HERA LHC workshop

2nd workshop on the implications of HERA for LHC physics

Summary of the WG2

Hadronic final states and jet energy flow

Part I: Theory

Conveners: C. Gwenlan (ZEUS), L. Lönnblad (Lund), E. Rodrigues (LHCb), G. Zanderighi(CERN)
Contact persons: S. Banerjee (CMS), J. Butterworth (ATLAS)

- Underlying event and minimum bias
- Rapidity gaps and survival probabilities
- Multi-jet topologies and multi-scale QCD
- Parton shower/ME matching

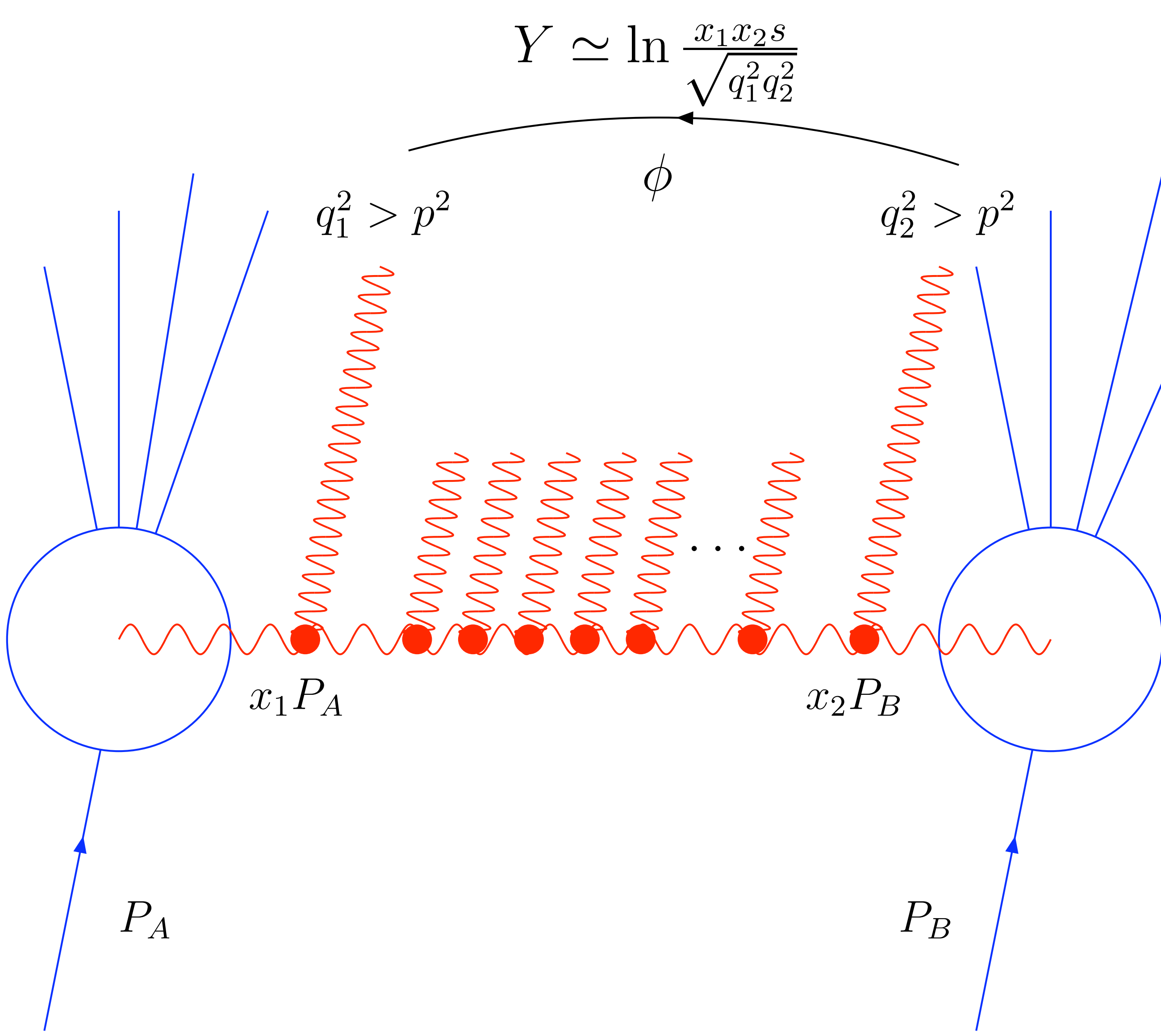
Topics addressed here

- NLL BFKL, multi Regge kinematics
- prompt photons and kt-factorization
- theory accuracy on determination of pdfs
- logarithms and validation of Monte Carlos
- jets issues (infrared safety, speed, jet-areas...)
- higher orders, subtraction schemes, Higgs, combining QED&QCD
  $\Rightarrow$ see talk of Sven Moch

Azimuthal angles in multi-Regge kinematics

Augustin Sabio-Vera

Mueller Navelet jets at hadron colliders



Leading jets widely separated in rapidity.
Allow radiation in between.
⇒ BFKL regime large logs

$$\ln(s/|t|) \sim Y$$

No radiation: jets back-to-back

Interested in azimuthal (de)-correlation between jets.

Azimuthal angles in multi-Regge kinematics

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$$\frac{d\hat{\sigma}\left(\alpha_s, \mathrm{Y}, p_{1,2}^2\right)}{d\phi} = \frac{\pi^2 \bar{\alpha}_s^2}{4\sqrt{p_1^2 p_2^2}} \sum_{n=-\infty}^{\infty} e^{in\phi}\, \mathcal{C}_n\left(\mathrm{Y}\right)$$

Fourier expansion

$$\mathcal{C}_n\left(\mathrm{Y}\right) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{d\nu}{\left(\frac{1}{4}+\nu^2\right)} \left(\frac{p_1^2}{p_2^2}\right)^{i\nu} e^{\chi\left(|n|, \frac{1}{2}+i\nu, \bar{\alpha}_s(p_1 p_2)\right)\mathrm{Y}}$$

Fourier coefficients

$$\chi\left(n, \gamma, \bar{\alpha}_s\right) \equiv \bar{\alpha}_s \chi_0\left(n, \gamma\right) + \bar{\alpha}_s^2 \left(\chi_1\left(n, \gamma\right) - \frac{\beta_0}{8 N_c} \frac{\chi_0\left(n, \gamma\right)}{\gamma\left(1-\gamma\right)}\right)$$

NLO kernel

$$\hat{\sigma}\left(\alpha_s, \mathrm{Y}, p_{1,2}^2\right) = \frac{\pi^3 \bar{\alpha}_s^2}{2\sqrt{p_1^2 p_2^2}}\, \mathcal{C}_0\left(\mathrm{Y}\right)$$

Integrated $\hat{\sigma}$ - only $\mathcal{C}_0$ survives

$$\langle \cos\left(m\phi\right) \rangle = \frac{\mathcal{C}_m\left(\mathrm{Y}\right)}{\mathcal{C}_0\left(\mathrm{Y}\right)}$$

