Substructure and Dynamics

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Outline

Jet cross-sections, perturbative QCD

Jet algorithms and Jet shapes

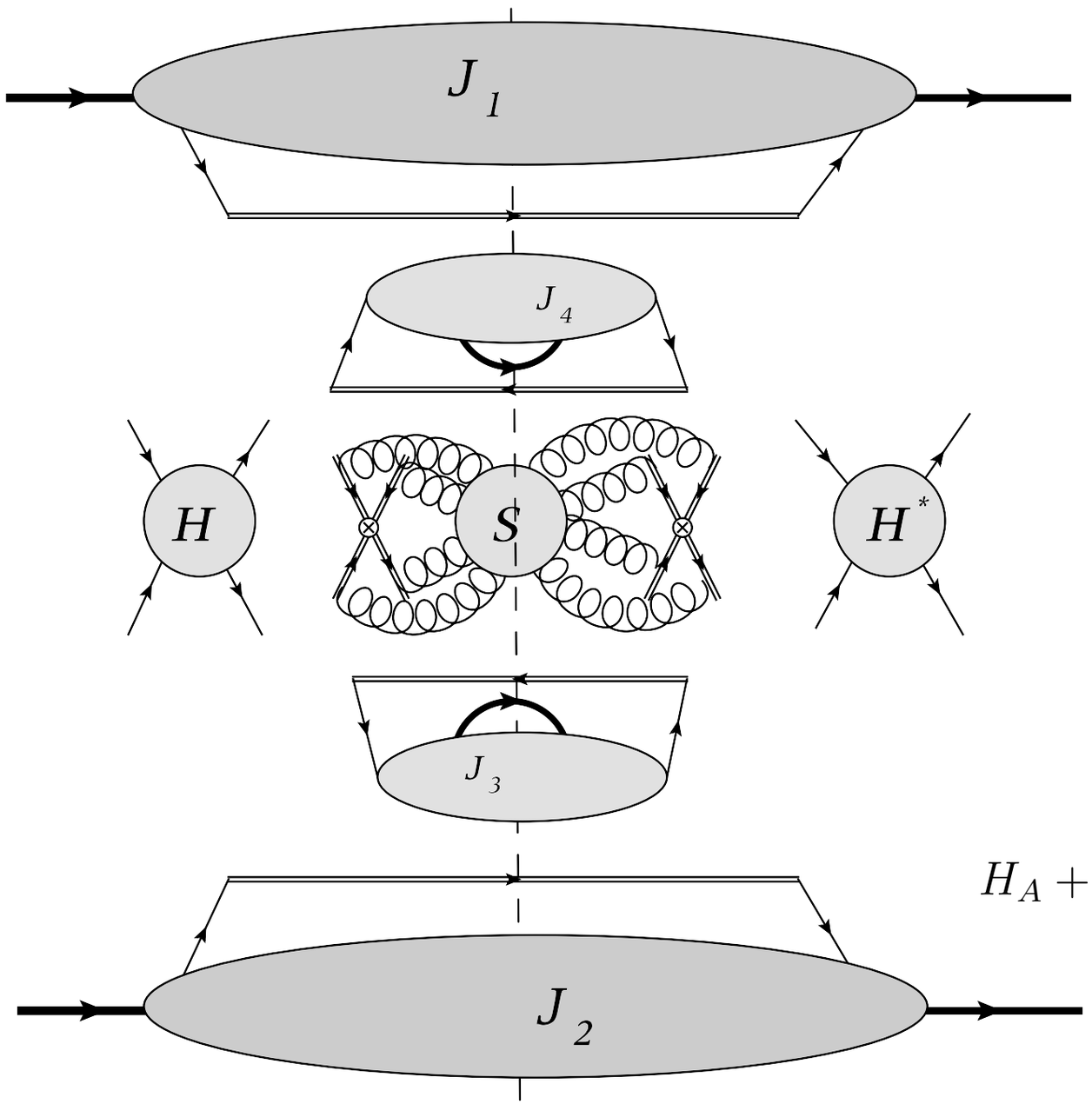
Color flow

Spin

Some Alternative Uses

Jet Cross-sections

$$\frac{d\sigma_{H_A H_B \to J_1 J_2}}{dp_T dm_{J_1}^2 dm_{J_2}^2 d\eta_1 d\eta_2} = \sum_{abcd} \int dx_a\, dx_b\, \phi_a(x_a)\, \phi_b(x_b) H_{ab\to cd}\left(x_a, x_b, p_T, \eta_1, \eta_2, \alpha_S(p_T)\right)$$
$$\times J_1^c(m_{J_1}^2, p_T \cosh\eta_1, R, \alpha_S(p_T))\; J_2^d(m_{J_2}^2, p_T \cosh\eta_2, R, \alpha_S(p_T))$$
$$S_{ab\to cd}(m_{J_1}, m_{J_2}, \eta_{1,2}, R)$$



$$H_A + H_B \to J(\mathcal{O}; p_{\rm T}, \eta; R) + X$$

Almeida, Lee, Perez, Sterman
Sung, Virzi (08)

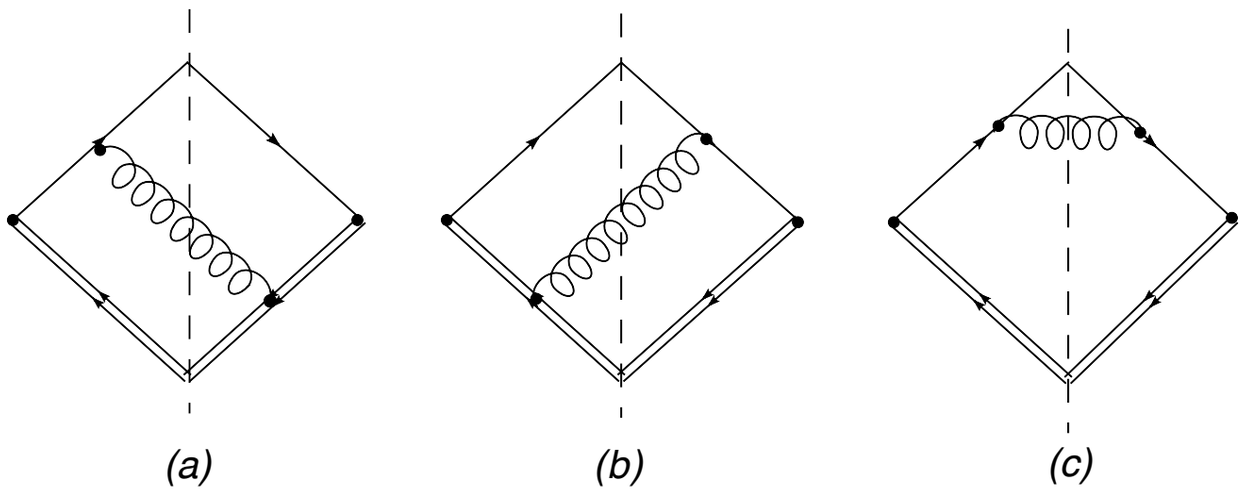
Jet functions

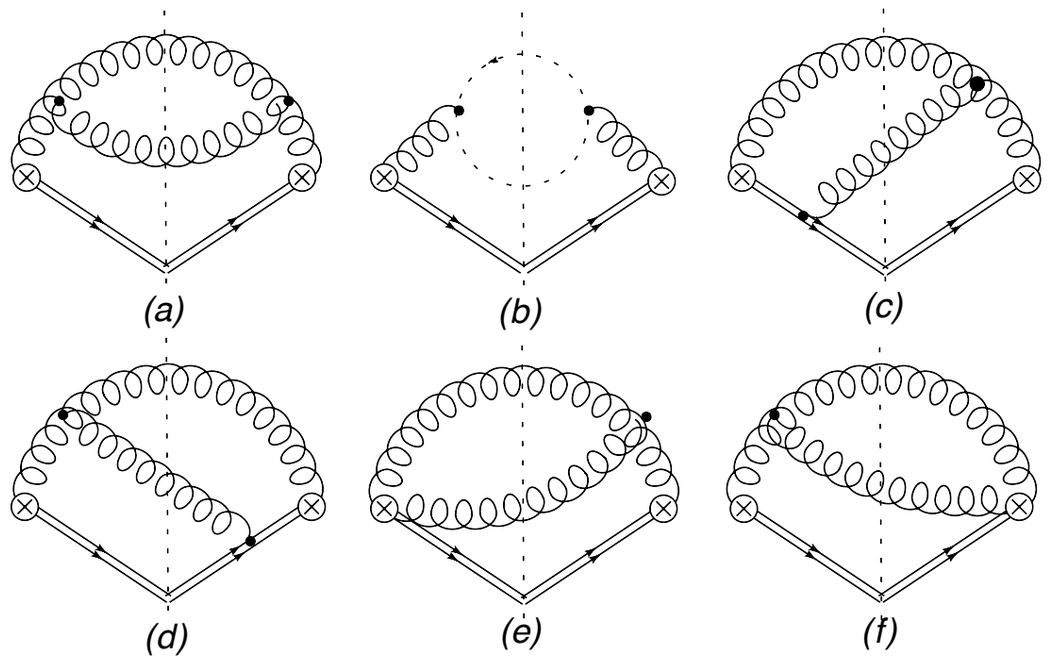
Quarks jets

$$J_i^q(m_J^2, p_{0,J_i}, R) = \frac{(2\pi)^3}{2\sqrt{2}\,(p_{0,J_i})^2}\frac{\xi_\mu}{N_c}\sum_{N_{J_i}} \mathrm{Tr}\left\{\gamma^\mu \langle 0|q(0)\Phi_\xi^{(\bar{q})\dagger}(\infty,0)|N_{J_i}\rangle\langle N_{J_i}|\Phi_\xi^{(\bar{q})}(\infty,0)\bar{q}(0)|0\rangle\right\}$$
$$\times\delta\left(m_J^2 - \tilde{m}_J^2(N_{J_i},R)\right)\delta^{(2)}(\hat{n}-\tilde{n}(N_{J_i}))\delta(p_{0,J_i}-\omega(N_{J_c})),$$

Gluons jets

$$J_i^g(m_J^2, p_{0,J_i}, R) = \frac{(2\pi)^3}{2(p_{0,J_i})^3}\sum_{N_{J_i}}\langle 0|\xi_\sigma F^{\sigma\nu}(0)\Phi_\xi^{(g)\dagger}(0,\infty)\,|N_{J_i}\rangle\langle N_{J_i}|\Phi_\xi^{(g)}(0,\infty)\,F_\nu^\rho(0)\xi_\rho|0\rangle$$
$$\times\delta\left(m_J^2 - \tilde{m}_J^2(N_{J_i},R)\right)\delta^{(2)}(\hat{n}-\tilde{n}(N_{J_i}))\delta(p_{0,J_i}-\omega(N_{J_c})).$$



