Medium tomography with jet clustering algorithms

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in collaboration with:

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Elastic and Diffractive Scattering 2009

Jets in heavy ion collisions

Jets will be of paramount importance to fully exploit the potential of the HIC program at the LHC

- Jets will be most abundant hard probes in HIC at the LHC
  From CMS HIC TDR (J. Phys. G: Nucl. Part. Phys. 34 2307)

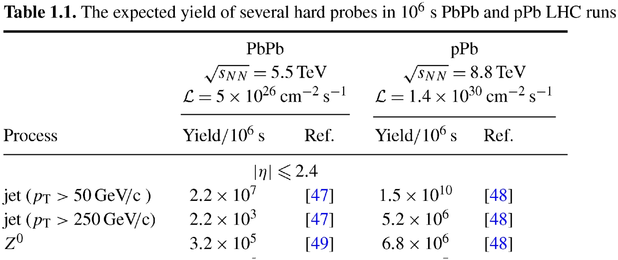


Table 1.1. The expected yield of several hard probes in 10^6 s PbPb and pPb LHC runs

	PbPb $\sqrt{s_{NN}} = 5.5$ TeV $\mathcal{L} = 5 \times 10^{26}$ cm^{-2} s^{-1}		pPb $\sqrt{s_{NN}} = 8.8$ TeV $\mathcal{L} = 1.4 \times 10^{30}$ cm^{-2} s^{-1}	
Process	Yield/10^6 s	Ref.	Yield/10^6 s	Ref.
	$\vert\eta\vert \leqslant 2.4$			
jet ($p_T > 50$ GeV/c)	2.2×10^7	[47]	1.5×10^{10}	[48]
jet ($p_T > 250$ GeV/c)	2.2×10^3	[47]	5.2×10^6	[48]
Z^0	3.2×10^5	[49]	6.8×10^6	[48]

Jets in heavy ion collisions

Jets will be of paramount importance to fully exploit the potential of the HIC program at the LHC

- Jets will be most abundant hard probes in HIC at the LHC
- Jets free of inclusive particle measurements biases
- Subleading jet fragments sensitive medium modeling details
- A solid pQCD baseline is required to detect and quantify medium effects

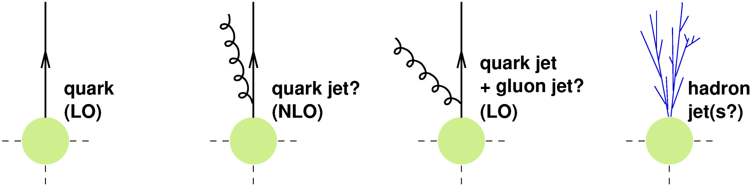
Open questions:

- To which extend can reconstructed QCD jets be disentangled from background?
- Which is the minimum size of medium effects which could then be disentangled?
- Can all the successful jet technology from *pp* be transferred to a HIC environment?

JET CLUSTERING TECHNOLOGY

Jets

Naively: a jet is a **bunch of collimated hadrons** ubiquitous in high energy collisions. Electrons and muons are fundamental, weakly coupled particles — it makes sense physically and experimentally to think of them as concrete objects. *Partons* (quarks, gluons) are not so simple...



- Partons split into further partons
- Jets are a a way of thinking of the 'original parton'
- A 'jet' is a **fundamentally ambiguous concept** (e.g. requires a resolution)

Jets (and partons!) are only meaningful once you've defined a jet algorithm.

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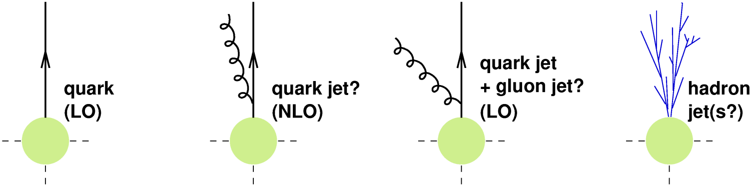

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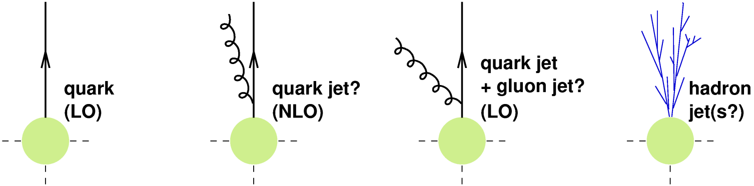

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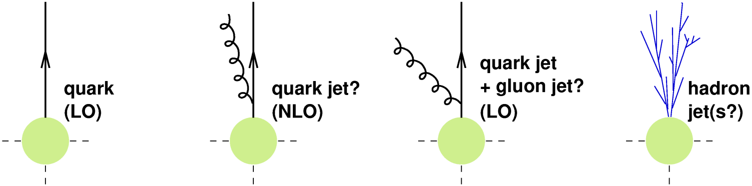

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Jet algorithm requirements

What is **needed** of a jet algorithm

- Must be infrared and collinear (IRC) safe
  soft emissions shouldn't change jets
  collinear splitting shouldn't change jets
- Must be identical procedure at parton level, hadron-level and experimental level
  So that theory calculations can be compared to measurements

What is **nice** for a jet algorithm

- Shouldn't be too sensitive to hadronization, underlying event and pileup, while being sensitive to perturbative radiation.
- Should be realistically applicable at detector level.
- Should allow fast implementations, to cope with the large particle multiplicities at hadronic colliders and in Heavy Ion Collisions.

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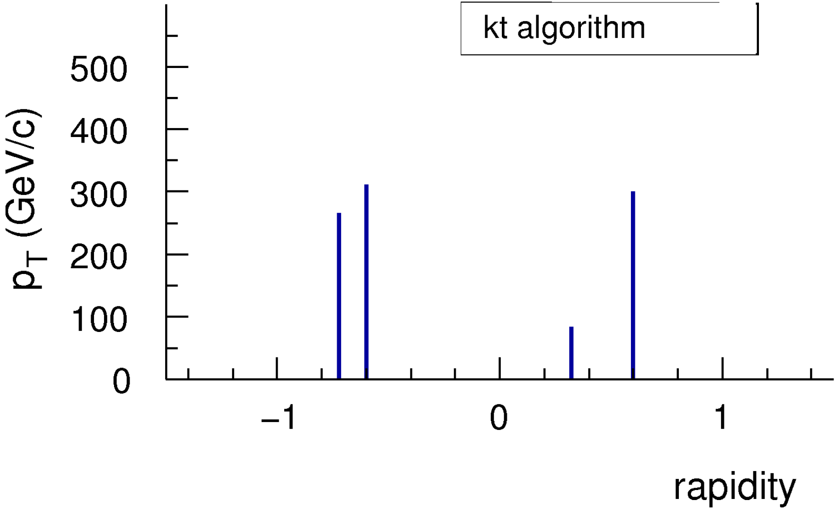

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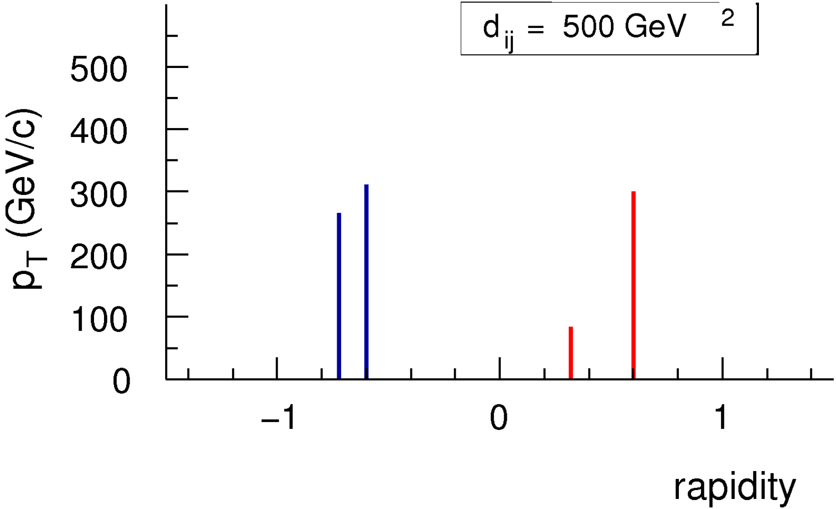

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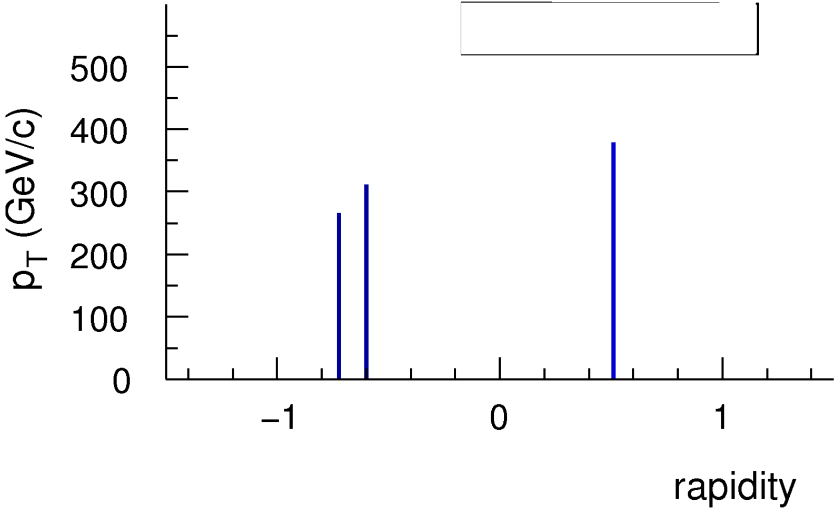

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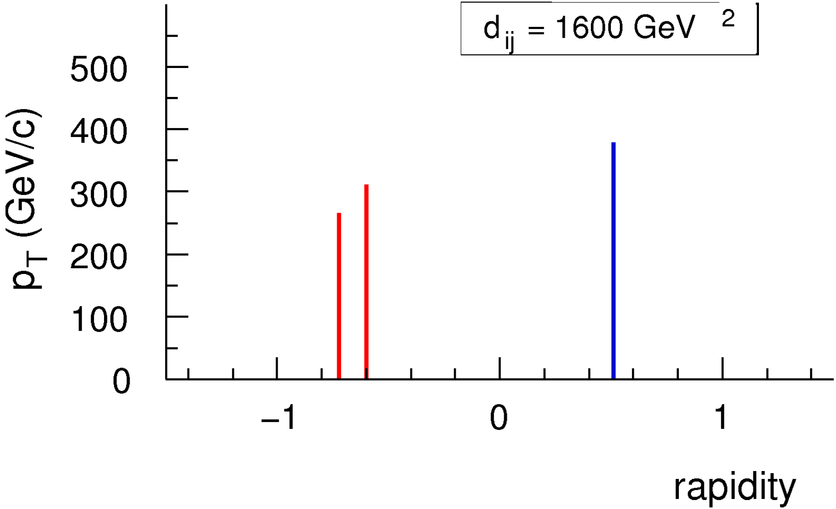

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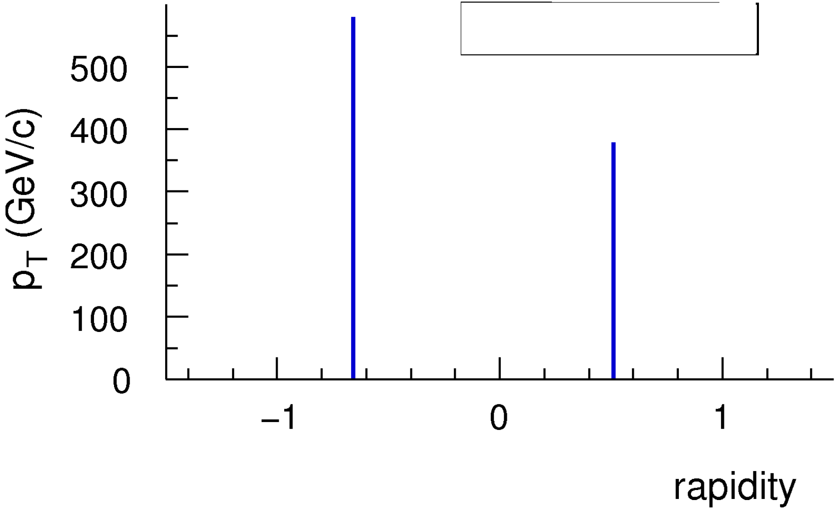

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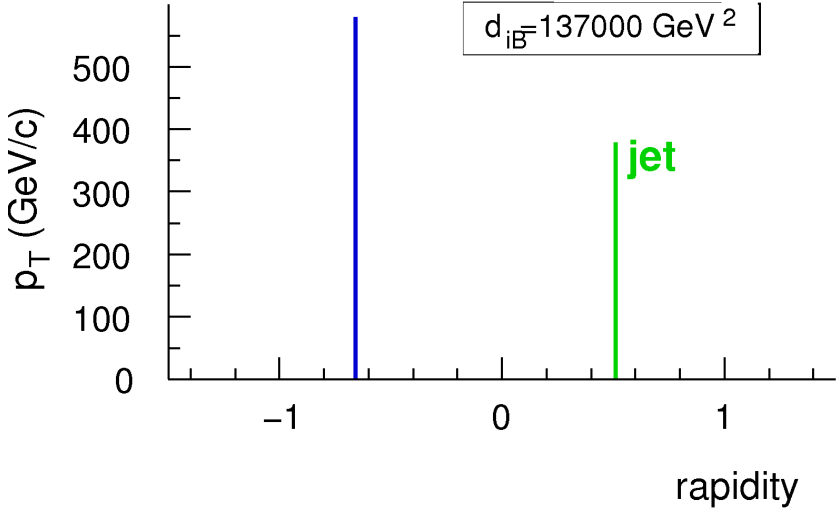