Moments - extract various $\mathcal{C}_m$

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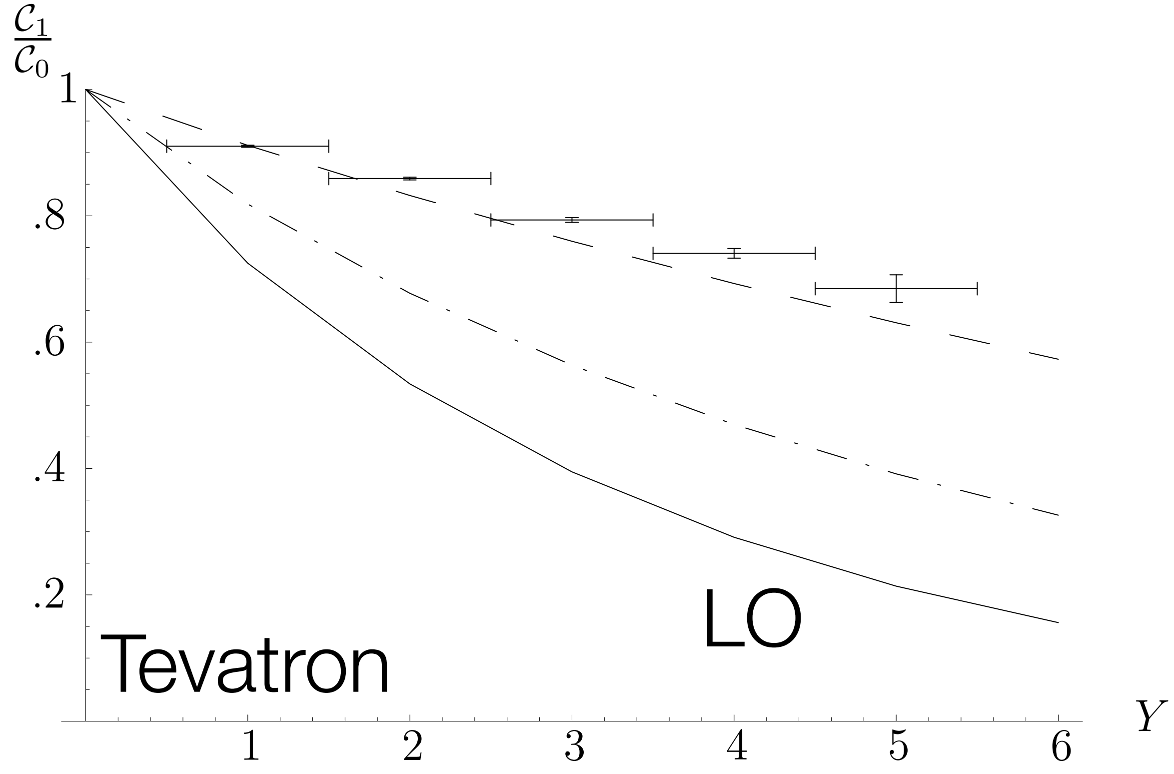

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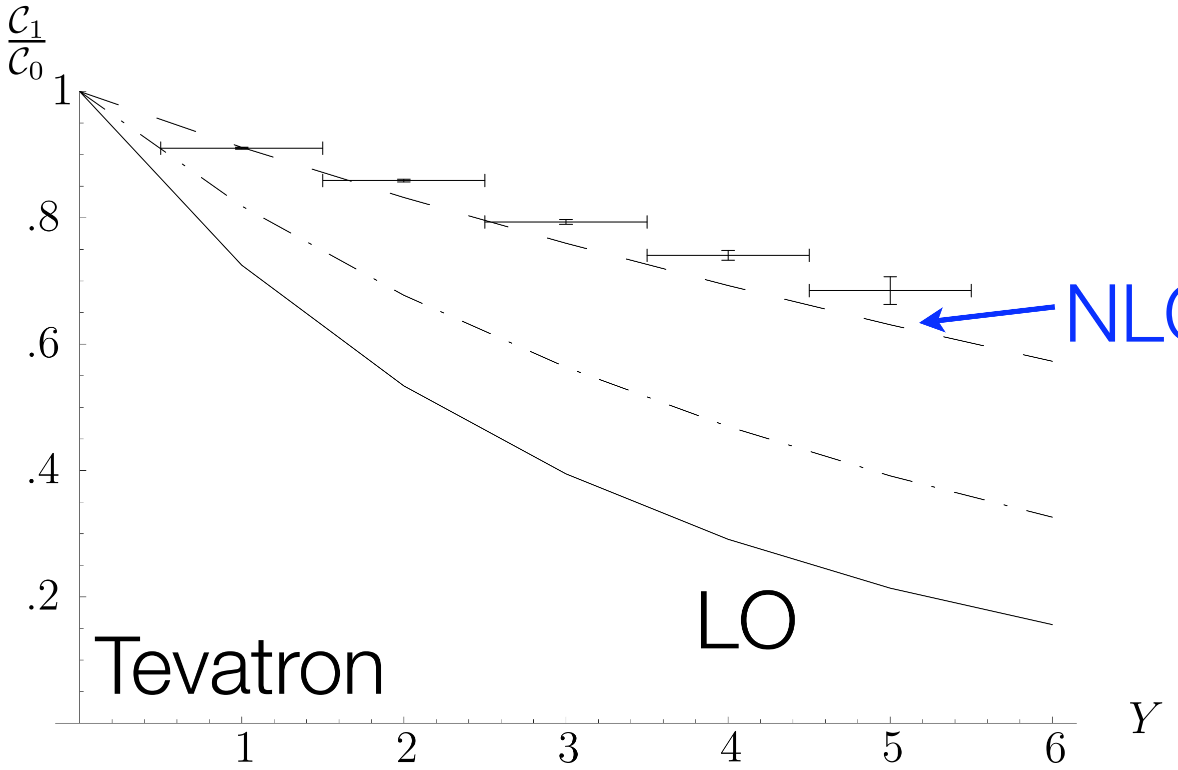

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NLO $\Rightarrow$ looks ok, but large ambiguity
need collinear resummation

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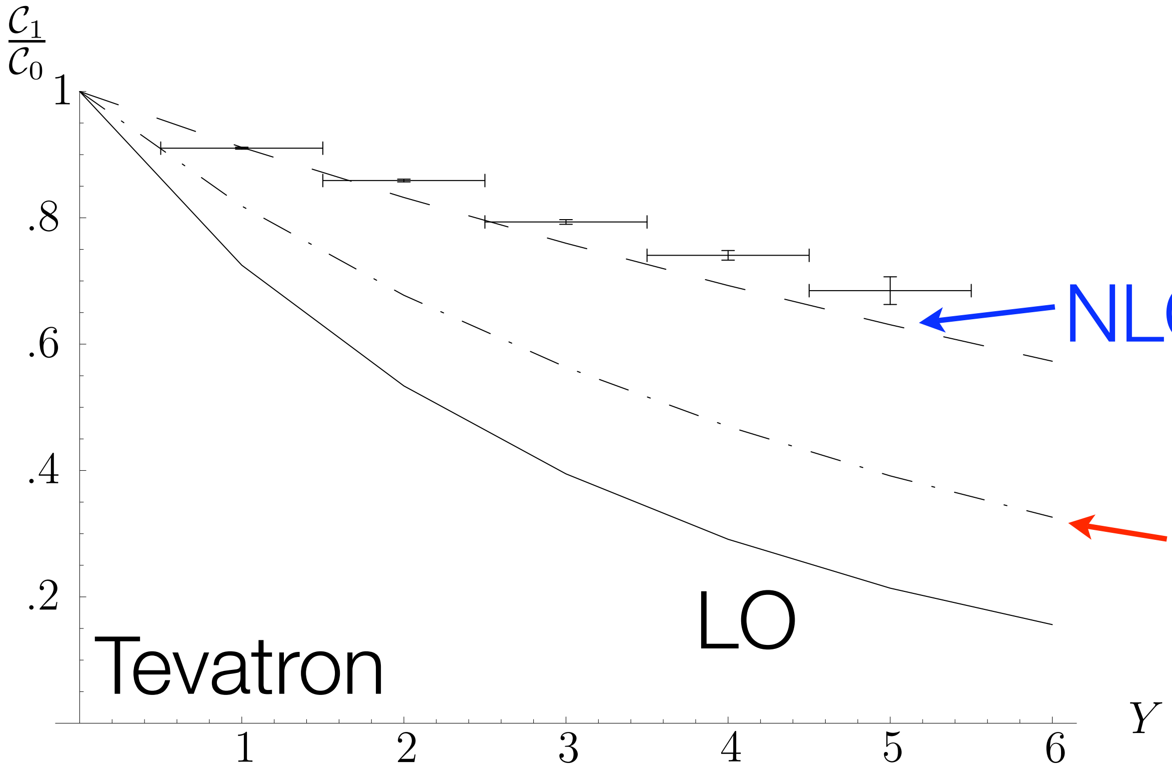

