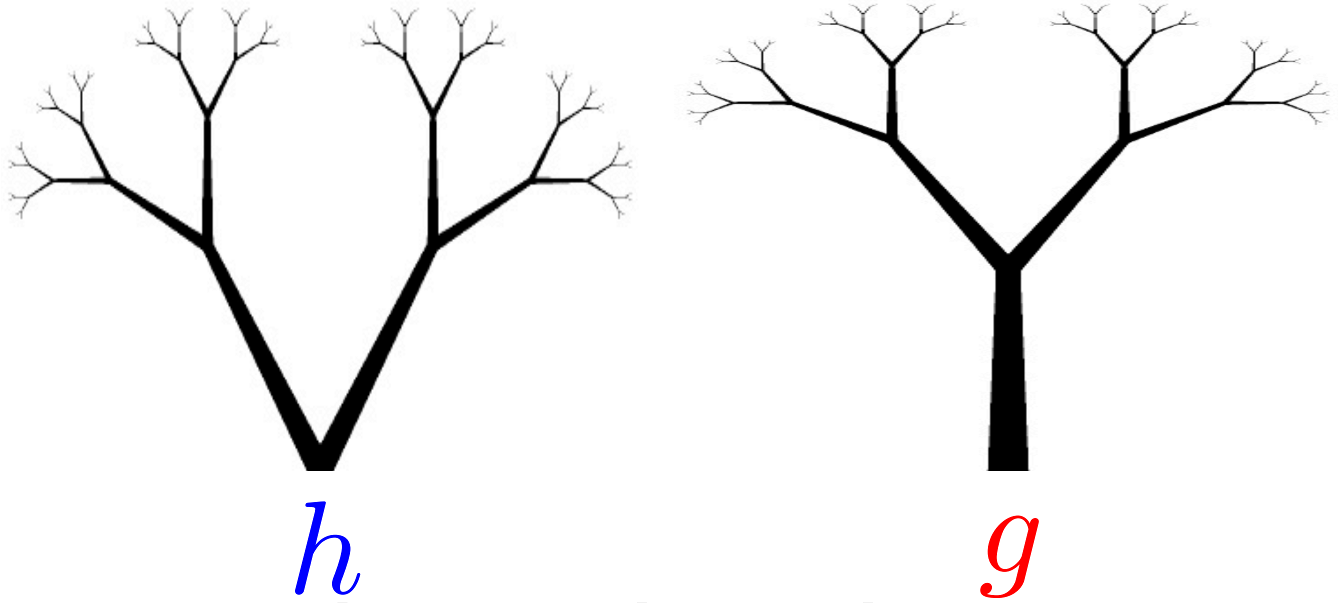
Planar flow



sult)

RD (09).

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); Soper & Spannowsky (10,11)

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

  Recently: Almeida, SL, Perez, Sterman, Sung & Virzi; Thaler & Wang (08); Thaler & Tilburg (10), 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 (11)

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"

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

Template Overlap Method

- **Template overlaps**: functional measures that quantify how well the energy flow of a physical jet matches the flow of a bo

$$|f\rangle = \frac{1}{N}\left(|t\rangle - \langle t|g\rangle |g\rangle\right)$$

infinite rejection power? ☺

|j>=set of particles or calorimete
|j>=|t>,|g>,etc, where:

$|t>$ = top distr
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Lunch table discussion with Juan Maldacena

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

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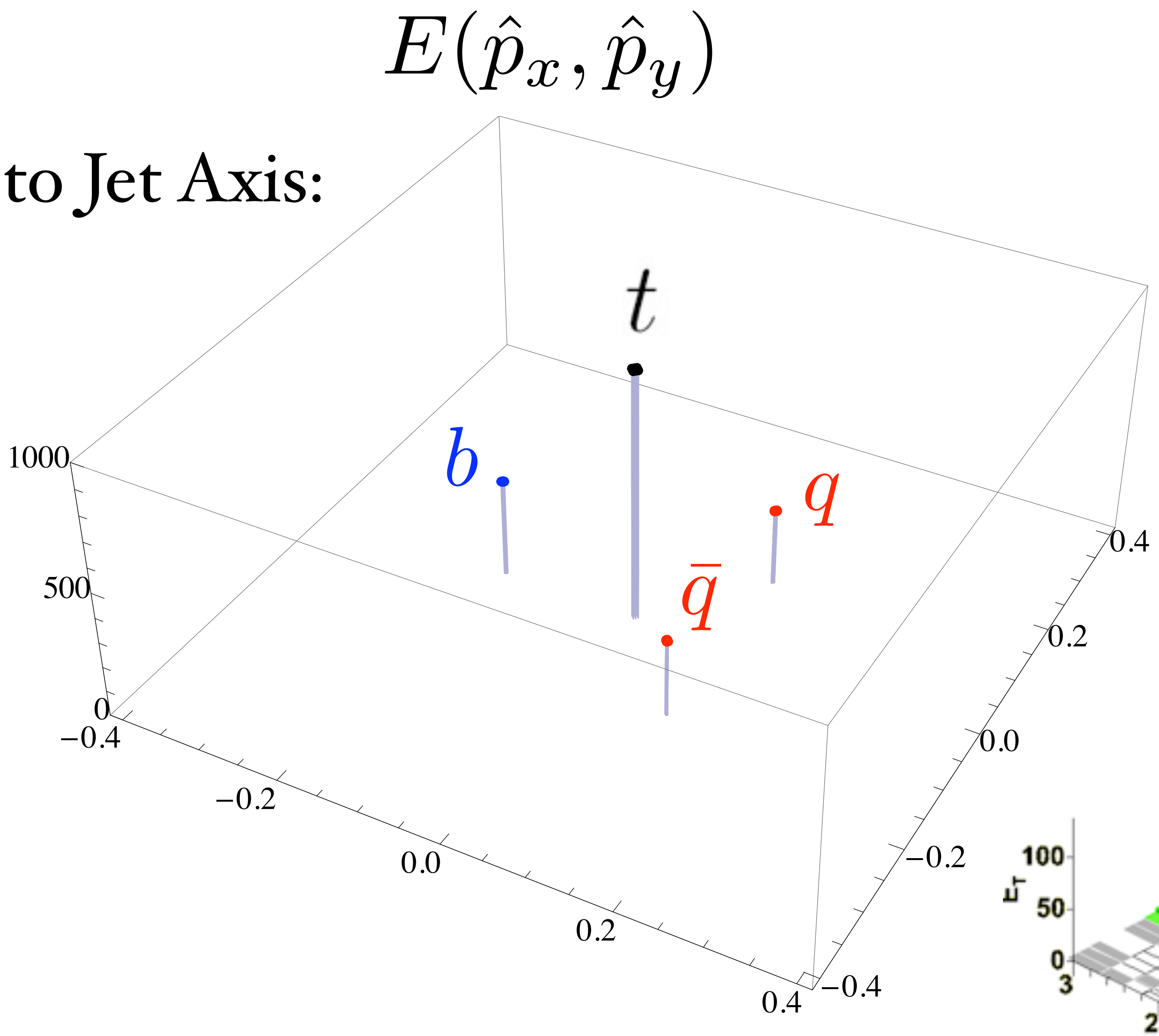
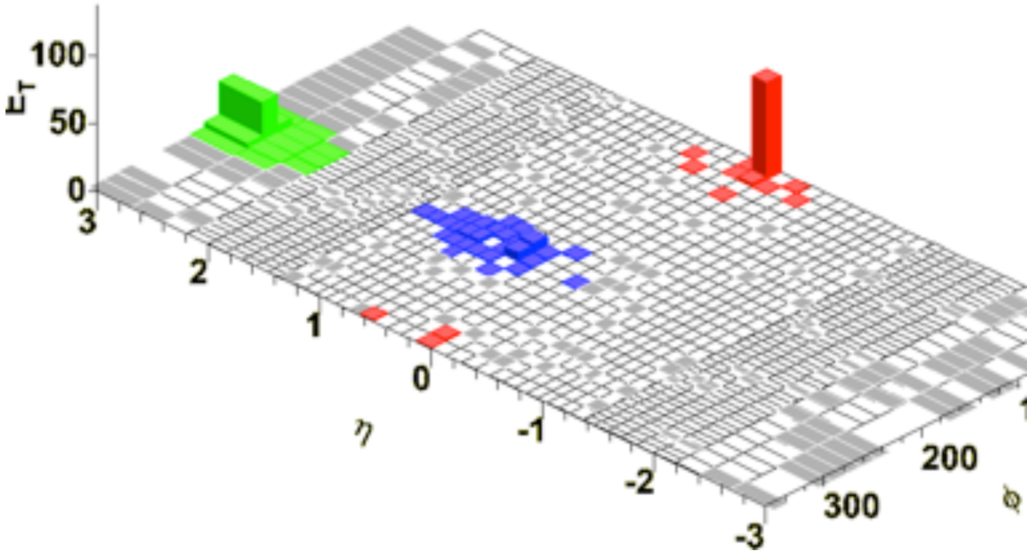
$$R = \left(\frac{<f|t>}{<f|g>}\right) \text{ is maximized.}$$

Example: The Golden Triangle

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

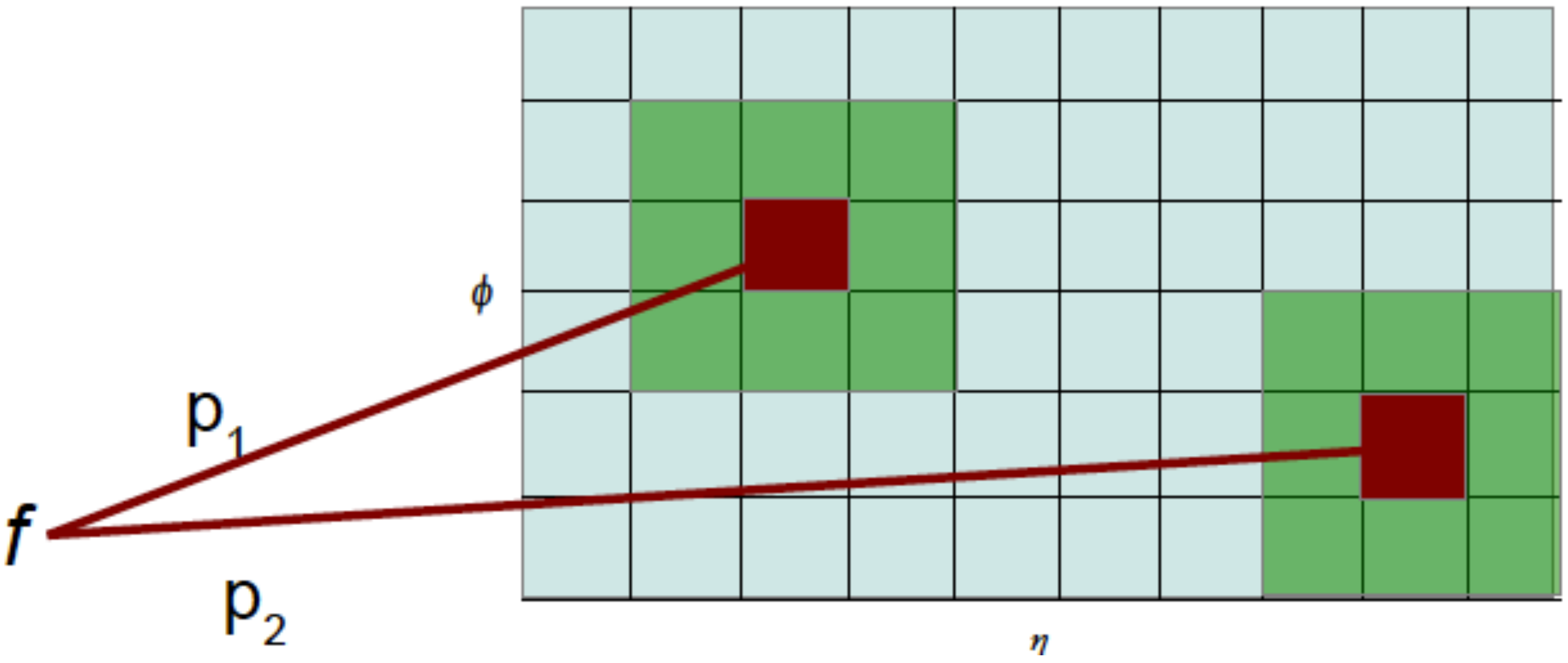
- For a given template, with direction of particle a, n_a and its energy $E_a^{(f)}$:

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

Two-particle Templates and Higgs Decay

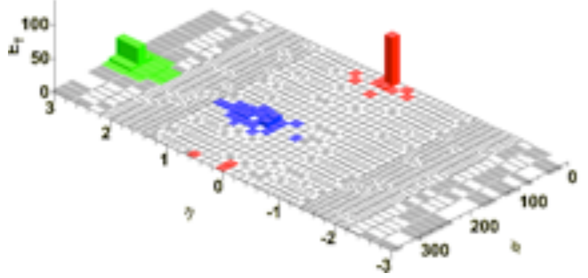
- Template Overlap with data discretization

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



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.

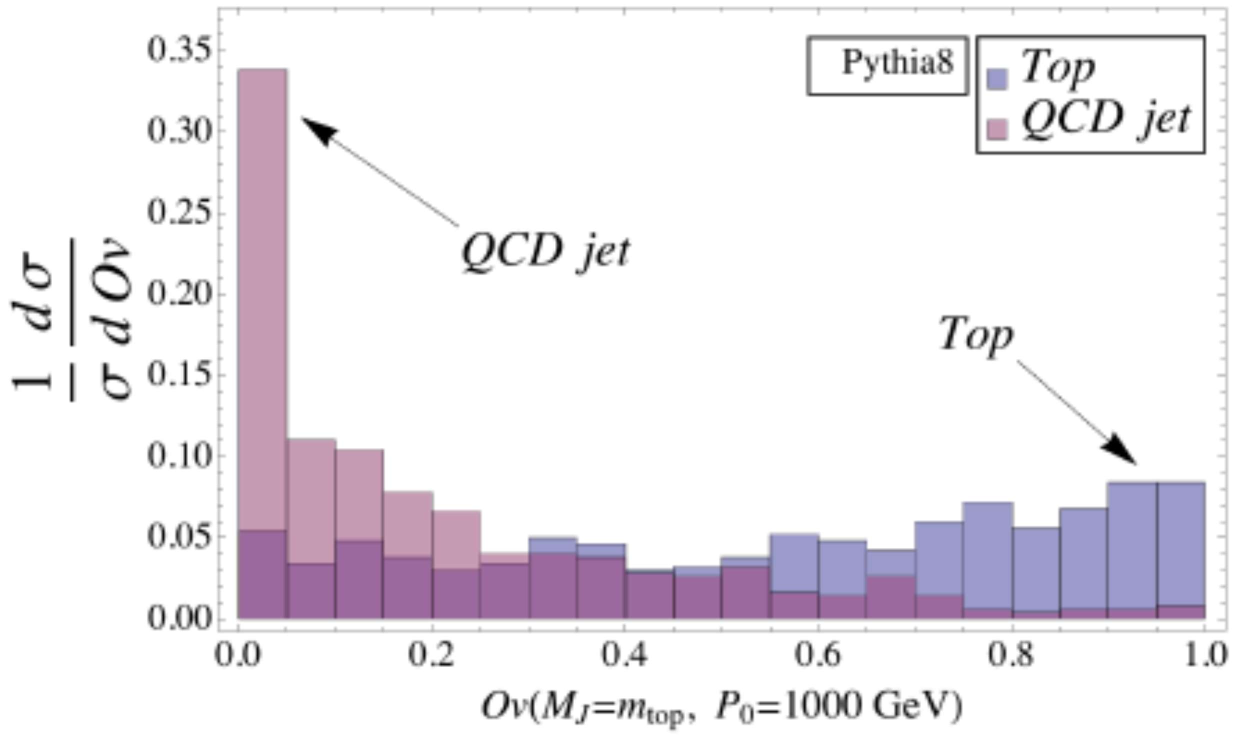


- ◆Template Overlap with data discretization

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

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

after mass cut

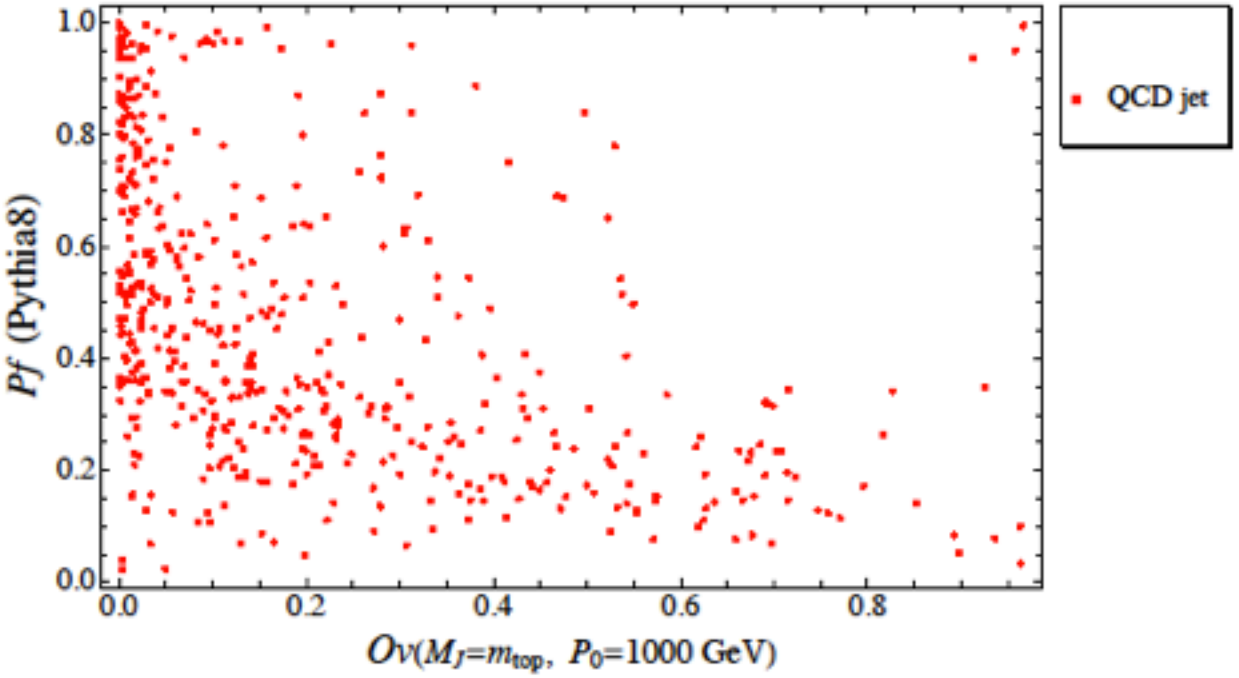


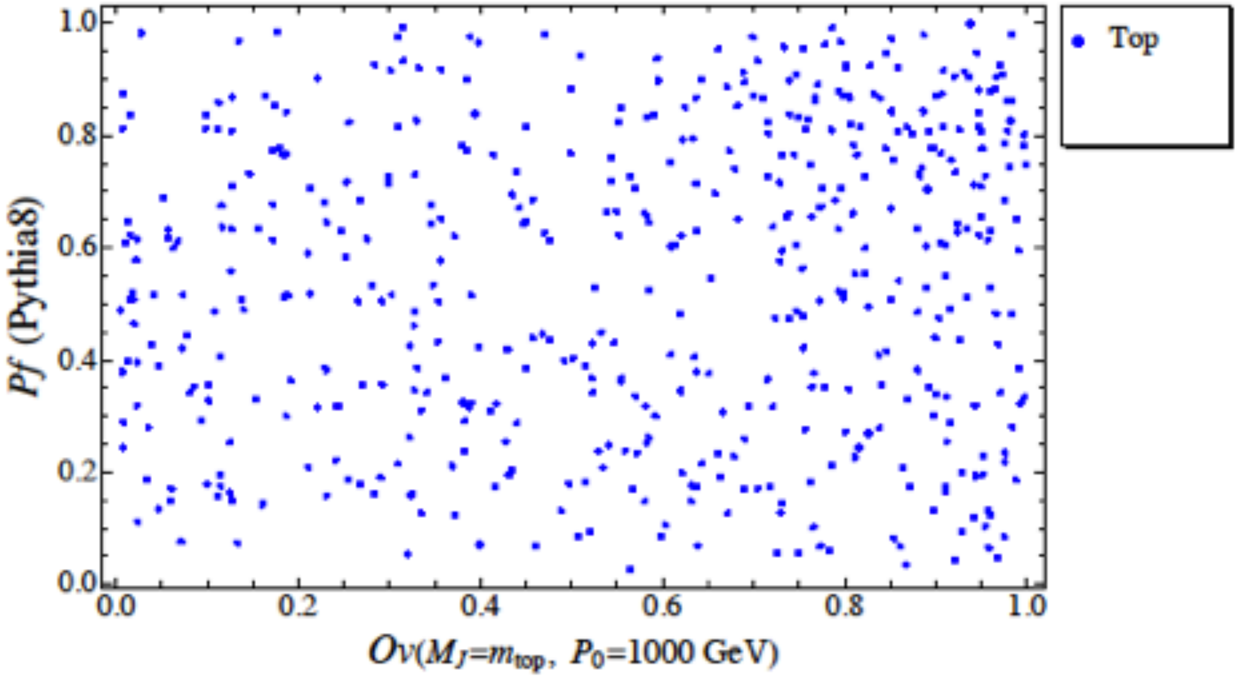
Three-particle Templates and Top Decay

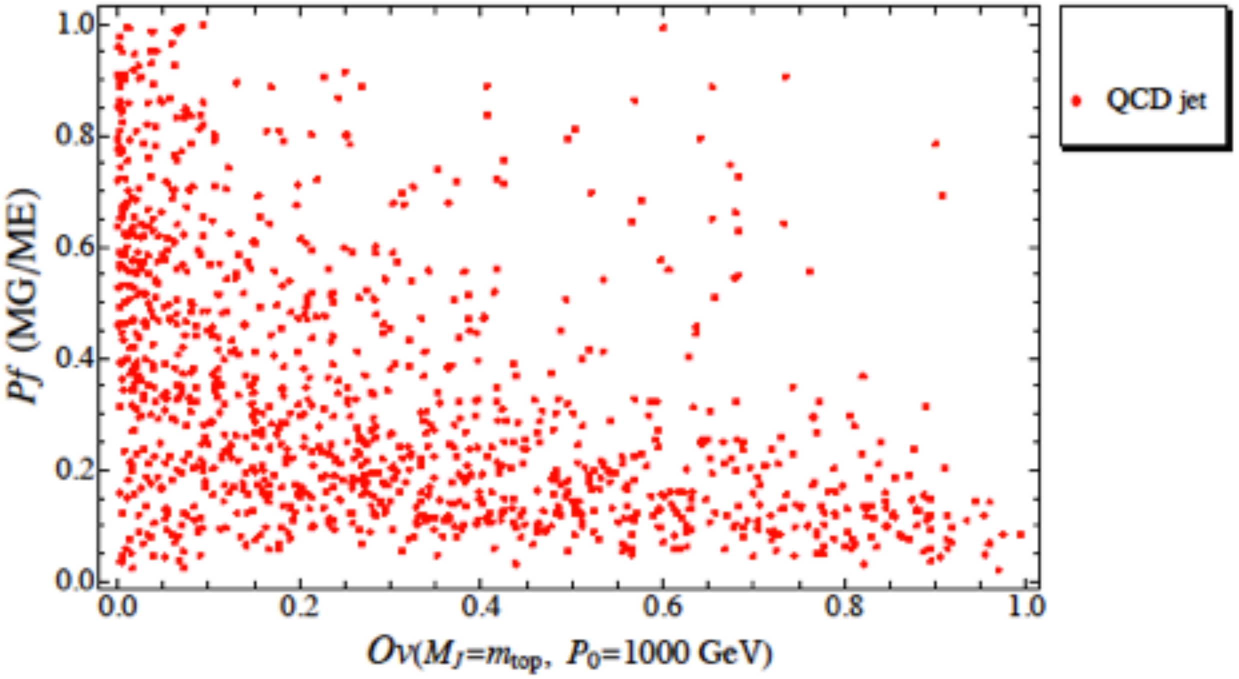
♦ Combined with "Planar flow"-
distinguishes between many three-jet events with large template overlaps.