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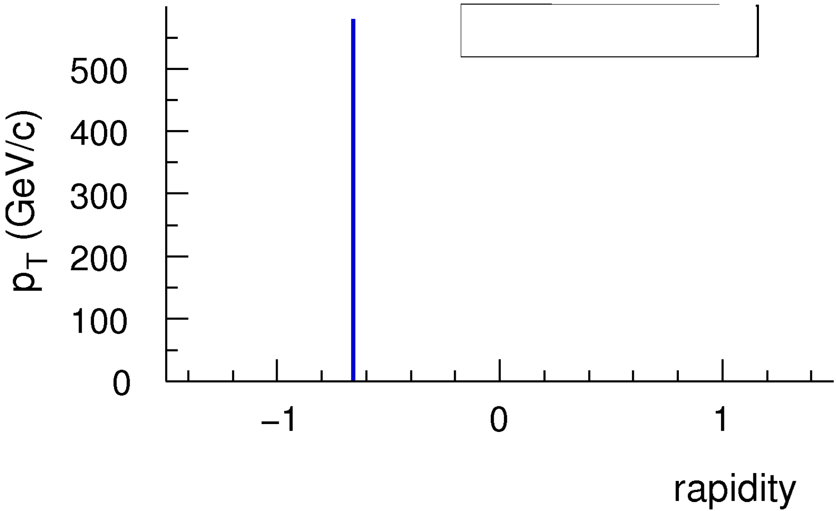

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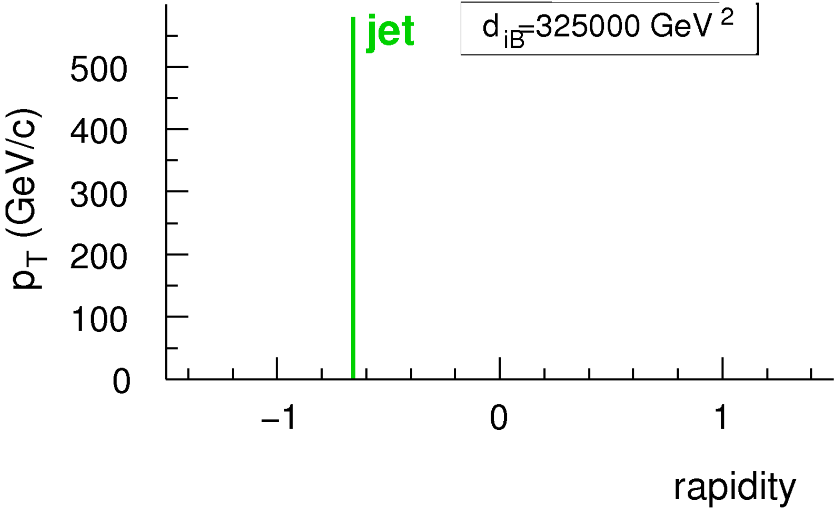
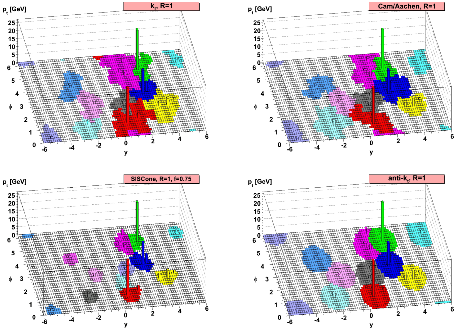


Recent developments

Sizable progress in jet algorithms in recent years (References: G. Salam, arXiv:0906.1833)

- Fast implementation of sequential recombination clustering algorithms (k_T, Cam/Aa)
- Jet areas ($A_{\rm jet} \neq \pi R^2$ in general)



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- Jet areas ($A_{\mathrm{jet}} \neq \pi R^2$ in general)
- New IRC safe jet algorithms (SISCone, anti-k_T) → Replacement for IRC unsafe cone algorithms (IR-SM like MidPoint and IC-PR like ATLAS cone)

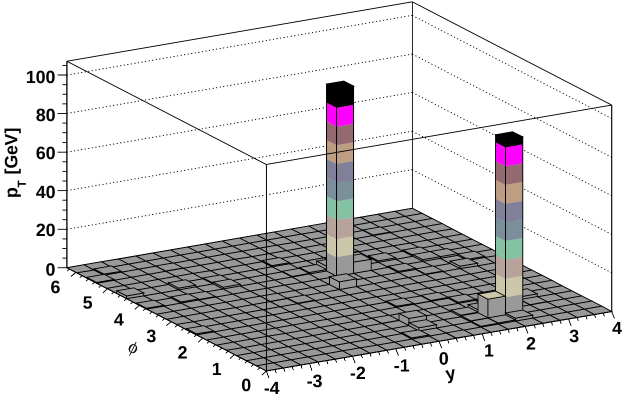
All these tools available from the `FastJet` package:

`http://www.lpthe.jussieu.fr/salam/fastjet/`

together with background subtraction methods

Jets in HIC $\longrightarrow$ A messy environment!

$pp \longrightarrow gg$ events with $p_T^{\text{jet}} \sim 100$ GeV and $R = 0.4$ - No PbPb



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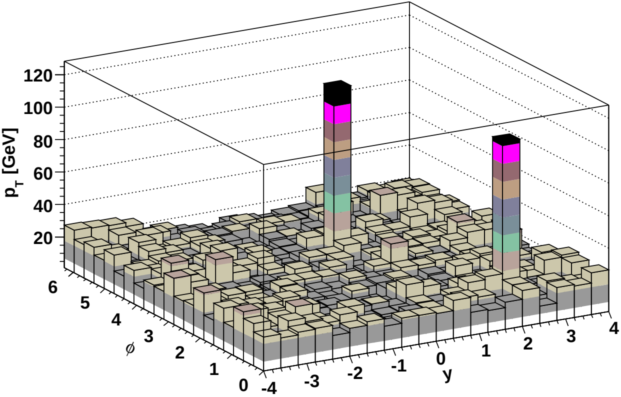

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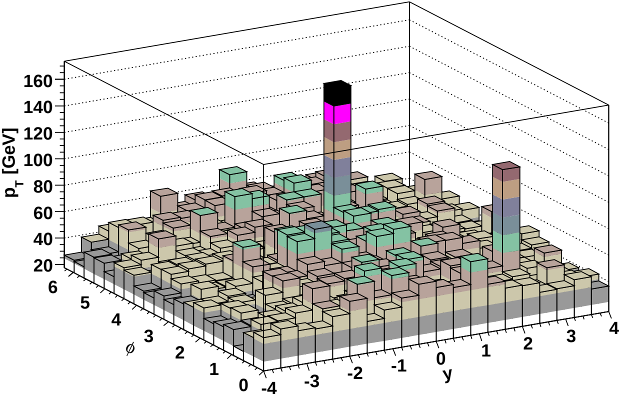


Jets @ RHIC

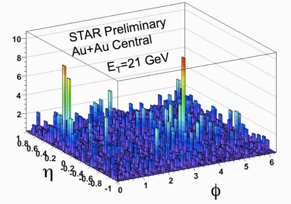
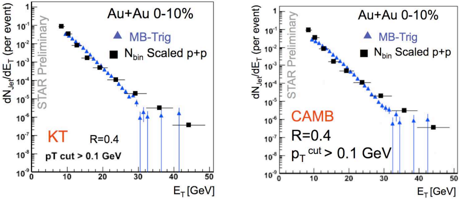


Fig. 1. 21 GeV di-jet reconstructed from a central Au+Au event at $\sqrt{s_{NN}} = 200$ GeV in the STAR detector [4, 5].

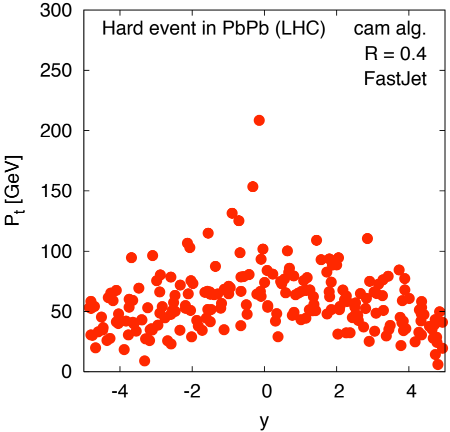


Jets already measured at `STAR @ RHIC`

1. Important information of medium effects
2. No suppression observed in the inclusive jet distribution (unlike in hadron production spectra)

Jet areas for Background subtraction

Data-driven method to estimate the background density per unit area ρ (from the Underlying Event) on an event-by-event basis



1.- Measure the p_T of all jets in event

Conceptuallly simple but powerful technique

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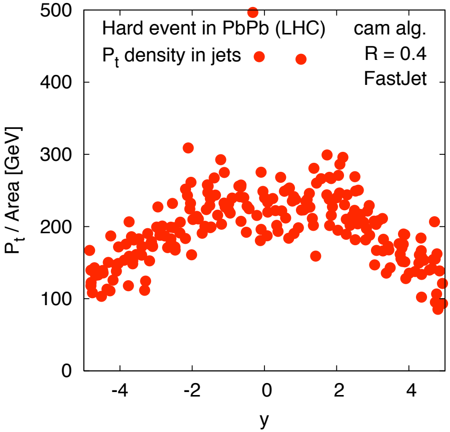

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Key observation → For UE jets, $p_T^{\text{jet}} \sim \rho(y,\phi) A_{\text{jet}}$

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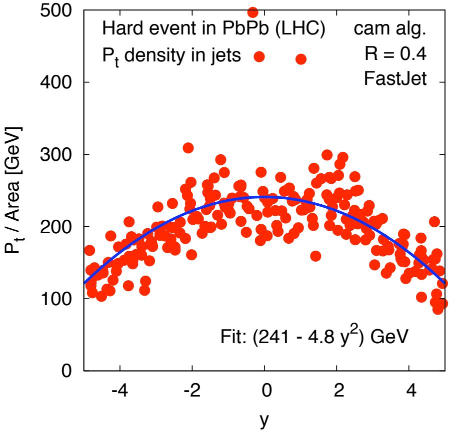

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(No unique strategy, HIC background very complex structure)

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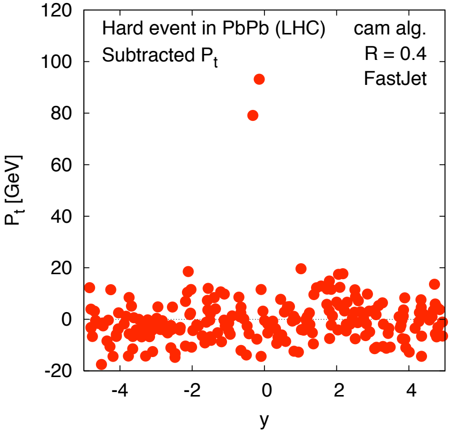

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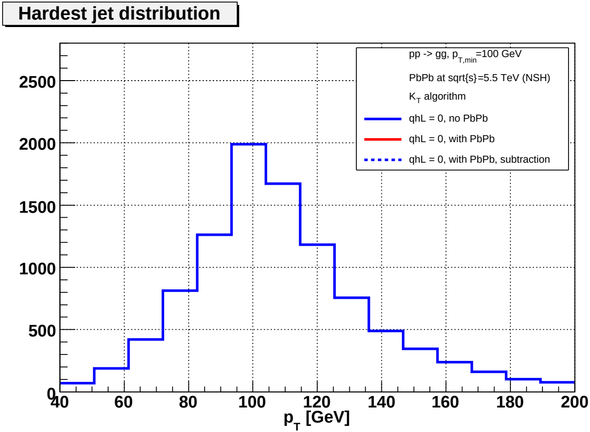
Key observation → For UE jets, $p_T^{\rm jet} \sim \rho(y,\phi) A_{\rm jet}$
3.- Determine $\rho(y,\phi)$
(Various strategy, HIC background very complex structure)
4.- Subtract $\rho(y,\phi)$ from the all jets using its area A_j

$$p_{\mu j}^{(\rm sub)} = p_{\mu j} - A_{\mu j}\,\rho(y,\phi) \qquad (1)$$

Conceptuallly simple but powerful technique

Background subtraction in practice

Inclusive jet distribution in pp dijet events embedded in LHC PbPb events
k_T algorithm with $R = 0.4$



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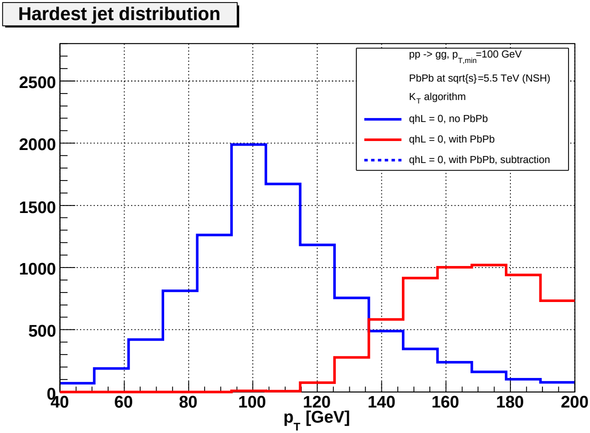