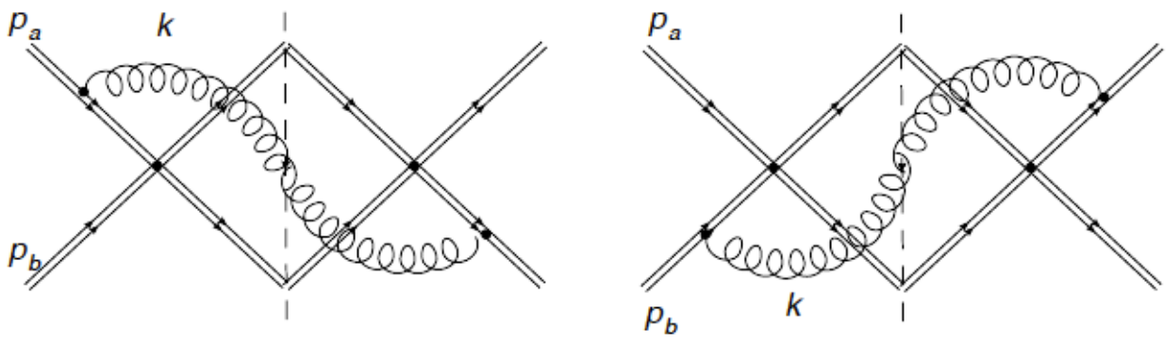


Almeida, Lee, Perez, Sung, Virzi (08)

Soft Function

$$S^f_{IJ} = \sum_{N_{J_i}} \langle 0|w^f_I(0)^\dagger_{a_i}|N\rangle\langle N|w^f_J(0)_{a_i}|0\rangle \times \delta\left(m_J^2 - \tilde{m}_J^2(N_{J_i}, R)\right)\delta^{(2)}(\hat{n} - \tilde{n}(N_{J_i})\delta(p_{0,J_i} - w(N_{J_c}))$$

$$w^f_I(x)_{a_i} = \Phi^{f_1}_{\xi_1,\{c_1,d_1\}}(\infty, 0; x)\Phi^{f_2}_{\xi_1,\{c_2,d_2\}}(\infty, 0; x)\left[\mathbf{C^f_I}\right]_{d_1,d_2;d_3,d_4} \times \Phi^{f_3}_{\xi_3,\{d_3,c_3\}}(0, -\infty; x)\Phi^{f_4}_{\xi_4,\{d_4,c_4\}}(0, -\infty; x)$$



$\sim R^2$

For collimated jets $\frac{d\sigma_{H_AH_B\to J_1X}(R)}{dp_T dm_J d\eta} = \sum_{abc}\int dx_a\, dx_b\, \phi_a(x_a)\,\phi_b(x_b) H_{ab\to cX}(x_a, x_b, p_T, \eta, R) \times J^c_1(m_J, p_T, R).$

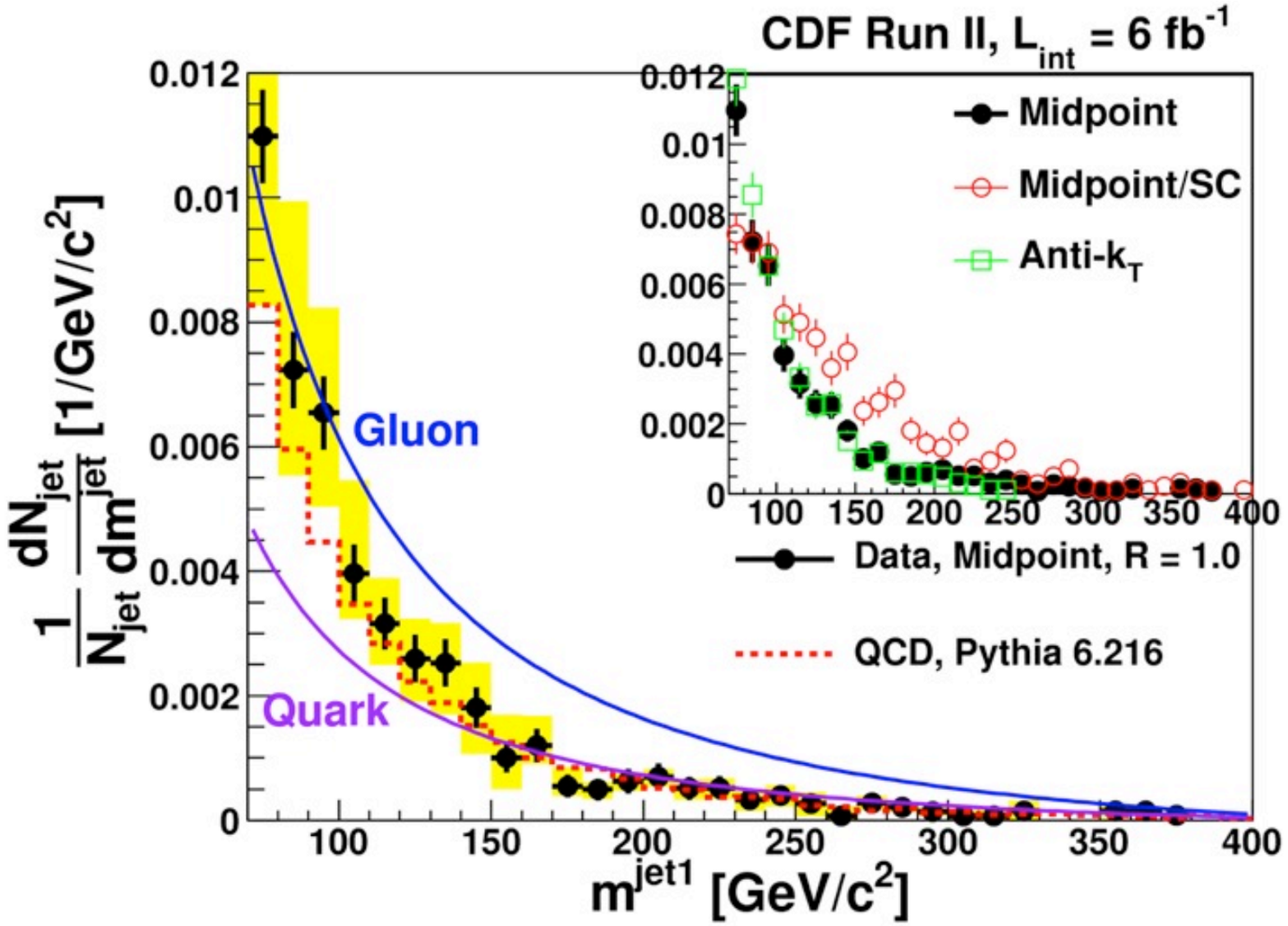
can be considered to be “Contamination” to the decay partial width.

Almeida, Lee, Perez, Sung (08)

Leading Log

Leading Contribution: Single Gluon Emission

$$J^{(f)} = 2\frac{\alpha_S}{\pi}\frac{C_f}{m_J}\log\left(\frac{p_T^2 R^2}{m_J^2}\right)$$



Almeida, Alon, Spannowsky 12

Resummation

These can perturbative expanded, to compute its fixed order contribution, or compute its evolution.

$$\mu^2 \frac{d}{d\mu^2} d\sigma_{H_1 H_2 \to J_1 J_2 X} = 0$$

$$\eta_i \frac{\partial}{\partial \eta_i} J_i = \mathcal{K}_i J_i$$

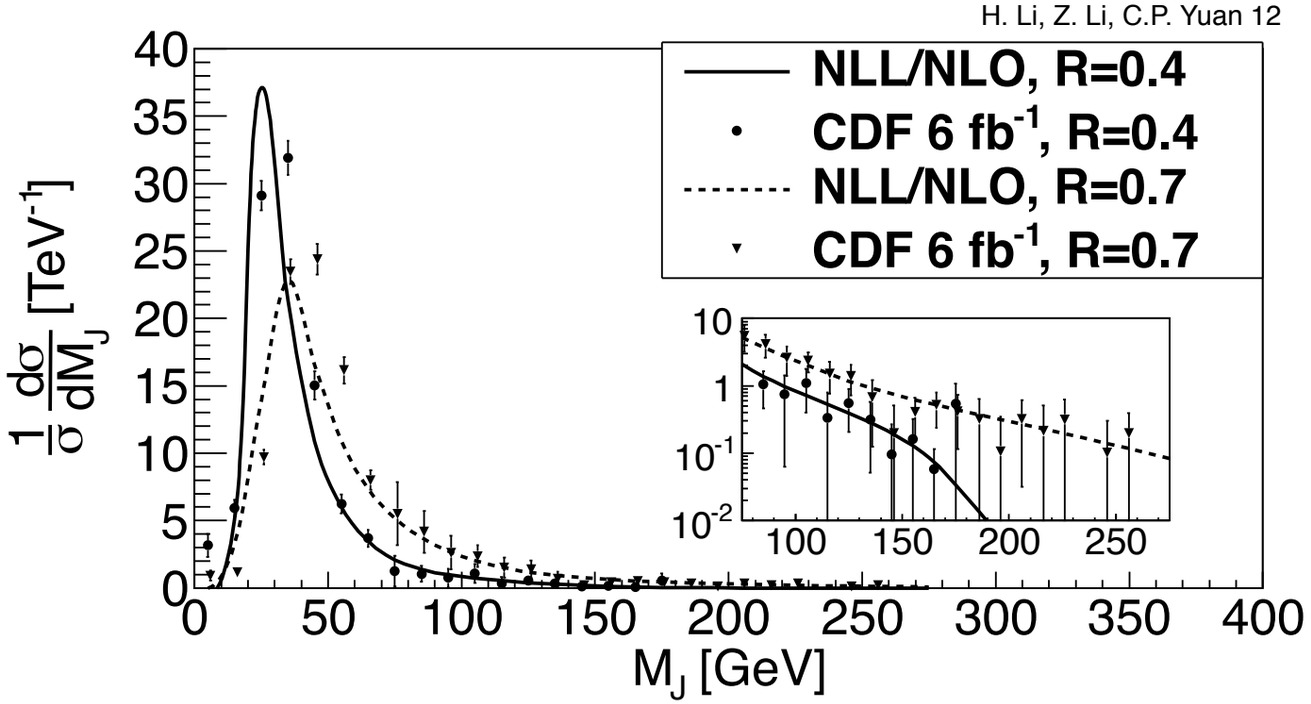
$$\bar{J}_q(N, P_T, \nu^2_{\rm fi}, R) \;=\; \bar{J}_q(N, P_T, \nu^2_{\rm in}, R) \exp[S_q(N, P_T, R)],$$