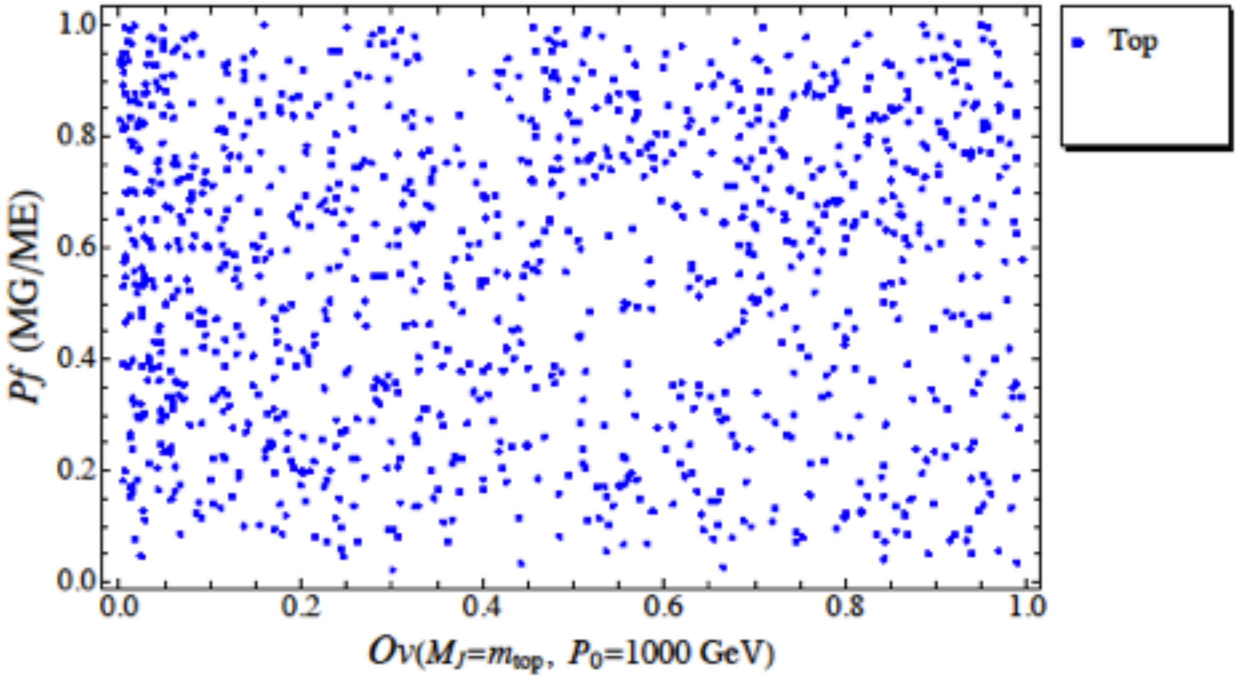
♦ In general, QCD events with large *Ov* will have significantly smaller planar flow than top decay events; for the QCD jets a large overlap would be a result of a kinematic "accident".

Three-particle Templates and Top Decay

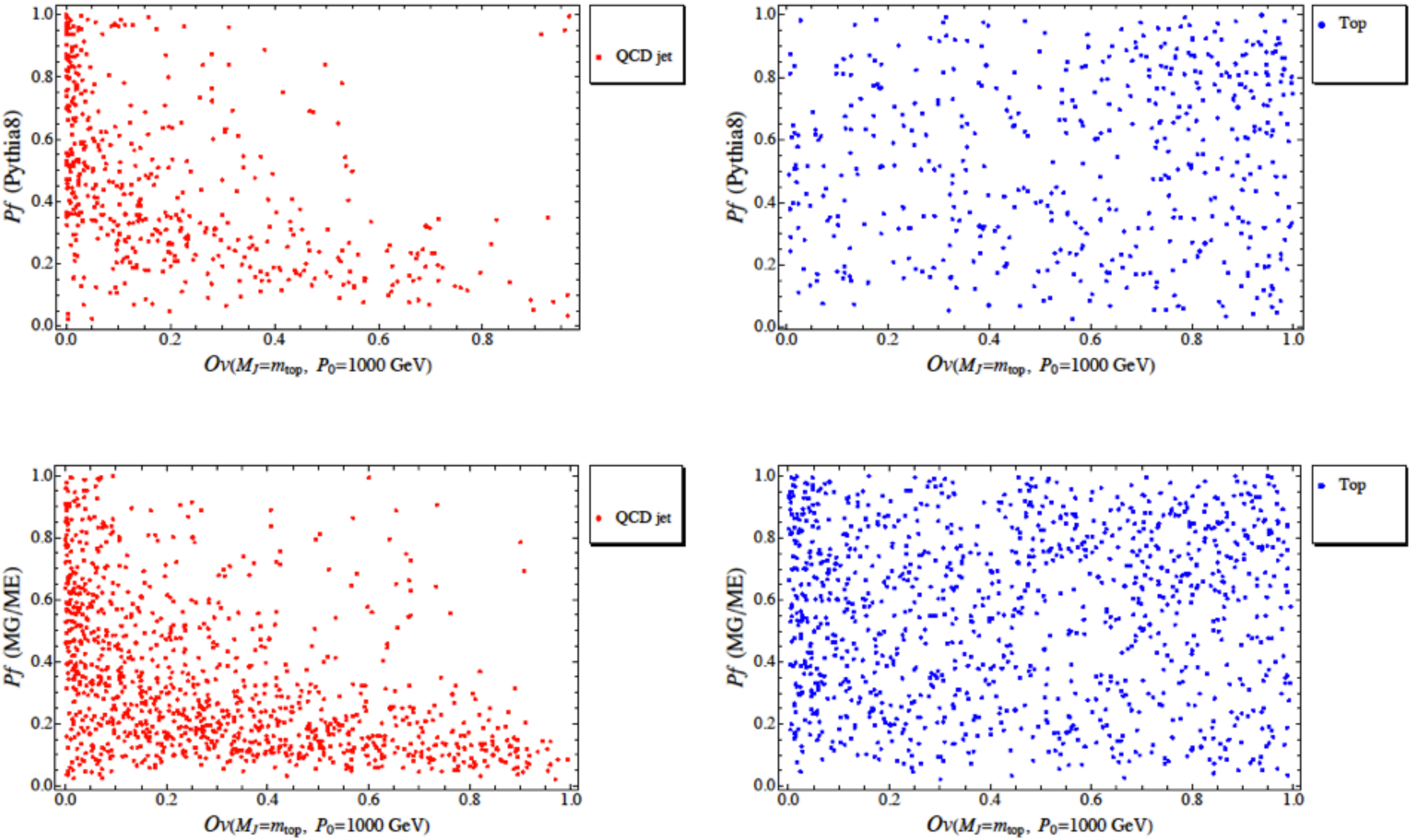




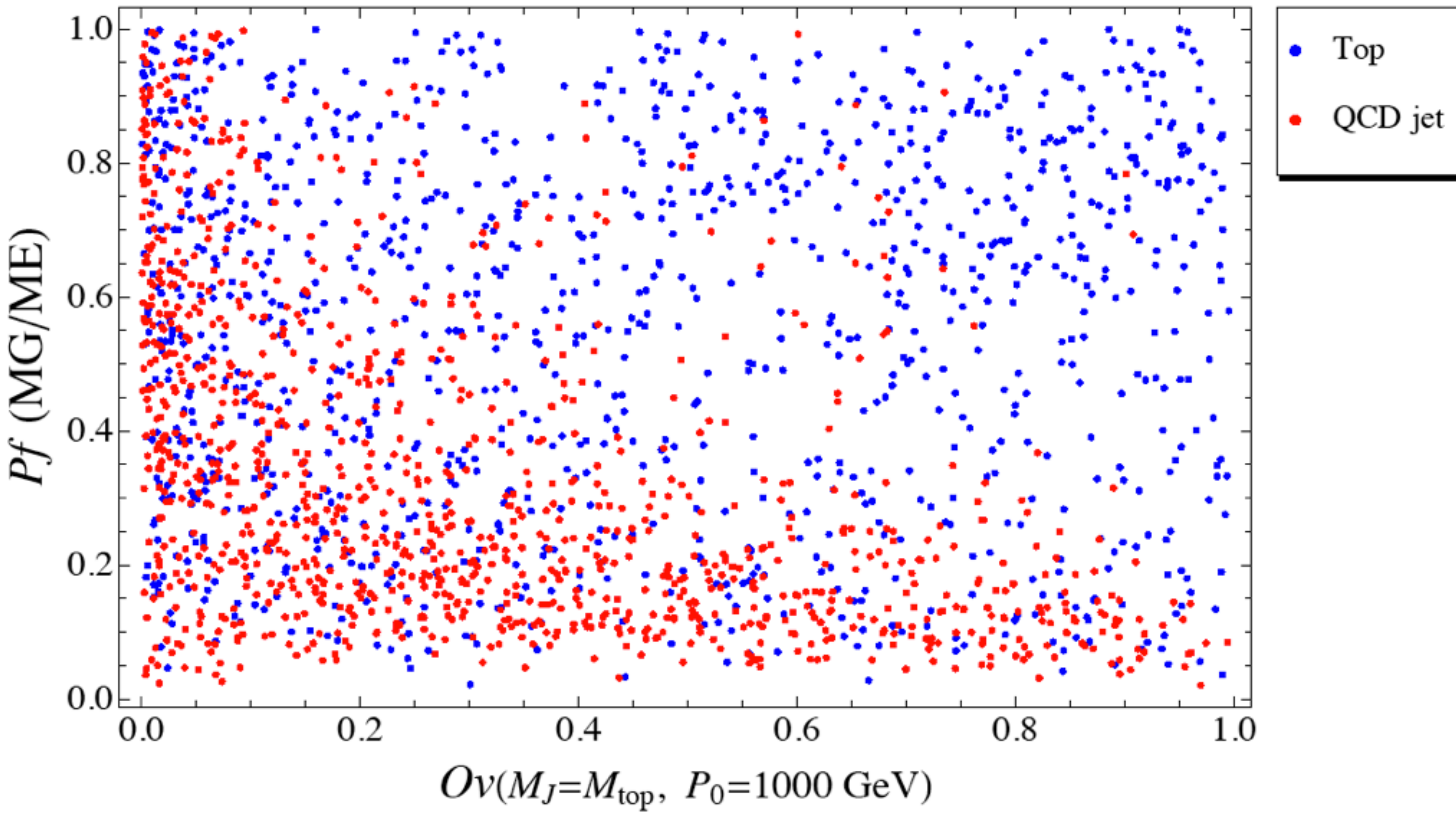




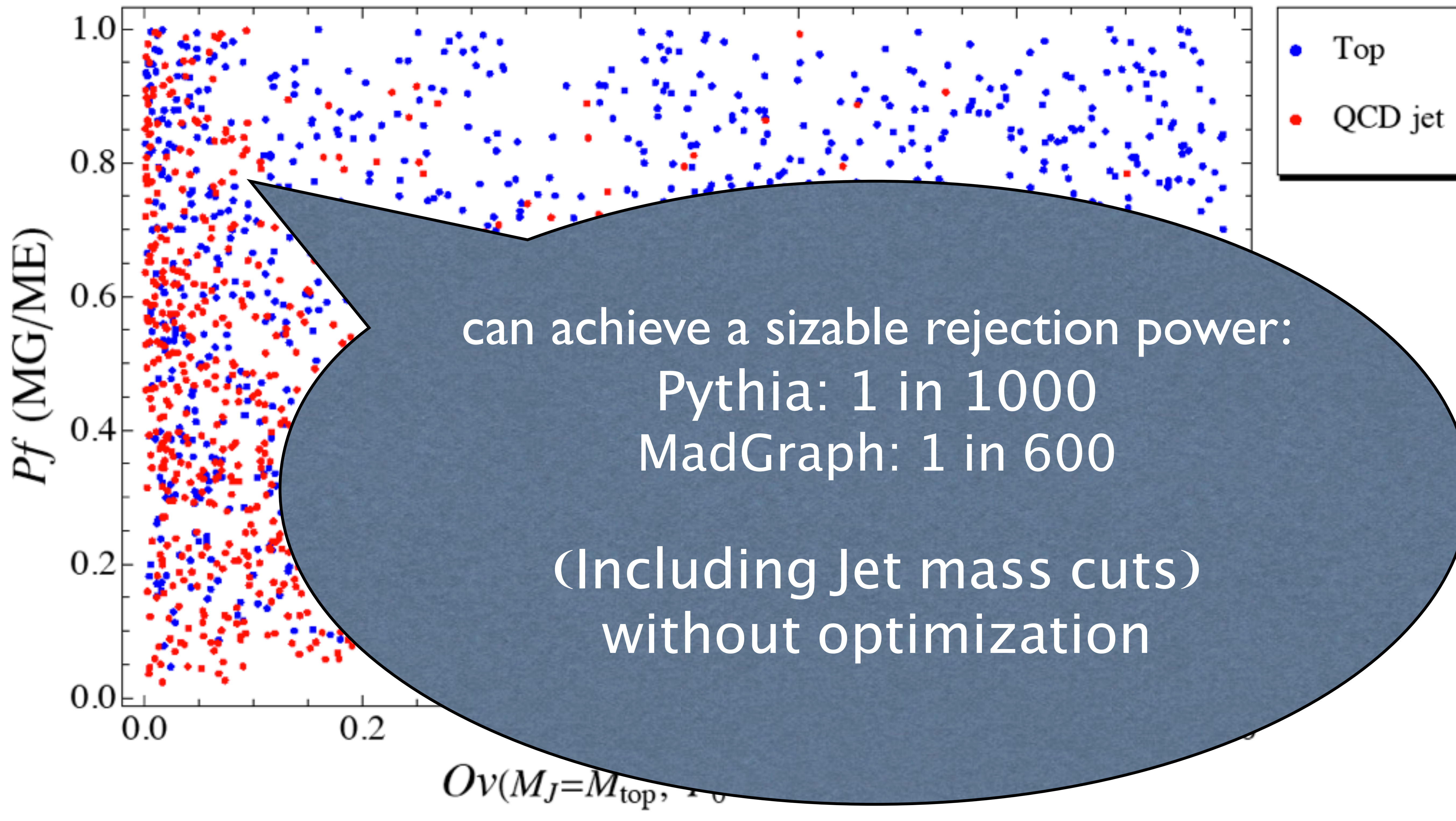
Three-particle Templates and Top Decay



Three-particle Templates and Top Decay



Three-particle Templates and Top Decay



can achieve a sizable rejection power:

Pythia: 1 in 1000

MadGraph: 1 in 600

(Including Jet mass cuts)