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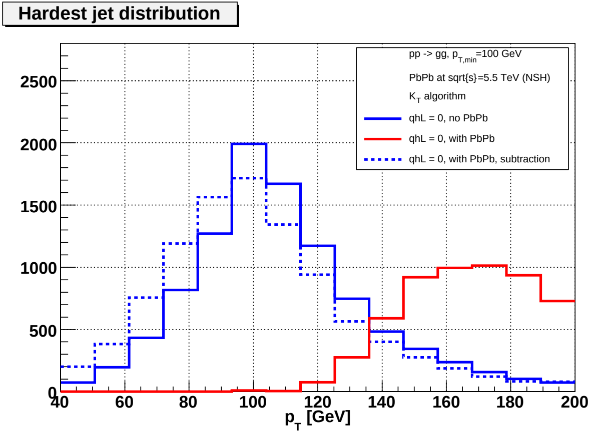
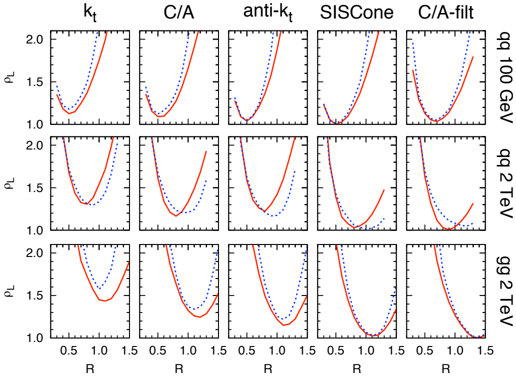


Jet algorithms performance in pp at LHC



Not all jet definitions equally good:

1. Too small-R → Hadronization effects
2. Too large-R → Underlying Event and Pile-Up

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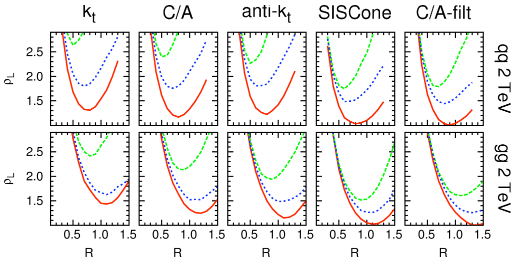

Not all jet definitions equally good:

1. Too small-R → Hadronization effects
2. Too large-R → Underlying Event and Pile-Up
   Same for High Luminosity LHC Pile-Up

`JetQuality`: Interactive tool compare jet definitions (JHEP 0812:032,2008)

http://www.lpthe.jussieu.fr/ salam/jet-quality/

MODELING MEDIUM EFFECTS

Medium effects

Implementation of different medium models in practical MC tools → Basic tool for both theorists and experimentalists!

Assess potential of different jet finding strategies in realistic environment → In HIC, understanding and subtracting the UE is also a theorist's task!!

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Medium effects from ACSW (Armesto et al, JHEP 0802:048,2008): radiative energy loss through modification of vacuum splitting functions.

$$P^{\rm tot}(z) = P^{\rm vac}(z) + \Delta P(z,t) \ , \quad \Delta P(z,t) \simeq \frac{2\pi t}{\alpha_s} \frac{dI^{\rm med}}{dzdt}$$

Implemented in modified `Pythia 6.4` *to* **Q-PYTHIA**: A fully exclusive MC for jet quenching in HIC

JETS IN MEDIUM
(Preliminary results)

Medium tomography

Quantifying medium effects → Example: inclusive jet distribution

- Theoretical prediction

$$R_{AA}^{\mathrm{theo}}(p_T) \equiv \frac{d\sigma^{\mathrm{pp+med}}/dp_T}{d\sigma^{\mathrm{pp}}/dp_T}$$

- Experimental measurement (no subtraction)

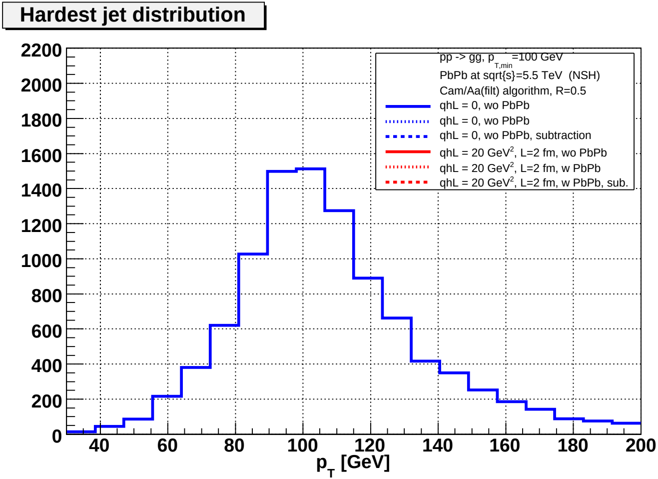
$$R_{AA}^{\mathrm{exp-1}}(p_T) \equiv \frac{d\sigma^{\mathrm{pp+med+PbPb}}/dp_T}{d\sigma^{\mathrm{pp}}/dp_T}$$

- Experimental measurement (subtraction)

$$R_{AA}^{\mathrm{exp-2}}(p_T) \equiv \frac{d\sigma^{\mathrm{pp+med+PbPb+sub}}/dp_T}{d\sigma^{\mathrm{pp}}/dp_T}$$

In real experimental measurements → Normalize to the average number of binary collisions

Inclusive jet distribution



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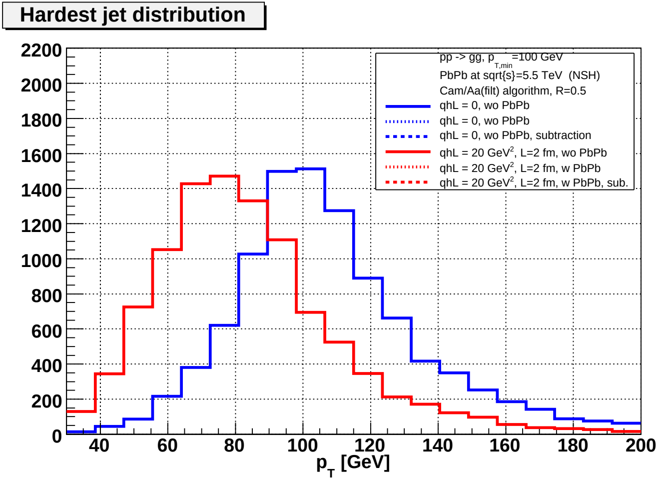

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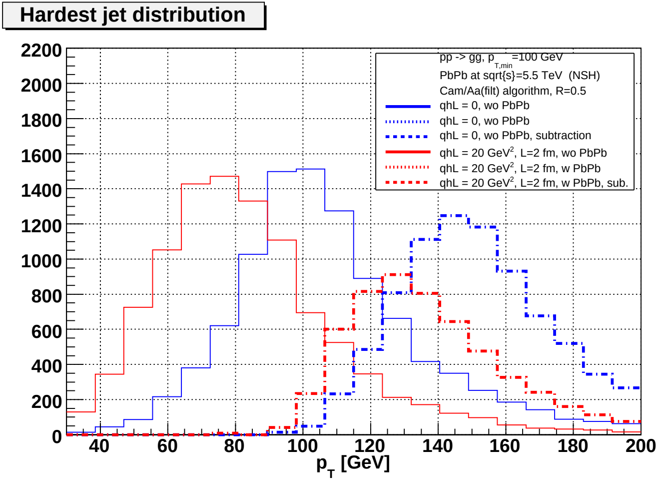

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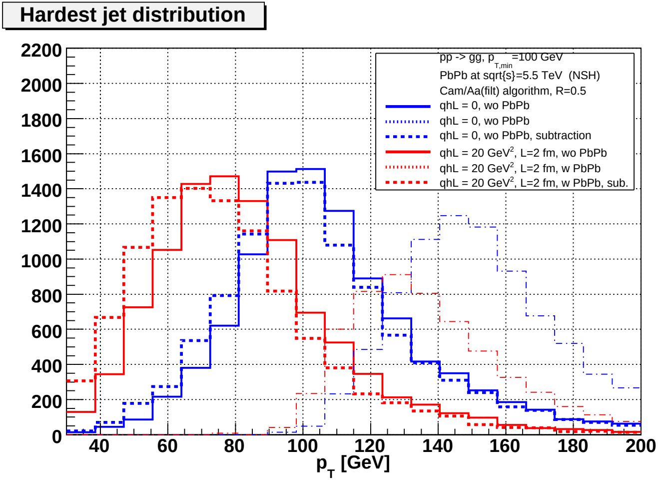

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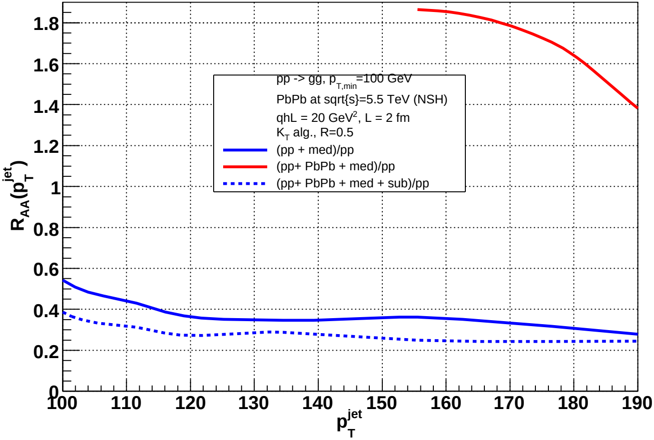
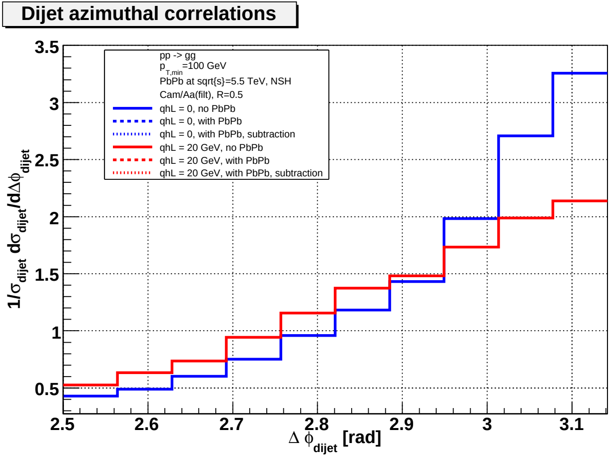


Dijet azimuthal correlations

Medium effects soften away-side correlations



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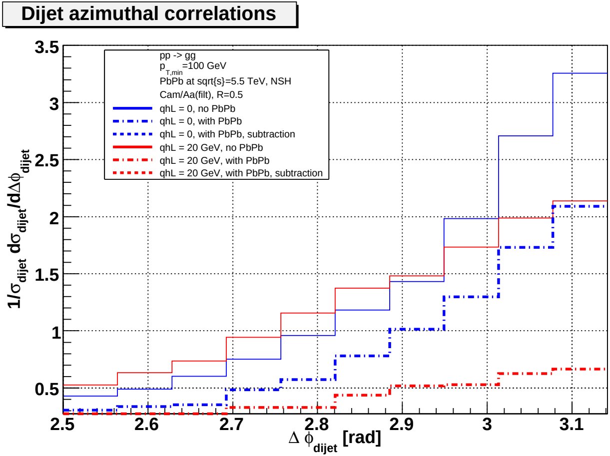

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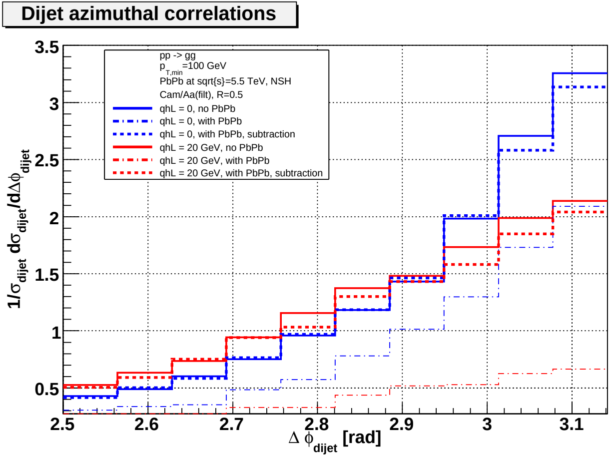
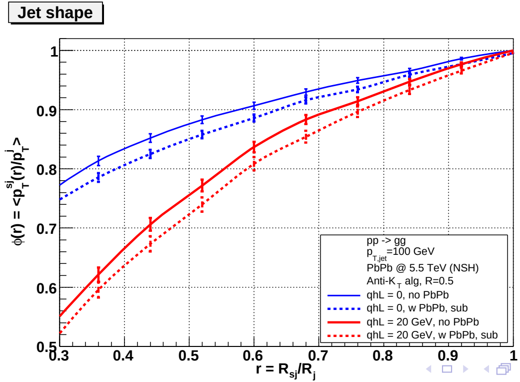


Jet shape

Jet substructure $\phi(r)$ useful discriminator of medium effects

Cluster jet constituents with $R_{\rm sj}$ ($r \equiv R_{\rm sj}/R_{\rm jet} < 1$) and keep hardest subjet with $p_T^{\rm sj} (\leq p_T^{\rm jet})$. $R_{\rm jet} = 0.5$, $0.15 \leq R_{\rm sj} \leq 0.5$