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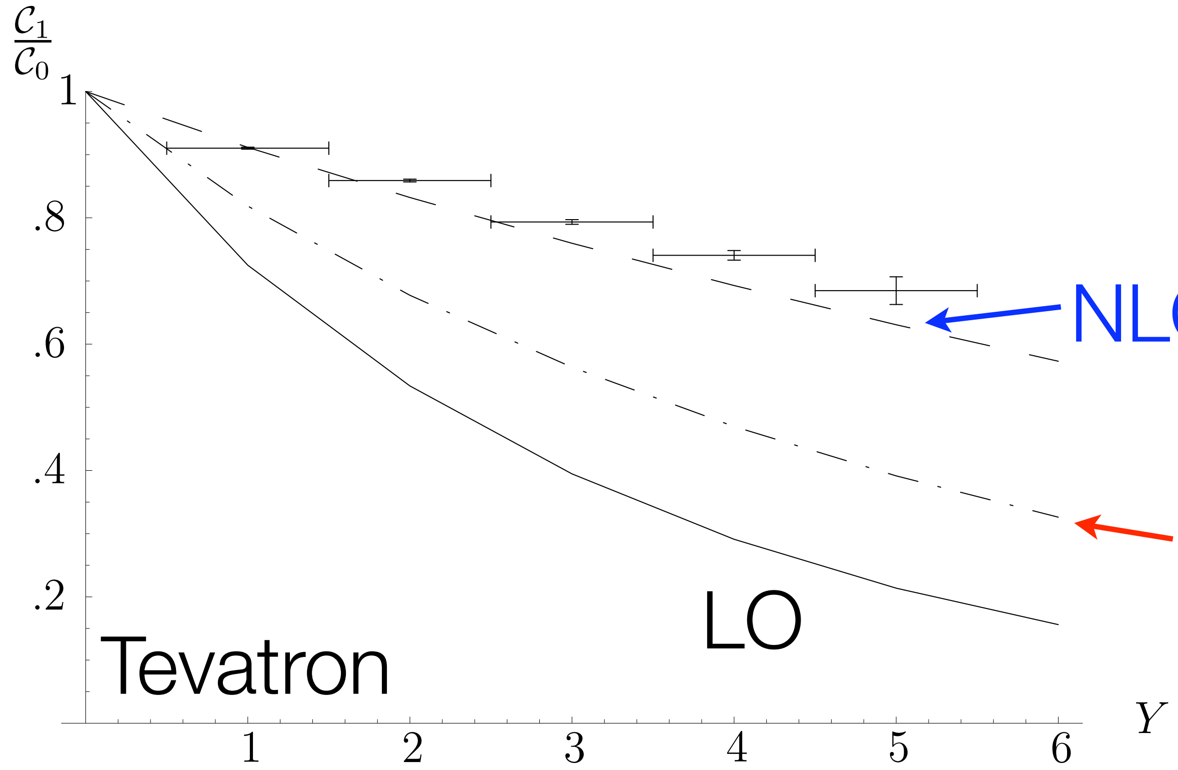

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Hope at LHC because of larger accessible rapidity distance
⇒ closer to asymptotic region

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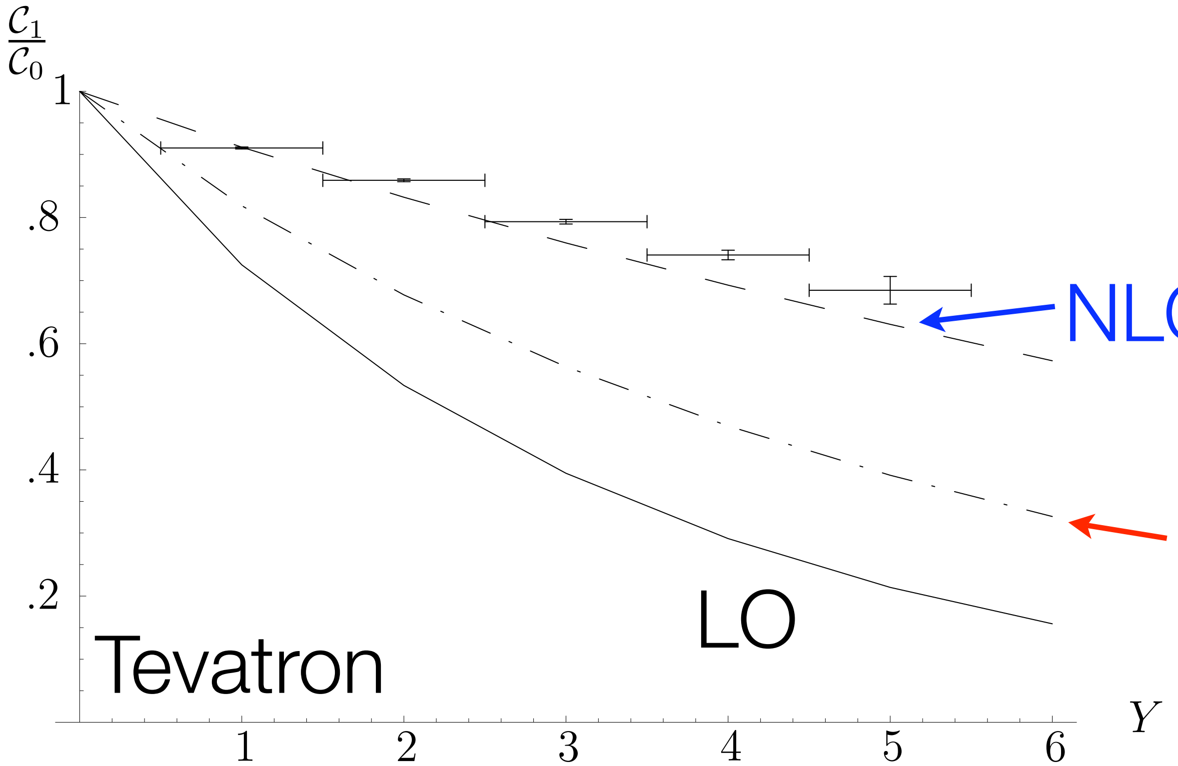

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NLO ⇒ looks ok, but large ambiguity need collinear resummation

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Comments: Herwig agrees with data. Maybe BFKL does not catch the relevant physics and a threshold resummation would do the job? Conversely, if one wants to find BFKL effects maybe this is not the right observable?

NLL BFKL for forward and Mueller Navalet jets

Christophe Royon

Forward jets at Hera in BFKL domain: $k_t^2 \sim Q^2$ with Q^2 not too large

NLL BFKL for forward and Mueller Navalet jets

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BFKL LO formalism

- BFKL LO forward jet cross section, saddle point approximation:

$$\frac{d\sigma}{dx dk_T dQ^2 dx_{jet}} = N \sqrt{\frac{Q^2}{k_T^2}} \alpha_S(k_T^2) \alpha_S(Q^2) \sqrt{A} \exp\left(4\alpha(log2)\frac{N_C}{\pi}\log(\frac{x_J}{x})\right) \exp\left(-A\log^2(\sqrt{\frac{Q}{k_T}})\right)$$

- 2 parameters in fits to $d\sigma/dx$: N, α

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- 2 parameters in fits to $d\sigma/dx$: N, α