without optimization

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

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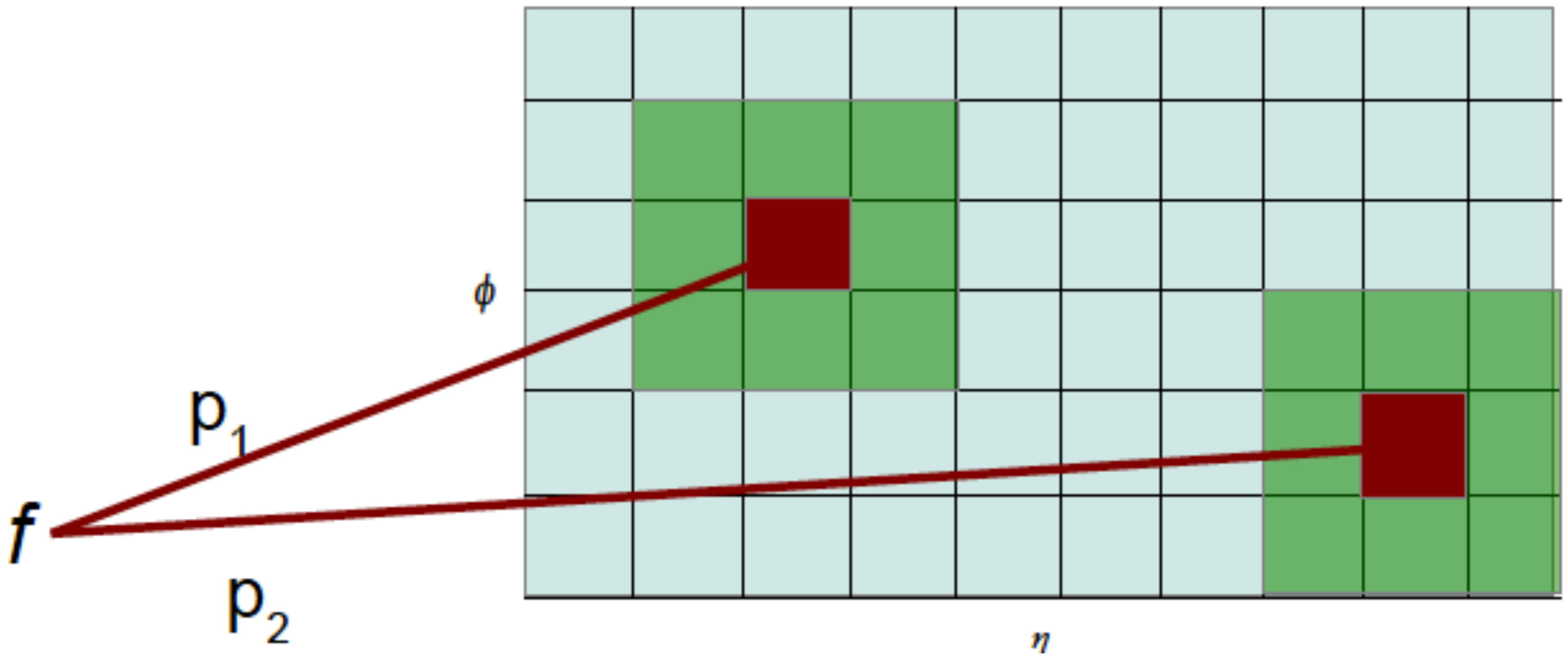
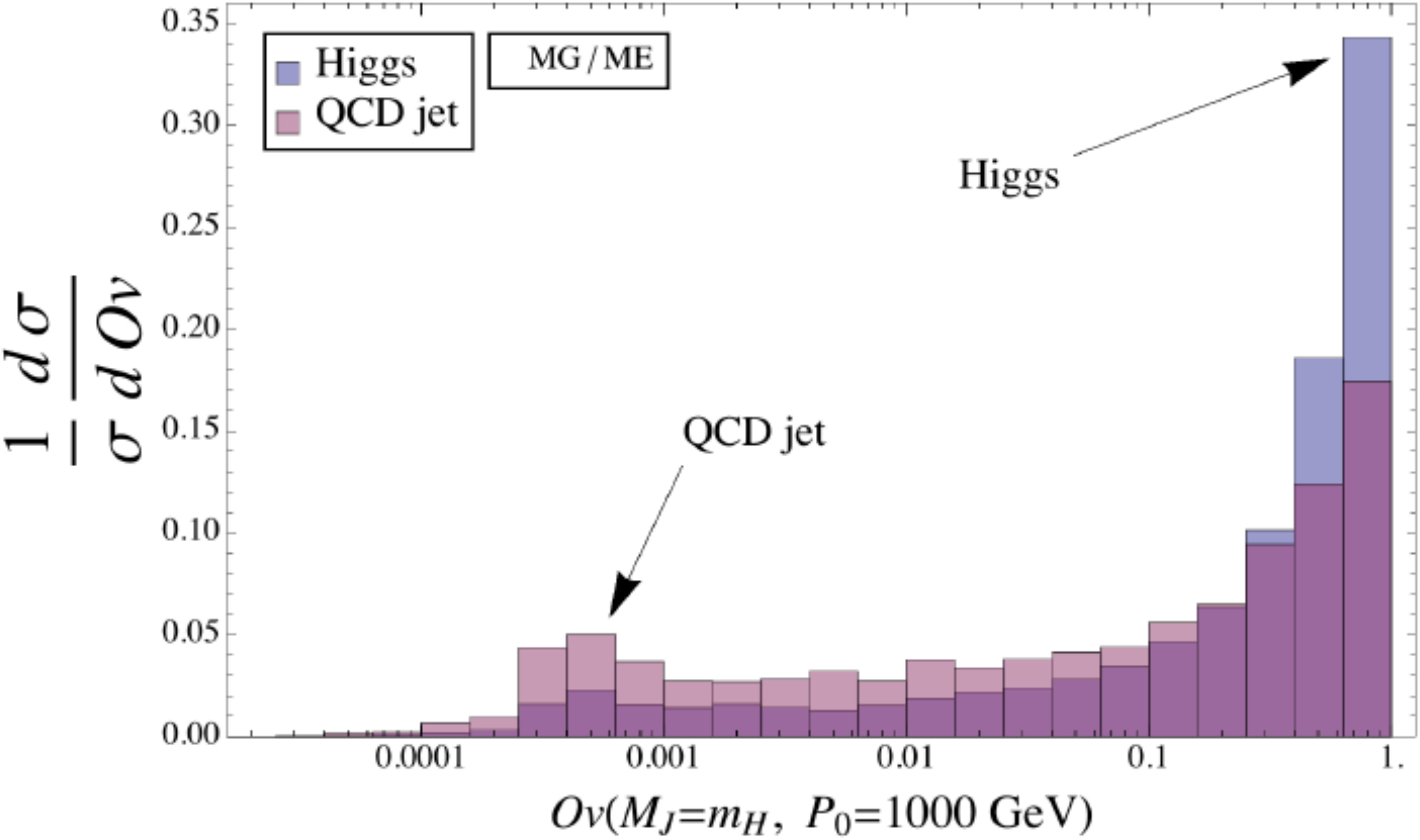
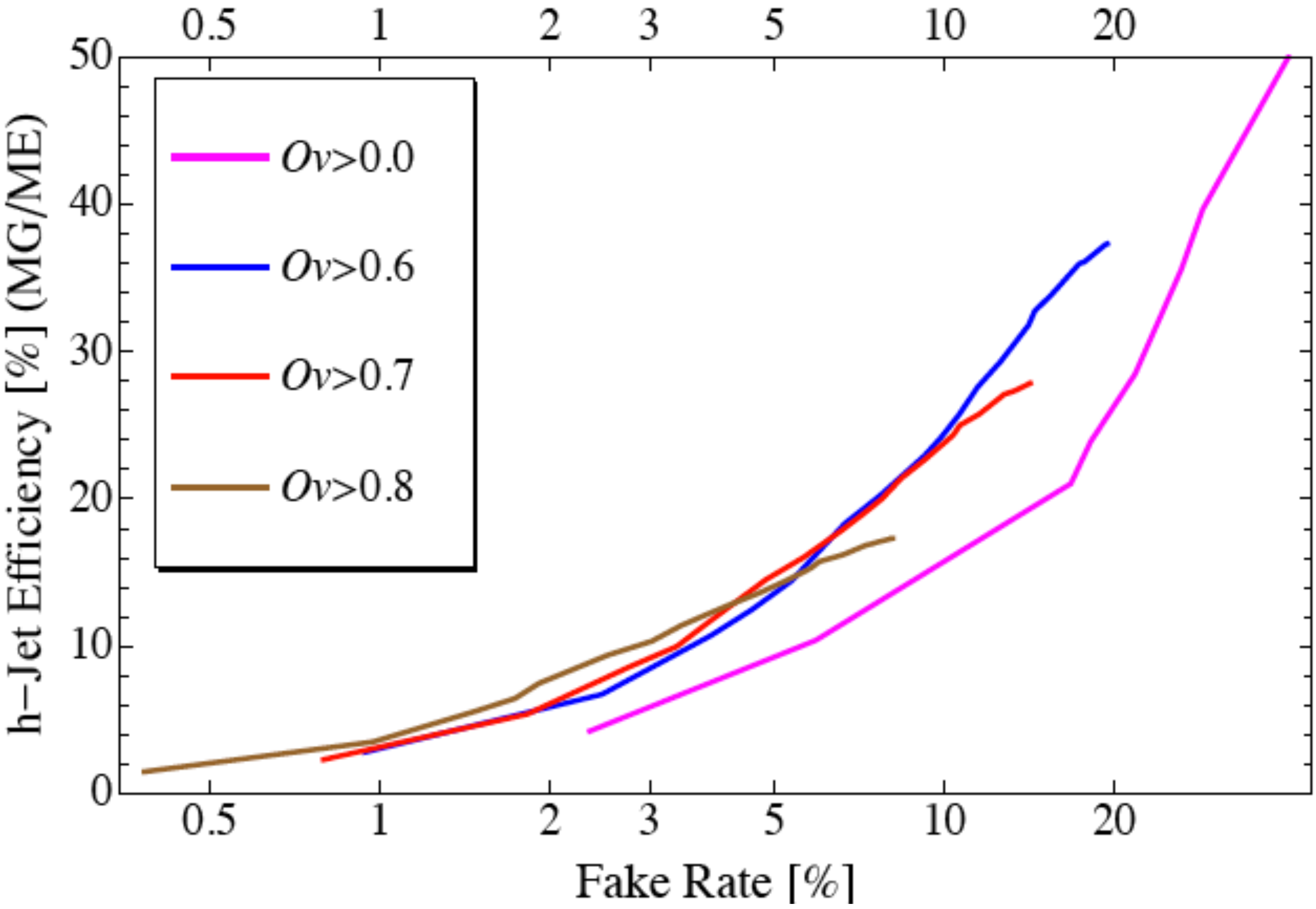


Two-particle Templates and Higgs Decay



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

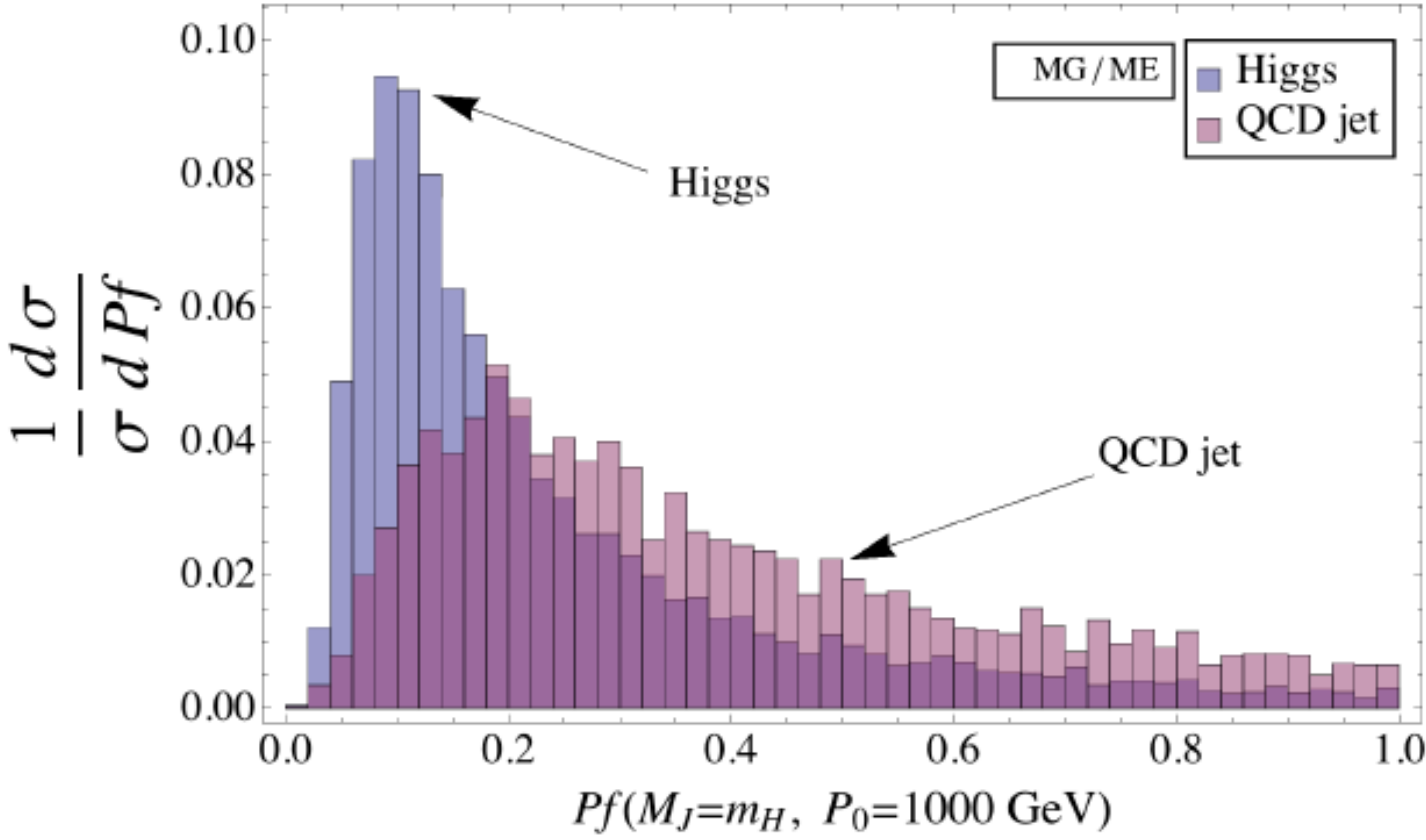
Two-particle Templates and Higgs Decay

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

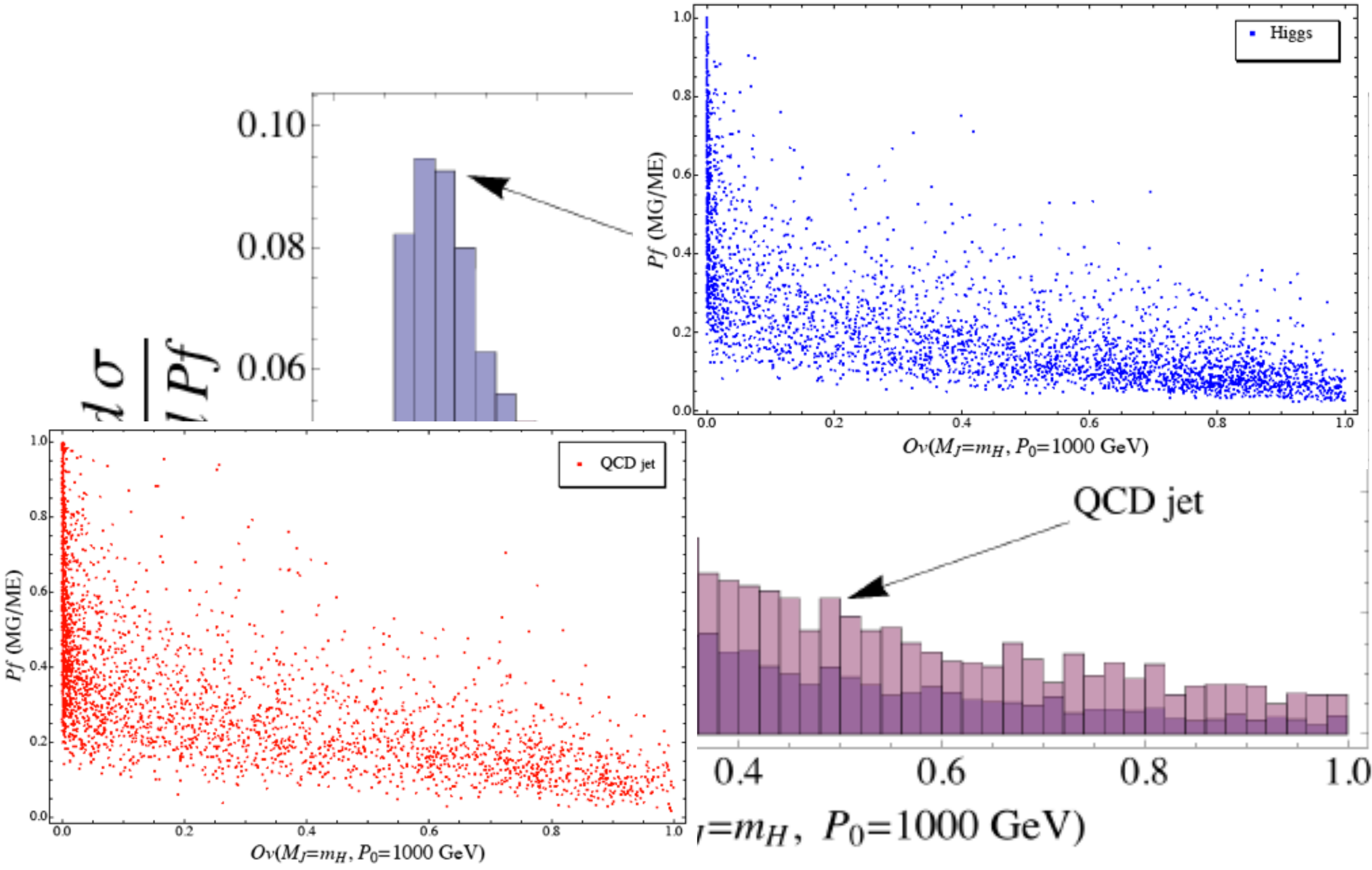
- The effects of higher-order effects can be partly captured by using Planar flow

(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

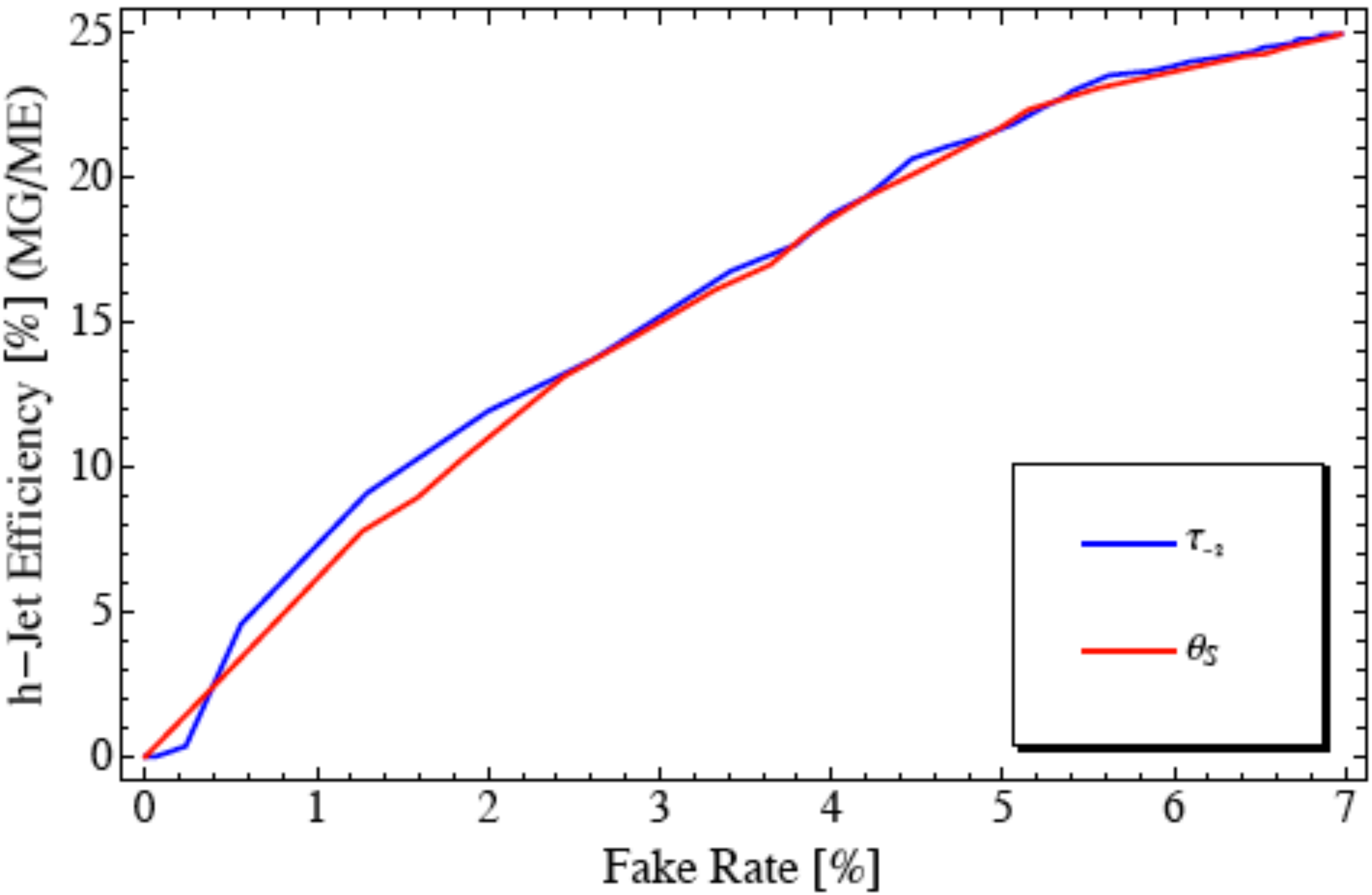
- Combined with angularity or Θ_s : can improved rejection power (Θ_s and angularities are related)

Two-particle Templates and Higgs Decay

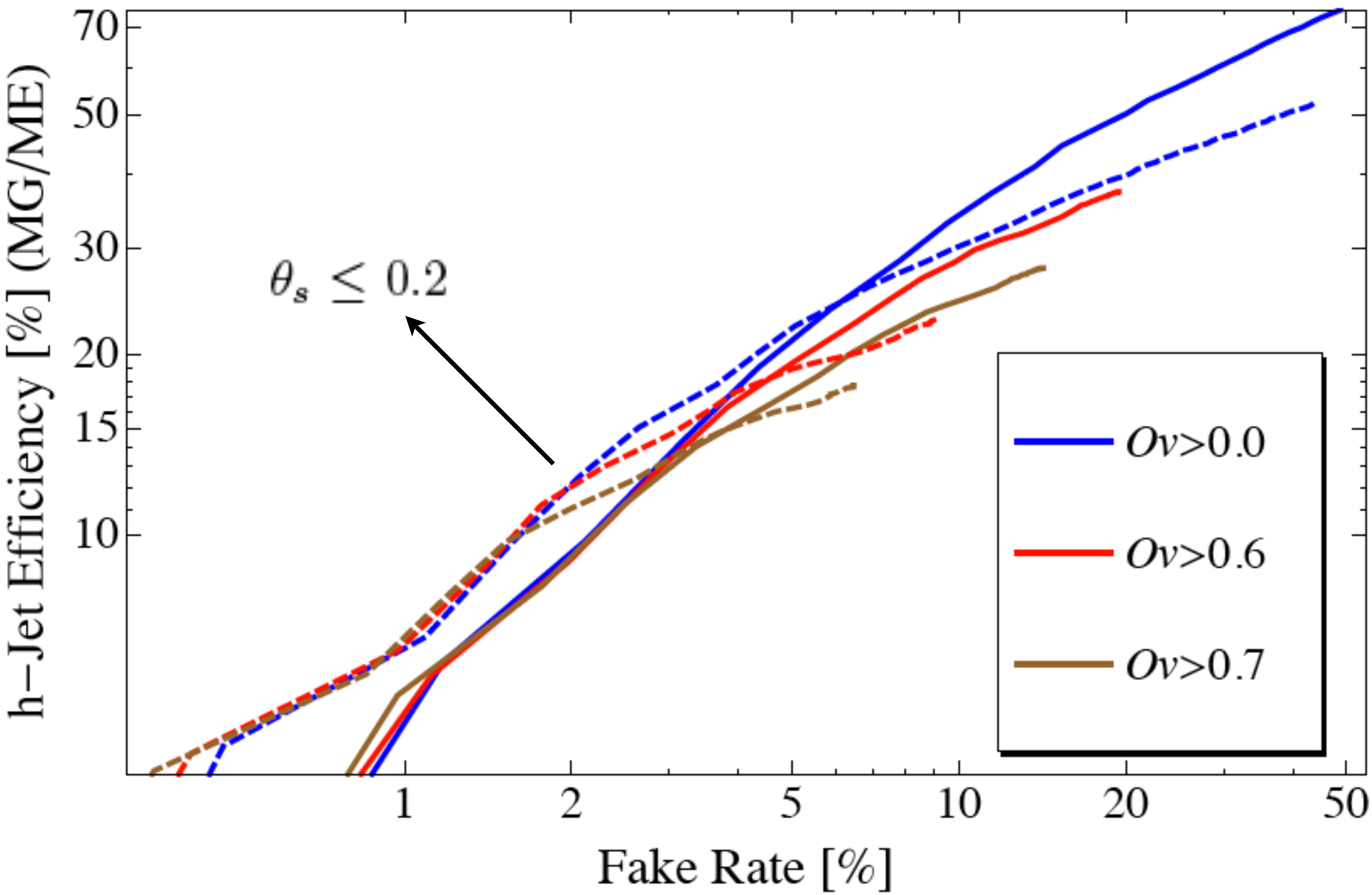
- Combined with angularity or Θ_s : can improved rejection power (Θ_s and angularities are related)

- 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.