With the anti-k_T algorithm (reduced backreaction)

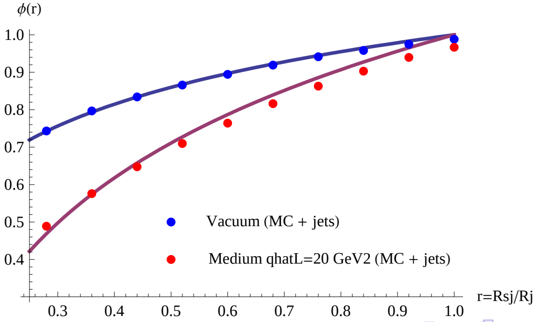


Jet shape - LL pQCD

If medium effects parametrized by $(1+f_{\rm med})$ in the singular part of the splitting functions (Borghini et al. 05) then

$$\phi_{\rm med}(r,f_{\rm med}) = 1 - \frac{\alpha_s}{\pi}\ln\frac{R_{\rm j}}{R_{\rm sj}}\left[C_A\left(\frac{3f_{\rm med}}{8}+2\ln 2-\frac{43}{96}\right)+\frac{7N_f T_R}{48}\right]$$

for $\alpha_s = 0.2$ and $f_{\rm med}\sim 3$ $[\phi_{\rm vac}(r)=\phi_{\rm med}(r,f_{\rm med}=0)]\rightarrow$ Agreement with $\phi(r)$ results from MC simulations + subjets ($L = 2$ fm, $\hat{q}L = 20$ GeV^2)



Summary

- Modern jet clustering algorithms and background subtraction related techniques are very promising tools to probe the new state of matter created in Heavy Ion collisions
- Full QCD jets can be disentangled from background (at least) down to 50 GeV, and medium effects in the ACSW model down to conservative estimations for medium parameters at the LHC
- The flexibility in jet algorithms allows the estimation of systematic uncertainties associated to background subtraction
- The approach presented in this talk on jet finding technology can be applied to study the effects of any model of medium effects and jet quenching: various models implemented in MC codes: Q-PYTHIA (Armesto et al., `JEWEL` (K. Zapp et al, arXiv:0804.3568, T. Renk, arXiv:0806.0305, `HYDJET`, `PYQUENCH` , ...
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EXTRA MATERIAL

Sequential recombination algorithms

Example: the k_t algorithm:

1. Calculate (or update) distances between all particles i and j, and between i and beam:

$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\frac{\Delta R_{ij}^2}{R^2}, \qquad d_{iB} = k_{ti}^2\,, \qquad \Delta R_{ij}^2 = \Delta y_{ij}^2 + \Delta\phi_{ij}^2$$

2. Find smallest of d_{ij} and d_{iB}
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Single parameter: R (like cone radius), whose natural value is $\mathcal{O}(1)$

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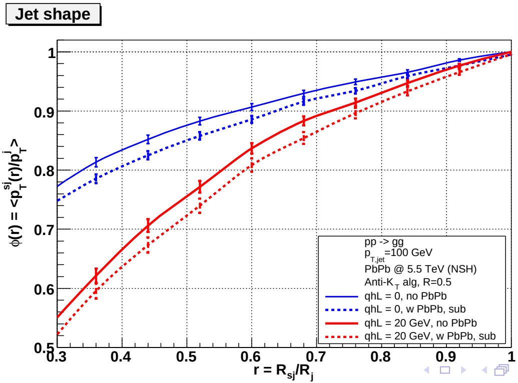
Jet shape

Jet substructure $\phi(r)$ useful discriminator of medium effects

Cluster jet constituents with $R_{\rm sj}$ $(r \equiv R_{\rm sj}/R_{\rm jet} < 1)$ and keep hardest subjet with $p_T^{\rm sj} (\leq p_T^{\rm jet})$. $R_{\rm jet} = 0.5$, $0.15 \leq R_{\rm sj} \leq 0.5$

With the anti-k_T algorithm (reduced backreaction)



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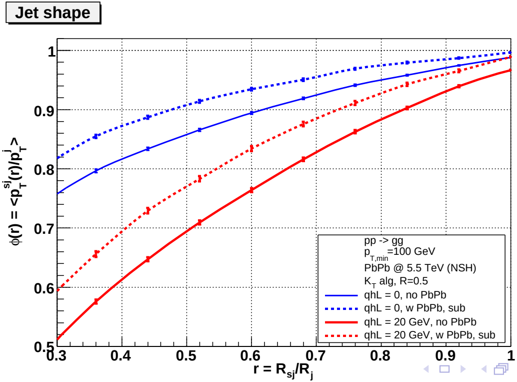
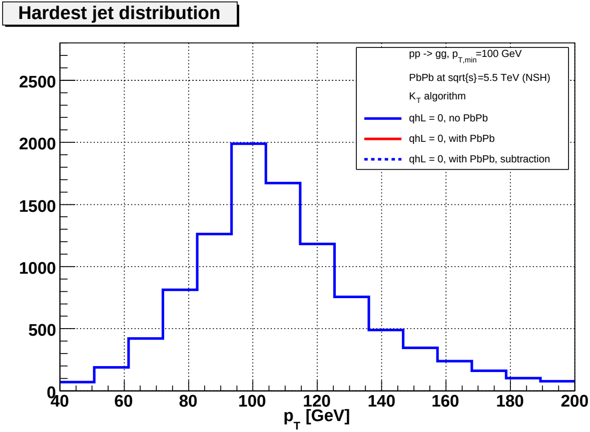
With the k_T algorithm (larger backreaction)



Background subtraction in practice

Inclusive jet distribution in pp dijet events embedded in LHC PbPb events
k_T algorithm with $R = 0.4$



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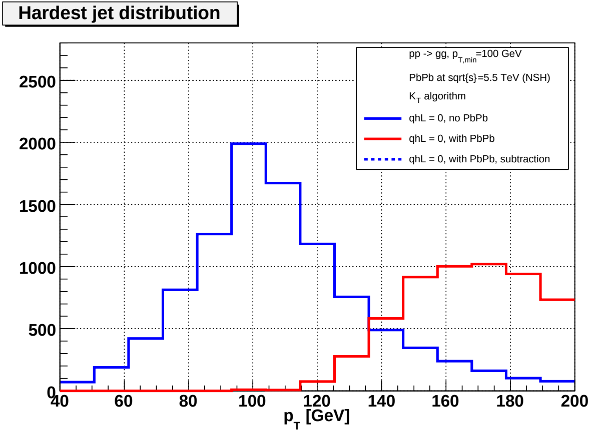

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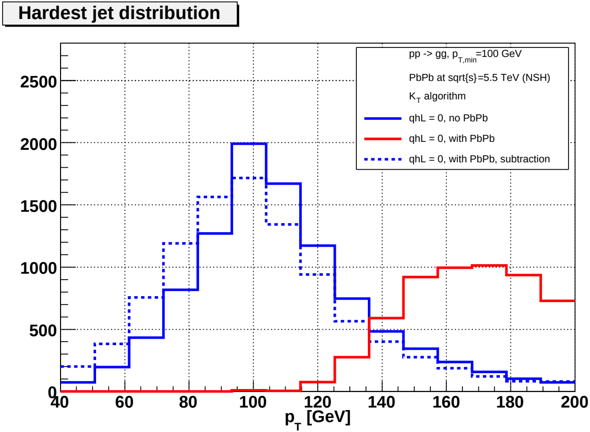
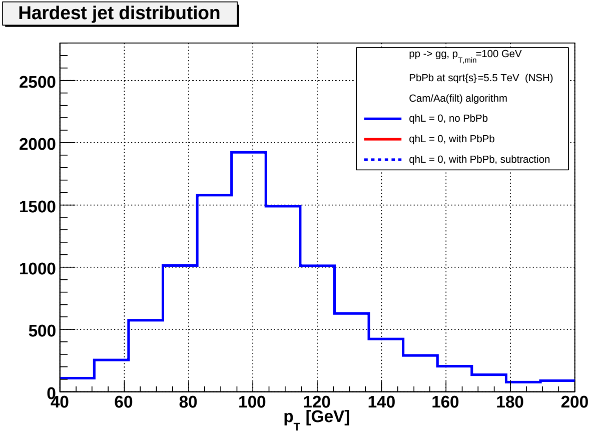


Background subtraction in practice

Inclusive jet distribution in pp dijet events embedded in LHC PbPb events
Cam/Aa(filt) algorithm with $R = 0.4$



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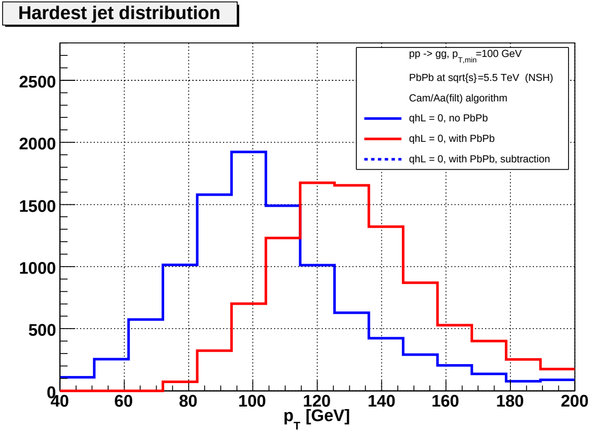

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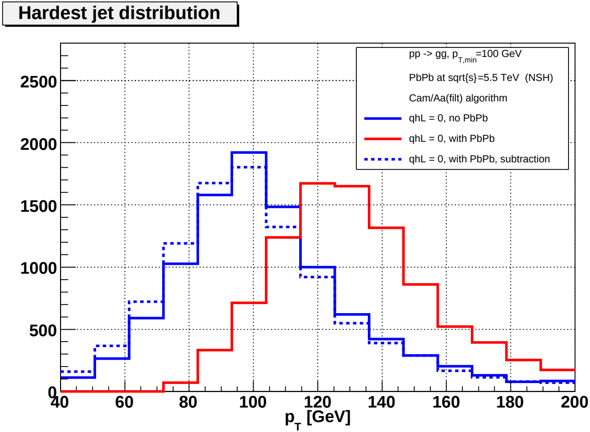

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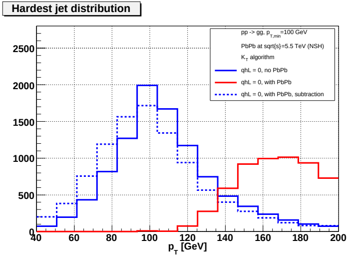
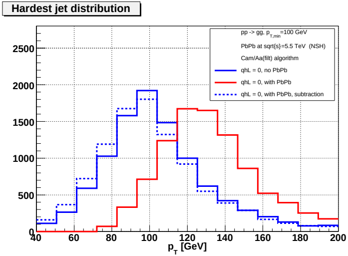
Inclusive jet distribution in pp dijet events embedded in LHC PbPb events
k_T and Cam/Aa(filt) algorithms with $R = 0.4$

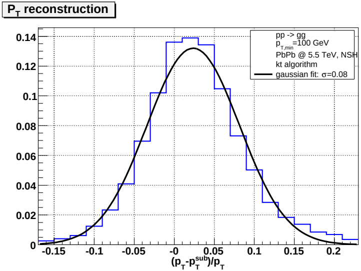


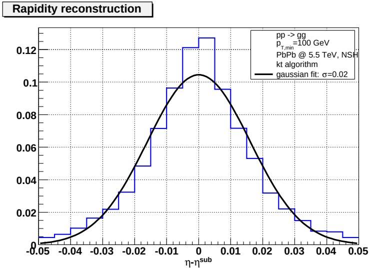


- Filtering decreases sizably the shift in p_T^j due to UE due a reduction in the jet area (from $\delta p_T^{UE} \sim 70$ with k_T to $\delta p_T^{UE} \sim 30$ with Cam/Aa(filt))
- Filtering reduces the UE contamination, similarly imposing a cut in p_T but with a IRC safe and unbiased method

Jet reconstruction

Compare reconstruction efficiency for pp jets ($p_T^{\rm jet} = 100$ GeV) and PbPb jets with UE(NSH) subtracted ($N_{mis\ id} \le 3\%$), k_t alg, R=0.4





Note effects of Back-reaction ($\sim 3\%$ correction)

Extract $\sigma_{p_T}^{\rm reco}$: figure of merit of jet reconstruction

Jet areas for Background subtraction

- Subtraction brings $p_{\mu j}^{(\mathrm{sub})}$ much closer to the original $p_{\mu j}$ value
- Subtraction improves sizably the jet resolution (event-by-event correction)
- No cut in the p_T of particles required (reduce potential biases)
- Subtraction is not meant to be perfect: various (in general small, computable) effects complicate picture: fluctuations of the background σ_ρ (observable)

$$\Delta p_t = A\rho \pm \sigma\sqrt{A} - L\,, \qquad \langle L\rangle = \mathcal{O}\left(\alpha_s \cdot A\rho \ln \frac{p_t}{A\rho}\right)$$

back-reaction to MB particles

$$\langle \Delta p_{t,\mathrm{JA},R}^{(G-L)} \rangle \simeq \int_{p_{tm}}^{p_{t1}} dp_{t2} p_{t2} \left[\frac{dP_{\mathrm{JA},R}^{(G)}}{dp_{t2}} - \frac{dP_{\mathrm{JA},R}^{(L)}}{dp_{t2}} \right] = \mathcal{B}_{\mathrm{JA},R}\, \rho \cdot \frac{C_1}{\pi b_0} \ln \frac{\alpha_s(\rho R^3)}{\alpha_s(p_{t1}R)}\,;$$

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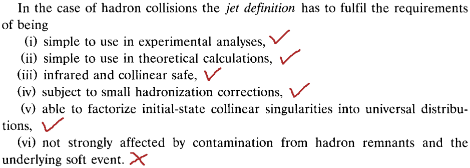
Filtering

Sequential recombination jet algorithms suffer from sizable UE corrections
From original k_T paper S. Catani et al., Nucl.Phys.B406:187-224,1993.