H. Li, Z. Li, C.P. Yuan 12

Resummed Jet Mass Distribution

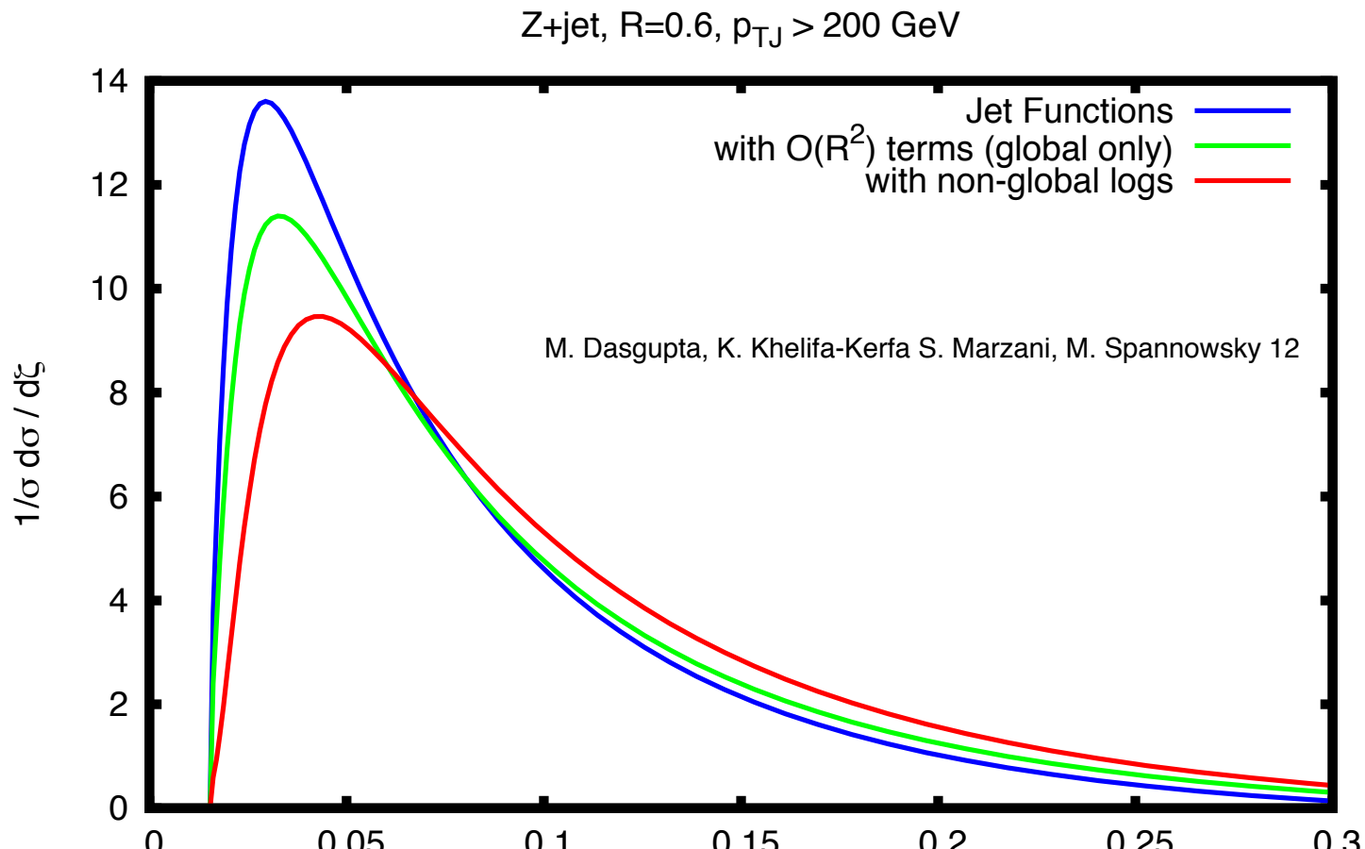
$$\frac{1}{\sigma}\frac{d\sigma}{dM_J^2} = \frac{1}{\sigma}\sum_f \int dP_T \frac{d\hat{\sigma}_f}{dP_T}(M_J^2, P_T) J_f^{\mathrm{NLL/NLO}}(M_J^2, P_T, R),$$

H. Li, Z. Li, C.P. Yuan 12



$$\bar{J}_q(N, P_T, \nu_{\mathrm{fi}}^2, R) \;=\; \bar{J}_q(N, P_T, \nu_{\mathrm{in}}^2, R)\exp[S_q(N, P_T, R)],$$

$$p_T > 400\mathrm{GeV}$$



BDRS type algorithms,

J. M. Butterworth, A. R. Davison, M. Rubin and G. P. Salam

Find a Fat jet, large size.

Better: energy/mass resolution of jet.
Worse: Contamination from radiation unrelated to final states

Then filter it, by deconstructing the jet and apply cuts to its subjets. Mainly using kinematic constraints

Top taggers

try to match the kinematic structure of top decay.

K. Rehermann and B. Tweedie

D. Kaplan, K. Rehermann, M. D. Schwartz and B. Tweedie,

J. M. Butterworth, B. E. Cox and J. R. Forshaw

J. Thaler and L. -T. Wang

T. Plehn, G. P. Salam and M. Spannowsky,

Jet Grooming

Recluster the jet and put cuts on the subjets, based on their pt, and relative distances.

Trimming/Filtering

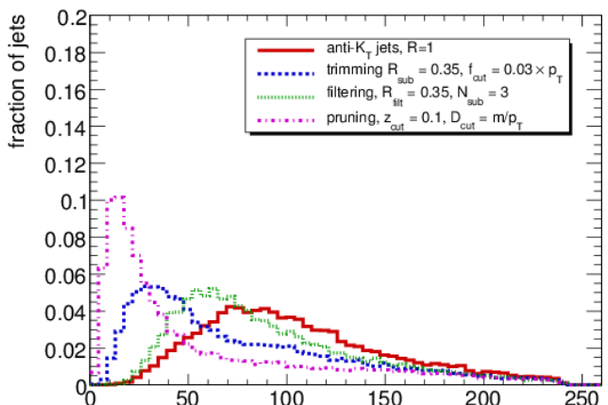
Recluster the jet and place cuts on the subjets, based on their

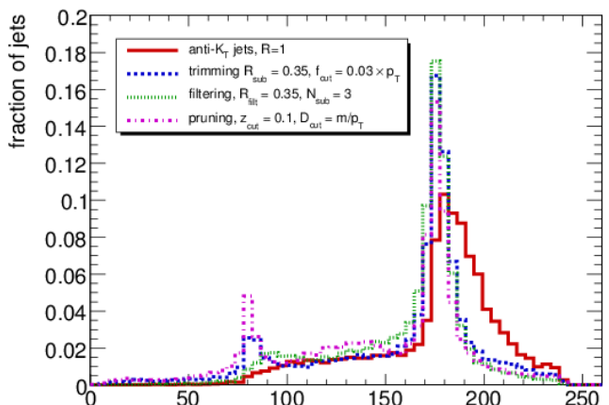
$$P_{T,j} > f \times \Lambda$$

Prunning

Recluster the jet until no pairs has $R_{ij} > D_{cut}$

Recluster such that the subjets $\frac{\min(\mathrm{p_{T,i}}, \mathrm{p_{T,j}})}{p_{T,ij}} > z_{cut}$





[arXiv:1012.5412 [hep-ph]

Jet Shapes

Another way Another way to proceed, is to compute observables for the entire jet.

$$\Psi(r) = \frac{1}{N} \sum_{J} \sum_{i \in J} \frac{p_T(0 < r_i < r)}{p_{T,J}}$$

Using the jet function resumation

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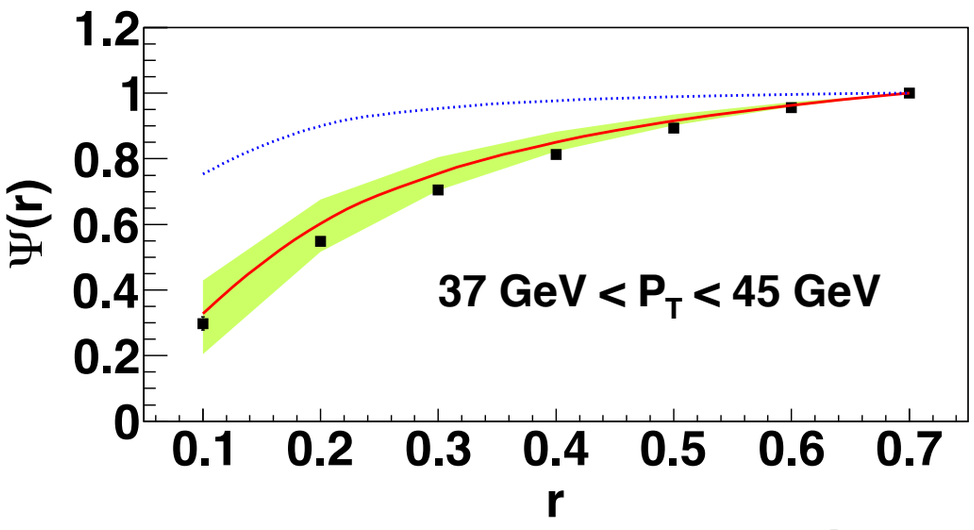
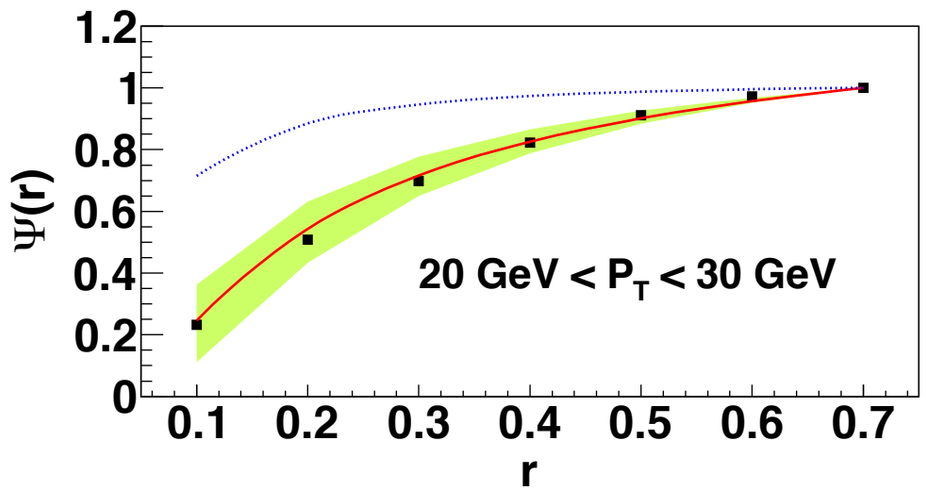
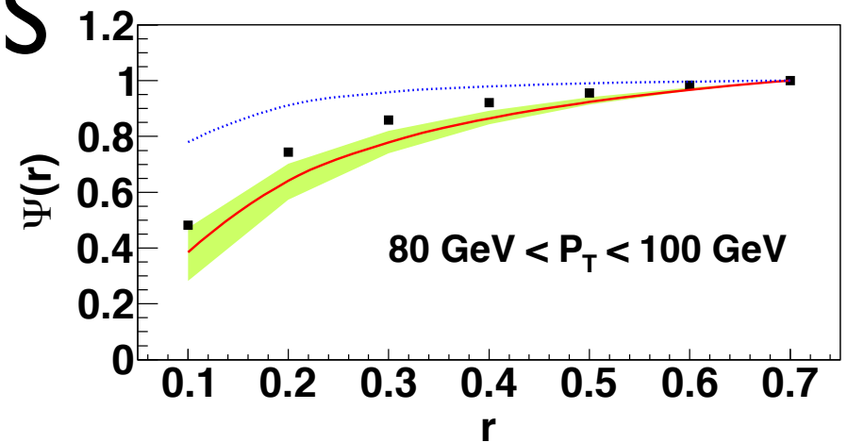