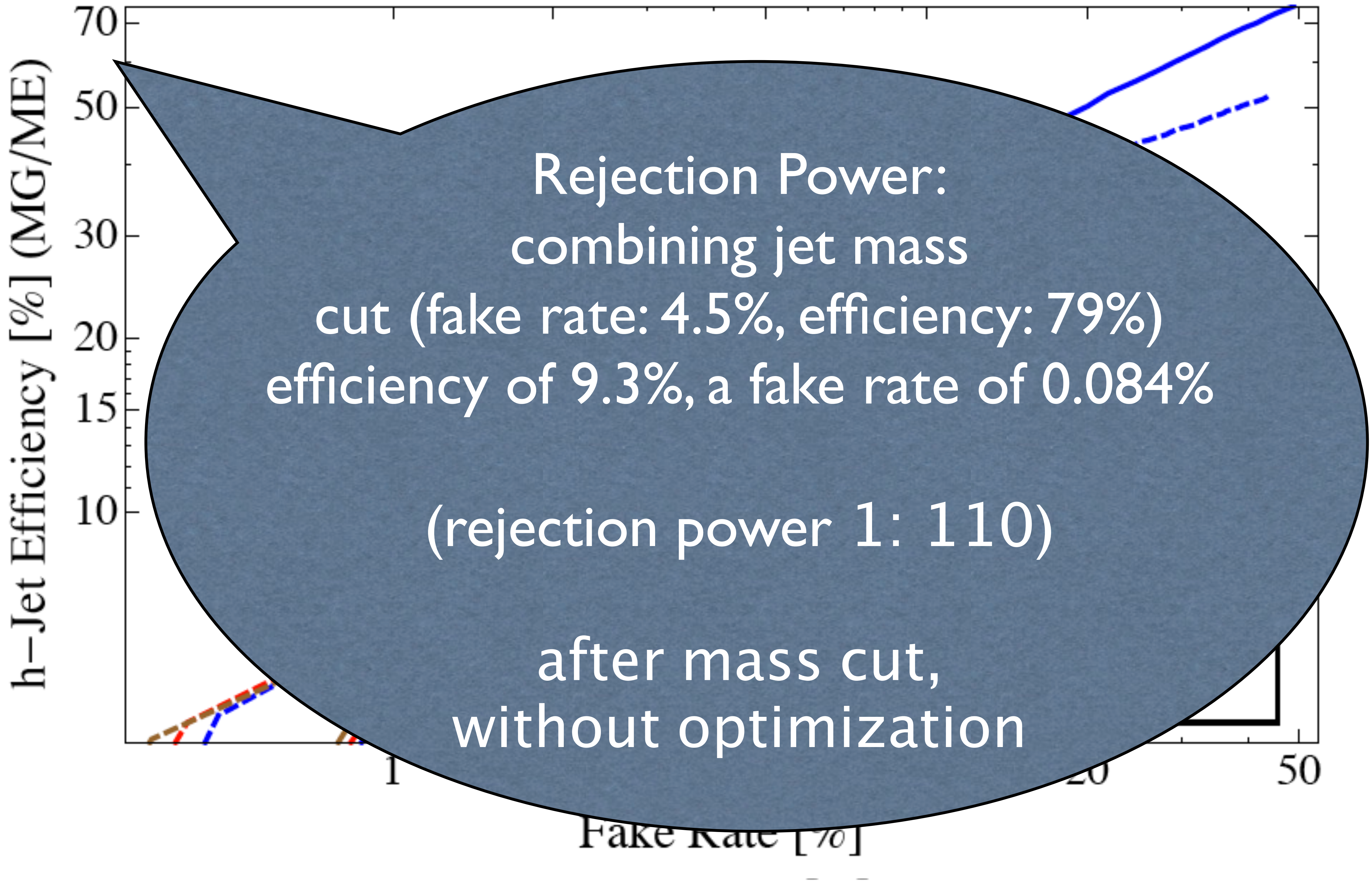
Two-particle Templates and Higgs Decay



Two-particle Templates and Higgs Decay



Two-particle Templates and Higgs Decay



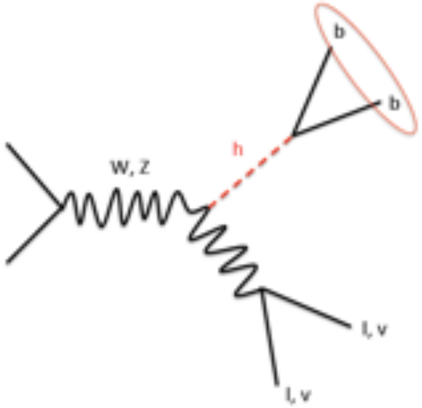
Rejection Power:
combining jet mass
cut (fake rate: 4.5%, efficiency: 79%)
efficiency of 9.3%, a fake rate of 0.084%

(rejection power 1: 110)

after mass cut,
without optimization

NLO Templates and Higgs Decay

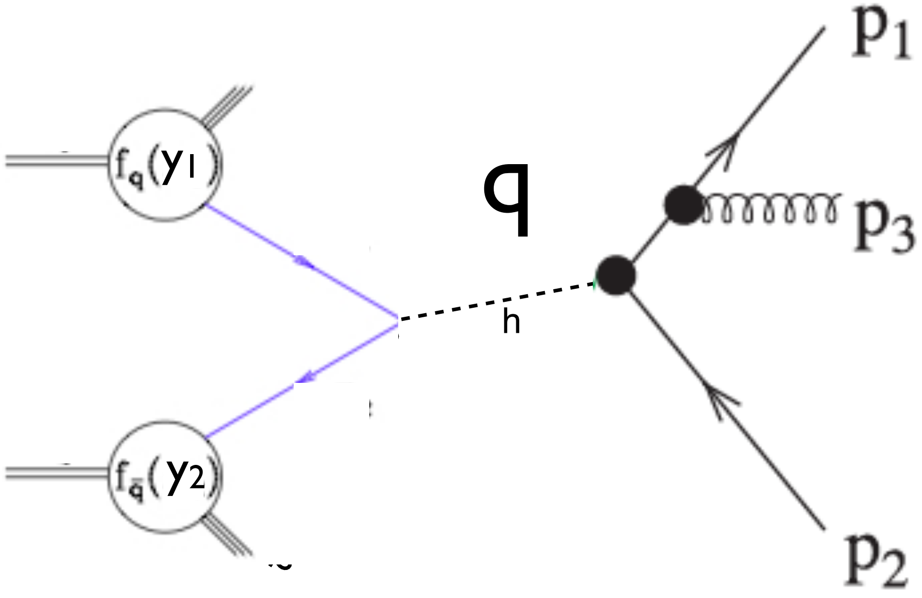
L. Almeida, O. Erdogan, J. Juknevich, SL, G. Perez, & G. Sterman (11)



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

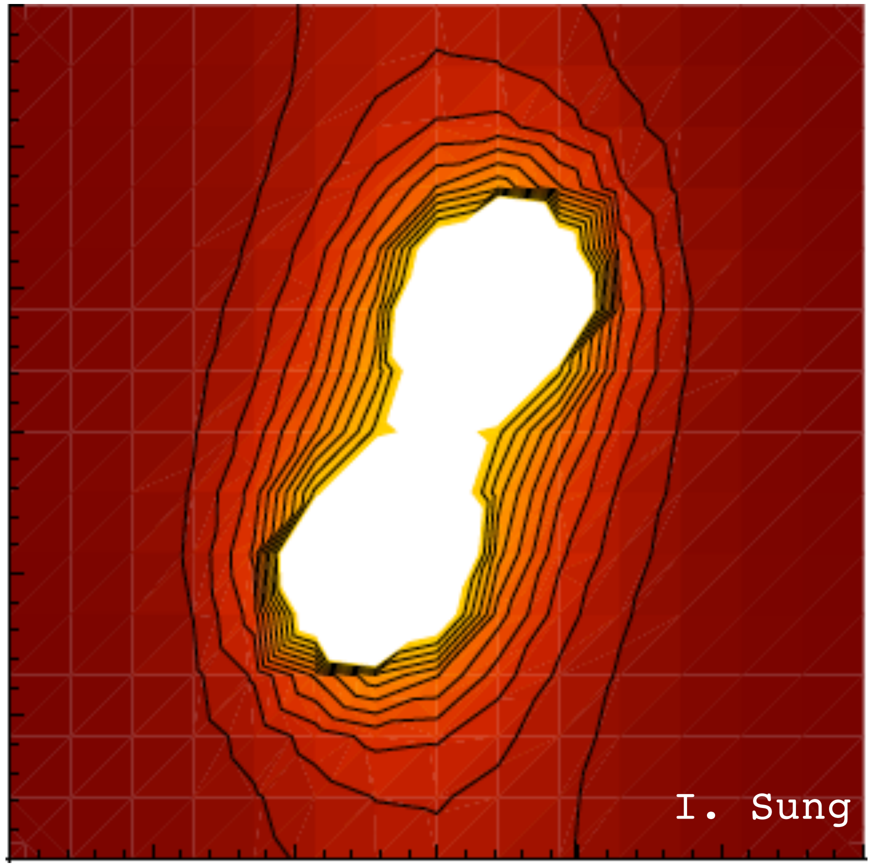
  I. Sung (09)
  J. Gallicchio and M. Schwartz (10),
  K. Black, J. Gallicchio, J. Huith, M. Kagan, M. Schwartz, B. Tweedie (10)

- NLO template:



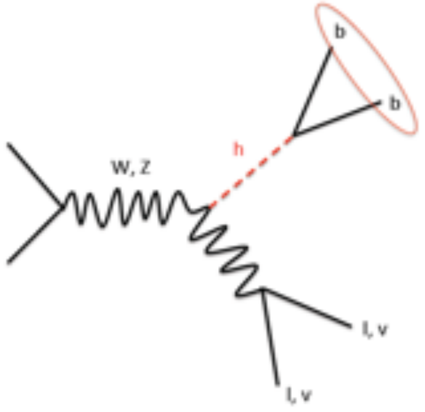
$$x_i = \frac{E_i}{\sqrt{s}/2} = \frac{2p_i \cdot q}{s}$$

$$0 < x_i < 1.$$



NLO Templates and Higgs Decay

L. Almeida, O. Erdogan, J. Juknevich, SL, G. Perez, & G. Sterman (11)



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

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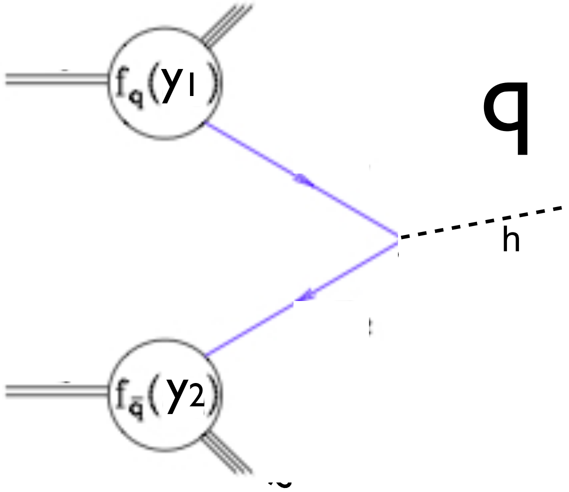
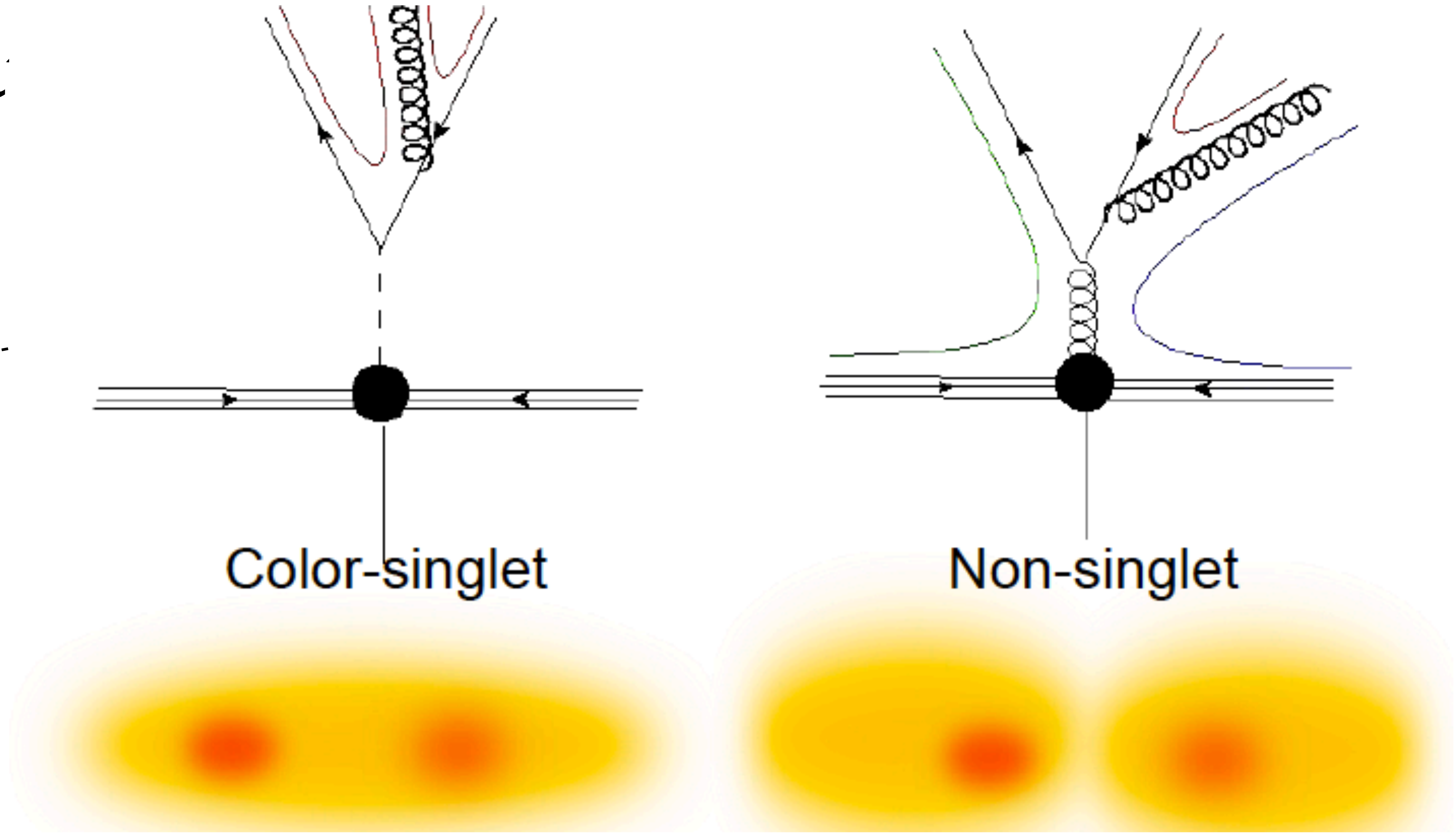
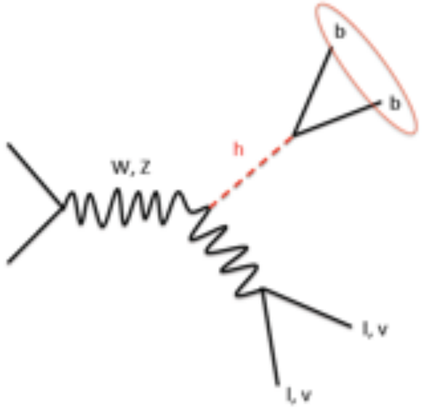
◆ NLO templa