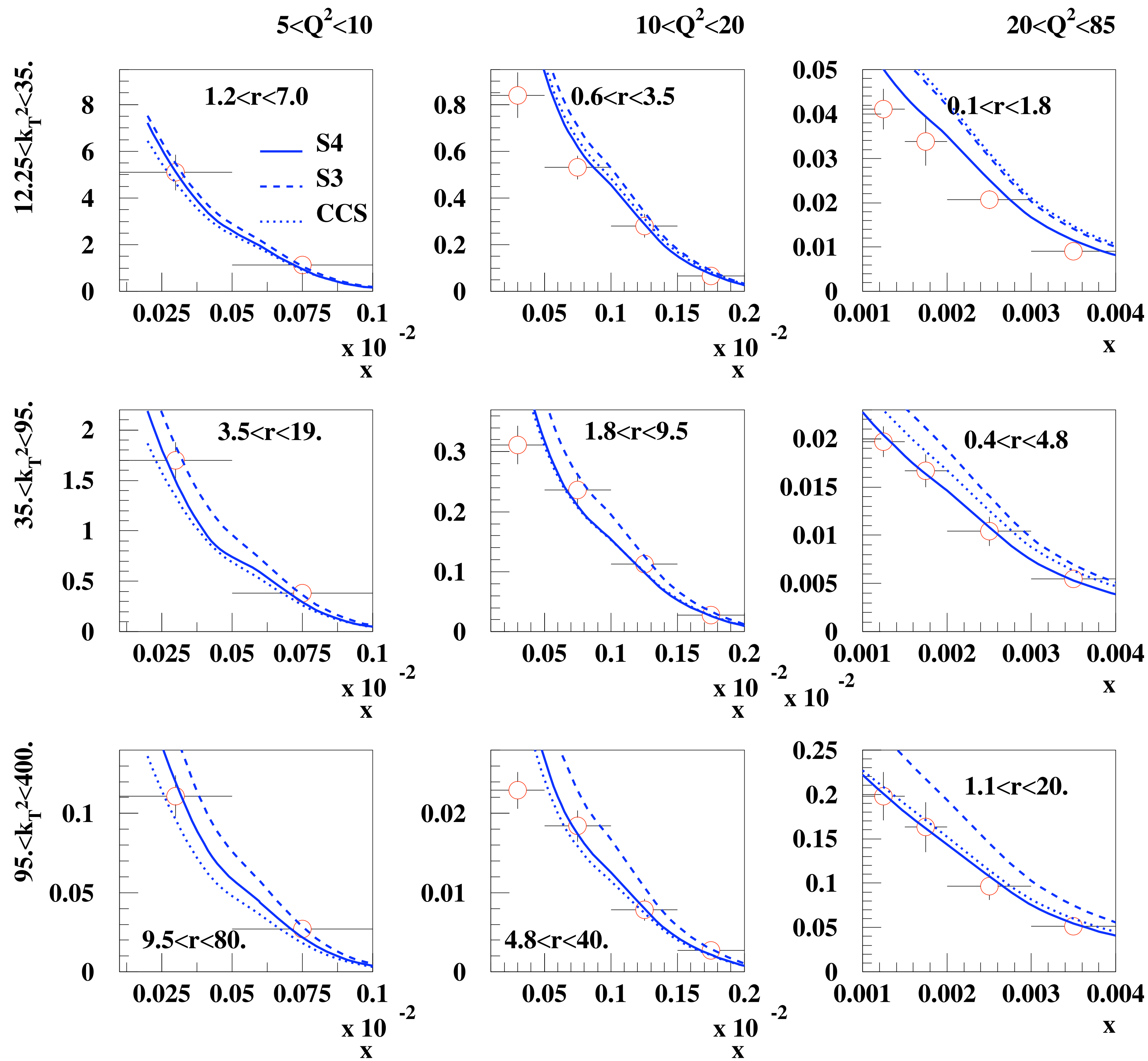
How to go to BFKL-NLL formalism?

- Simple idea: Keep the saddle point approximation, and use the BFKL NLO kernel

$$\frac{d\sigma}{dx} = N \left(\frac{Q^2}{k_T^2}\right)^{power} \alpha_S(k_T^2)\alpha_S(Q^2) \sqrt{A}$$
$$\exp\left(\alpha_S(k_T Q)\frac{N_C}{\pi}\chi(\gamma_C)\log(\frac{x_J}{x})\right)$$
$$\exp\left(-A\alpha_S(k_T Q)\log^2(\sqrt{\frac{Q}{k_T}})\right)$$

- Only free parameter in the BFKL NLL fit: absolute normalisation

NLL BFKL for forward and Mueller Navalet jets



Christophe Royon

$d\sigma/dx$ data small sensitivity NLL BFKL
$\Rightarrow$ study triple differential distribution

d σ/dx dk$_T$^{2} d Q^2 - H1 DATA

NLL BFKL for forward and Mueller Navalet jets

Christophe Royon

- DGLAP NLO fails to describe forward jet data
- First BFKL NLL description of H1 and ZEUS forward jet data: very good description
- BFKL NLL gives a good description of data over the full range: first success of BFKL higher order corrections, shows the need of these corrections
- Same kind of processes at the Tevatron and the LHC: Mueller Navelet jets
- Study the $\Delta\Phi$ between jets dependence of the cross section: Following A. Sabio Vera, F. Schwennsen hep-ph/0702158

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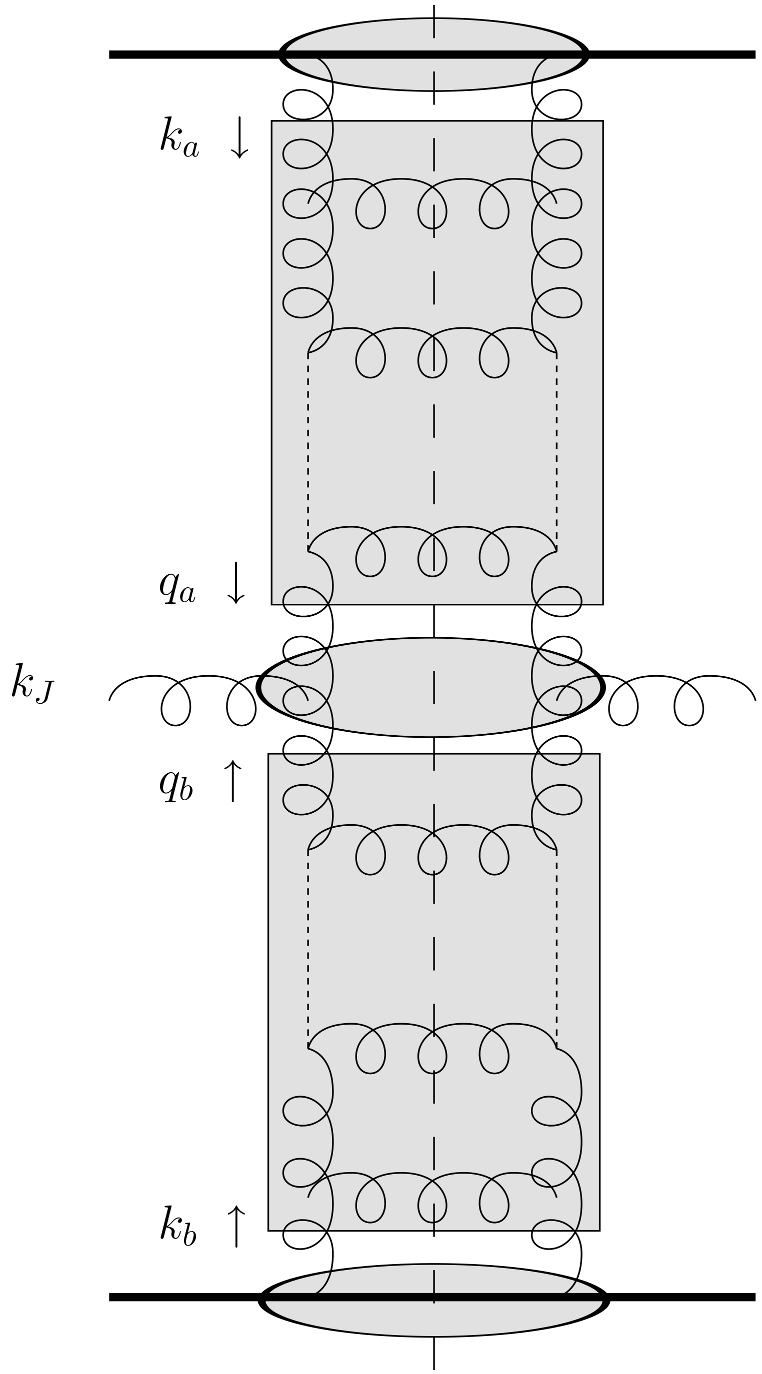
Controversial point: audience claimed that the saddle point approximation is not warranted

Central jet-vertex in kt-factoriztion at NLO

Inclusive single-jet production @ NLO with BKFL

Florian Schwensen



$$\frac{d\sigma}{d^2\mathbf{k}_{Jet}dy_{Jet}} = \int \frac{d^2\mathbf{k}_a}{2\pi\mathbf{k}_a^2} \int \frac{d^2\mathbf{k}_b}{2\pi\mathbf{k}_b^2} \Phi_A(\mathbf{k}_a)\Phi_B(\mathbf{k}_b)$$

$$\times \int d^2\mathbf{q}_a \int d^2\mathbf{q}_b \int \frac{d\omega}{2\pi i}\left(\frac{s_{AJ}}{s_0}\right)^{\omega} f_\omega(\mathbf{k}_a,\mathbf{q}_a)$$

$$\times \mathcal{V}(\mathbf{q}_a,\mathbf{q}_b;\mathbf{k}_{Jet},y_{Jet})$$

$$\times \int \frac{d\omega'}{2\pi i}\left(\frac{s_{BJ}}{s'_0}\right)^{\omega'} f_{\omega'}(-\mathbf{q}_b,-\mathbf{k}_b)$$

Impact factors

Emission vertex

BFKL eq. for Green functions

$$\omega f_\omega(\mathbf{k}_a,\mathbf{k}_b) = \delta^{(2)}(\mathbf{k}_a-\mathbf{k}_b) + \int d^2\mathbf{k}\,\mathcal{K}(\mathbf{k}_a,\mathbf{k})f_\omega(\mathbf{k},\mathbf{k}_b)$$

Central jet-vertex in kt-factoriztion at NLO

Changes at NLO:

Florian Schwensen

Q: Can we just replace the LO expressions for impact factors, kernel and Green's function by their NLO counterparts?