In the case of hadron collisions the *jet definition* has to fulfil the requirements of being

(i) simple to use in experimental analyses, ✓
(ii) simple to use in theoretical calculations, ✓
(iii) infrared and collinear safe, ✓
(iv) subject to small hadronization corrections, ✓
(v) able to factorize initial-state collinear singularities into universal distributions, ✓
(vi) not strongly affected by contamination from hadron remnants and the underlying soft event. ✗

Improve performance with automatic post-processing: Filtering

1. Cluster **all the particles in the event** with a given jet definition (JA_1,R_1).
2. Take **each of the jets** of event and **cluster its constituents** with another jet definition (JA_2,R_2) with $R_2 < R_1$ →**Set of subjets** of original jet.
3. **Keep the n_{sj} subjets of a jet with largest p_T** and **throw way the remaining subjets**.
4. Original jets are replaced merging the selected subjets

(See J. Butterworth et al., (arXiv:0802.2470 [hep-ph]))

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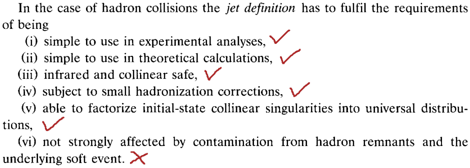

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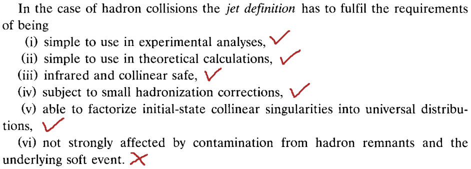

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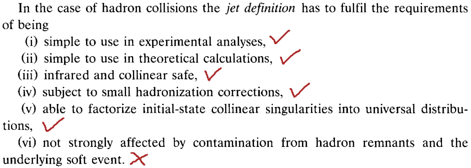

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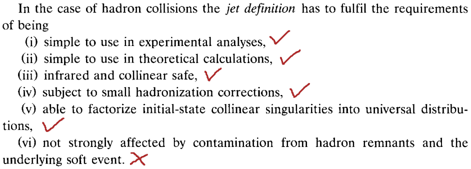

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(iii) infrared and collinear safe, ✓
(iv) subject to small hadronization corrections, ✓
(v) able to factorize initial-state collinear singularities into universal distributions, ✓
(vi) not strongly affected by contamination from hadron remnants and the underlying soft event. ✗

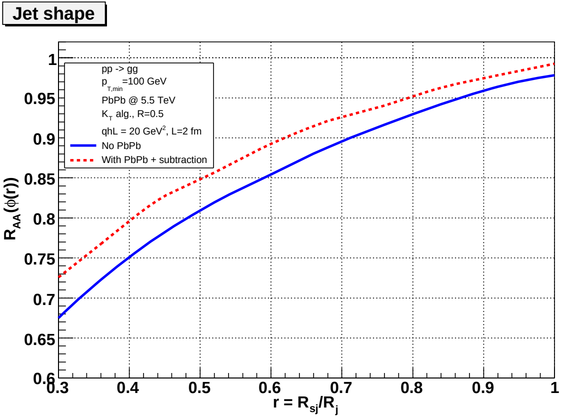
Improve performance with automatic post-processing: Filtering

1. Cluster **all the particles in the event** with a given jet definition (JA_1,R_1).
2. Take **each of the jets** of event and **cluster its constituents** with another jet definition (JA_2,R_2) with $R_2 < R_1$ →**Set of subjets** of original jet.
3. **Keep the n_{sj} subjets of a jet with largest p_T** and **throw way the remaining subjets**.
4. Original jets are replaced merging the selected subjets

(See J. Butterworth et al., (arXiv:0802.2470 [hep-ph]))

Jet shape

$$R_{AA}\left(\phi(r)\right) \equiv \phi_{\rm pp+med+PbPb+sub}(r)/\phi_{\rm pp}(r)$$



UE Background simulation

Simulation of the soft background expected in HIC at the LHC → embed *pp* event into a min-bias PbPb event @ 5.5 ATeV (central collisions $b \leq 3$ fm) simulated with PSM from N. S. Amelin, et al., Eur. Phys. J. C **22** (2001) 149.
PSM is a two-component MC model for HIC:

1. Soft collisions leading to strings (DPM: valence strings $\propto N_{\rm part}$ + sea strings $\propto N_{\rm coll}$) which might interact forming color ropes
2. Semi-hard collisions generated through `Pythia` (+ GRV94 + EKS98)

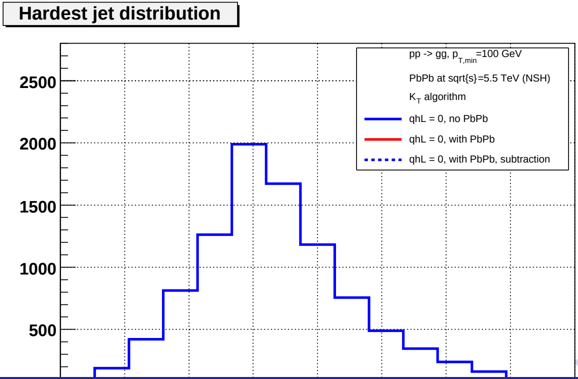
Options	$\langle N_{\rm particles} \rangle$	$\left\langle \frac{dN}{d\eta}\Big\|_{\eta=0} \right\rangle$	$\left\langle \frac{dN_{\rm ch}}{d\eta}\Big\|_{\eta=0} \right\rangle$
PbPb with semi-hard events (SH)	$4.7 \cdot 10^4$	5350	3020
PbPb wo semi-hard events (NSH)	$2.7 \cdot 10^4$	2230	1230

Azimuthal asymmetry generated trough an induced elliptic flow with $v_2 = 0.05$ for $p_T \leq 4$ GeV particles
Effect of different MC models for HIC background → work in progress

Background subtraction in practice

Inclusive jet distribution in pp dijet events embedded in PbPb events

k_T algorithm with $R = 0.4$ k_T algorithm with $R = 0.4$ k_T algorithm with $R = 0.4$ Cam/Aa(filt) algorithm with $R = 0.4$ Cam/Aa(filt) algorithm with $R = 0.4$ Cam/Aa(filt) algorithm with $R = 0.4$



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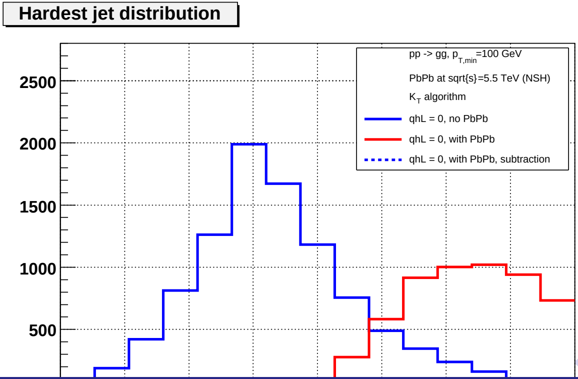

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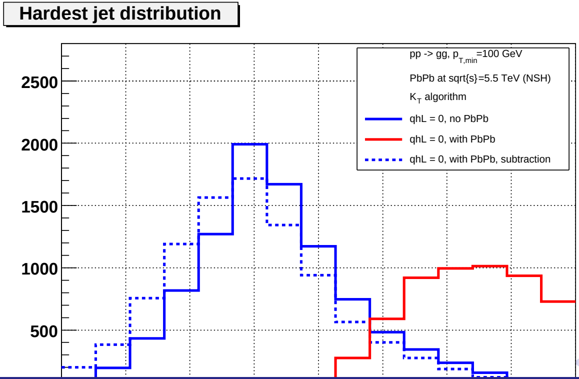

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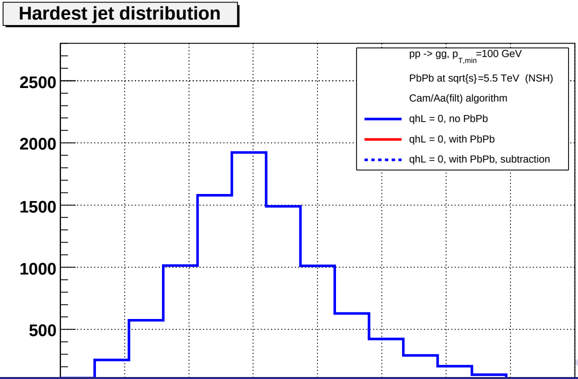

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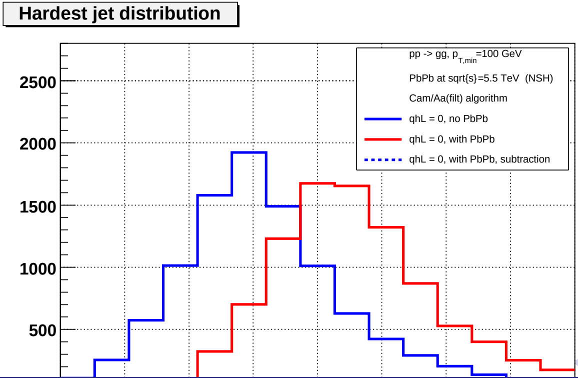

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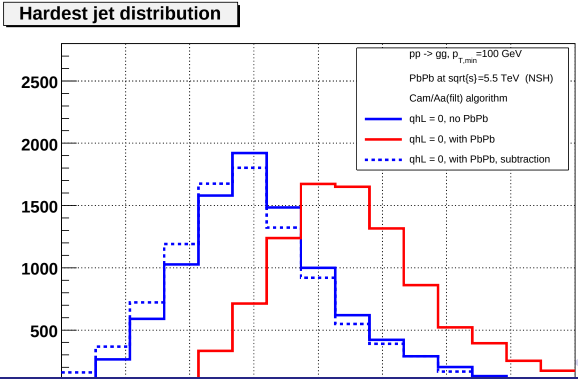


Background subtraction

Data-driven method to estimate the background density per unit area ρ (from the Underlying Event) on an event-by-event basis

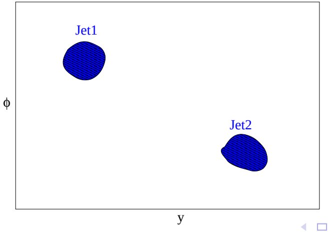
Key observation → For UE jets, $p_T^{\text{jet}} \sim A_{\text{jet}}$

$$\rho \equiv \text{median}\left[\left\{\frac{p_{tj}}{A_j}\right\}\right] \tag{2}$$

and subtract it from the hard jets using its area A_j

$$p_{\mu j}^{(\text{sub})} = p_{\mu j} - A_{\mu j}\,\rho \pm \sigma_\rho \sqrt{A_j} \tag{3}$$

Circular range of $D = 3R$ centered on jet axis (reduce sensitivity to UE structure)



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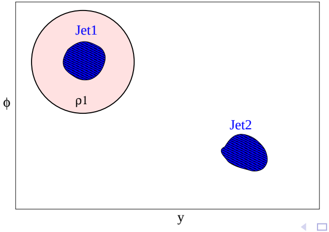

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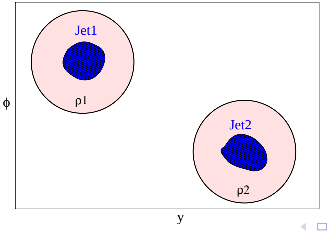

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Circular range of $D = 3R$ centered on jet axis (reduce sensitivity to UE structure)

- Subtraction improves sizably the jet resolution
- Subtraction brings $p_{\mu j}^{(\rm sub)}$ close to the original $p_{\mu j}$ value
- However, subtraction is not meant to be perfect: various (small, computable) effects complicate picture: fluctuations of the background σ_ρ (observable), back-reaction

$$\langle \Delta p_{t,{\rm JA},R}^{(G-L)} \rangle \simeq \int_{p_{tm}}^{p_{t1}} dp_{t2}p_{t2}\left[\frac{dP_{{\rm JA},R}^{(G)}}{dp_{t2}} - \frac{dP_{{\rm JA},R}^{(L)}}{dp_{t2}}\right] = \mathcal{B}_{{\rm JA},R}\,\rho\cdot\frac{C_1}{\pi b_0}\ln\frac{\alpha_s(\rho R^3)}{\alpha_s(p_{t1}R)}\,,$$

Medium effects

Medium effects from ACSW Armesto et al, JHEP 0802:048,2008: radiative energy loss through modification of vacuum splitting functions.