NLO Templates and Higgs Decay

L. Almeida, O. Erdogan, J. Juknevich, SL, G. Perez, & G. Sterman (11)



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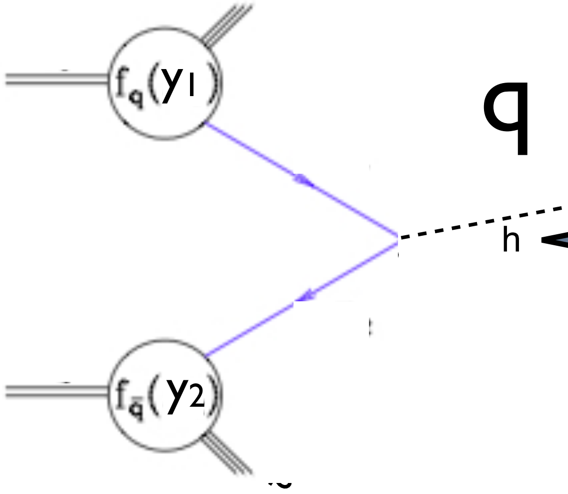
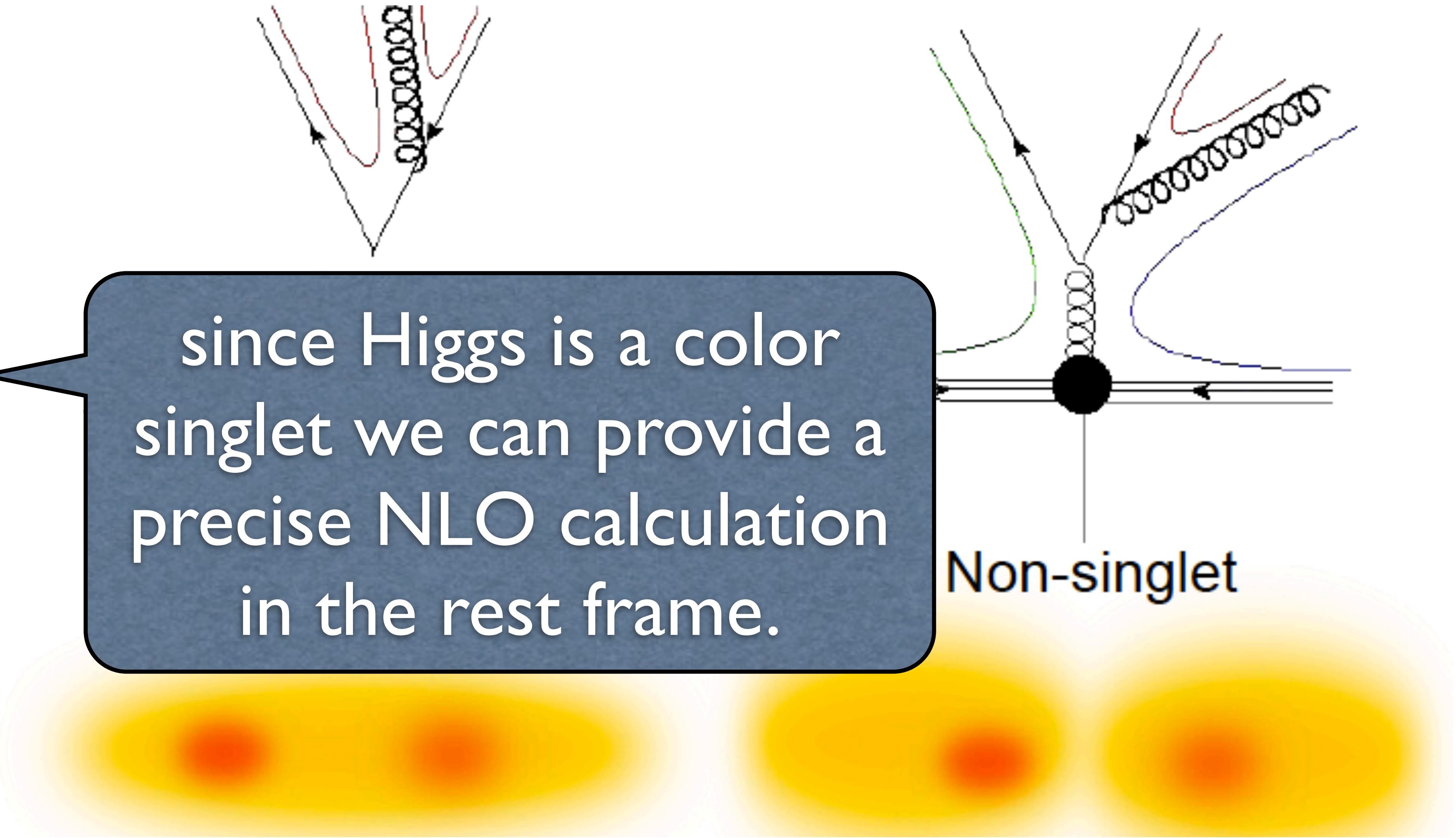
```

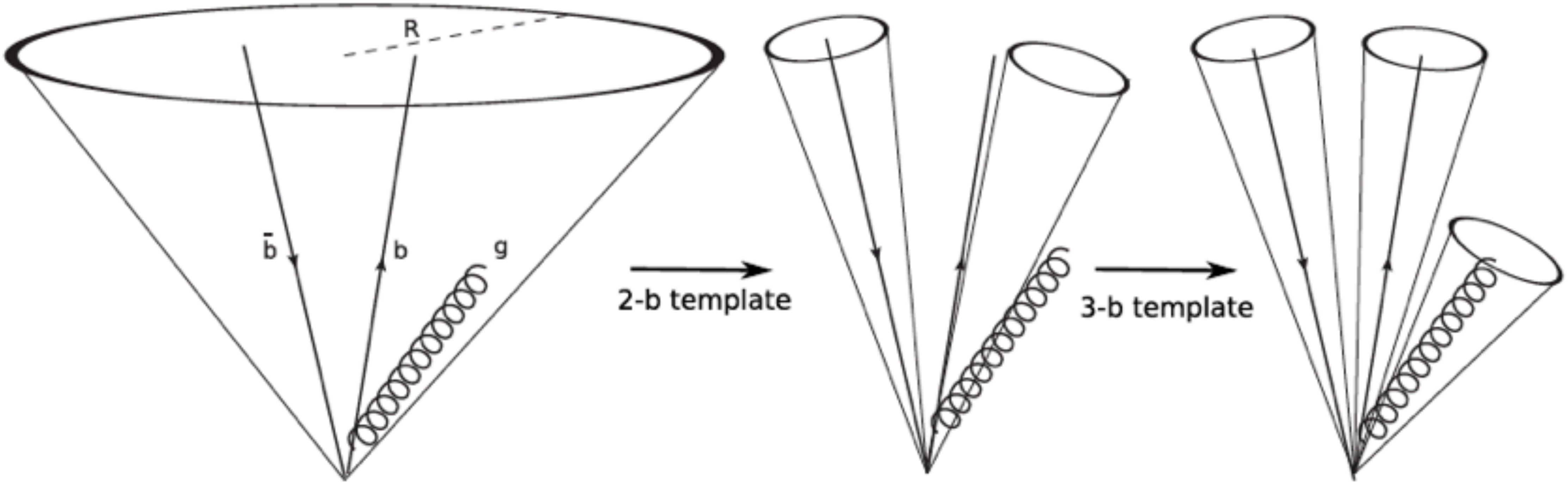
- NLO templa



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



Higgs NLO template, cont’



$l \cos\theta$.

3 (90)

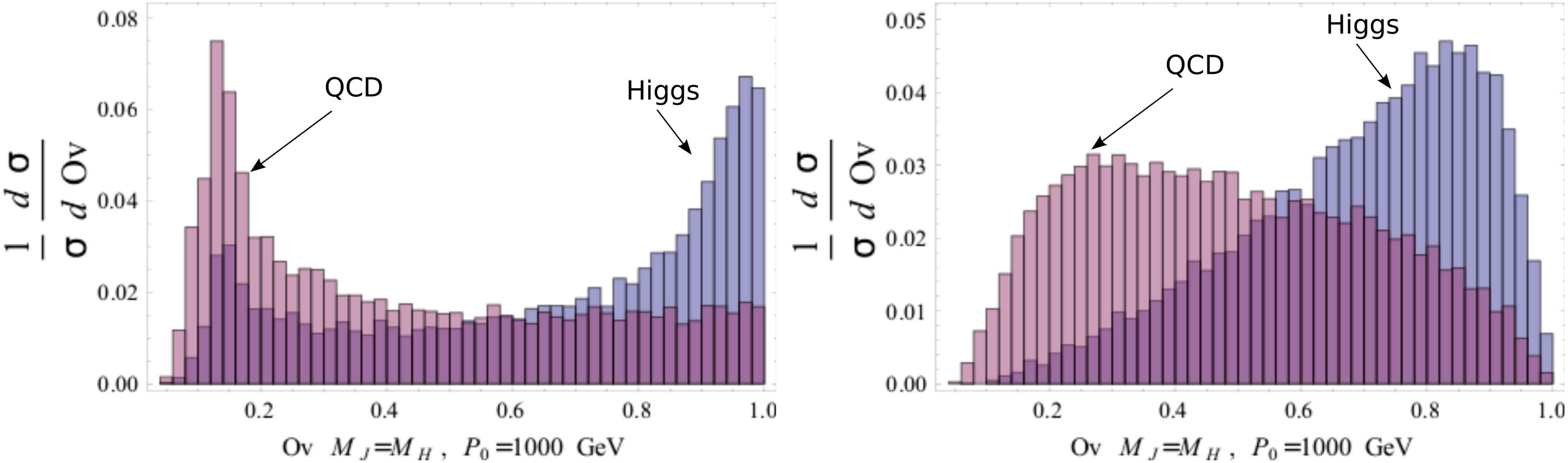
$$|f\rangle = |h\rangle^{(\mathrm{NLO})} = |p_1, p_2, p_3\rangle$$

Three Euler angles
ψ, θ, φ

Two energy fractions
x_1, x_2

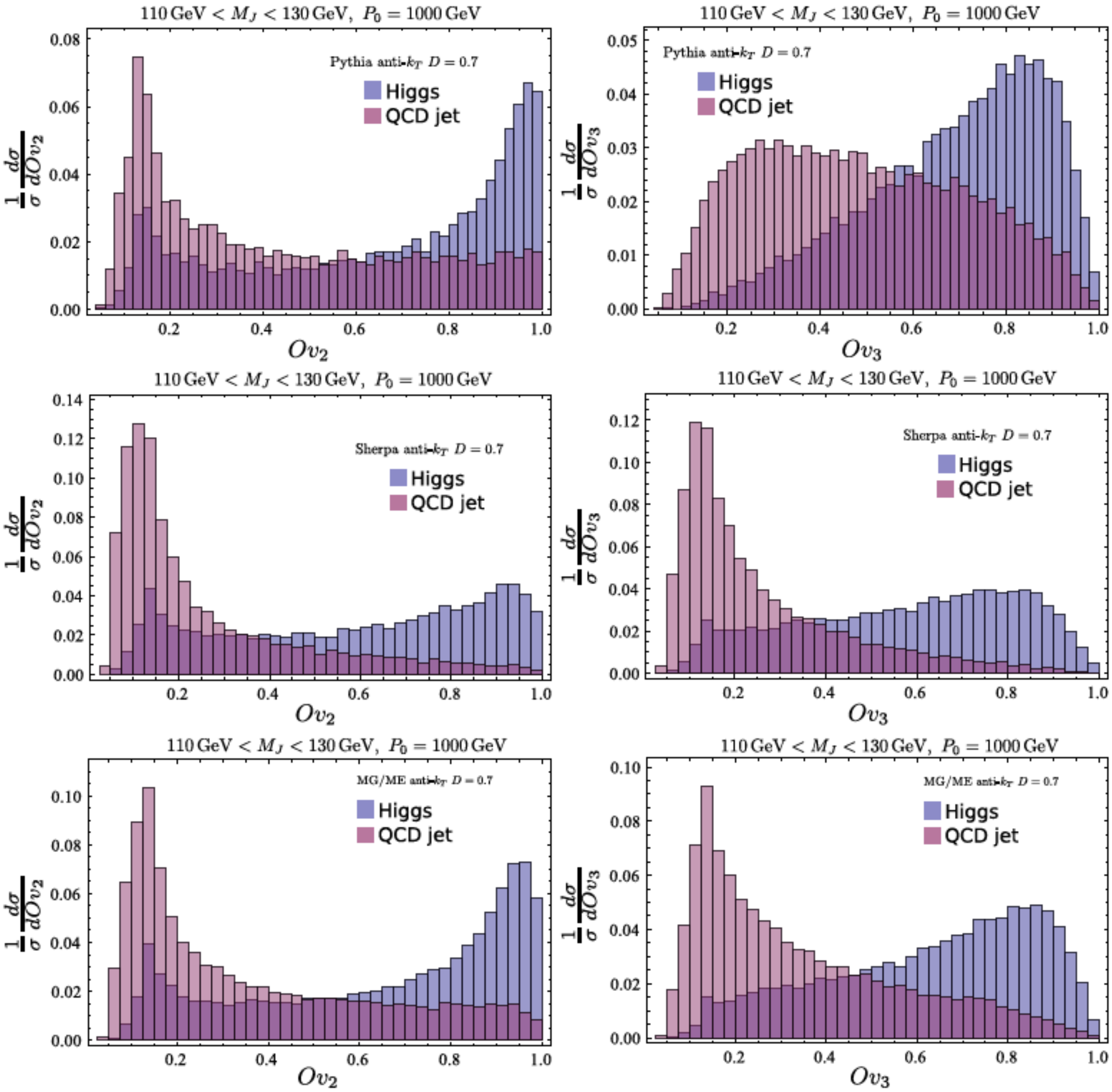
$$p_a^\mu(x_1, x_2, \psi, \theta, \phi) = L_z(\gamma) R_z(\psi) R_x(\theta) R_z(\phi)\, p_a^\mu|_{P_J^z=0}(x_1, x_2)$$

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

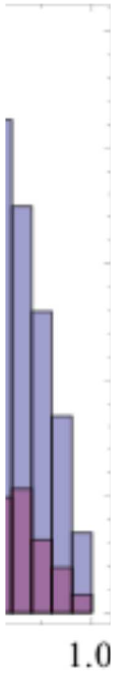


Histograms of template overlap Ov with Higgs jets and QCD jets from Pythia 8, for $R = 0.5$, 950 GeV$\leq P_0 \leq$1050 GeV, 110 GeV$\leq m_J \leq$130 GeV and $m_{higgs} = 120$ GeV using 2-body templates (Left) and 3-body templates (Right).

st’



$\frac{1}{\sigma}\frac{d\sigma}{}$

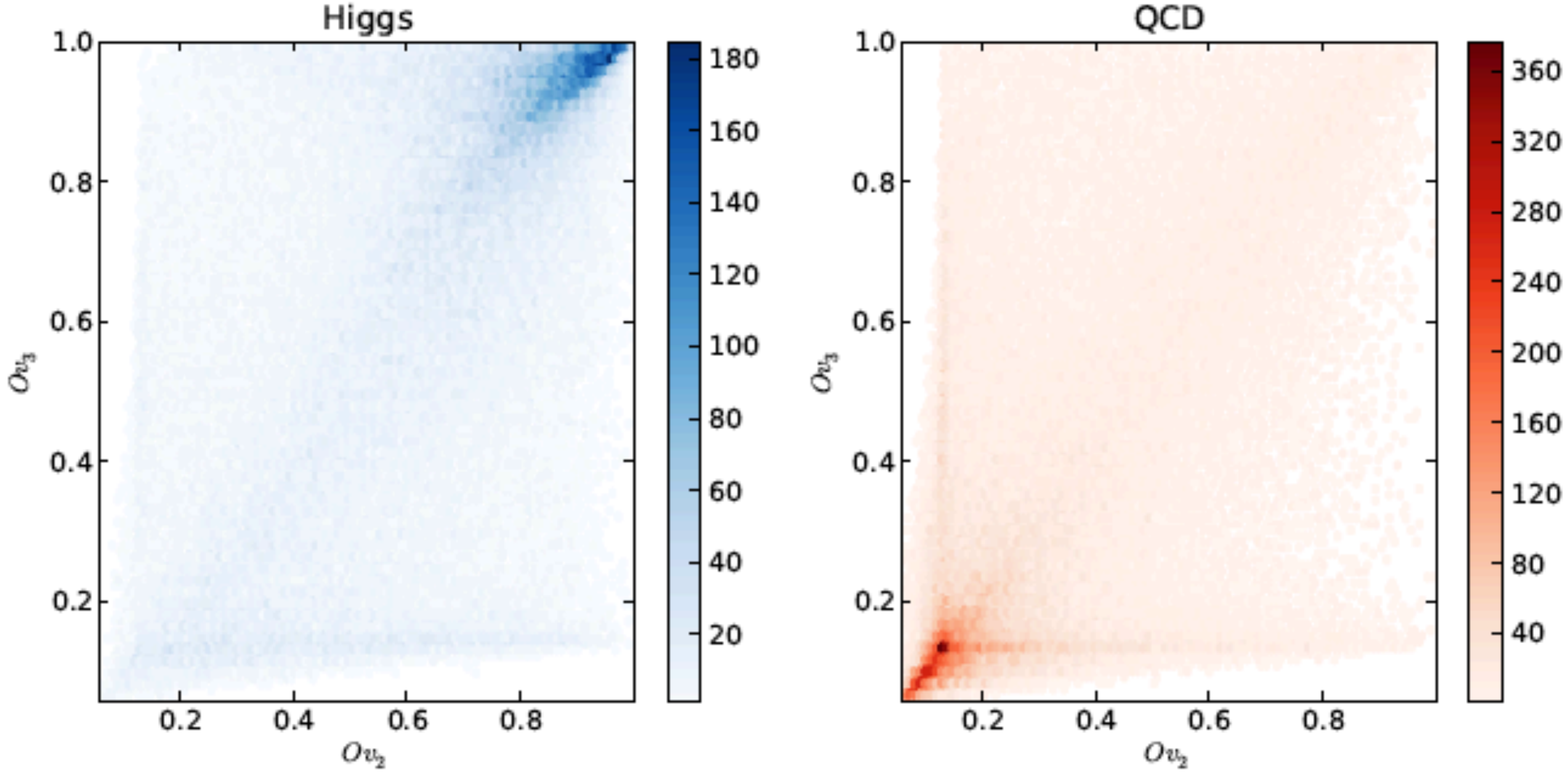


8, for

$R =$ ‑body

temp

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



Density plots of 2-body overlap *vs.* 3-body overlap for boosted Higgs and QCD jets with $R = 0.7$ and same number of events (20000).

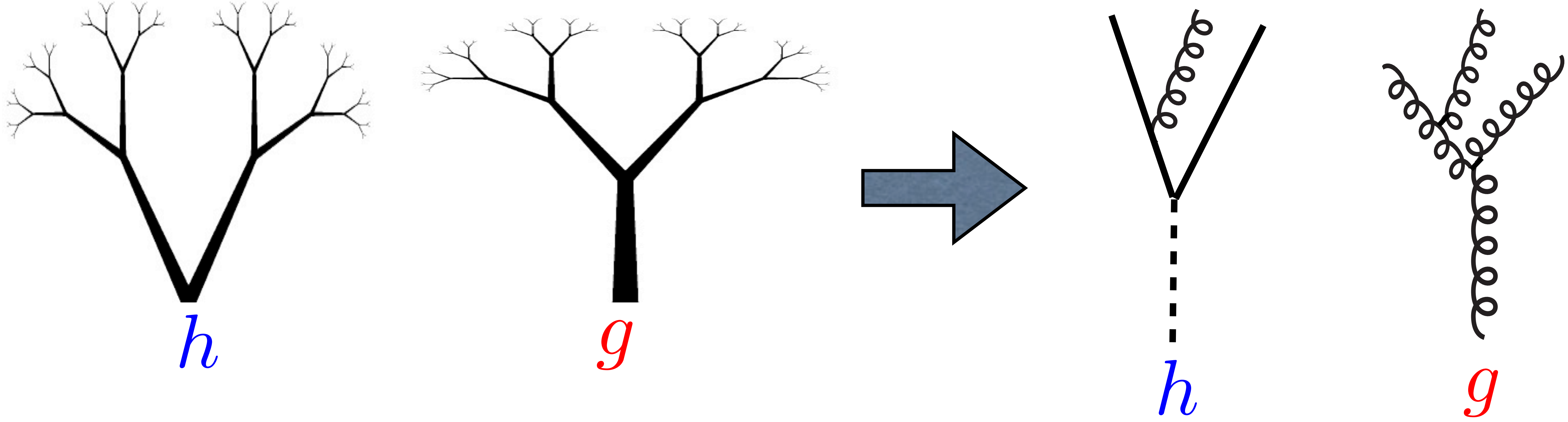
Can do better than that ...

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

Can do better than that ...

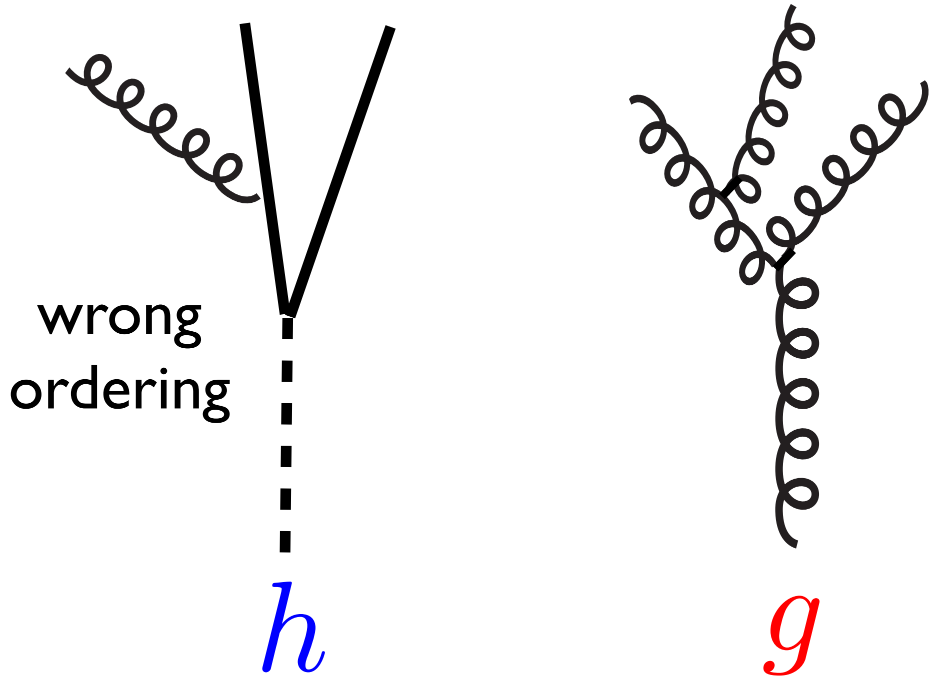
- Max template *Ov* => access to partonic information.

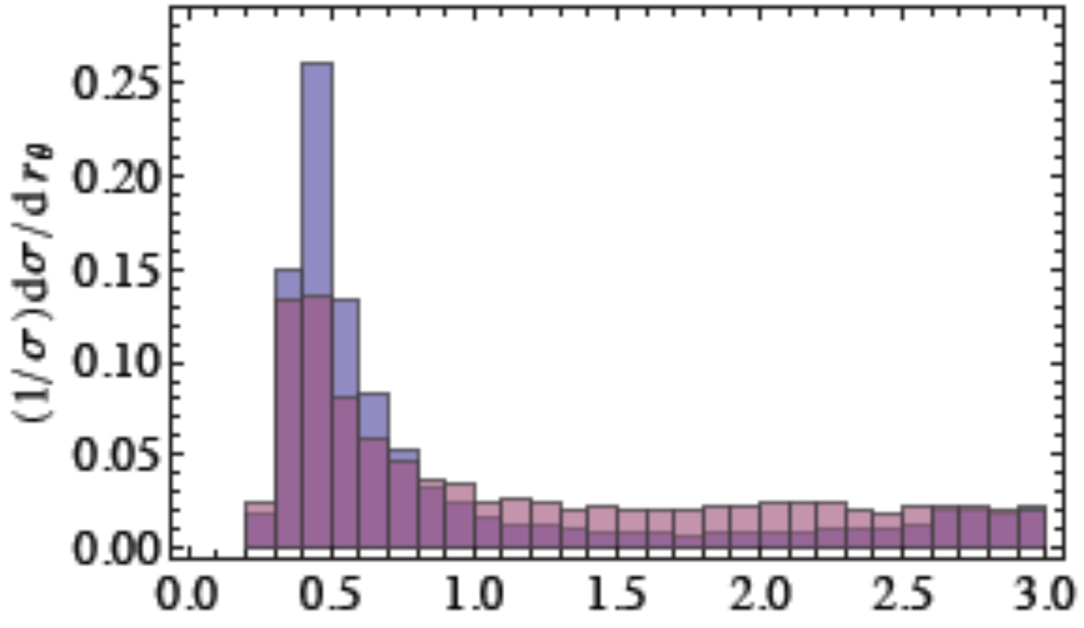
However, templates are purely 3-prong kinematics
 => If S & B were genuinely only 3body then both would always yield large overlaps => no separation. ☹



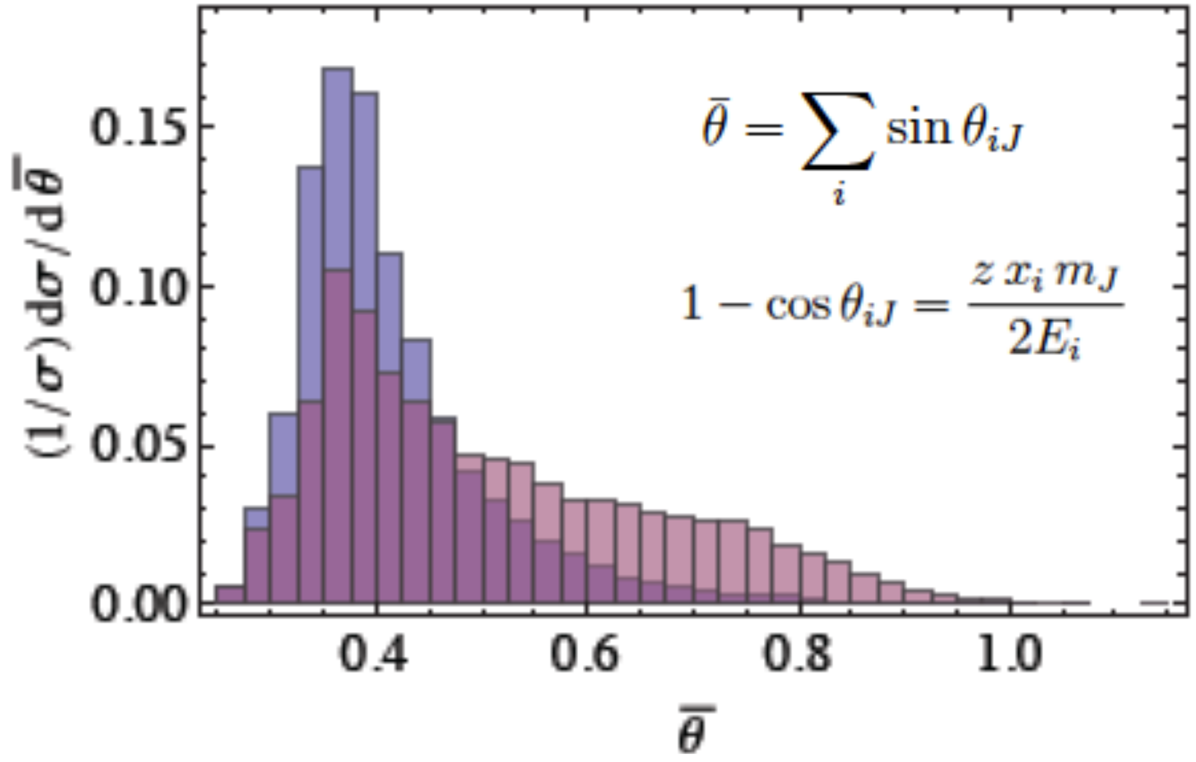
Distributions of some of 5 variables differ!

- Can use angular ordering:





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



$$\bar{\theta} = \sum_i \sin\theta_{iJ}$$