A: NO!

Central jet-vertex in kt-factoriztion at NLO

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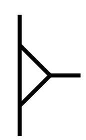
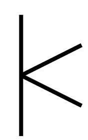
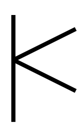
- at NLO $\mathcal{K}_{\text{real}} \sim$  $+ \int$ 
- for  two possibilities:
  - both together form a jet
  - one forms the jet, other one unresolved

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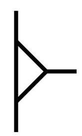
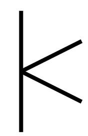
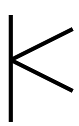
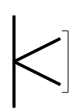
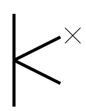
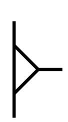
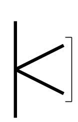
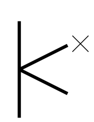
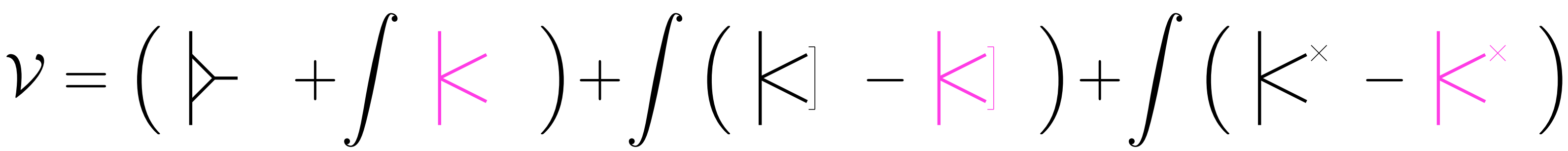
- at NLO $\mathcal{K}_{\text{real}} \sim$  $+ \int$ 
- for  two possibilities:
  - both together form a jet
  - one forms the jet, other one unresolved
- define distance in rapidity-azimuthal angle space
  $R_{12} = \sqrt{(y_1 - y_2)^2 + (\phi_1 - \phi_2)^2}$
  - $\theta(R_0 - R_{12})$: 
  - $\theta(R_{12} - R_0)$: 
- open integration to extract jet

$\mathcal{V} \sim$  $+ \int$  $+ \int$ 

Central jet-vertex in kt-factoriztion at NLO

Florian Schwensen

- real and virtual parts with different $x_{1,2}$ configurations $\rightsquigarrow$ different $g(x_1, q_a)g(x_2, q_b)$ $\rightsquigarrow$ cancellation of divergences?



YES

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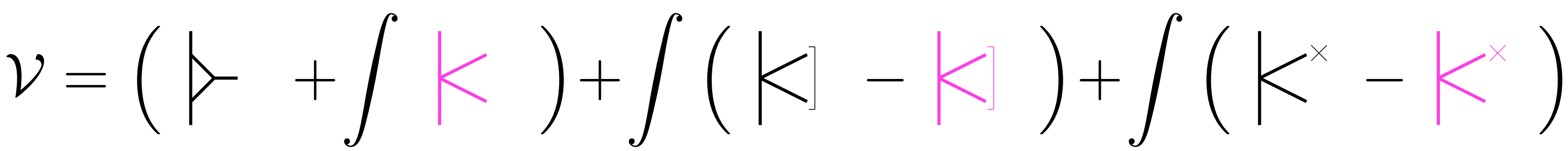


YES

- extended NLO BFKL to obtain the NLO jet vertex in kt-factorization
- procedure allows one to use a jet algorithm in the BFKL kernel
- method can be used for NLO jet-vertex in $\gamma^*\gamma^*$ and hh inclusive single jet production

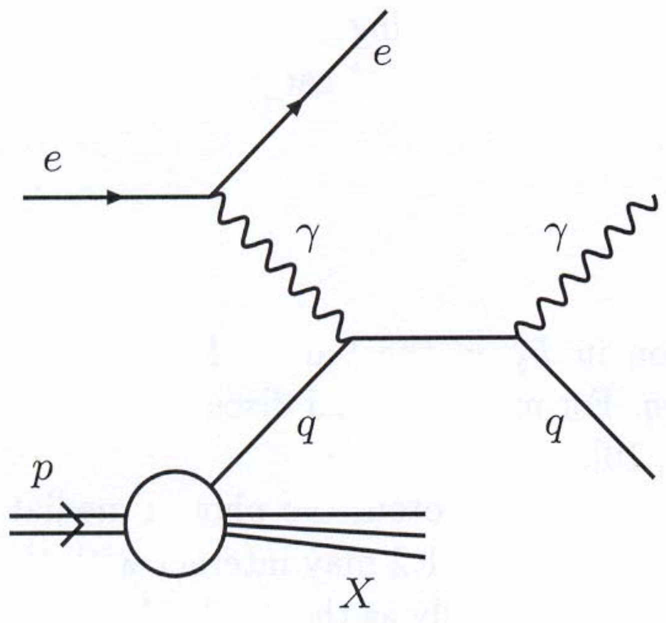
This analysis: a contribution to the more general question of how to formulate kt factorization at NLO

Prompt photons with kt-factorization at high E

Nikolai Zotov

Prompt photon's are:

- coupled to the interacting quarks
- provide a clear information about the QCD dynamics
- insensitive to the effects of final state hadronization
- sensitive to the parton distribution functions (PDFs)



Motivation

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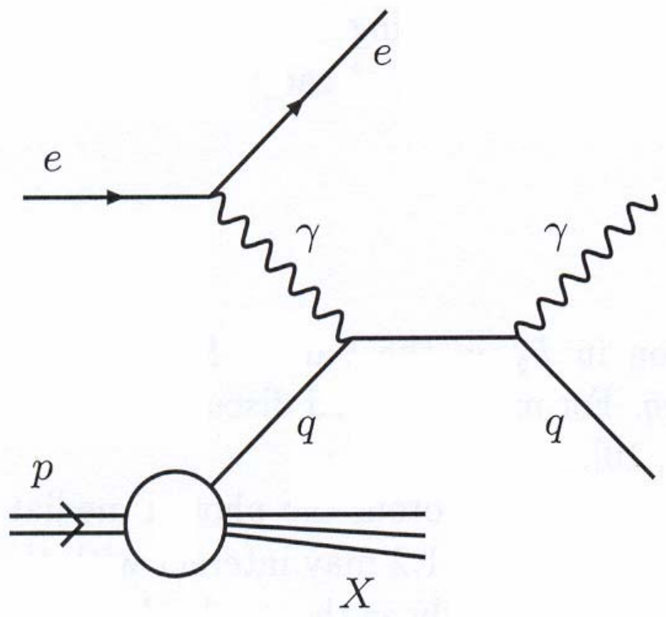

Motivation

Status

NLO pQCD

- 30—40% below the HERA data (specially in the rear η^{γ} region)
- not describe the shape of transverse energy E_T^{γ} distribution at Tevatron
- not describe the ratio of cross sections $\sigma(630\,\mathrm{GeV})/\sigma(1800\,\mathrm{GeV})$ at Tevatron

Prompt photons with kt-factorization at high E

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k_T -smearing?