$$P^{\rm tot}(z) = P^{\rm vac}(z) + \Delta P(z,t)\ , \quad \Delta P(z,t) \simeq \frac{2\pi t}{\alpha_s}\,\frac{dI^{\rm med}}{dzdt}\ , \quad \hat{q} \equiv \frac{\left\langle q_\perp^{2,{\rm med}}\right\rangle}{\lambda}$$

Implemented in modified `Pythia 6.4` → **Q-PYTHIA**

Samples generated for $pp \to gg$ for medium length $L = 2$ fm and transport coefficient $2\ {\rm GeV}^2 \le \hat{q}L \le 20\ {\rm GeV}^2$

$$\omega\frac{dI}{d\omega\, d\mathbf{k}_\perp} = \frac{\alpha_s\, C_R}{(2\pi)^2\,\omega^2}\, 2{\rm Re}\int_0^\infty dy_l \int_{y_l}^\infty d\bar{y}_l \int d\mathbf{u}\, e^{-i\mathbf{k}_\perp\cdot\mathbf{u}}\, e^{-\frac{1}{2}\int_{\bar{y}_l}^\infty d\xi\, n(\xi)\,\sigma(\mathbf{u})}$$
$$\times\ \frac{\partial}{\partial\mathbf{y}}\cdot\frac{\partial}{\partial\mathbf{u}}\int_{\mathbf{y}=0=\mathbf{r}(y_l)}^{\mathbf{u}=\mathbf{r}(\bar{y}_l)}\mathcal{D}\mathbf{r}\,\exp\left[i\int_{y_l}^{\bar{y}_l} d\xi\,\frac{\omega}{2}\left(\dot{\mathbf{r}}^2 - \frac{n(\xi)\sigma(\mathbf{r})}{i\,\omega}\right)\right]\ .$$

$$\omega\frac{dI}{d\omega\, d\mathbf{k}_\perp} = \omega\frac{dI^{\rm vac}}{d\omega\, d\mathbf{k}_\perp} + \omega\frac{dI^{\rm med}}{d\omega\, d\mathbf{k}_\perp}\ , \quad n(\xi)\,\sigma(\mathbf{r}) \simeq \frac{1}{2}\,\hat{q}(\xi)\,\mathbf{r}^2\ , \omega = (1-z)E$$

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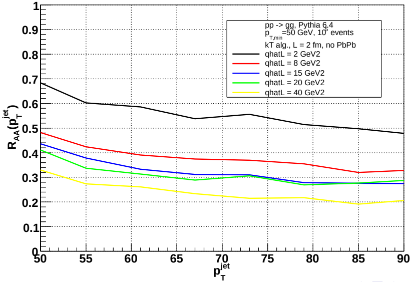
Nuclear suppression $R_{AA}(p_T^{\rm jet}) \equiv \left(d\sigma^{\rm med}/dp_T^{\rm jet}\right) \Big/ \left(d\sigma^{\rm vac}/dp_T^{\rm jet}\right)$ for $R = 0.4$:



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Note that our jet finding technology can be applied to study the effects of any model of medium effects and jet quenching:

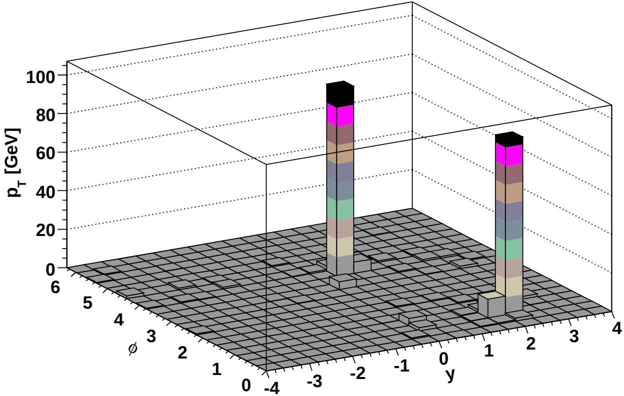
Our program:

1. Study jet finding in HIC for a generic medium effects model (this talk)
2. Determine which observables are more suited to discriminate between models of jet quenching
3. Useful tools: Implementation of different models in practical Monte Carlo showering programs

   `JEWEL`, K. Zapp et al, arXiv:0804.3568, see also U. Wiedemann's talk
   T. Renk, arXiv:0806.0305
   L. Cunqueiro talk
   others: `HYDJET`, `PYQUENCH` , ...

A typical dijet event

$pp \longrightarrow gg$ events with $p_T^{\rm jet} \sim 100$ GeV and $R = 0.4$ - No PbPb



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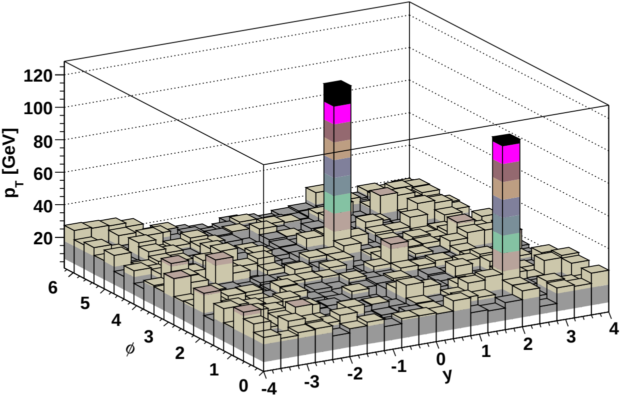
$pp \rightarrow gg$ events with $p_T^{\rm jet} \sim 100$ GeV and $R = 0.4$ - PbPb model NSH



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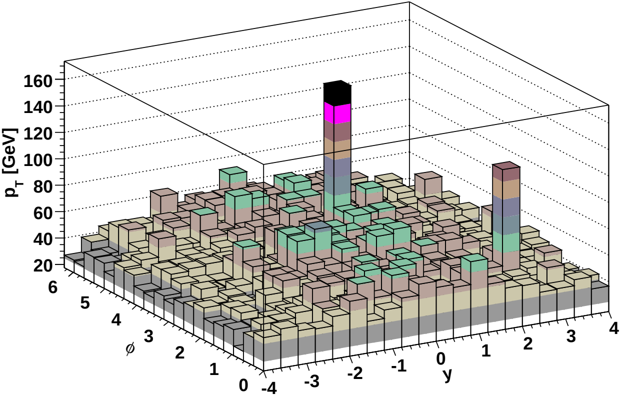
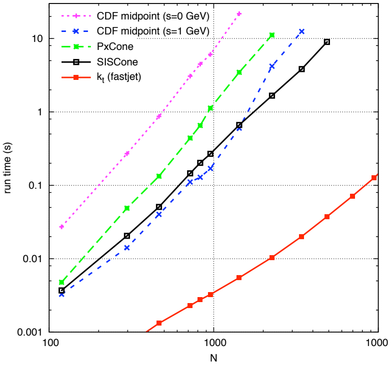


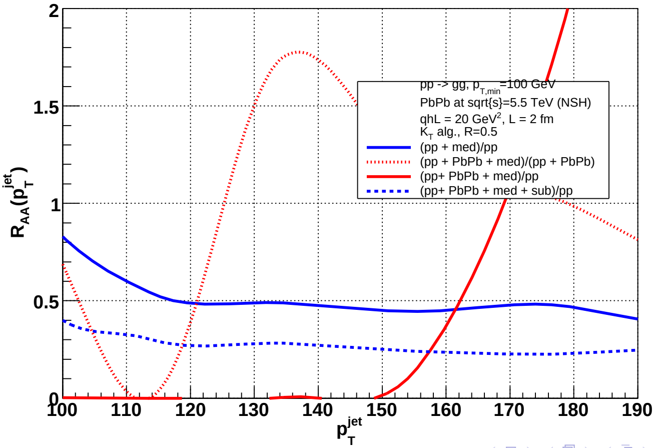
Speed

Modern jet finding tools allow fast implementations to cope with large LHC multiplicities $N \sim 800 - 4000$ for pp, $N \sim 40000$ for HIC
In `FastJet`, seq. reco. algs. like k_T, the time it takes to cluster N particles scales as as $N \ln N$ (not N^3!)



Inclusive jet distribution

$R_{AA}(p_T)$ for the hardest jet distribution with the k_T algorithm at $R = 0.5$

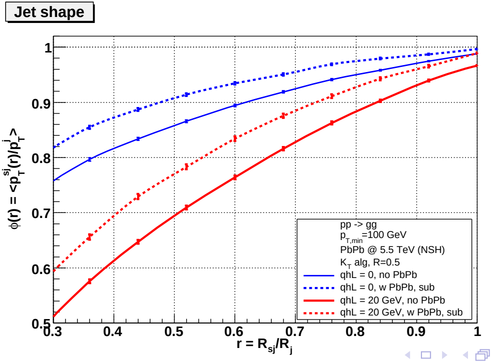


The Anti-k_T algorithm

The Anti-k_T algorithm (M. Cacciari et al., arXiv:0802.1189) has a very reduced sensitivity to Back-Reaction:

$$\Delta p_T^{\mathrm{BR}}\Big|_{k_T} \sim 5\mathrm{GeV}\ , \qquad \Delta p_T^{\mathrm{BR}}\Big|_{\mathrm{Anti}-k_T} \sim 1\mathrm{GeV}$$

for $p_T^{\mathrm{jet}} \sim 100$ GeV, $R = 0.5$, $\rho \sim 150$ GeV.



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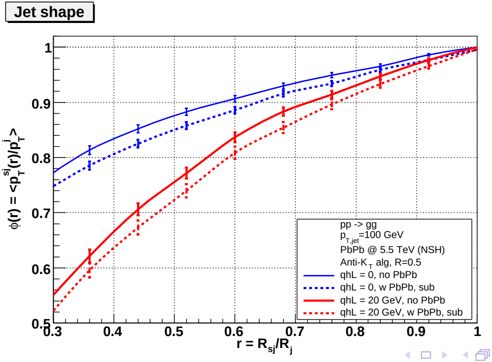
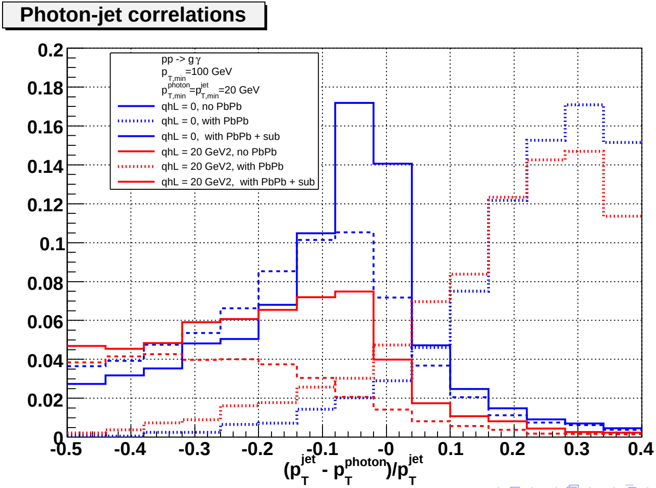


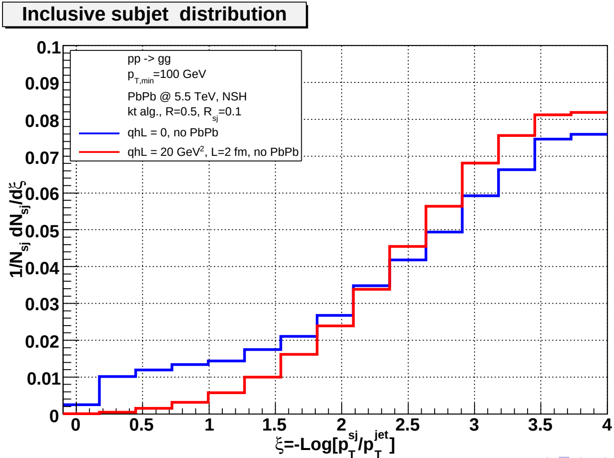
Photon-jet correlations

Photons offer an unbiased calibration of jet energy



Subjet distribution

Distribution of subjets with a hard jet (the IRC safe observable related to the hump-backed plateau)



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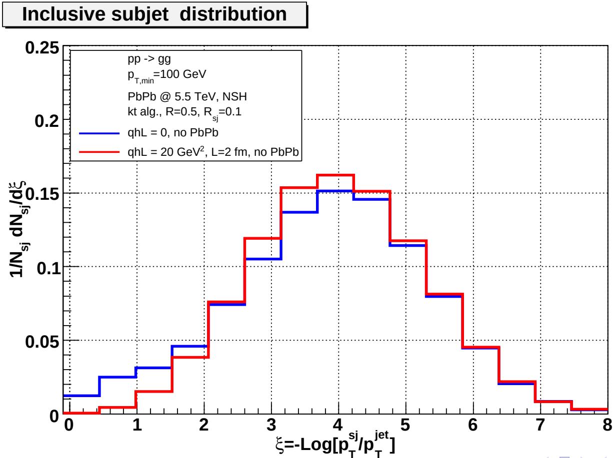


Quenching weights

The approach of AQSZ reproduces the *quenching weights*

$$D(x,t) = \Delta(t) D(x,t_0) + \Delta(t) \int_{t_0}^{t} \frac{dt_1}{t_1} \frac{1}{\Delta(t_1)} \int \frac{dz}{z} P(z) D\left(\frac{x}{z}, t_1\right) . \qquad (4)$$

$$P(z) = P^{\rm vac}(z) + \Delta P(z), \quad \Delta(t) = \Delta^{\rm vac}(t) \Delta^{\rm med}(t), \qquad (5)$$

$$p_0 = \exp\left[- \int d\omega \int d\mathbf{k}_\perp \frac{dI^{\rm med}}{d\omega d\mathbf{k}_\perp} \right], \qquad (6)$$

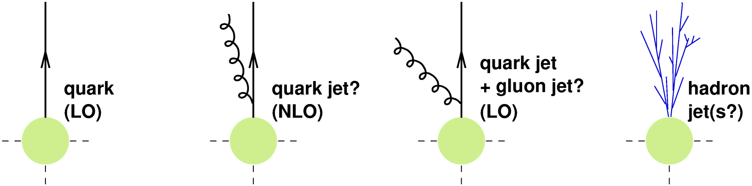
$$p(\epsilon) = p_0 \sum_{n=1}^{\infty} \prod_{i=1}^{n} \int d\omega_i \int d\mathbf{k}_{\perp i} \frac{dI^{\rm med}}{d\omega_i d\mathbf{k}_{\perp i}} \delta\left(\epsilon - \sum_{j=1}^{n} \frac{\omega_i}{E} \right) \qquad (7)$$

$$D(x,t) \simeq p_0 \, D^{\rm vac}(x,t) + \int \frac{d\epsilon}{1-\epsilon} p(\epsilon) \, D^{\rm vac}\left(\frac{x}{1-\epsilon}, t \right) . \qquad (8)$$

Jets

Naively: a jet is a **bunch of collimated hadrons** ubiquitous in high energy collisions.