$$1 - \cos\theta_{iJ} = \frac{z\,x_i\,m_J}{2E_i}$$

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

Distributions of some of 5 variables differ!

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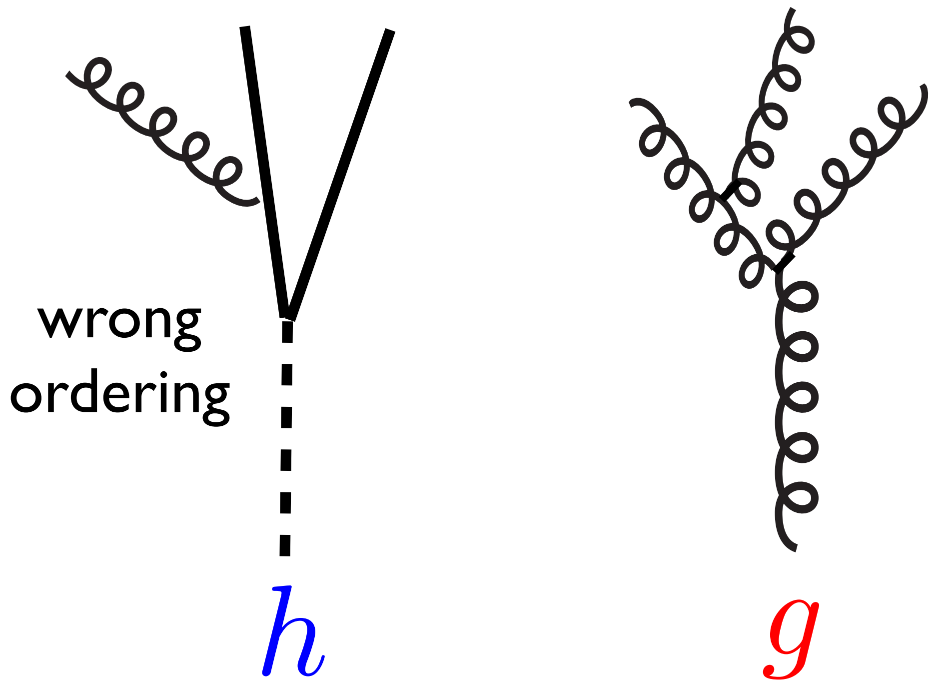
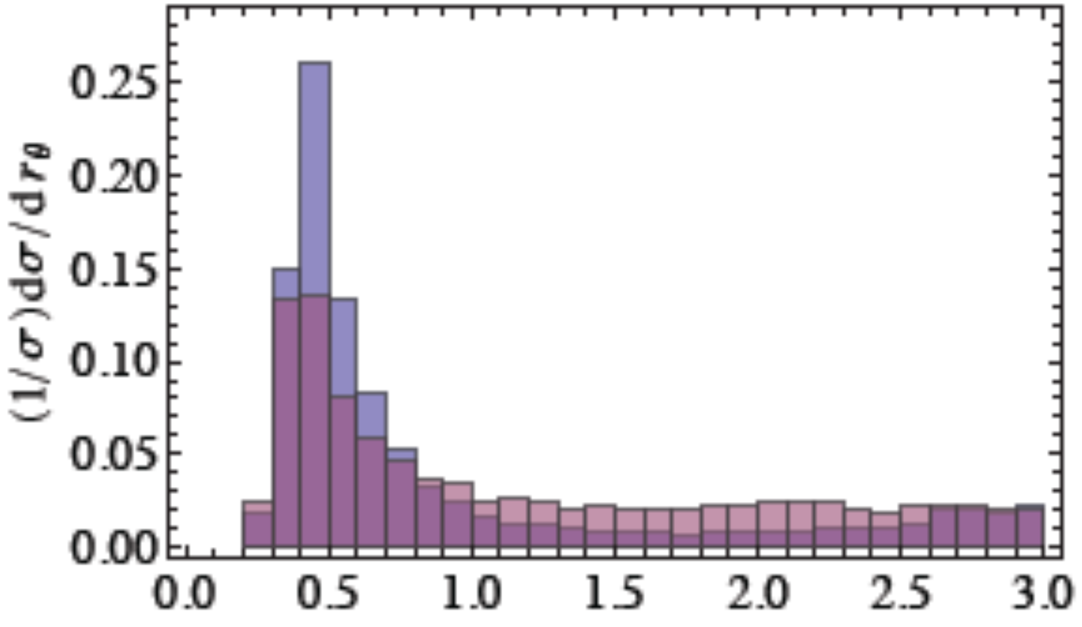
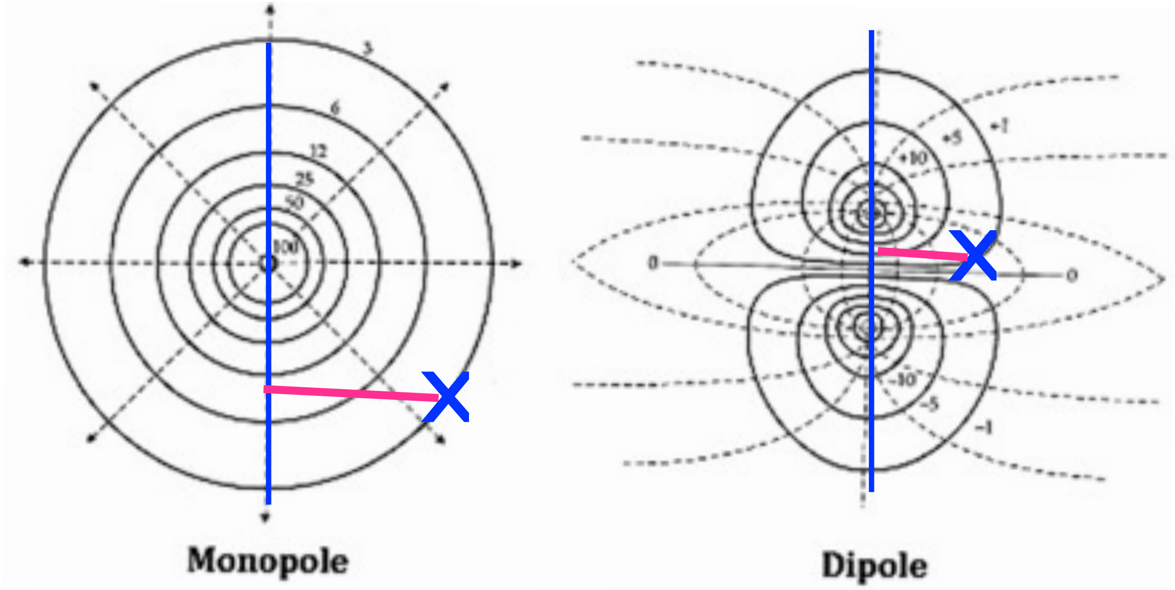




$$r_\theta = \min\{\theta_{13}/\theta_{12}, \theta_{23}/\theta_{12}\}$$

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



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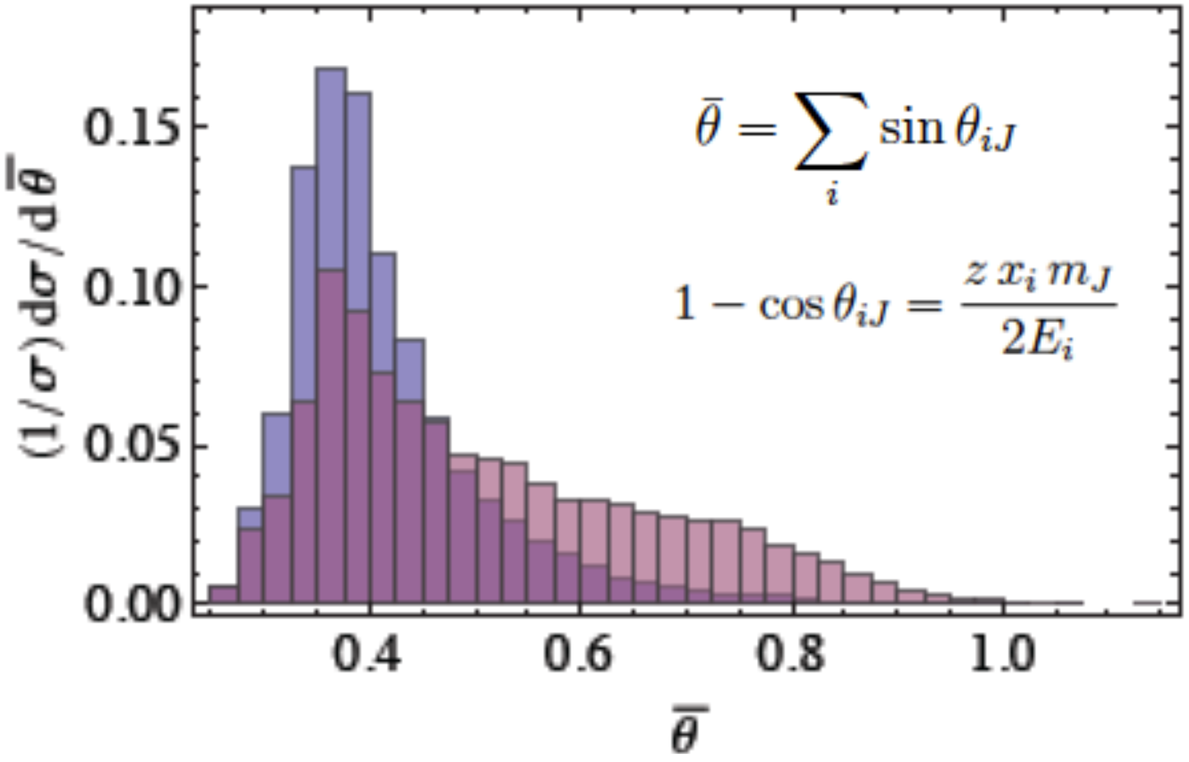

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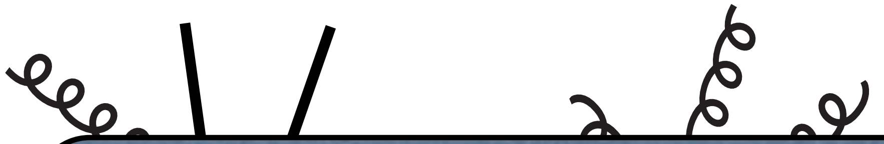
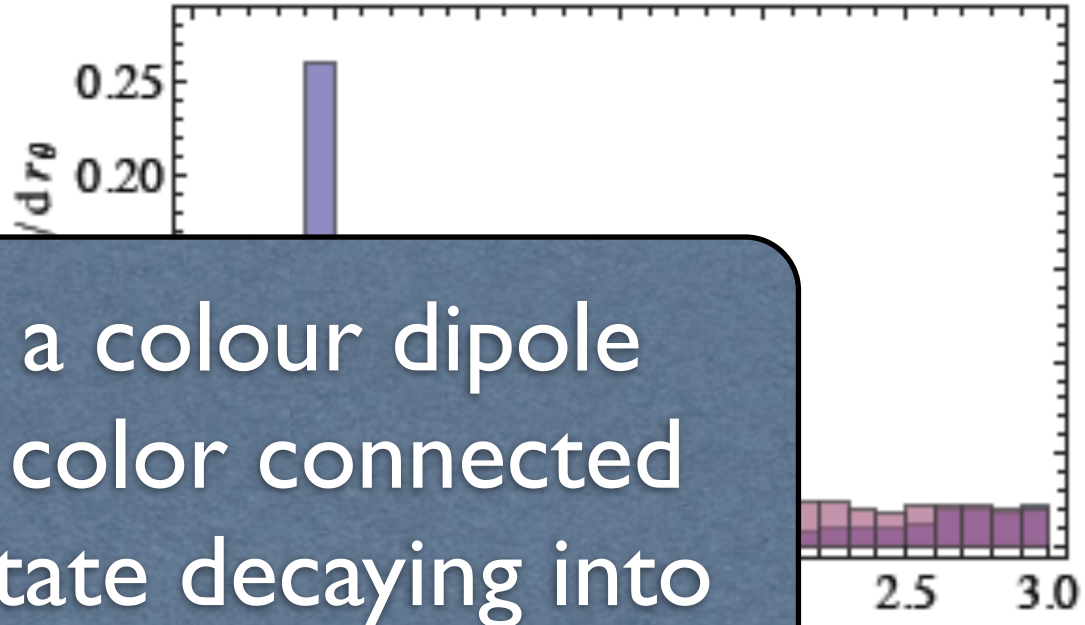
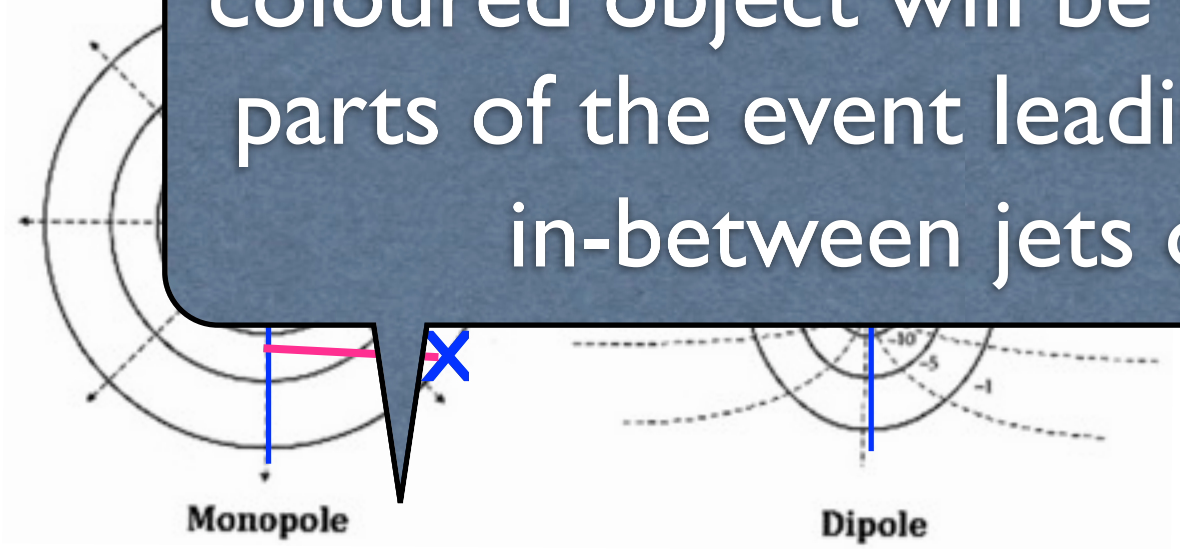


wh
ord



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.

- C



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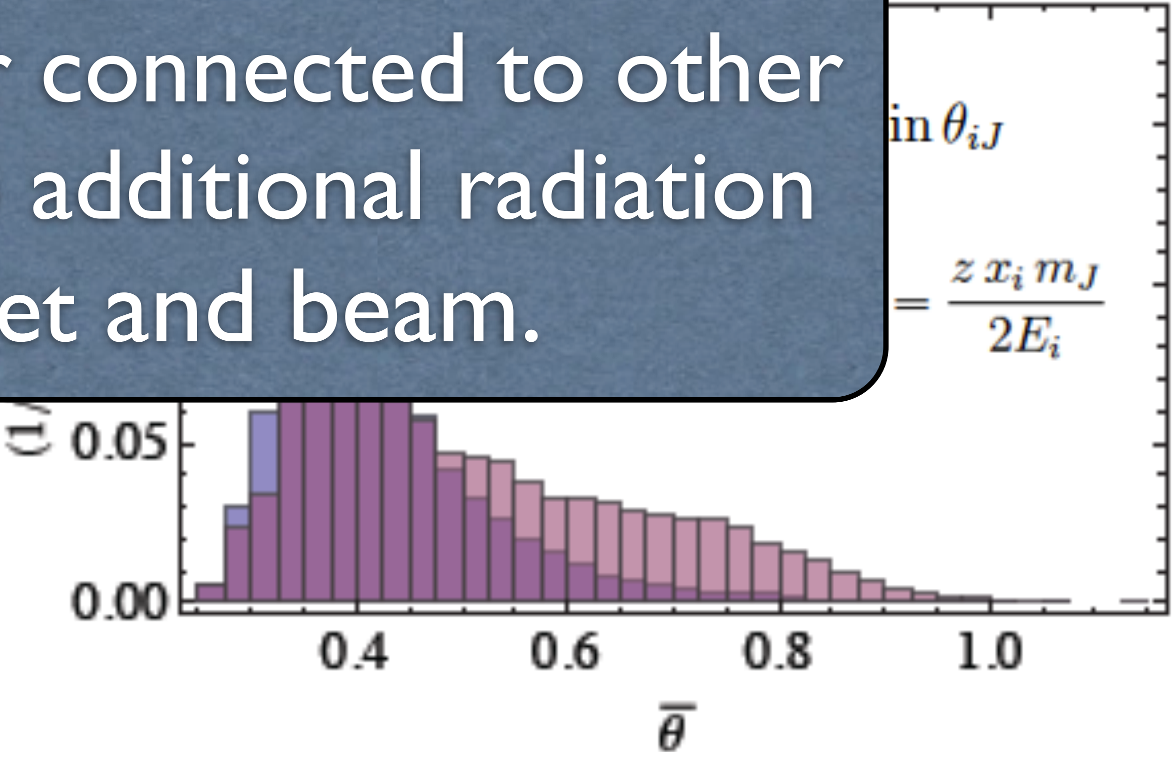
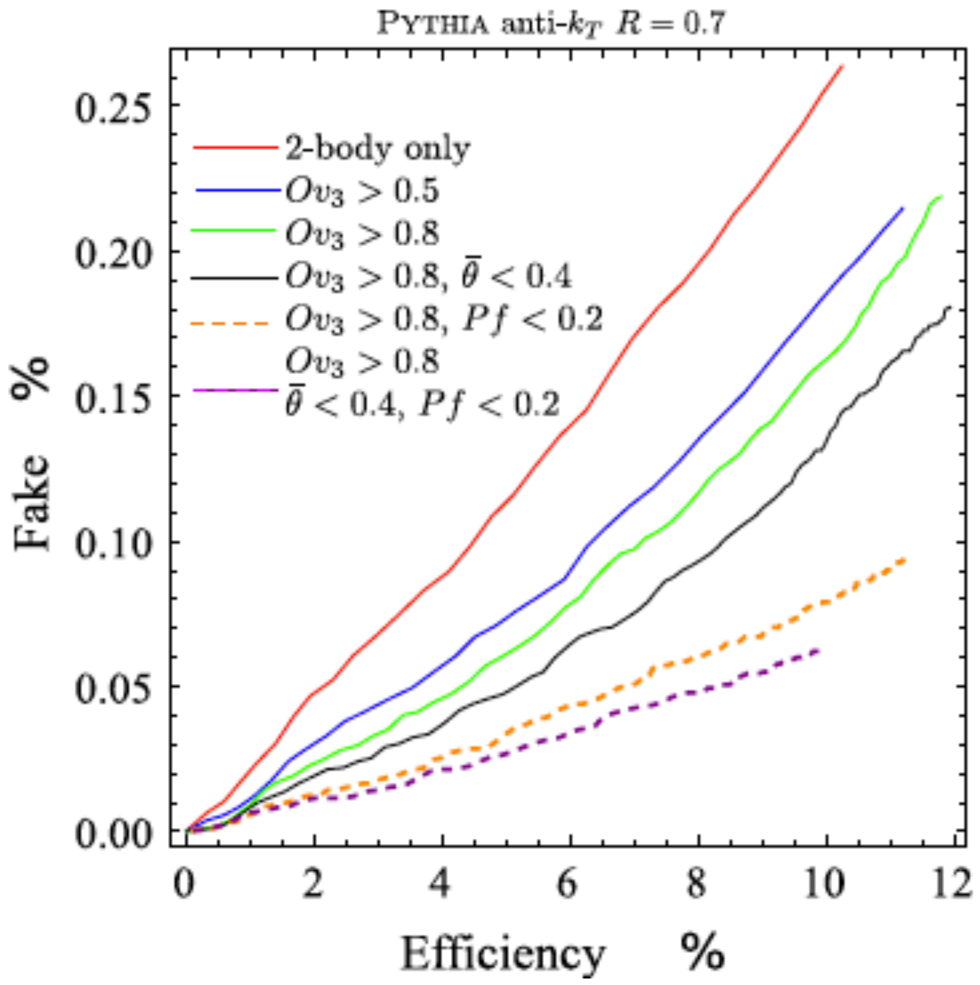


Fake vs. efficiency 2-body vs. 3-body

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



MC	Jet mass cut only		Mass cut + Ov +$\bar{\theta}$+ Pf	
	Higgs-jet efficiency [%]	fake rate [%]	Higgs-jet efficiency [%]	fake rate [%]
PYTHIA 8	70	10	10	0.05
MG/ME	70	10	10	0.05
SHERPA	60	10	10	0.05

Table 2: 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 $m_H = 120$ GeV.

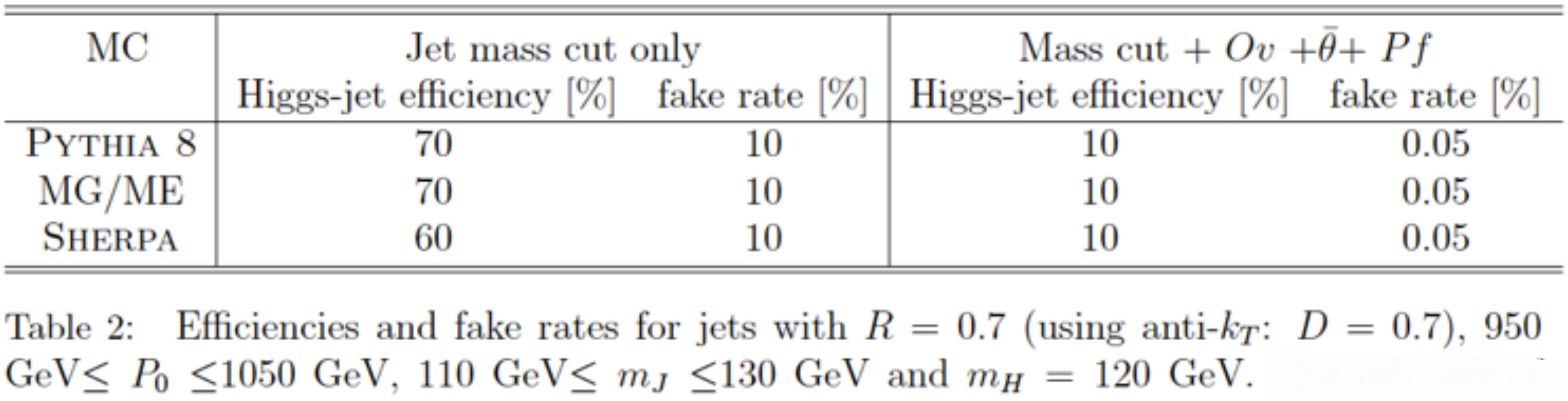
Fake vs. efficiency 2-body vs. 3-body

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

Naive rejection power (eff'/fake rate) -

Pythia8 & MG/ME:
better than
1 in 200

without optimization and without
b-tagging!



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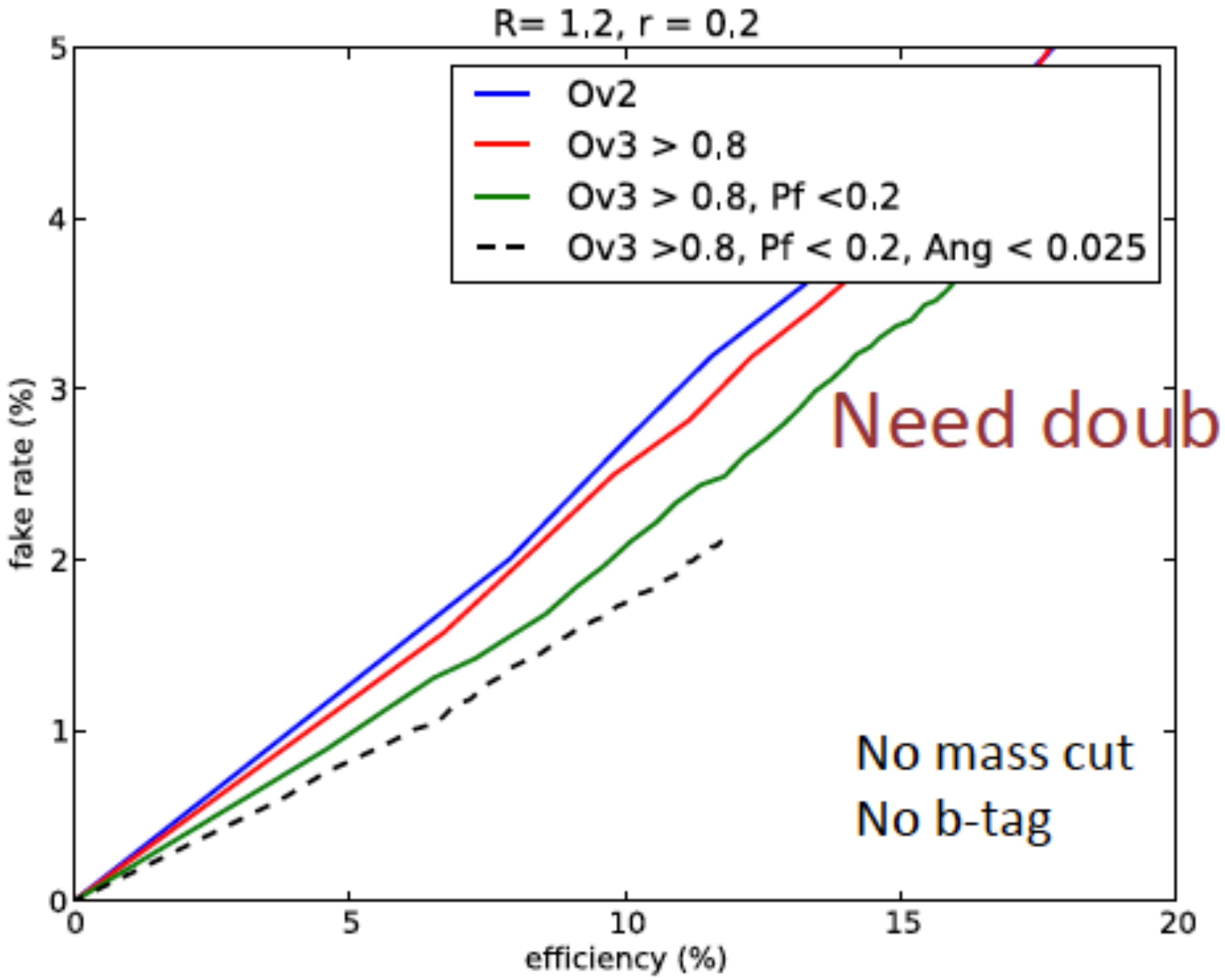
Work in progress (PT >200 GeV with pileup)

Mihailo Backovic , Jose Juknevich, Gilad Perez, Jan Winter, Weizmann Group

Rejection Rate



Need double b tag

For 10 % efficiency rejection
Factor of ~ 5.

Total rejection factor:

15 - *mass cut*
x 40 - *b-tagging*
x 5 - *template+pf*

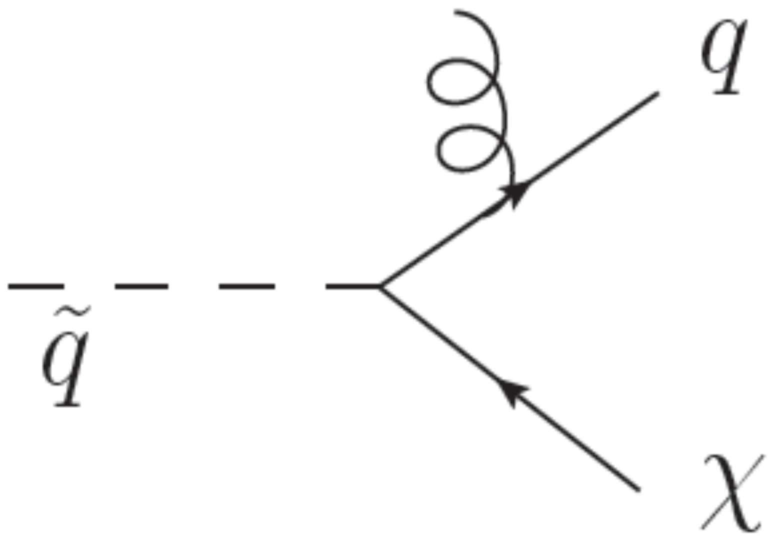
= 3000