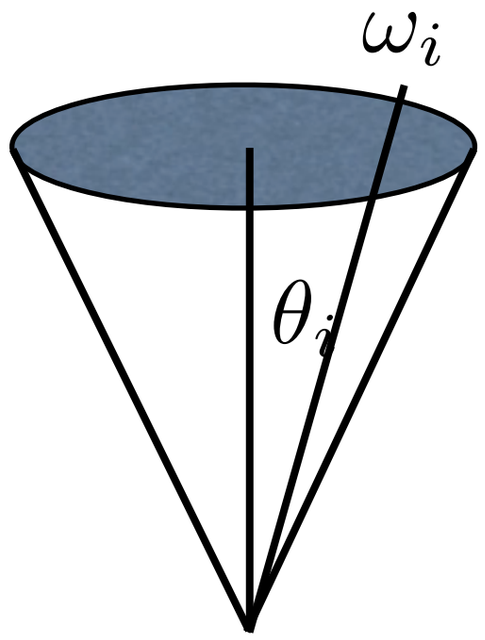
CDF

CMS



Angularities

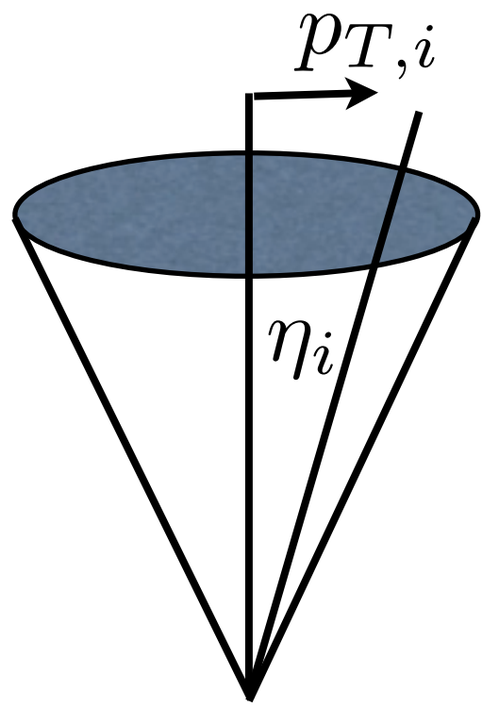
$$\tau^a = \omega_i \cos\theta_i (1 - \sin\theta_i)^{1-a}$$



$$a = 0 \rightarrow \tau_0 = 1 - T$$

In the jet's invariant frame

$$\tau^a = \sum_i p_{T,i} e^{(1-a)\eta_i}$$



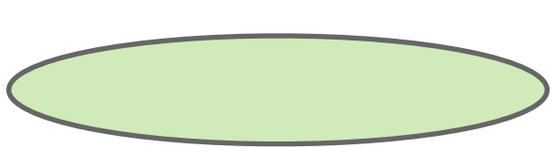
2-Moment Tensor

$$\mathcal{I} \equiv \sum_{i \in \text{jet}} p_{\text{T}}^{i} \begin{pmatrix} \Delta\eta_i^2 & \Delta\eta_i\Delta\phi_i \\ \Delta\eta_i\Delta\phi_i & \Delta\phi_i^2 \end{pmatrix}$$

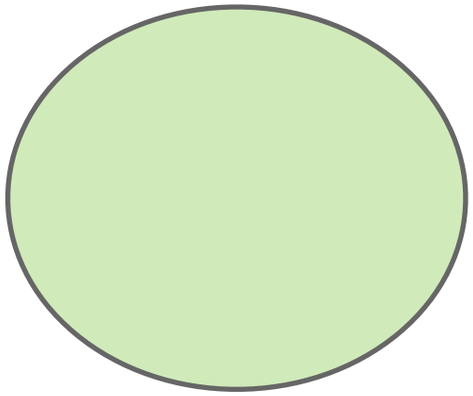
"jet inertia"

$$\text{Broading} = \text{TrI}$$

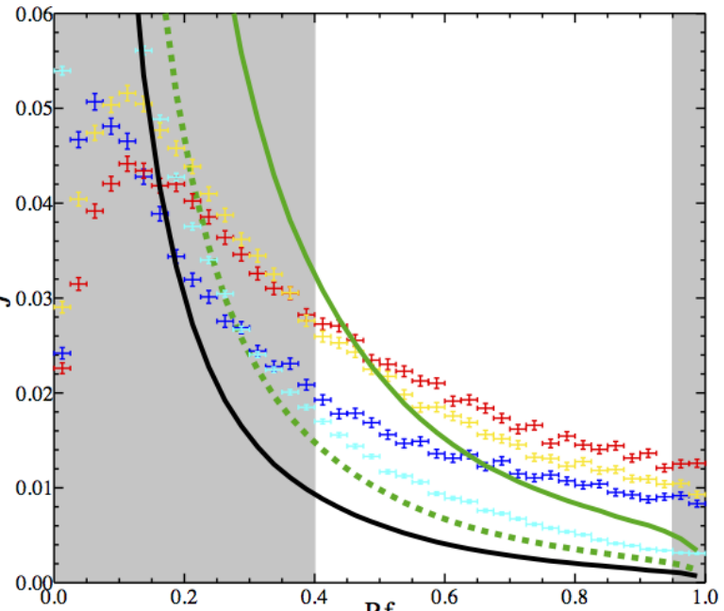
$$P_f = 4\frac{\text{DetI}}{(\text{TrI})^2}$$



$P_f \sim 0$

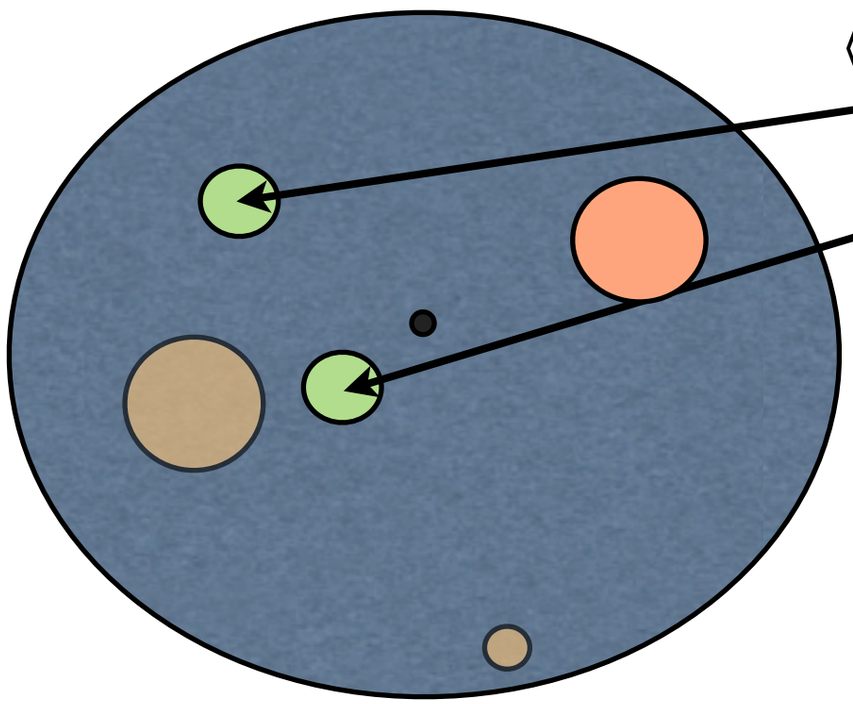


$P_f \sim 1$

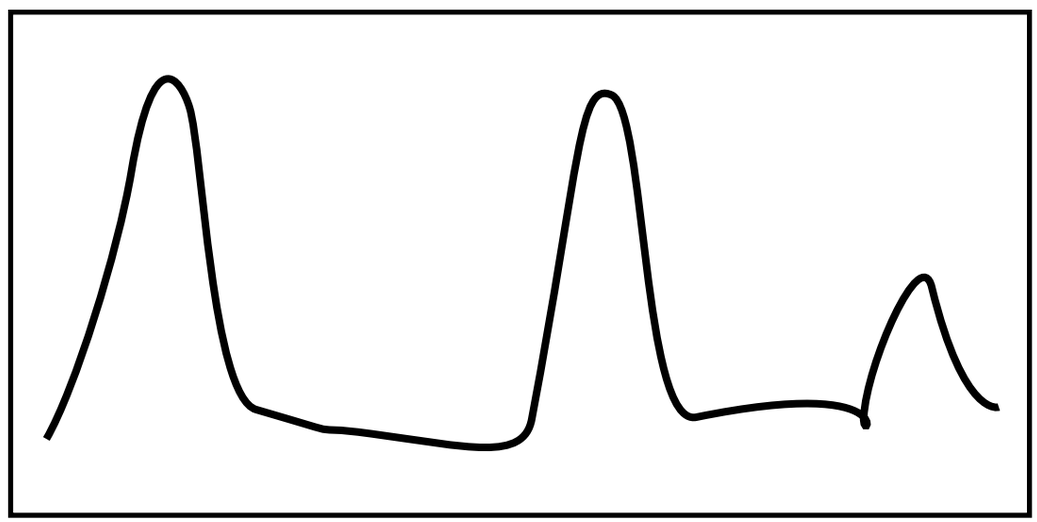


Field, Gur-Ari, Kosower, Mannelli, Perez

Energy Energy Correlation



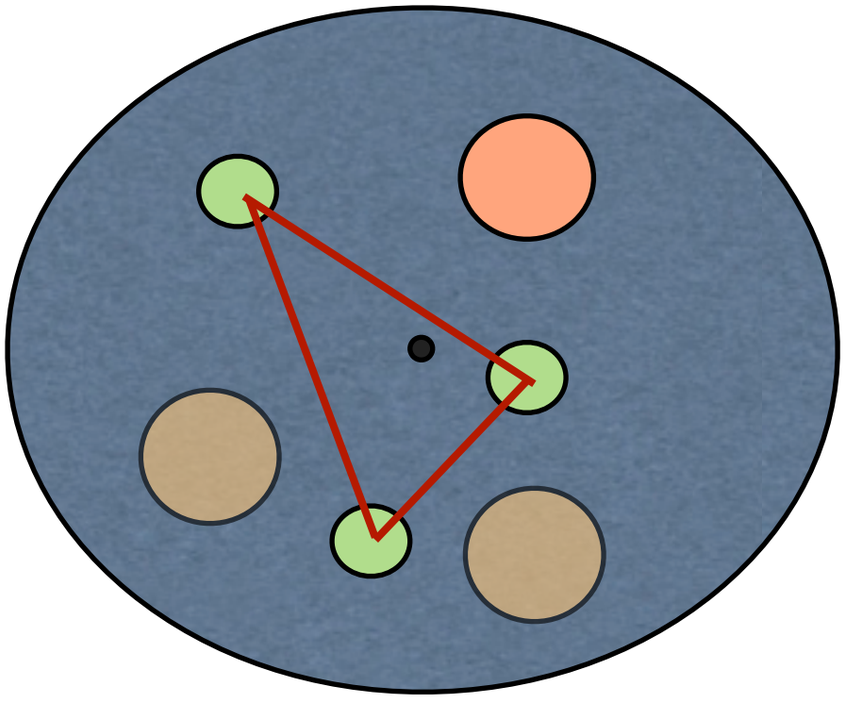
$$\langle E_1(\eta_1,\phi_1)E_2(\eta_2,\phi_2)\rangle = f(E_1,E_2,r_{ij})$$