- additional intrinsic transverse momentum k_T of the incoming partons is introduced in NLO calculations
- it is assumed that this k_T have a Gaussian-like distribution
- $\langle k_T \rangle \sim 0.5\,\mathrm{GeV}$ at UA6 and $\langle k_T \rangle \sim 2\,\mathrm{GeV}$ at Tevatron

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Another possibility

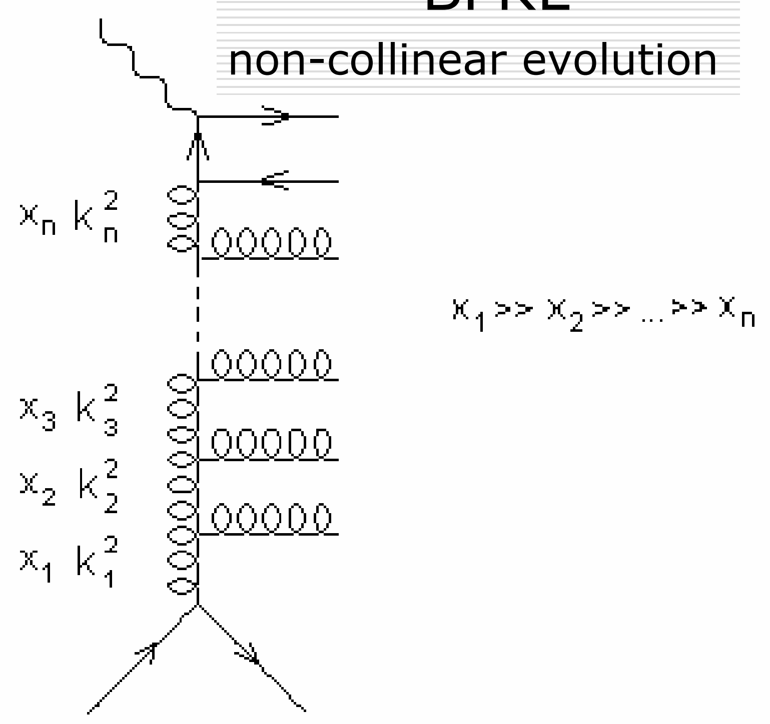
Simple k_T-smearing picture can be modified in the framework of k_T-factorization (or semihard) approach of QCD

In this approach, the partonic transverse momentum is generated in the course of the non-collinear parton evolution

- based on the BFKL or CCFM evolution equations
- can incorporate the leading $\ln 1/x$ terms

BFKL

non-collinear evolution



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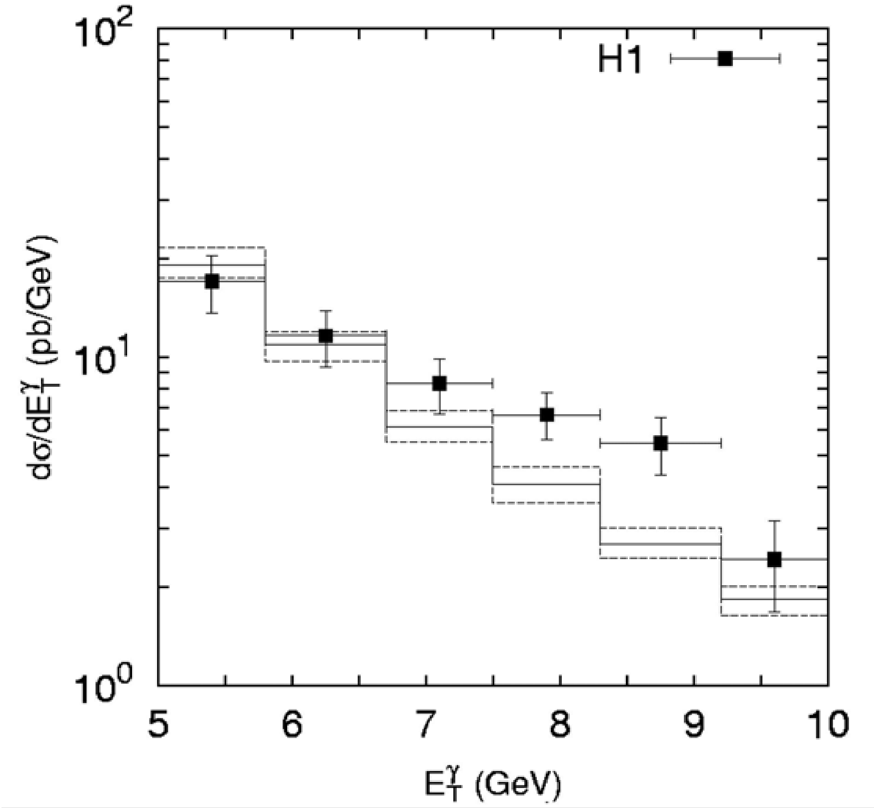
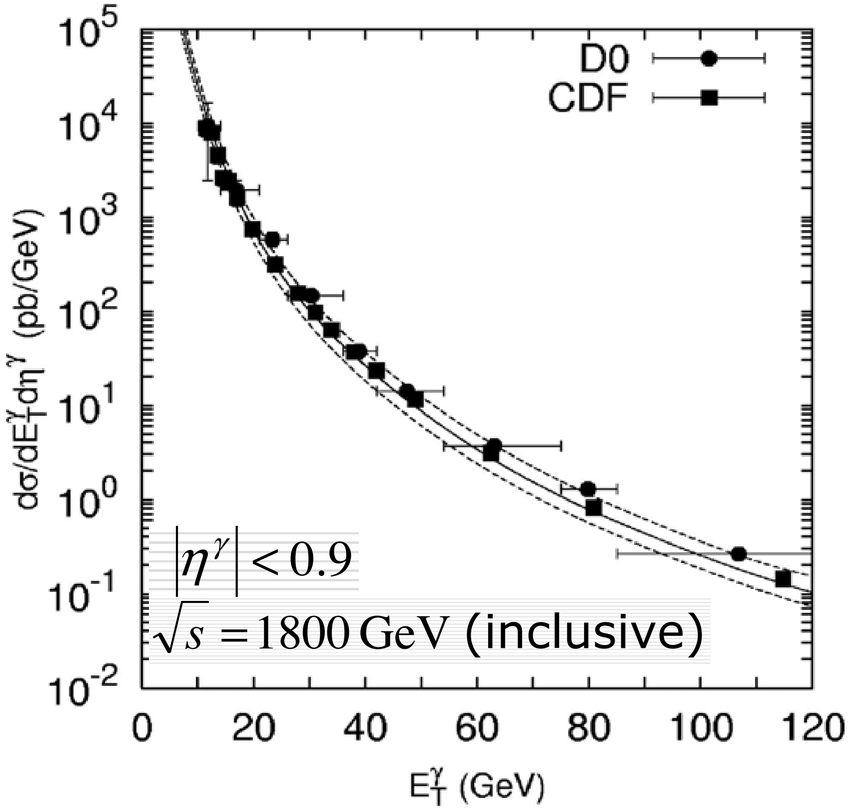




- k_T -factorization approach of QCD gives a reasonable description of the recent HERA and Tevatron data
- Realistic predictions at LHC

Hope to include in the pdf fits prompt photons at the LHC because of higher statistics

Power corrections from an s-channel approach

Francesco Hautmann

Motivation:

Proton structure at small x:

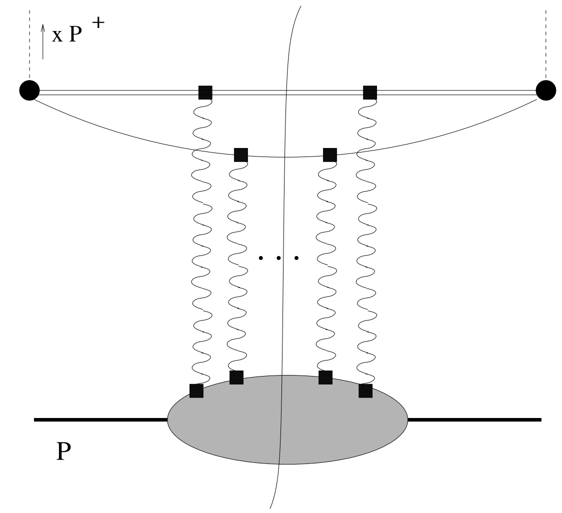
- investigated extensively at HERA
- valuable input in LHC physics program

Gluon distribution at $x \lesssim 10^{-2}$ determined from DIS data at high energies and moderate Q^2

▷ power corrections from multi-parton correlations potentially significant?