New Physics Searches? Example: light stop decay

with Kim, Kim, and Zupan

- We focus on simple example of two body decay
  e.g. light stop decaying into top and MET (neturalino or gravitino)

$$\tilde{t} \to t\chi$$



- HQET +HSET

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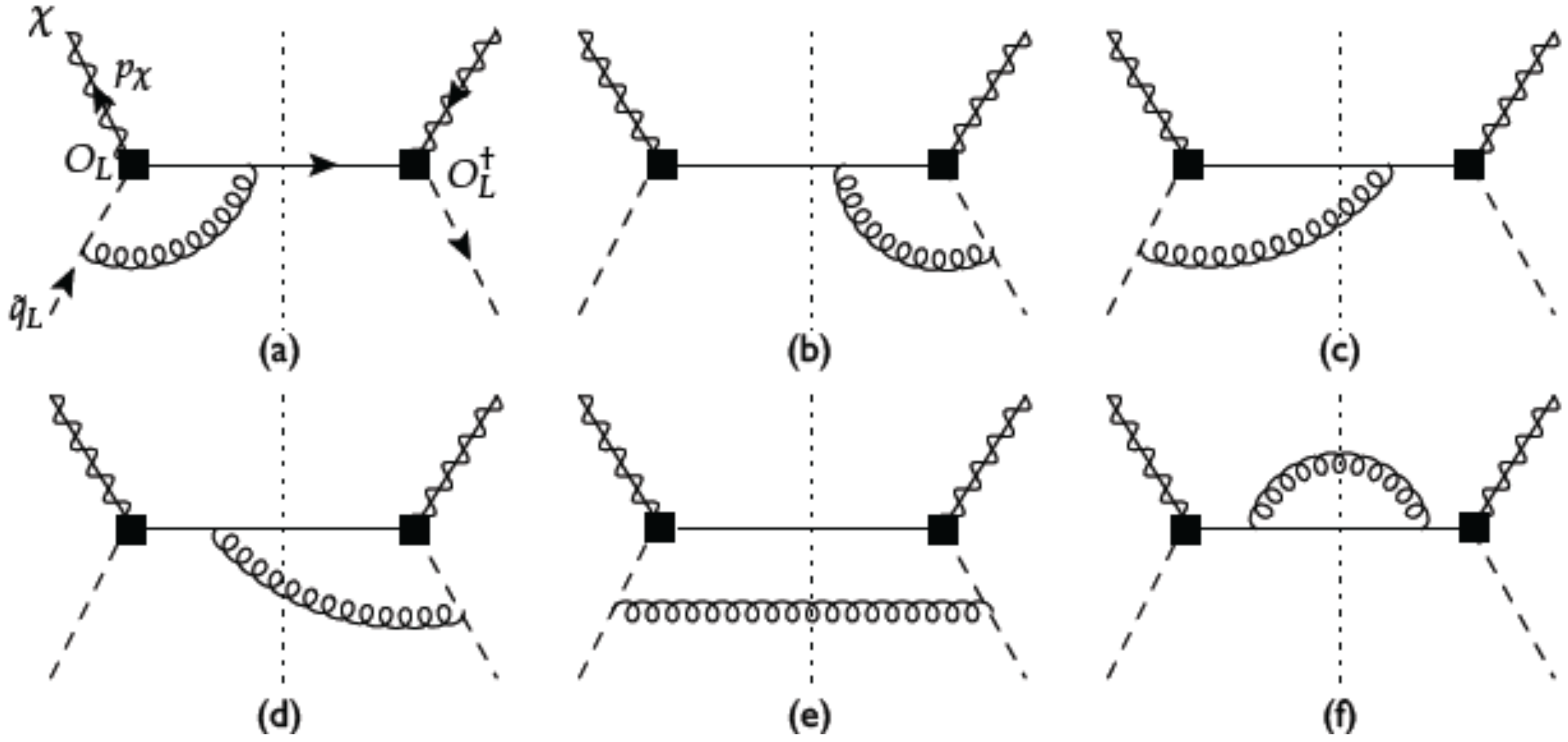

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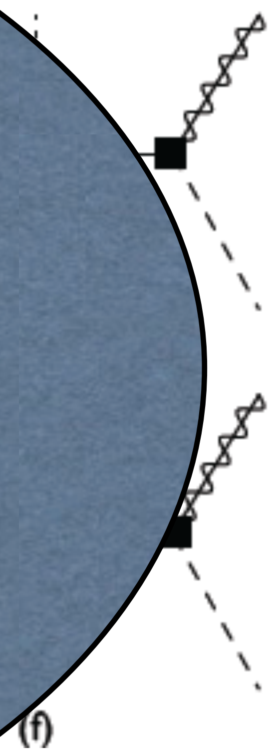


Template with MET, and generalized M_{T2}, etc

- HQET +HSE

Summary

- ◆ Template overlaps: new class of infrared safe jet observables, based on functional comparison of the energy flow in data with the flow in selected templates of partonic states.

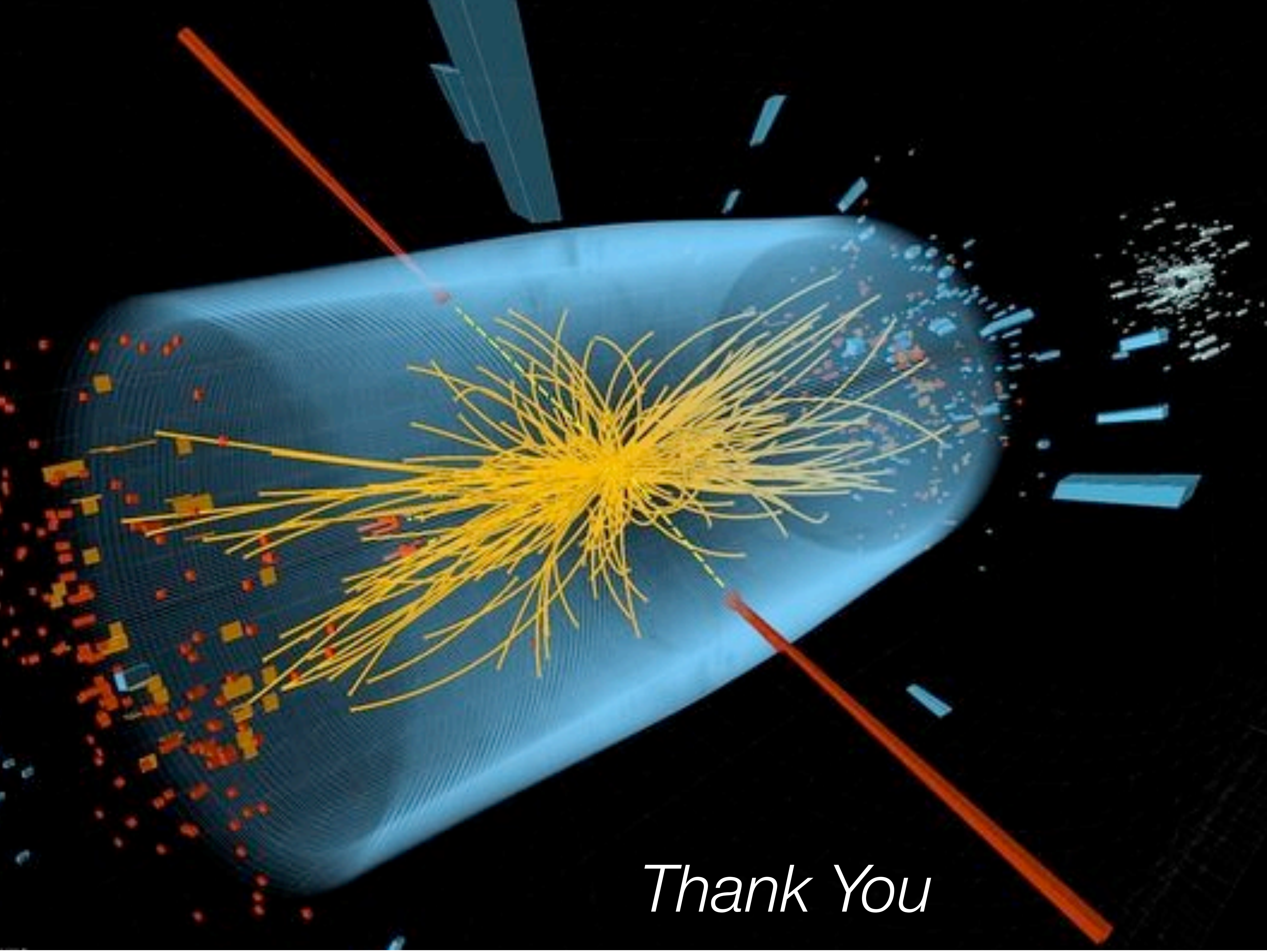
- ◆ Can use our knowledge of the signal to design a custom analysis for each resonance.

- ◆ Allows for systematic improvement

  e.g. by incorporating the effect of gluon emission,
  by weighting according to the lowest order matrix elements.

- ◆ Can have a large effect when combined with jet shapes or other jet substructure.

- ◆ Many applications for NP searches.



Thank You

Backups

NLO Planar Flow for Higgs Decay

- NLO Planar flow for Higgs:

$$\frac{1}{\sigma_0}\frac{d\sigma^{\rm NLO}}{d{\rm Pf}} = \frac{\alpha_s C_F}{8\pi^2}\int dx_1 dx_2 d(\cos\theta)d\phi\,\frac{(1-x_1-x_2)^2+1}{(1-x_1)(1-x_2)}\times\,\delta\left({\rm Pf}-\frac{E_J^3}{E_1E_2E_3}\,S\cos^2\theta\right)$$

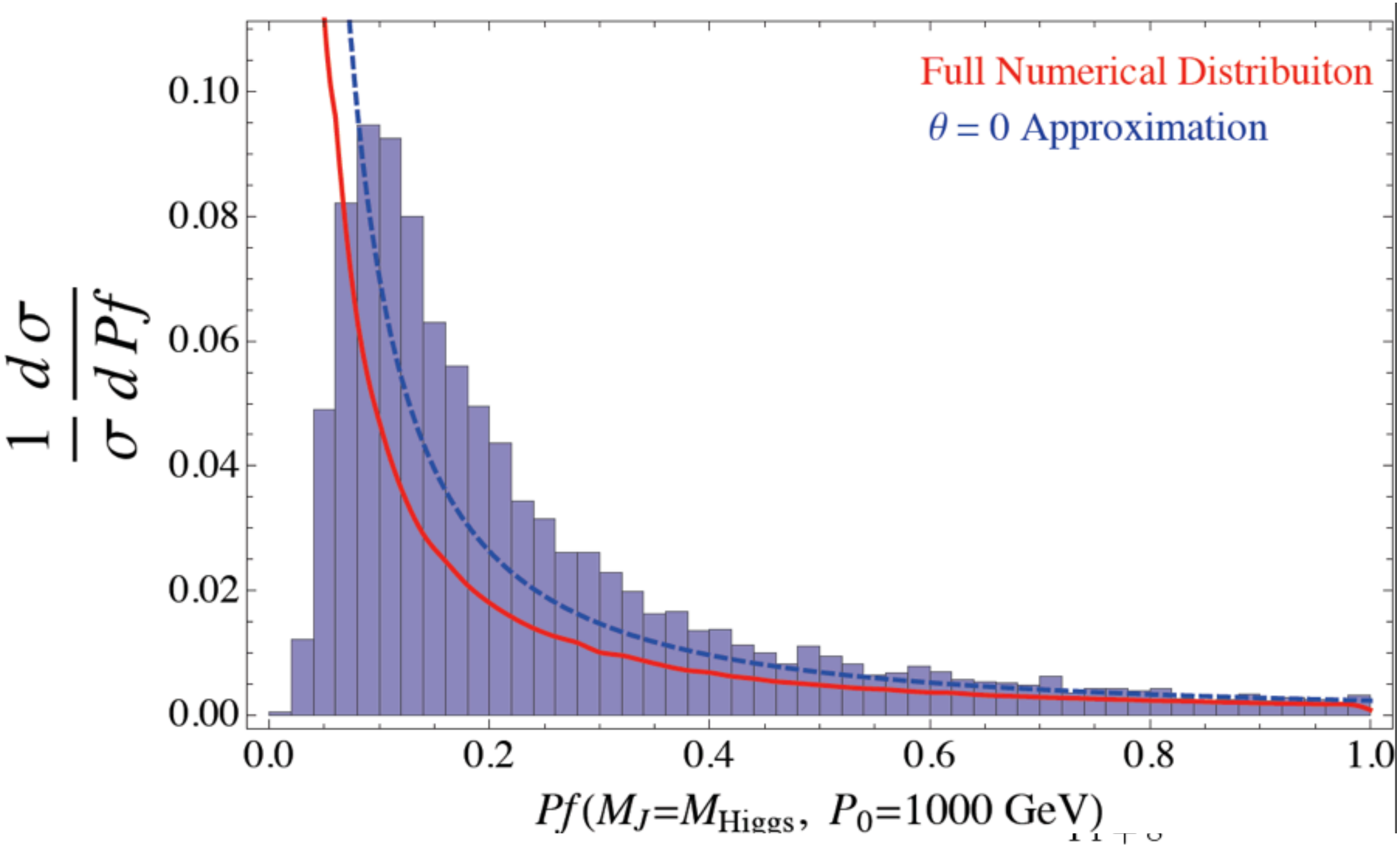
$$m_H/E_J \ll 1$$

- θ≈0 approximaiton:

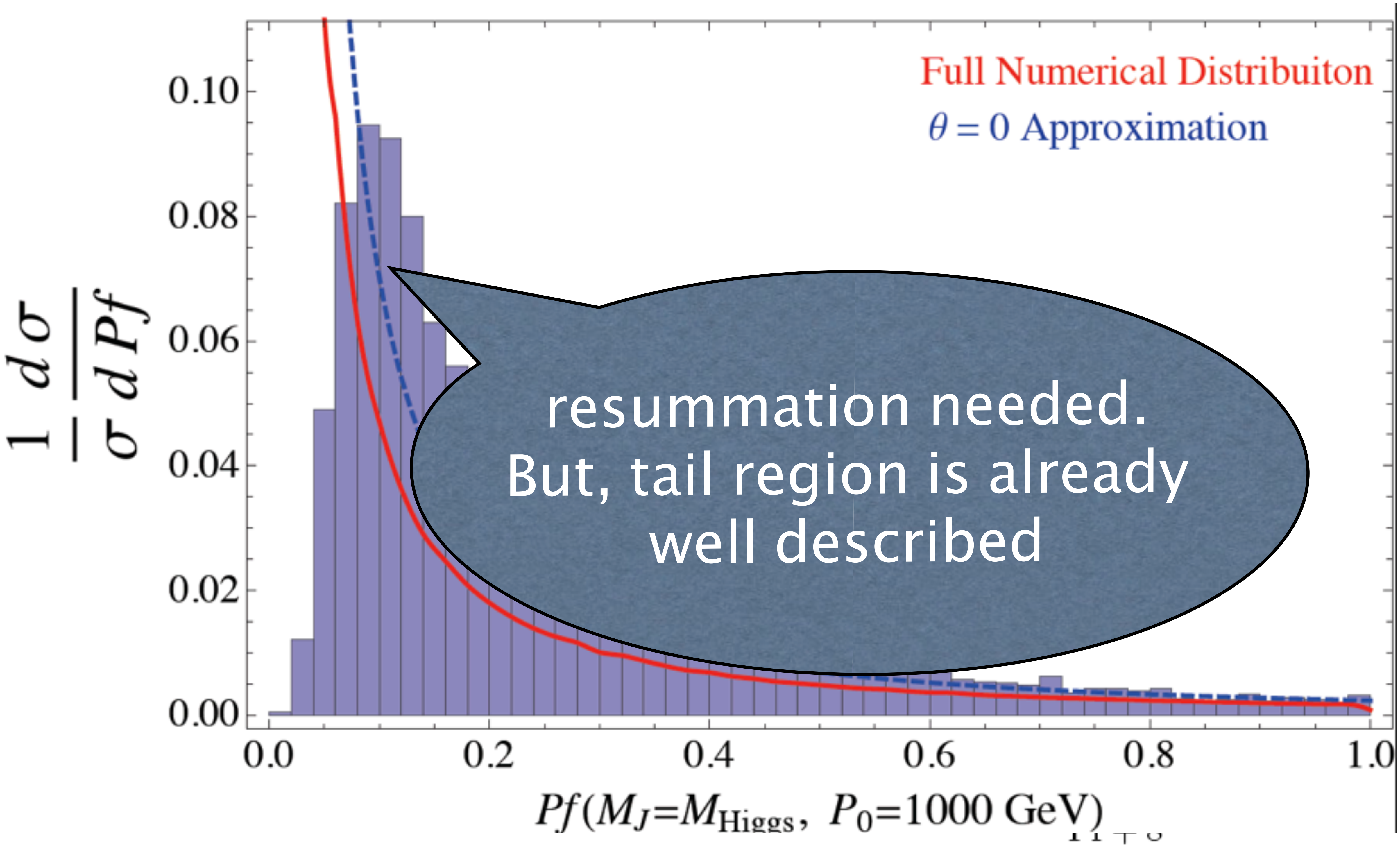
$$\frac{1}{\sigma_0}\frac{d\sigma^{(3)}}{d{\rm Pf}} = \frac{\alpha_s}{2\pi}{\rm C_F}\int_{x_2^-}^{x_2^+} dx\,\frac{8x\left[{\rm Pf}((x-3)x^2+4x)+8x((x-1)x+1)-8\right]}{{\rm Pf}({\rm Pf}+8)^2(\frac{8}{{\rm Pf}+8}-x)\sqrt{(\frac{8}{{\rm Pf}+8}-x)(x_2^+-x)(x_2^--x)x}}$$

$$x_2^\pm = \frac{2({\rm Pf}+2)-4\sqrt{1-{\rm Pf}}}{{\rm Pf}+8}$$

NLO Planar Flow for Higgs Decay



NLO Planar Flow for Higgs Decay



resummation needed.
But, tail region is already
well described

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