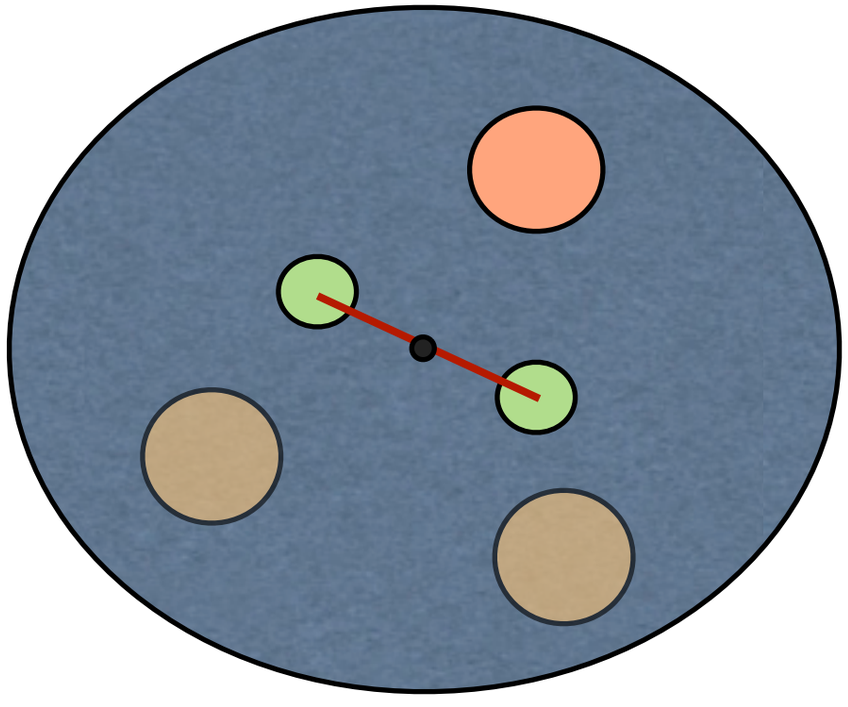
r_{ij}

$$\langle E(\eta_1,\phi_1)E(\eta_2,\phi_2)E(\eta_3,\phi_3)\rangle$$

Templates



$$\langle E(\eta_1, \phi_1) E(\eta_2, \phi_2) E(\eta_3, \phi_3) \rangle$$



$$\langle E_1(\eta_1, \phi_1) E_2(\eta_2, \phi_2) \rangle$$

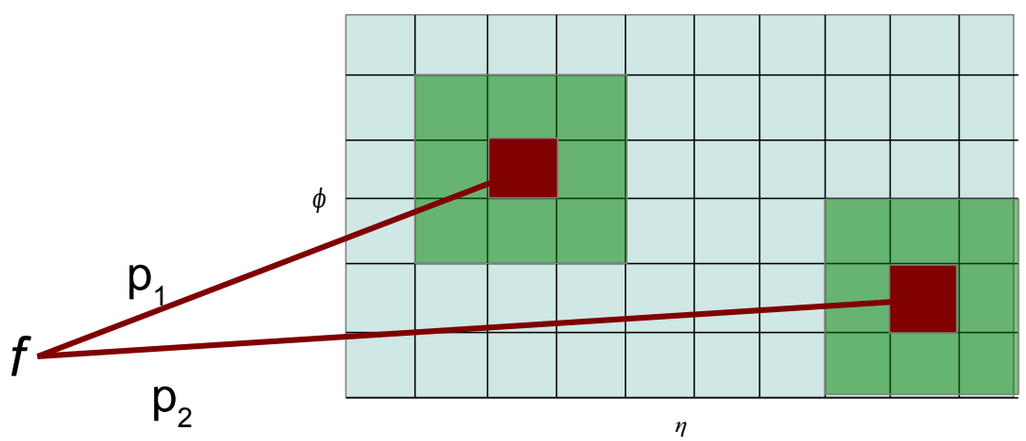
Overlap

$$Ov = \int d\Omega \left[\frac{dE(j)}{d\Omega} - \frac{dE(f)}{d\Omega} \right] F(\Omega, f)$$

$F(\Omega, f)$ is a weight function, smooth enough for the distribution to be IRsafe

For example: Weighting the energy by

$\max\left[0, 1 - (\eta^2 + \phi^2)/R\right] \rightarrow$ picking out cones



Gaussian Filtering weights the pT by a gaussian distribution

(jet finder)

Template Overlap

Almeida, Perez, Seung, Sung, Sterman

Almeida, Juknevich Orzan, Perez, Seung, Sterman

M. Backovi, J. Juknevich

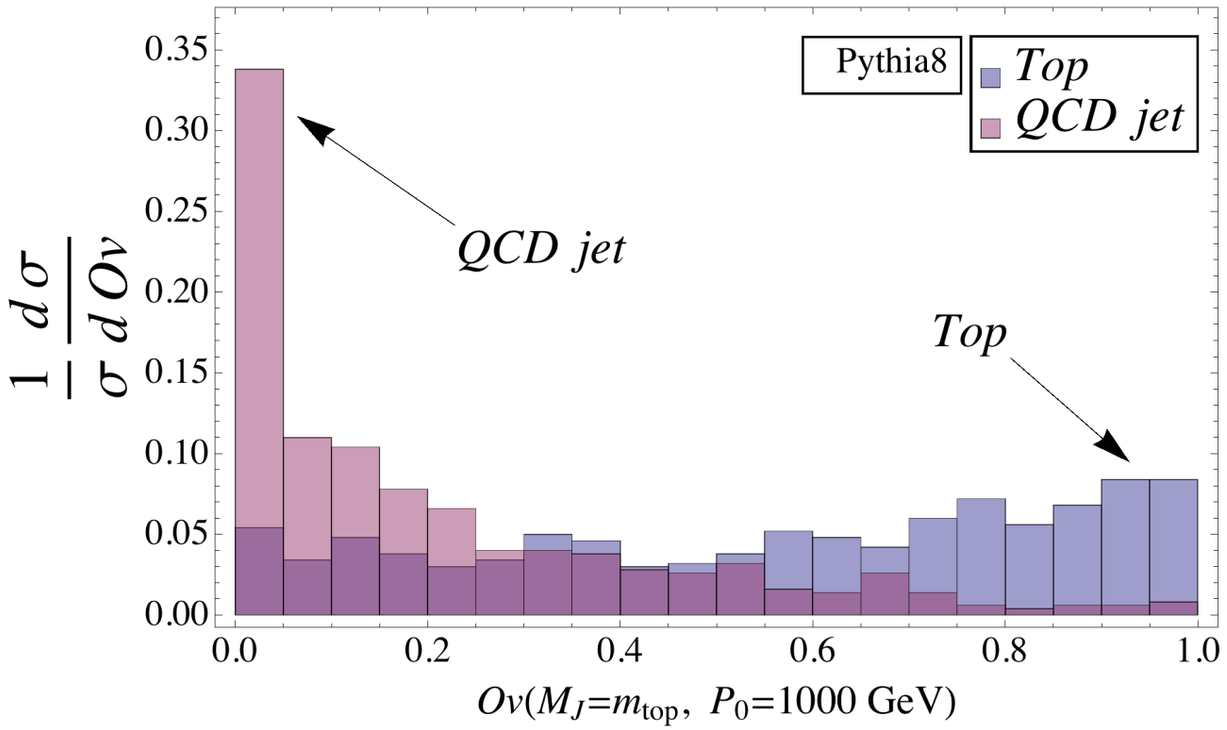
M. Backovi, J. Juknevich, G. Perez

$$Ov_N(j, f[j]) = \max_{\{f\}} \left[\exp\left[-\sum_{a=1}^{N} \frac{1}{\sigma_a^2} \left(\epsilon\, p_{T,a} - \sum_{i \in j} p_{T,i}\, F(\hat{n}_i, \hat{n}_a) \right)^2 \right] \right]$$