- $F_2 \sim \Sigma$ (flavor-singlet quark)
- $\dot{F}_2$ driven by gluon

$$\Rightarrow \dot{F}_2 \sim \dot{\Sigma} \sim P_{qg} \otimes G \;\; [1 + \mathcal{O}(1/Q^2)] + \text{ quark term}$$



Power corrections from an s-channel approach

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parton picture

— systematic factorization of pdf's and hard scattering at large Q^2

— calculability of higher order perturbative corrections

s-channel picture

— no systematic factorization; contributions to all orders in $1/Q^2$

— basic degrees of freedom are described by matrix elements of Wilson lines ("color dipoles" at simplest level)

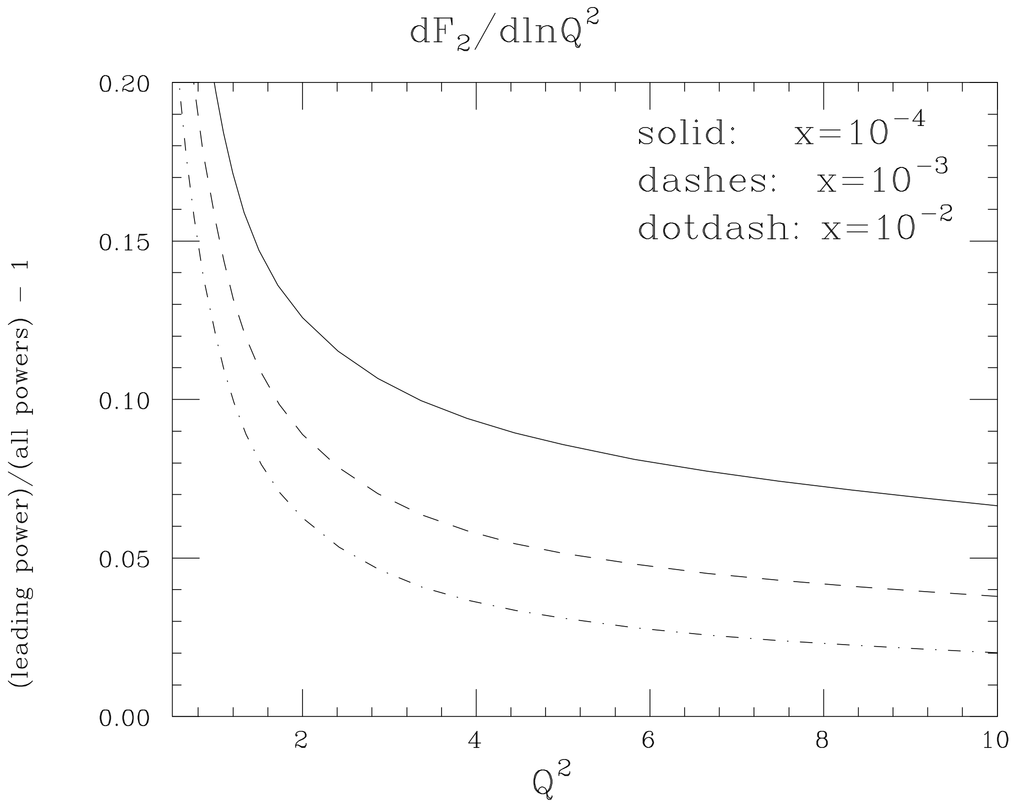
— possibility to incorporate nonperturbative small-x dynamics ("saturation")

Aim: connect the two pictures with enough precision so as to identify the power correction to $dF_2/d\ln Q^2$

Basic idea: expand F in powers of $1/Q^2$

- identify factorized partonic result using previous answer for renormalized f_q
- determine the power correction from the remainder

Power corrections from an s-channel approach



Francesco Hautmann

$$\frac{dF_T}{d\ln Q^2} = \left(\frac{dF_T}{d\ln Q^2}\right)_{\rm LP} + \sum_{n=1}^{\infty} R_n \frac{\lambda_n^2}{(Q^2)^n}$$

Expand in powers of $1/Q^2$, at low Q^2 and x. Identity the power correction by subtracting the leading-power.

$\Rightarrow$ power expansion does not look to be breaking down

but: slow fall-off for medium Q^2 (e.g., $1/Q^\lambda$, $\lambda = 1.2$, in $[1, 10]$ GeV^2 for $x \simeq 10^{-3}$)

- Rather extensive approximations used (high-energy, dipole approximation); modeling of nonperturbative matrix element; summation of power expansion: can we do better?

Question: what happens for F_L? are there cancellations in F_2 from F_T and F_L?

All orders and non-global observables

Gennaro Corcella

Non-global observables are sensitive to radiation in a limited region of the phase space

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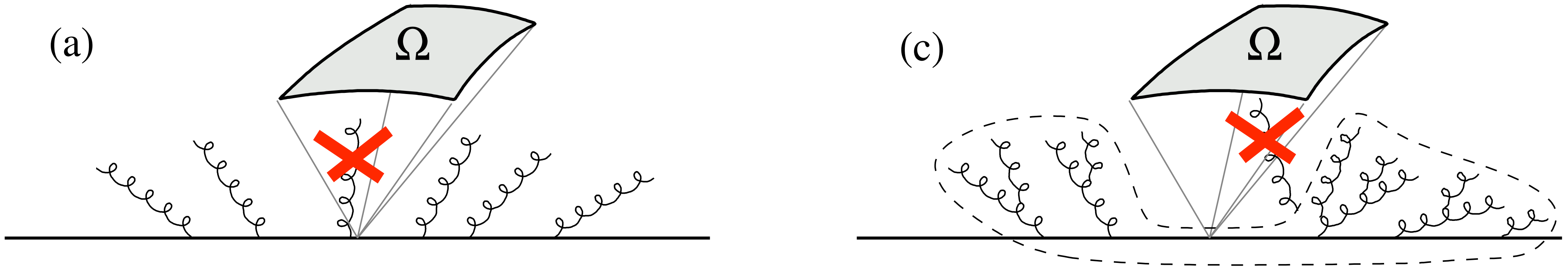
Non-global observables are sensitive to radiation in a limited region of the phase space

Multiple radiation from a $q\bar{q}$ dipole in a region Ω



Contributions $\alpha_S^2 L^2$: non-global logarithm

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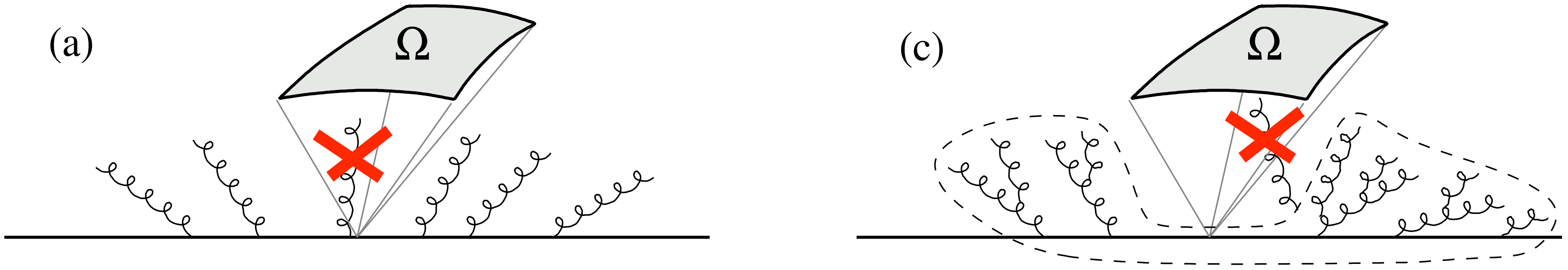

Contributions $\alpha_S^2 L^2$: non-global logarithm

$$E_t = \sum_{i \in \Omega} E_{ti} \qquad \Sigma(Q, Q_\Omega) = \frac{1}{\sigma} \int_0^{Q_\Omega} \frac{d\sigma}{dE_t} dE_t = \exp(-4C_F A_\Omega t) S(t)$$

$\exp(-4C_F A_\Omega t)$: **exponentiation of primary radiation (angular ordering)**

$S(t) = \sum_{n=2} S_n t^n$: **non-global logarithms, due to correlated gluon emissions**