Electrons and muons are fundamental, weakly coupled particles — it makes sense physically and experimentally to think of them as concrete objects. *Partons* (quarks, gluons) are not so simple...



- Partons split into further partons
- Jets are a a way of thinking of the 'original parton'
- A 'jet' is a fundamentally ambiguous concept (e.g. requires a resolution)

Jets are only meaningful once you've defined a jet algorithm

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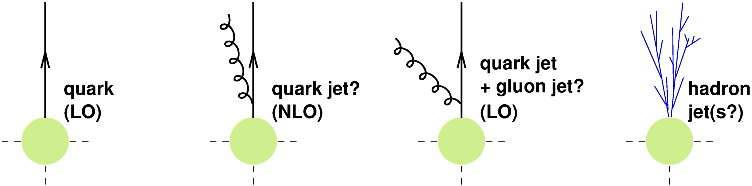

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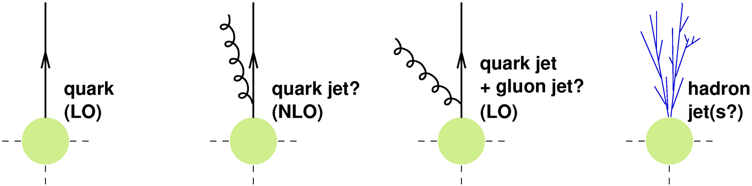

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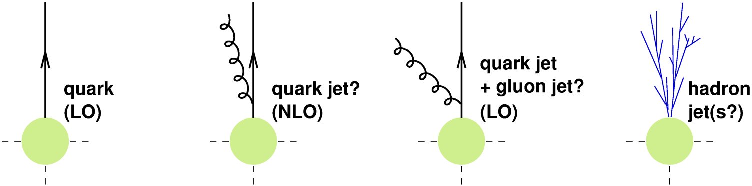

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Sequential recombination algorithms

Example: the k_t algorithm:

1. Calculate (or update) distances between all particles i and j, and between i and beam:

$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\frac{\Delta R_{ij}^2}{R^2}, \qquad d_{iB} = k_{ti}^2\,, \qquad \Delta R_{ij}^2 = \Delta y_{ij}^2 + \Delta\phi_{ij}^2$$

2. Find smallest of d_{ij} and d_{iB}
   - If d_{ij} is smallest, recombine i and j (add result to particle list, remove i, j)
   - if d_{iB} is smallest call i a jet (remove it from list of particles)
3. If any particles are left, repeat from step 1.

One parameter: R (like cone radius), whose natural value is 1
k_t algorithm attempts approximate inversion of the QCD shower branching process → Theoretical sound basis.

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k_t algorithm attempts approximate inversion of the QCD shower branching process → Theoretical sound basis.

Sequential recombination algorithms

Example: the k_t algorithm:

1. Calculate (or update) distances between all particles i and j, and between i and beam:

$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\frac{\Delta R_{ij}^2}{R^2}, \qquad d_{iB} = k_{ti}^2\,, \qquad \Delta R_{ij}^2 = \Delta y_{ij}^2 + \Delta\phi_{ij}^2$$

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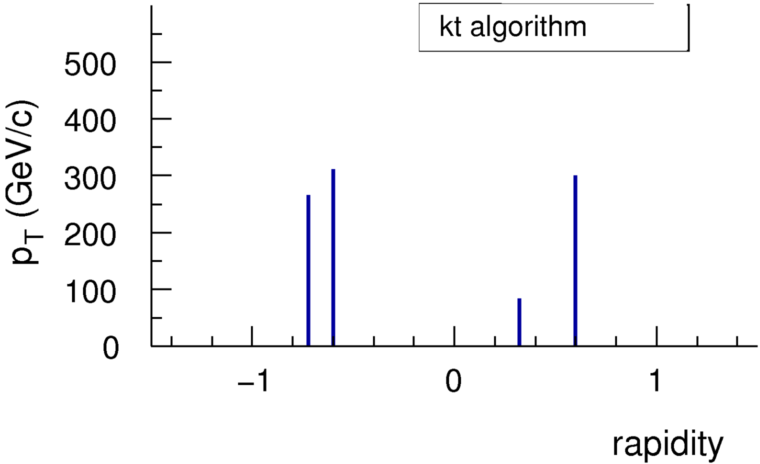
k_t algorithm in action ($R = 1$)



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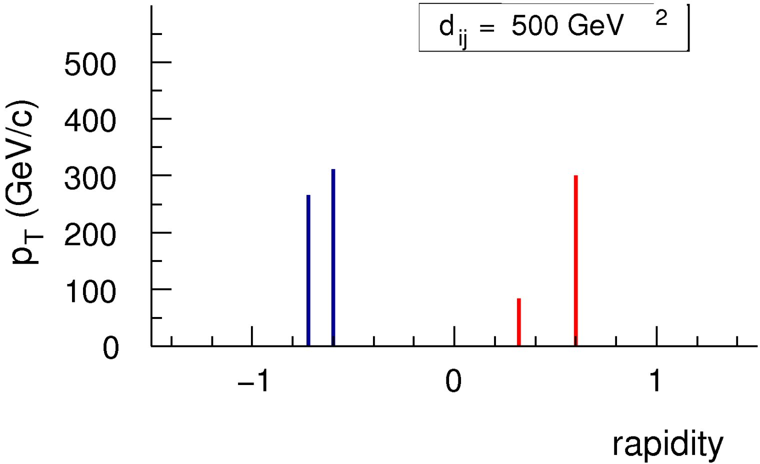

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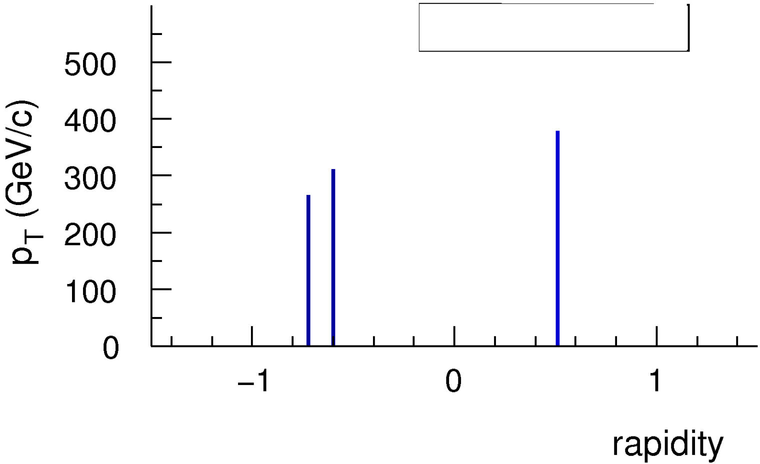

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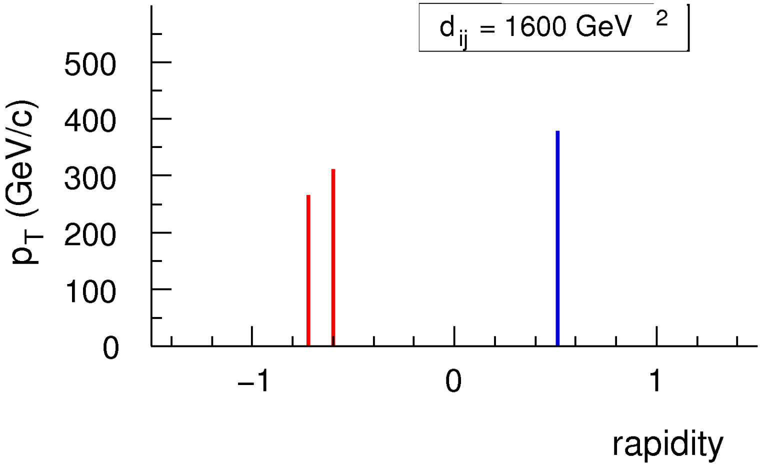

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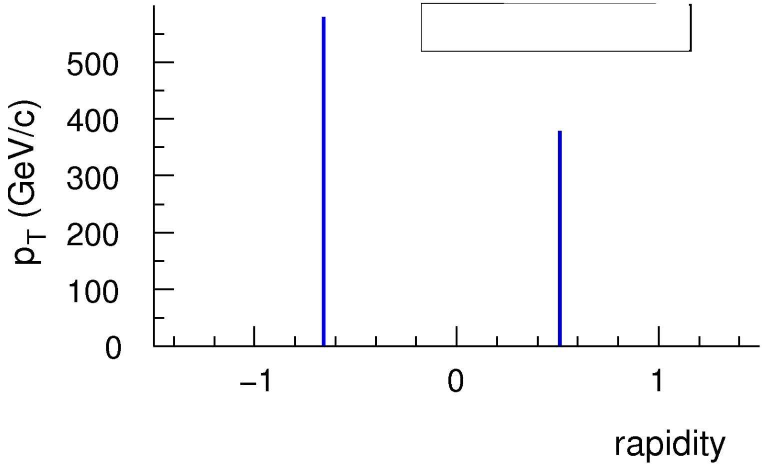

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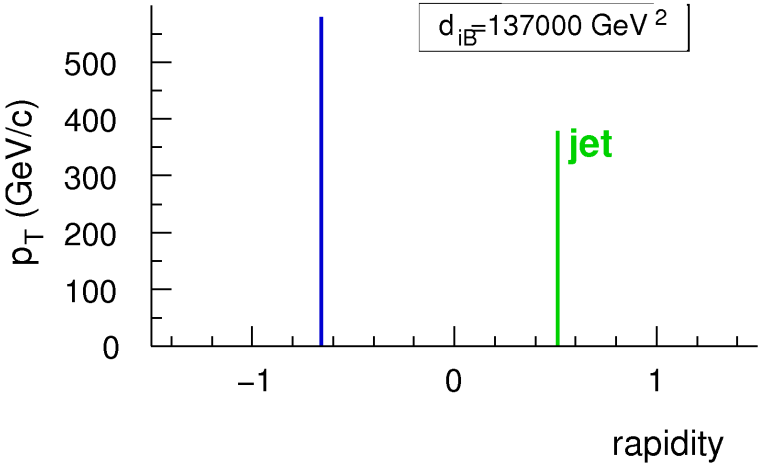

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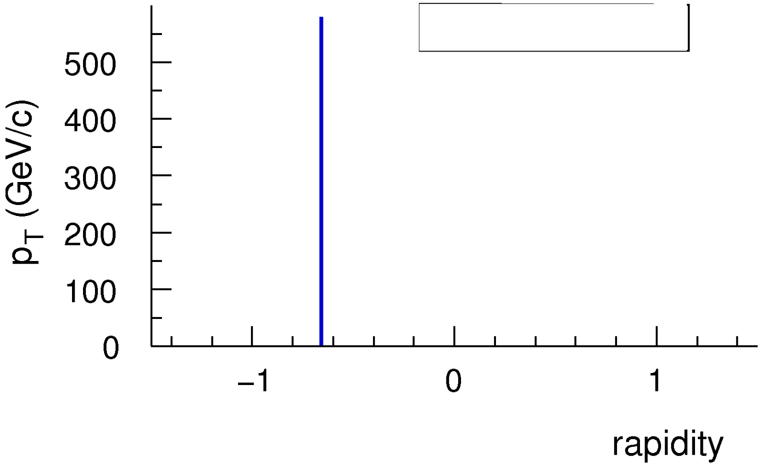