Now available in Hepforge

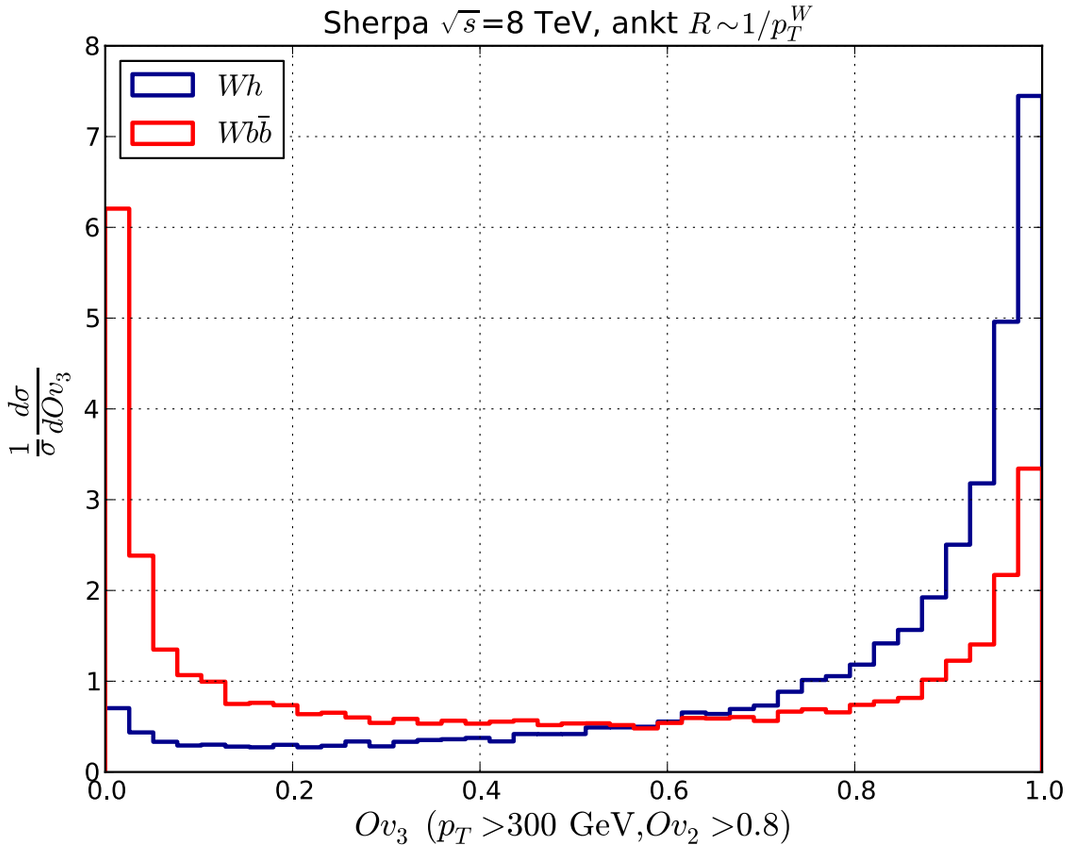
M. Backovi, J. Juknevich

Template Overlap



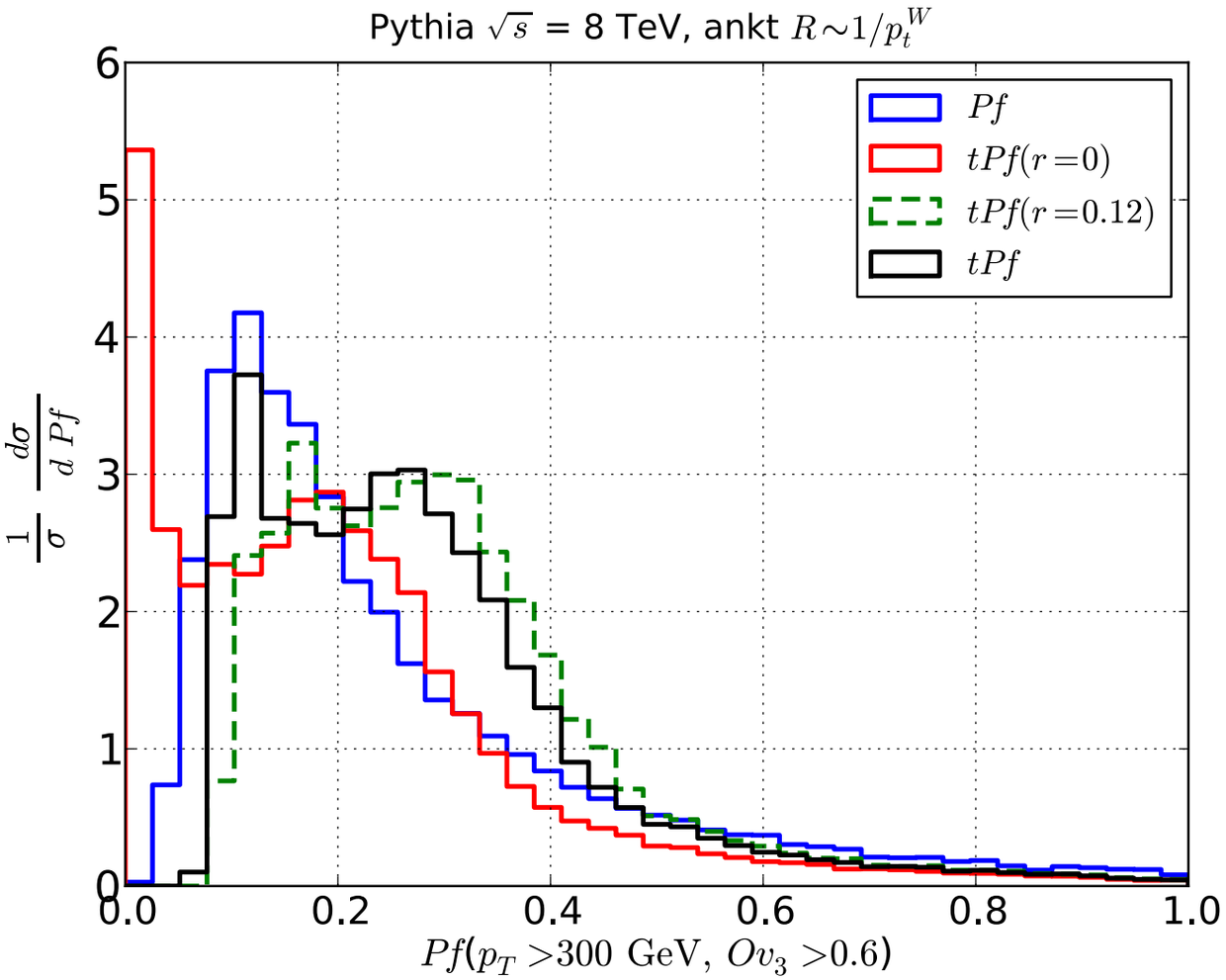
Almeida, Perez ,Seung, Sung, Sterman

Almeida, Erdozan ,Seung, Sung, Sterman



M. Backovi, J. Juknevich, G. Perez

Template Observables



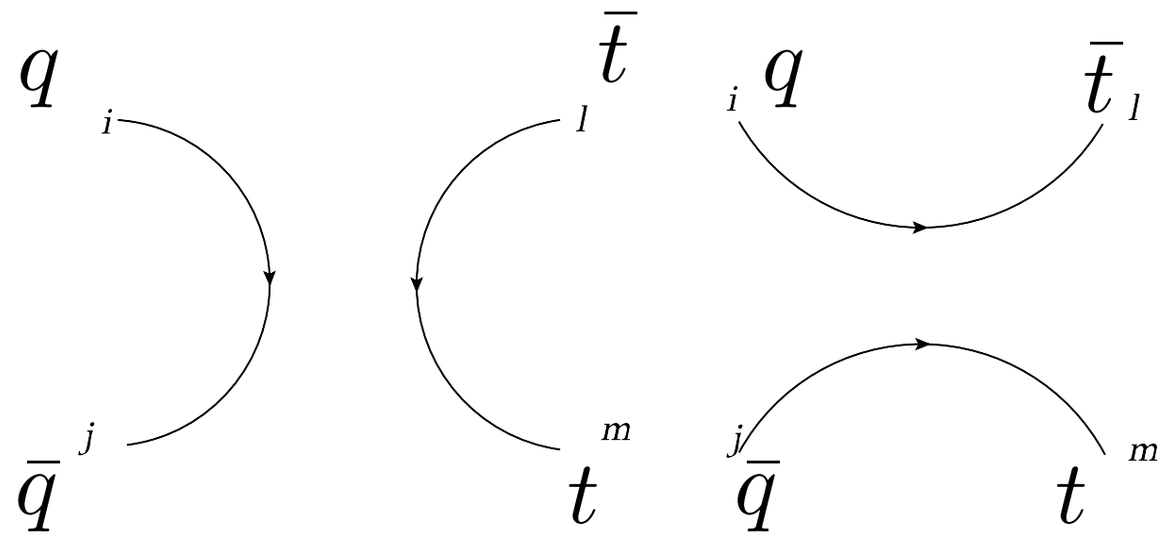
After using overlap, computing the planar flow.

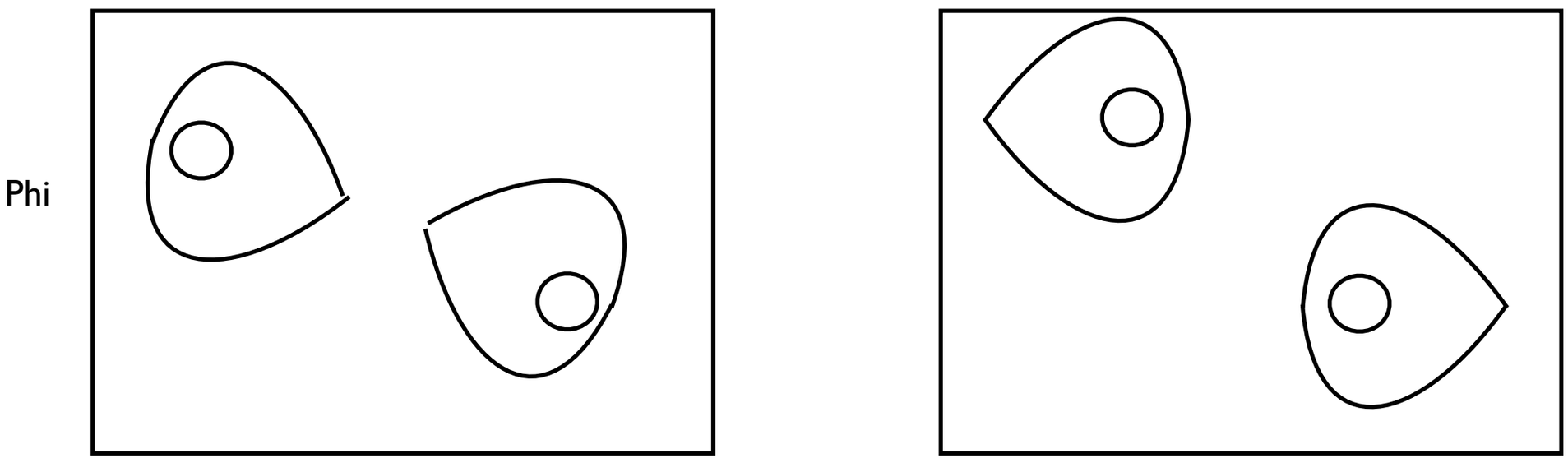
Colo(u)r Structure/Colo(u)r Flow

While jets are made of hadrons, the hard scattering is not colourless, and the effects of this interaction can/might be still be observed within the jet.