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

a ≤2 for IR safety

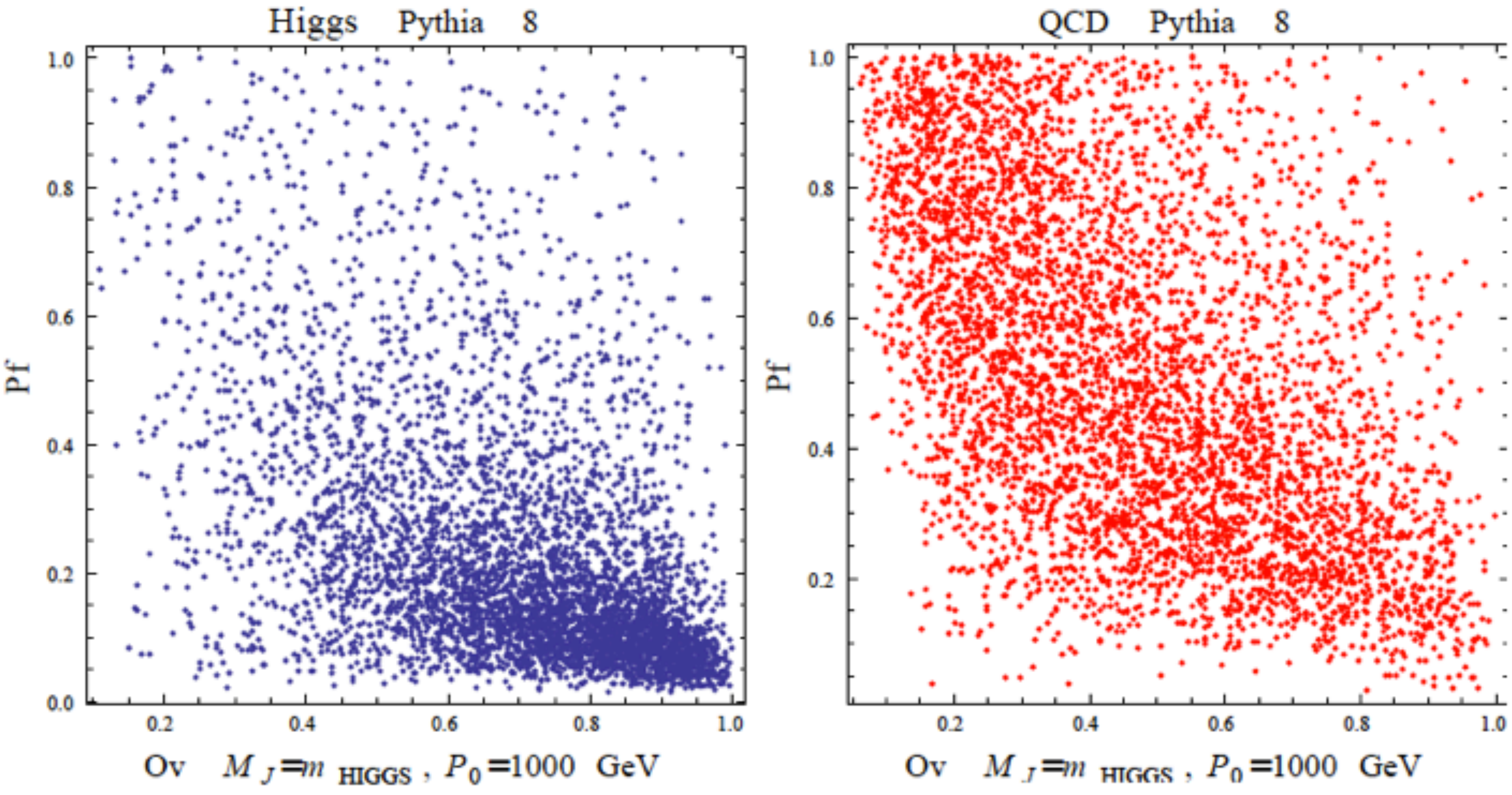
- Angularities distinguish between Higgs and QCD jets:

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

V.S.

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

NLO Higgs Template Ov with Pf



Scatter plots of planar flow Pf *vs.* template overlap Ov for Higgs jets and QCD jets from PYTHIA, for $R = 0.7$, 950 GeV$\leq P_0 \leq$1050 GeV, 110 GeV$\leq m_J \leq$130 GeV using three-body templates.

Things we can do nothing about

$$at\ \sqrt{s} \sim 7TeV$$

MCFM

	Wj+Zj	Wh+Zh
NLO (LO Γ)	32.8 pb	4.4 fb
NLO (NLO Γ)	32.8 pb	6.2 fb
K (LO Γ)	2.5	1.6
K (NLO Γ)	2.5	1.6
Pythia (m_j cut, w/ K fact.)	1.2 pb	3.2 fb
Pythia (no m_j cut, w/ K fact.)	39.4 pb	8.1 fb

With 5 fb^{-1} expect
15 events w/ the mass cut
and
40 events w/o the mass cut

$$\begin{aligned} \frac{S}{B}(115GeV < m_j < 135GeV) &= \frac{33..2fb}{1.2pb} \approx 3\times 10^{-3} \\ \frac{S}{B}(m_j > 0) &= \frac{8.2fb}{39.4pb} \approx 2\times 10^{-4} \end{aligned}$$

Not much but
Better than nothing!

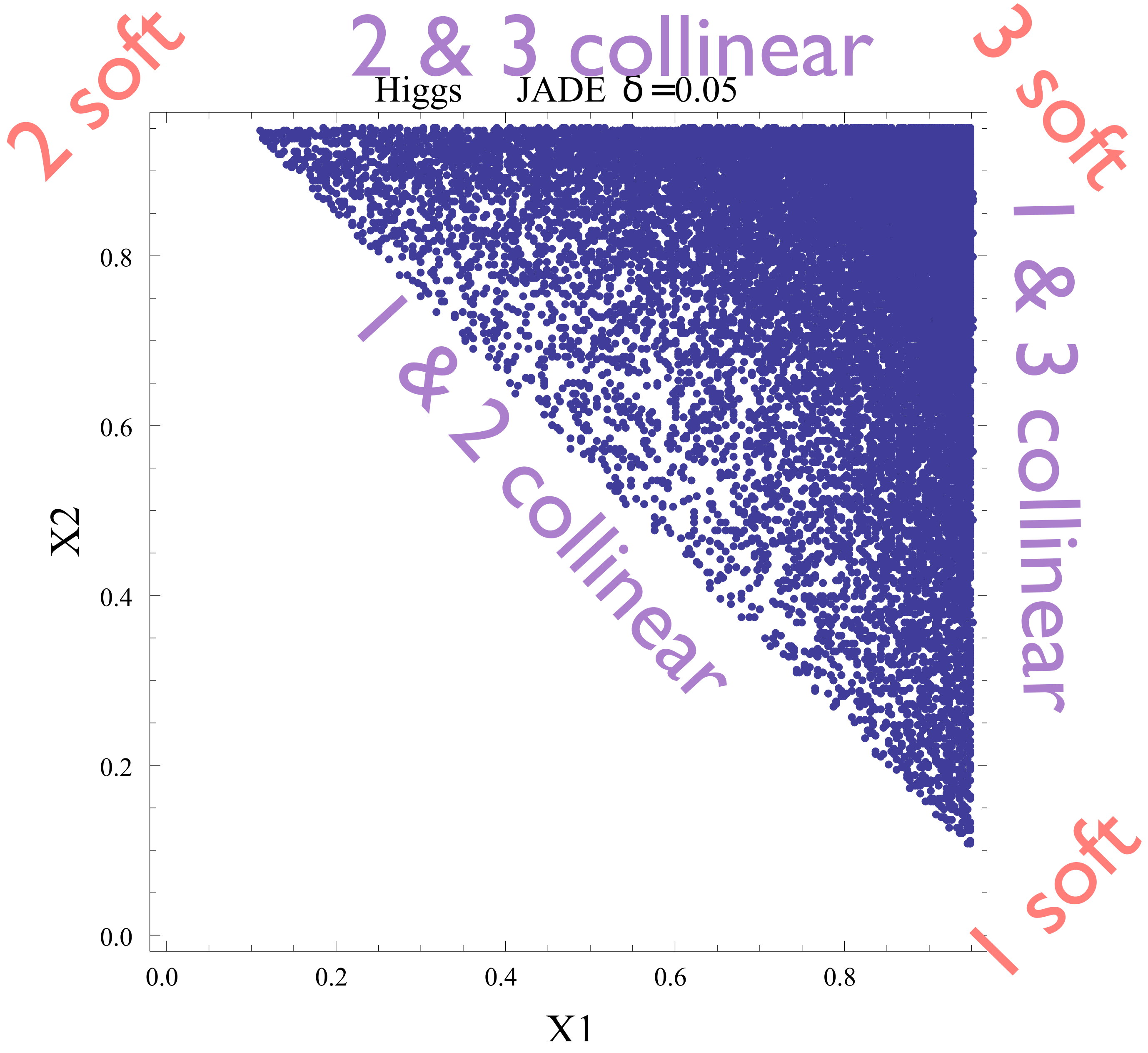
NLO Templates and Higgs Decay

- Differential cross section at NLO:

$$\frac{d\Gamma}{\Gamma_0} = \frac{1}{4\pi} d\phi\, d\cos\theta$$

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

Drees & Hikasa, PLB (90)



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

separate 2 vs 3-jet case by cut on in terms of the invariant mass of the pair of nearly-collinear partons

$$y_{ij} = \frac{(p_i+p_j)^2}{m_H^2} = (x_i + x_j - 1) > y$$

Higgs NLO template, cont'

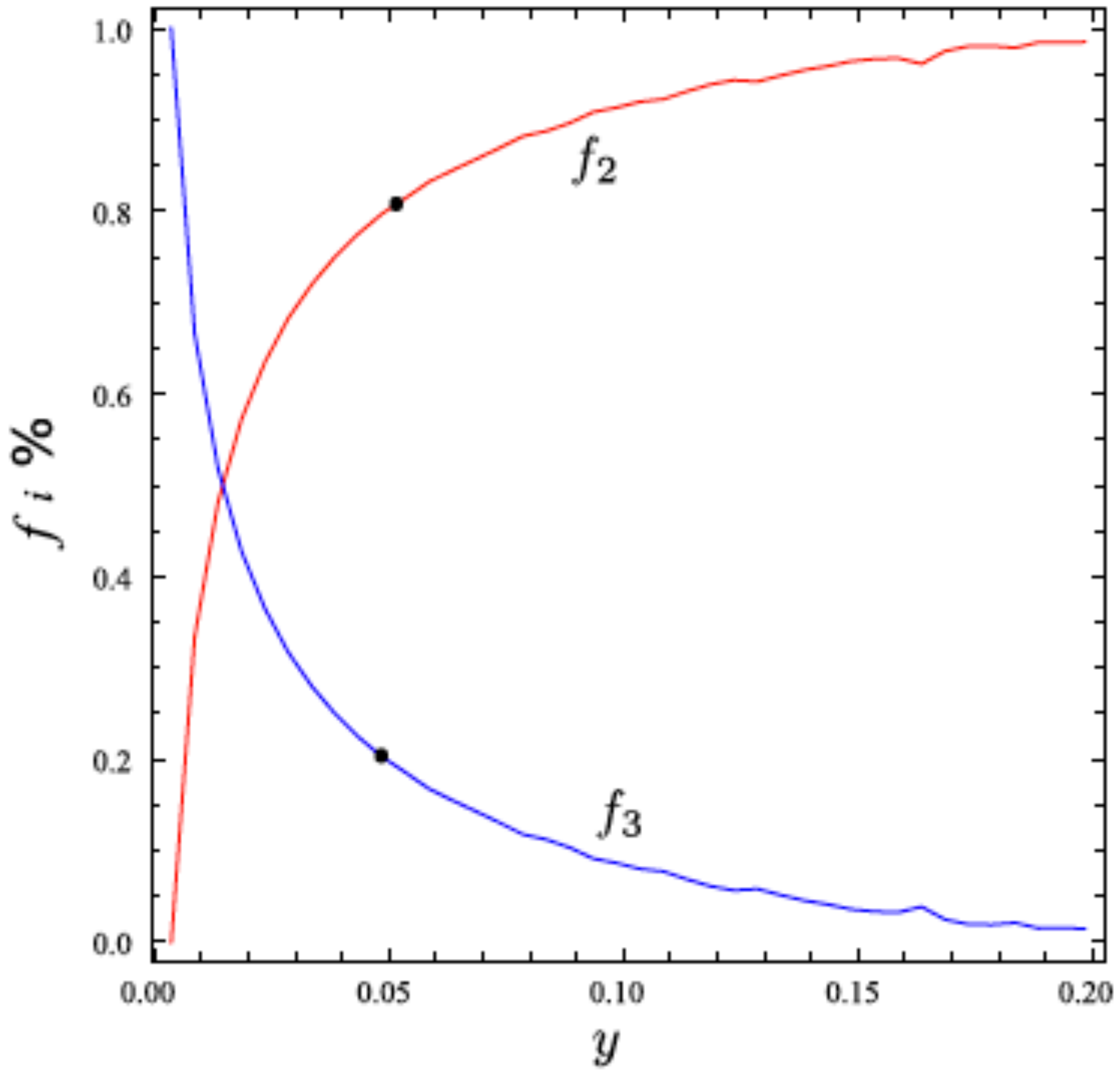
$$\sigma^{NLO} = \sigma(2\,\text{jet}) + \sigma(3\,\text{jet}) \qquad \sigma(n\,\text{jet}) = f_n\,\sigma$$

$$f_2 = 1 - f_3$$

$$|f\rangle = |h\rangle^{(\mathrm{LO})} = |p_1, p_2\rangle\,,$$

$$|f\rangle = |h\rangle^{(\mathrm{NLO})} = |p_1, p_2, p_3\rangle\,.$$

$$y_{ij} = \frac{(p_i + p_j)^2}{m_H^2} = (x_i + x_j - 1) > y$$



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