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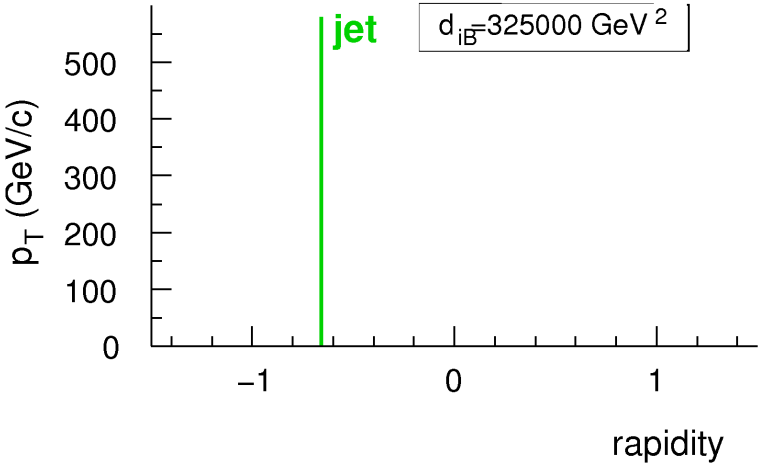
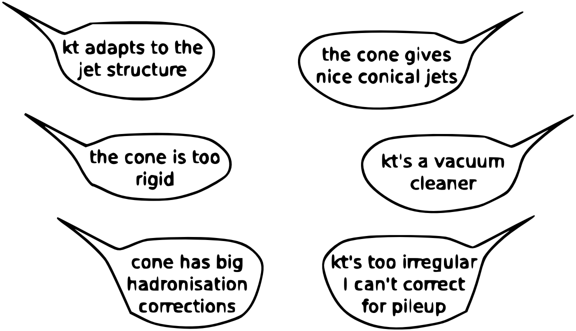


Jet Folklore

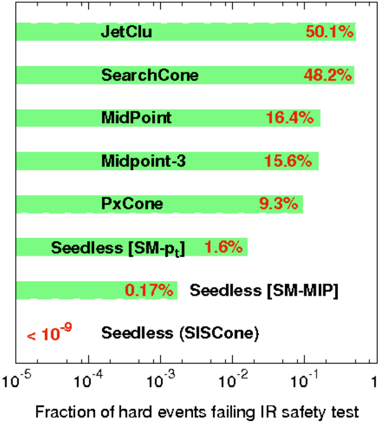
Jet discussions: polarised, often driven by unquantified statements



Several more include: *Infrared safety does not matter from a practical point of view,* k_T *is worse at hadron colliders than cone,* k_T *too slow* ...
Instead let's turn this discussion quantitative!

Infrared safety

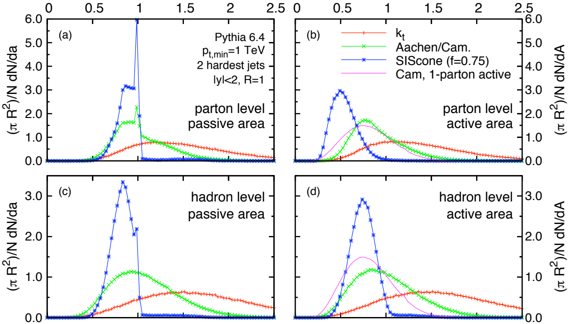
For JetClu (similar to Atlas cone), half of events fails IRC safety tests.
Even for the MidPoint cone algorithm, 15% of events fail the test!



The area of a jet

The area of a jet is only meaningful for IRC algorithms.
Active area → Cover the (η, ϕ) plane with *ghosts* (very soft particles) and cluster the event → Number of ghosts proportional to jet area (Cacciari, Salam and Soyez 08).

Jet area differs greatly from naive πR^2 even for cone algorithms.



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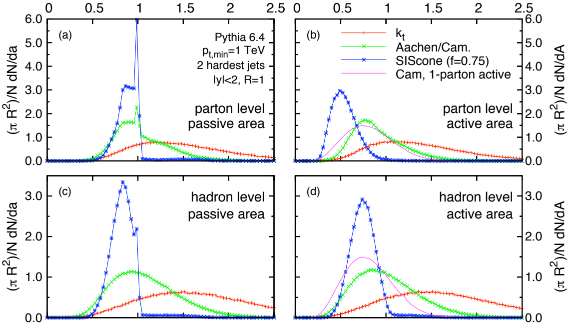
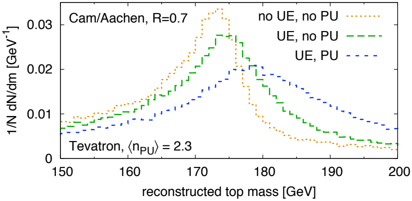


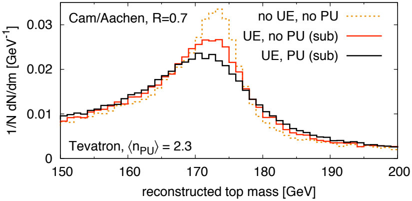
Background subtraction

Jet areas provide a technique to subtract Underlying Event and specially the Pile-up. (important at high-Lumi LHC) (Cacciari and Salam 07).

Determine the noise density per unit area $\rho = \text{median}\left[p_T^{\text{jet}}/A_{\text{jet}}\right]$ and subtract:

$$p_{\text{jet}}^{\text{sub}} = p_{\text{jet}} - A_{\text{jet}}\rho$$





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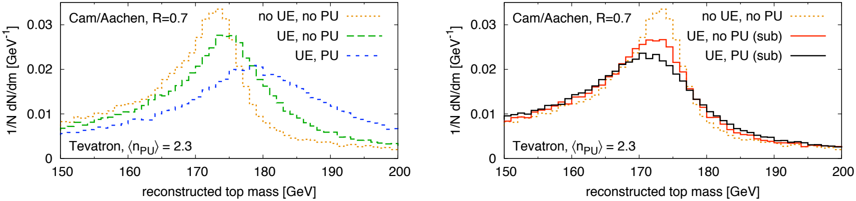
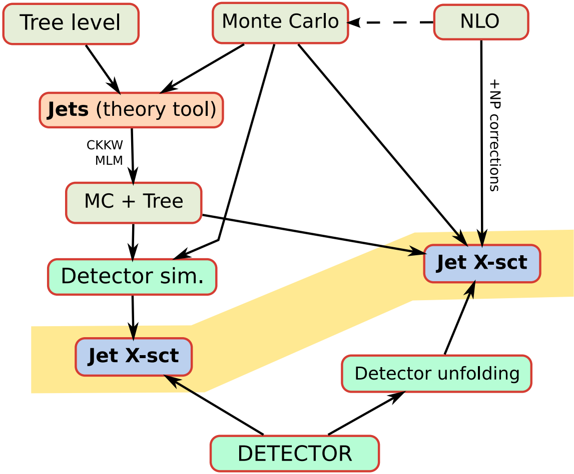


QCD flowchart

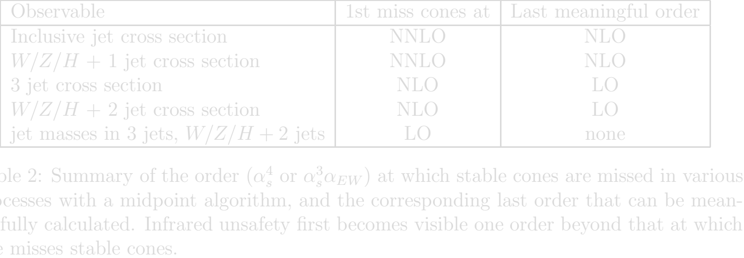


Jet (definitions) provide central link between expt., “theory” and theory

Infrared safety

Cone algorithms have been known to suffer from Infrared and Collinear unsafety for many years.

For the CDF MidPoint cone algorithm:



Observable	1st miss cones at	Last meaningful order
Inclusive jet cross section	NNLO	NLO
$W/Z/H$ + 1 jet cross section	NNLO	NLO
3 jet cross section	NLO	LO
$W/Z/H$ + 2 jet cross section	NLO	LO
jet masses in 3 jets, $W/Z/H + 2$ jets	LO	none

Table 2: Summary of the order (α_s^4 or $\alpha_s^3\alpha_{EW}$) at which stable cones are missed in various processes with a midpoint algorithm, and the corresponding last order that can be meaningfully calculated. Infrared unsafety first becomes visible one order beyond that at which one misses stable cones.

Theory investment in NLO computations: ~ 50 people $\times$ 10 years $\sim 30 - 50$ million \$ $\longrightarrow$ Lost if IRC unsafe jet algorithms used!

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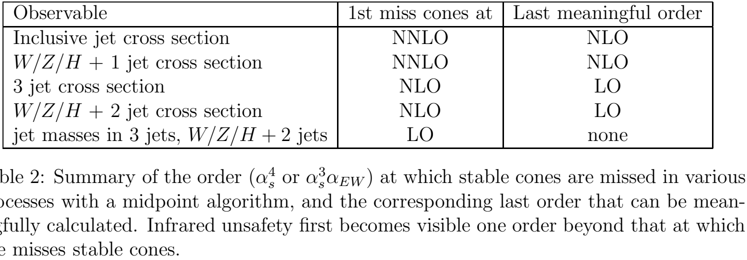

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Analytical understanding of jets

The p_T of a jet gets modified by perturbative corrections, hadronisation and underlying event (Dasgupta, Magnea and Salam 07)

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\begin{aligned}
\delta p_T^{\mathrm{pert}} &= \alpha_s L_F p_T \ln R/\pi + \mathcal{O}(R) \\
\delta p_T^{\mathrm{hadr}} &= -2 C_F \mathcal{A}(\mu_I)/R + \mathcal{O}(R) \\
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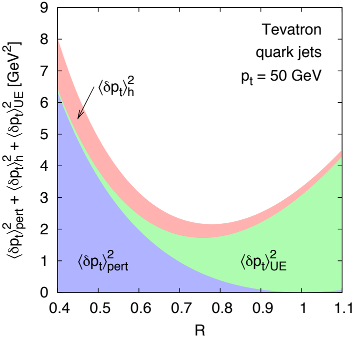

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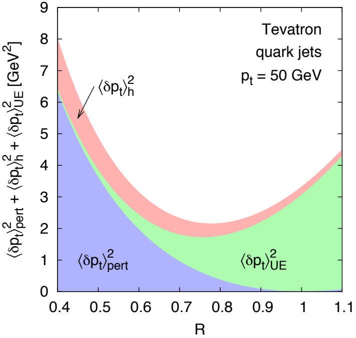

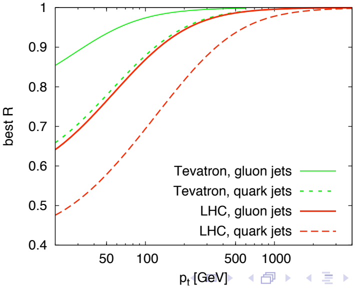

UE Background simulation

Simulation of the soft background expected in HIC at the LHC → embed *pp* event into a min-bias PbPb event @ 5.5 ATeV (central collisions $b \leq 3$ fm) simulated with PSM from N. S. Amelin, et al., Eur. Phys. J. C **22** (2001) 149.

PSM is a two-component MC model for HIC:

1. Soft collisions leading to strings (DPM: valence strings $\propto N_{\mathrm{part}}$ + sea strings $\propto N_{\mathrm{coll}}$) which might interact forming color ropes
2. Semi-hard collisions generated through `Pythia` (+ GRV94 + EKS98)

UE Background simulation

Two options (different multiplicity and y and p_T spectra) studied for the UE MC background:

- Only soft collisions, no semi-hard collisions (NSH): *easy* scenario
- With semi-hard collisions (SH): *conservative* scenario

Process	$\langle N_{\rm particles} \rangle$	$\left\langle \frac{dN}{d\eta}\Big\vert_{\eta=0} \right\rangle$	$\left\langle \frac{dN_{\rm ch}}{d\eta}\Big\vert_{\eta=0} \right\rangle$	$\left\langle \rho_{(\eta,\phi)=(0,0)} \right\rangle$	T [s]
$pp \rightarrow gg$	160	30	15	0.5 GeV	$2 \cdot 10^{-4}$
$pp \rightarrow gg(+\mathrm{PbPb/SH})$	$4.7 \cdot 10^4$	5350	3020	450 GeV	1.2
$pp \rightarrow gg(+\mathrm{PbPb/NSH})$	$2.7 \cdot 10^4$	2230	1230	150 GeV	0.2

Clustering timings with the k_T algorithm with a Intel(R)Xeon 2.66 Ghz
Jet clustering timings scales as $N_{\rm part} \ln N_{\rm part}$
All particles of the event included in clustering, no p_T cut

Inclusive jet distribution

p_T^{jet} [GeV]	JetAlg	MC back	Mis-ID jets	$\sigma_{p_T}^{\rm reco}$ [GeV]
100	k_T	NSH	3%	11
		SH	7%	18
	Cam/Aa(filt)	NSH	1%	8
		SH	3%	14
50	k_T	NSH	8%	9
		SH	18%	15
	Cam/Aa(filt)	NSH	3%	7
		SH	12%	13

- The $\sigma_{p_T}^{\rm reco}$ of the subtracted jets is not very sensitive to absolute $p_T^{\rm jet}$ scale
- In the good(bad) background scenario, NSH(SH), $p_T^{\rm jet} = 50$ GeV jets can be reconstructed without cuts in p_T of input particles with relative uncertainty ($\sigma_{p_T}^{\rm reco}/p_T^{\rm jet} \sim 0.15(0.26)$)
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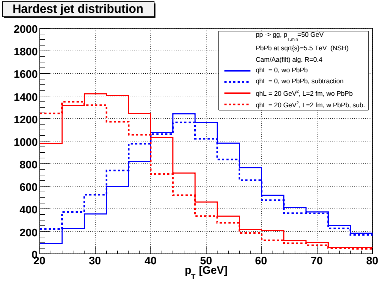

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