A clear view can be obtained from the leading color structure of the scattering

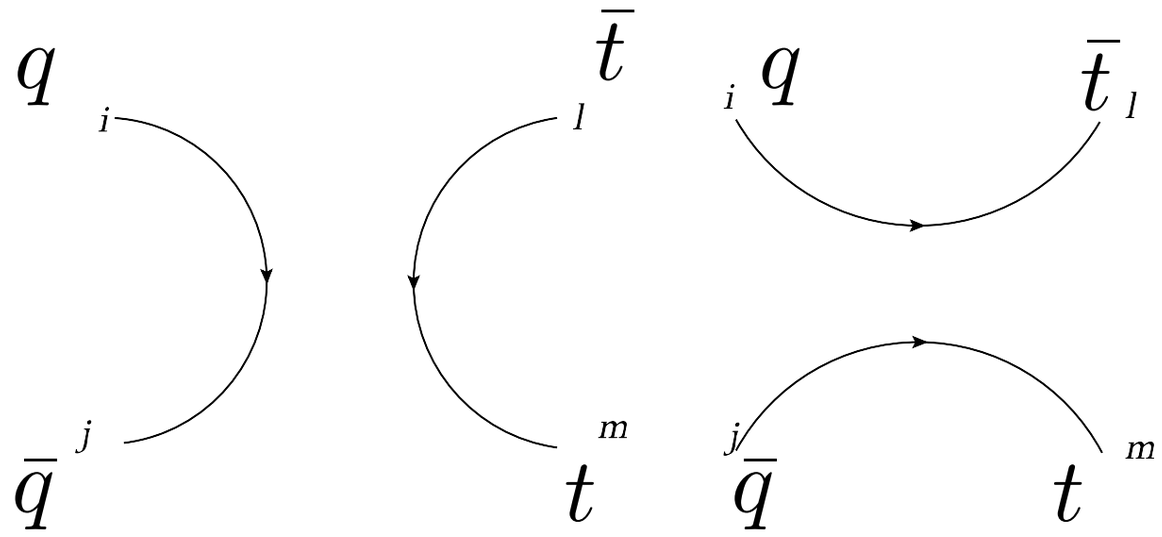
$q\bar{q} \to t\bar{t}$ example

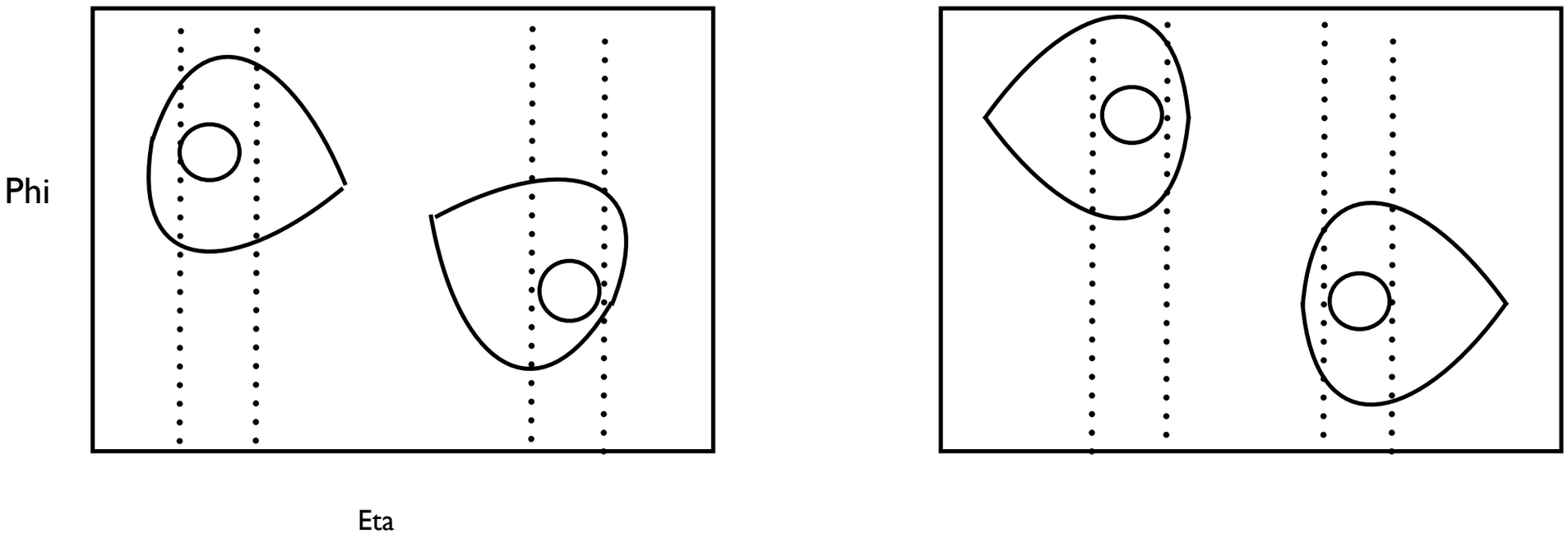




Gap in Energy

$q\bar{q} \to t\bar{t}$ example

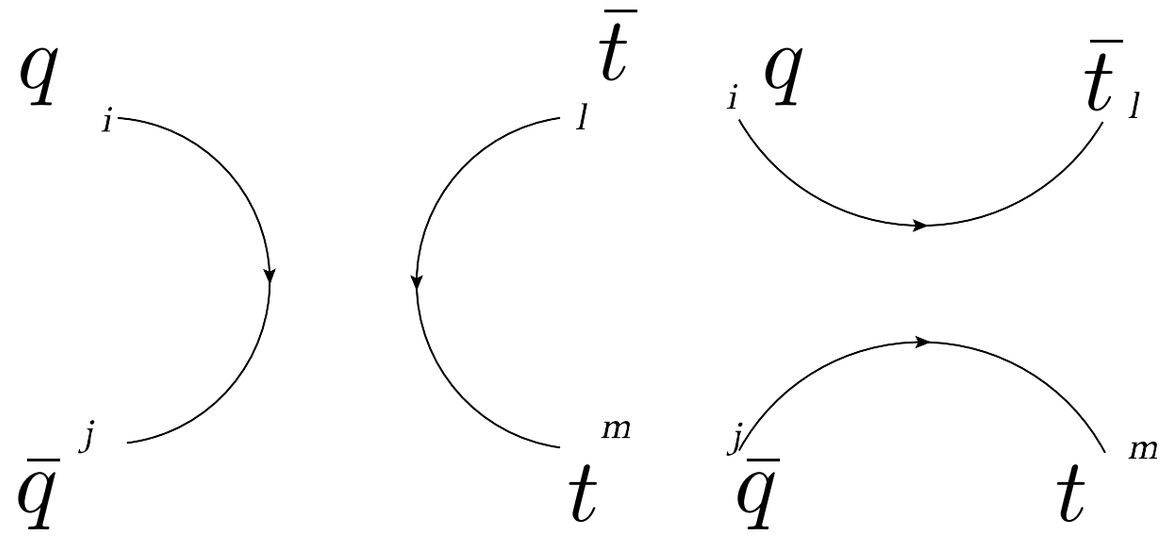


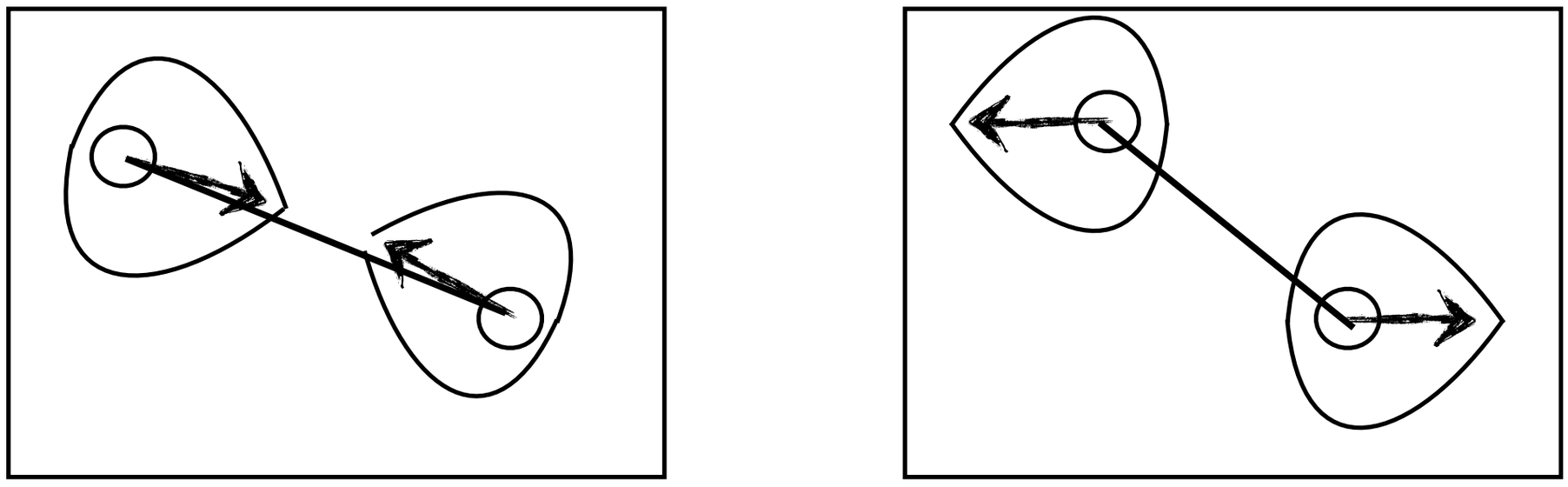


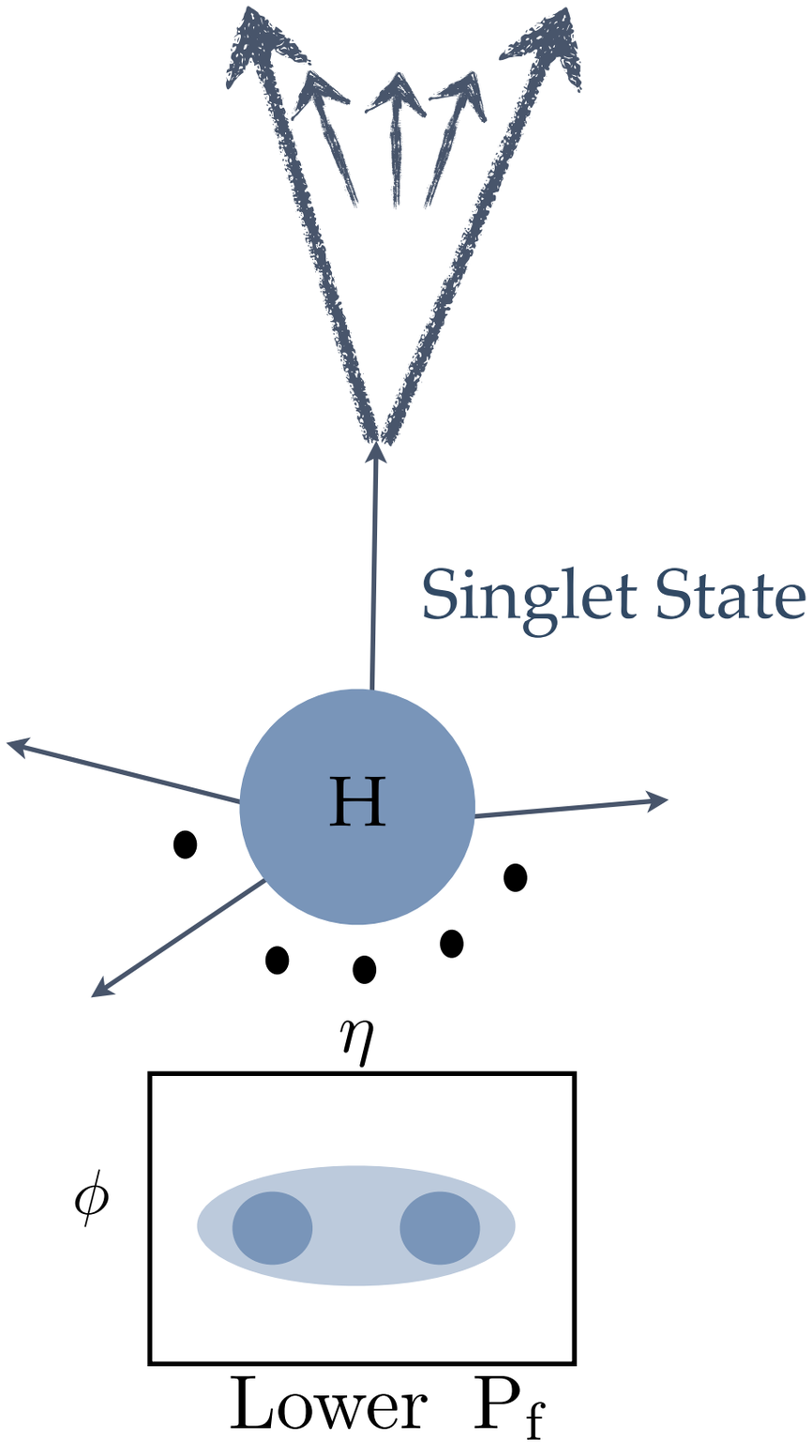
Pull Angle

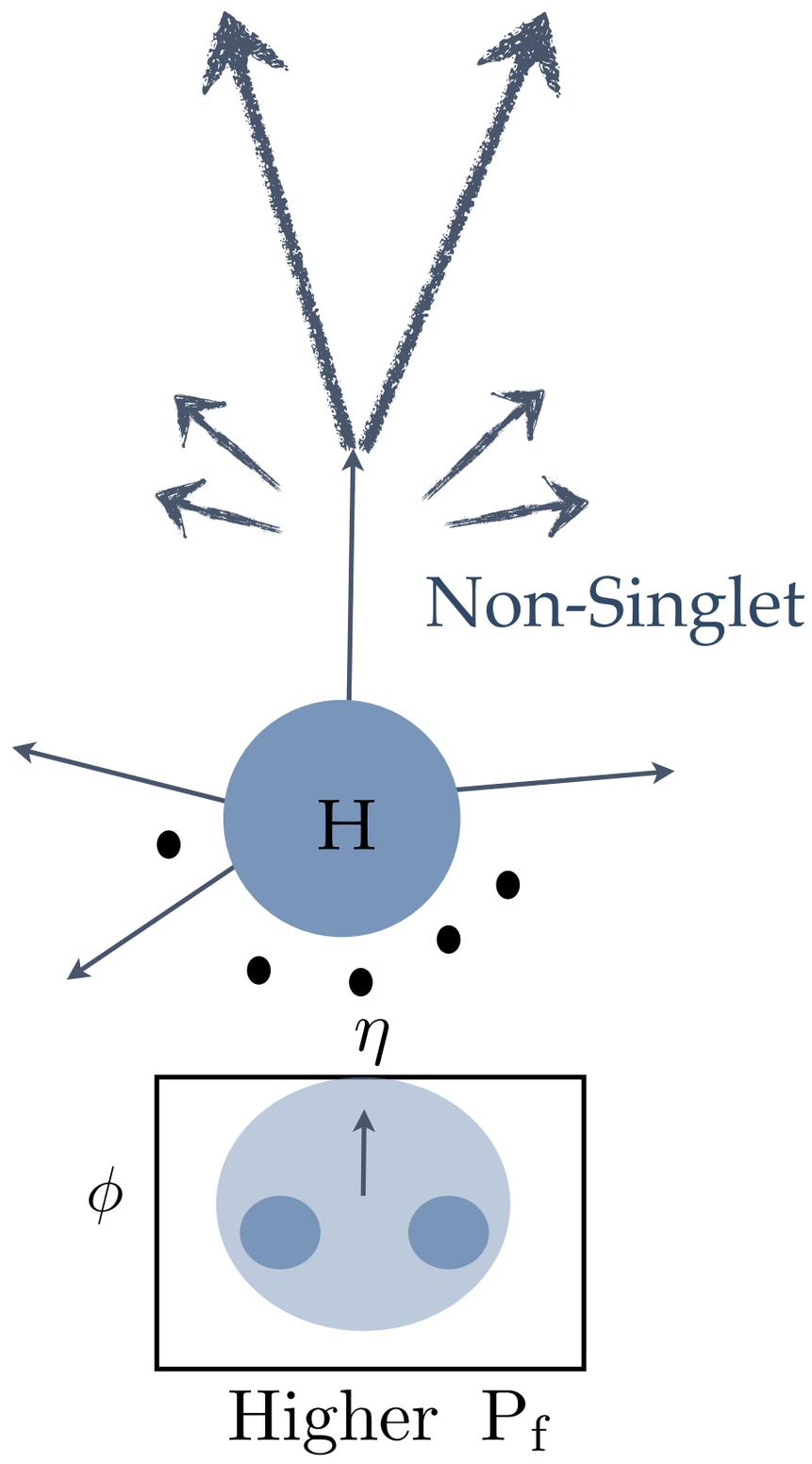
Gallicchio, Schwartz 12

$q\bar{q} \to t\bar{t}$ example

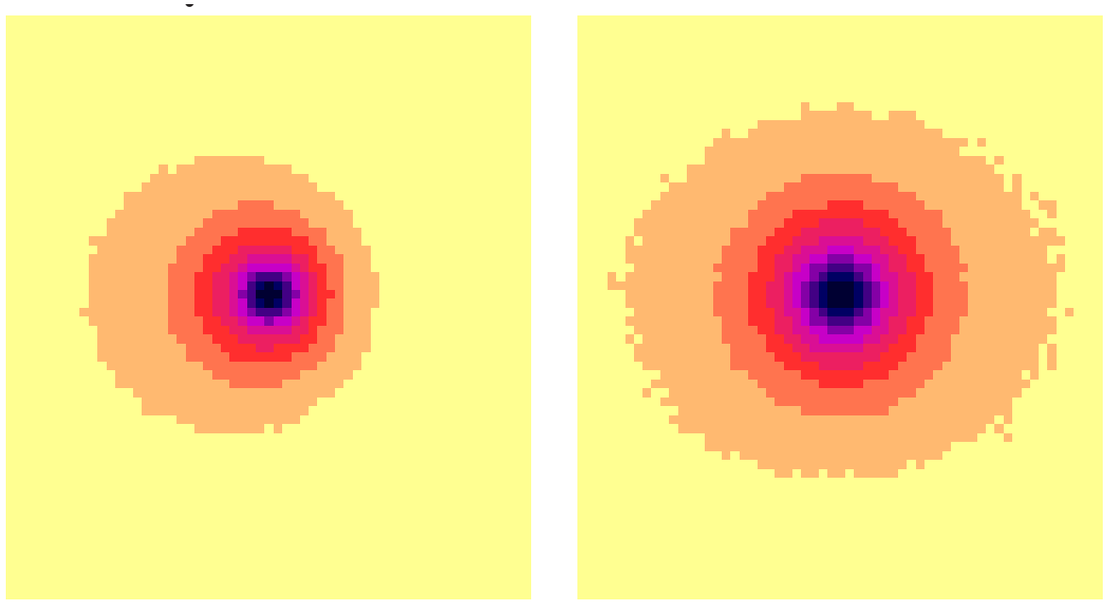




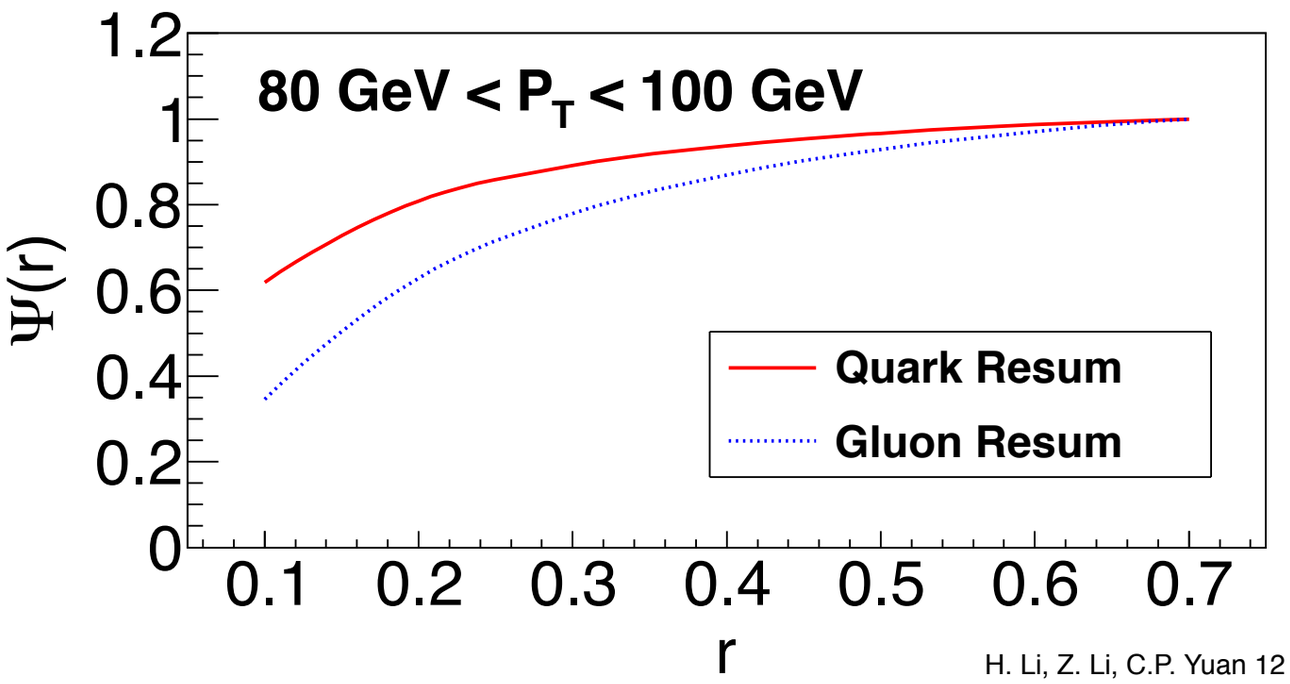

Singlet State
H
η
ϕ
Lower P_f


Non-Singlet
H
η
ϕ
Higher P_f

Quark versus Gluon Jets



Gallicchio, Schwartz 12



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Pile-up

Piles up everything that we have yet to compute!
Mainly it is associated with spectator collision, due to simultaneous pp collision along the beam pipe.

Should be incoherent to "main" scattering. Therefore it spatially behaves like soft radiation.

Adds a low-pt noise to the entire event, this can highly affects some jet shapes, since they are sensitive to the energy distribution.

Pile-up

Cacciari, Salam 10
Alon, Duchovni, Perez, Pranko, Sinervo 11
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This uncertainty can be accounted for once we understand the jet's shapes dependencies on pile-up 4-momenta.

$$(\rho\cos\phi, \rho\sin\phi, (\rho+\rho_m)\sinh\eta, (\rho+\rho_m)\cosh\eta)\delta\phi\delta\eta$$

$$\mathcal{O}_{jet}(\rho,\rho_m) = \mathcal{O}_{jet}(0,0) + \rho\partial_\rho\mathcal{O} + \rho_m\partial_{\rho_m}\mathcal{O} + \rho\rho_m\partial_{\rho,\rho_m}\mathcal{O}$$

It would be great to have a theoretical understanding of pile-up distribution, that could be accounted for in the computation of the observables a priori.

Since fitting methods might remove substructure information that is not incoherent to the hard the scattering. However for the soft radiation modelled above, substructure can be in some cases completely recovered.

Summary

Resummation allows us to obtain an all order results, for the structure and observables associated with jets.

Additional Observables allows us to pick features of the dynamics that we are interested in. i.e. colour flow

Their uses can go far beyond the LHC, especially in situations where the dynamics are not well understood