All orders and non-global observables

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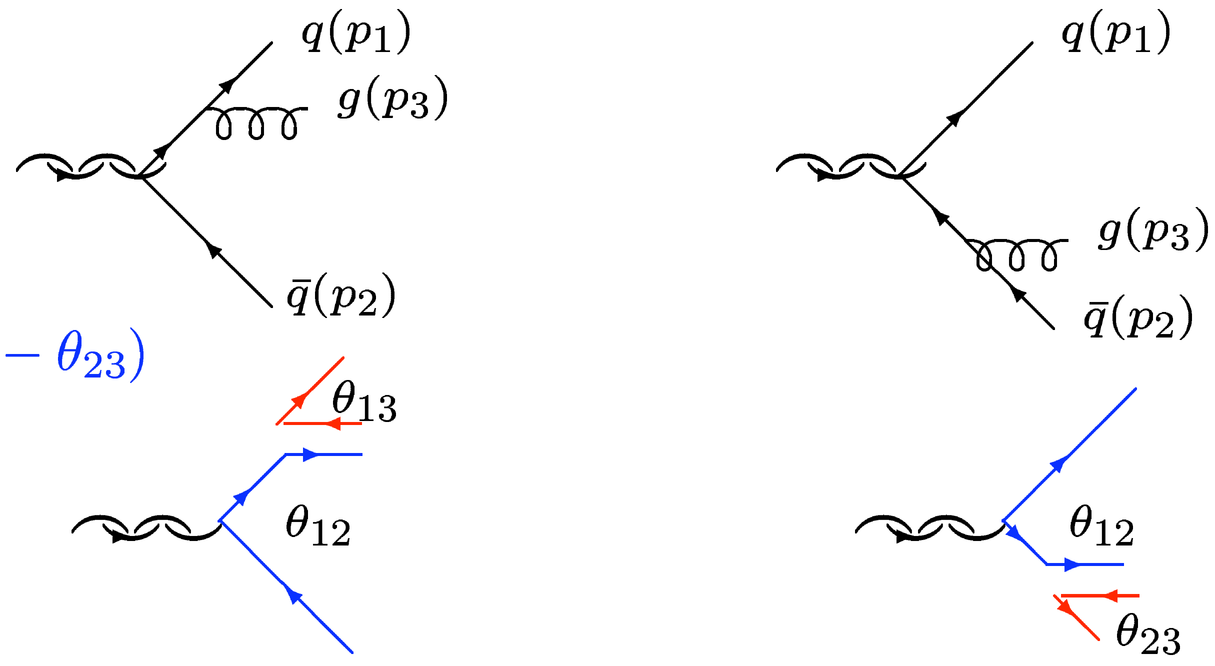
Angular ordering



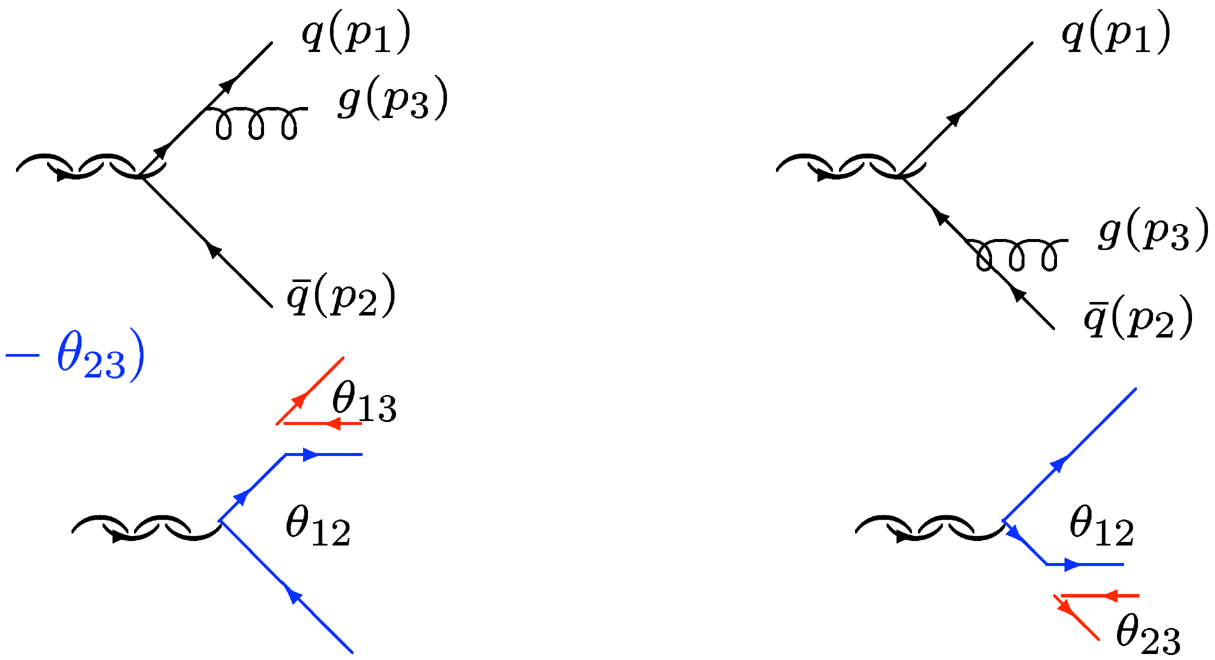
After azimuthal average:

$$W \longrightarrow \frac{1}{1-\cos\theta_{13}}\Theta(\theta_{12}-\theta_{13})+\frac{1}{1-\cos\theta_{23}}\Theta(\theta_{12}-\theta_{23})$$

All orders and non-global observables

Gennaro Corcella

Angular ordering



After azimuthal average:

$$W \quad \longrightarrow \quad \frac{1}{1-\cos\theta_{13}}\Theta(\theta_{12}-\theta_{13}) + \frac{1}{1-\cos\theta_{23}}\Theta(\theta_{12}-\theta_{23})$$

Monte Carlo event generators are often tuned to non-global observables

All orders and non-global observables

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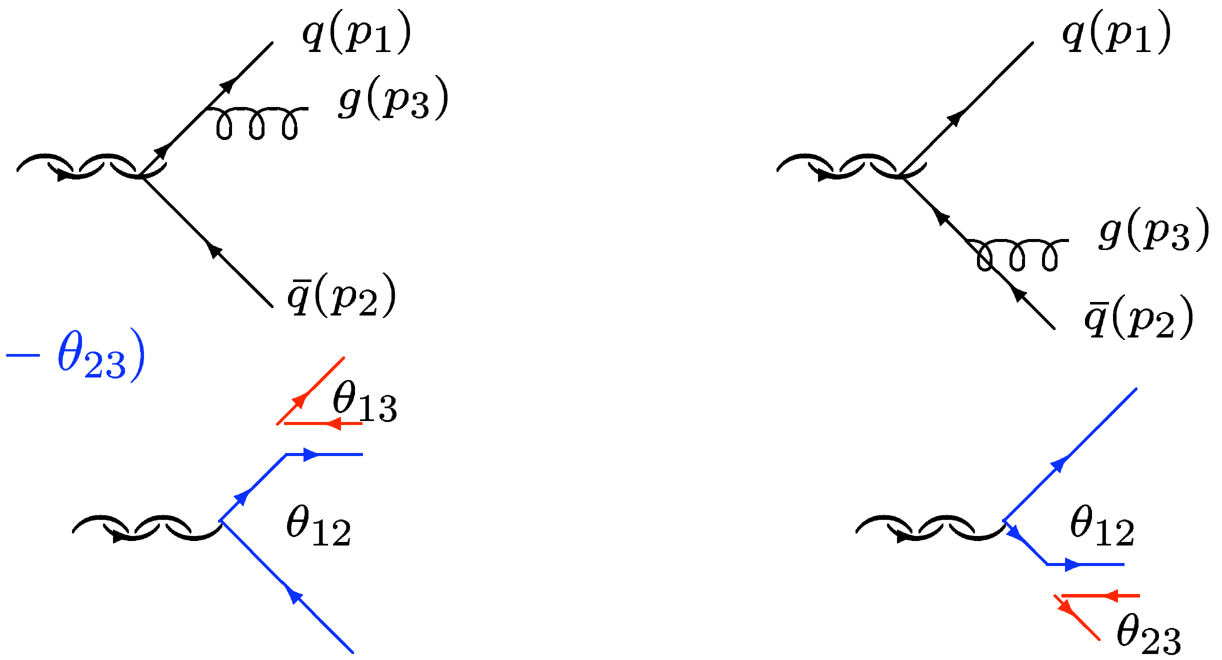

Monte Carlo event generators are often tuned to non-global observables

Angular ordering catches a relevant part of non-global logarithms

All orders and non-global observables

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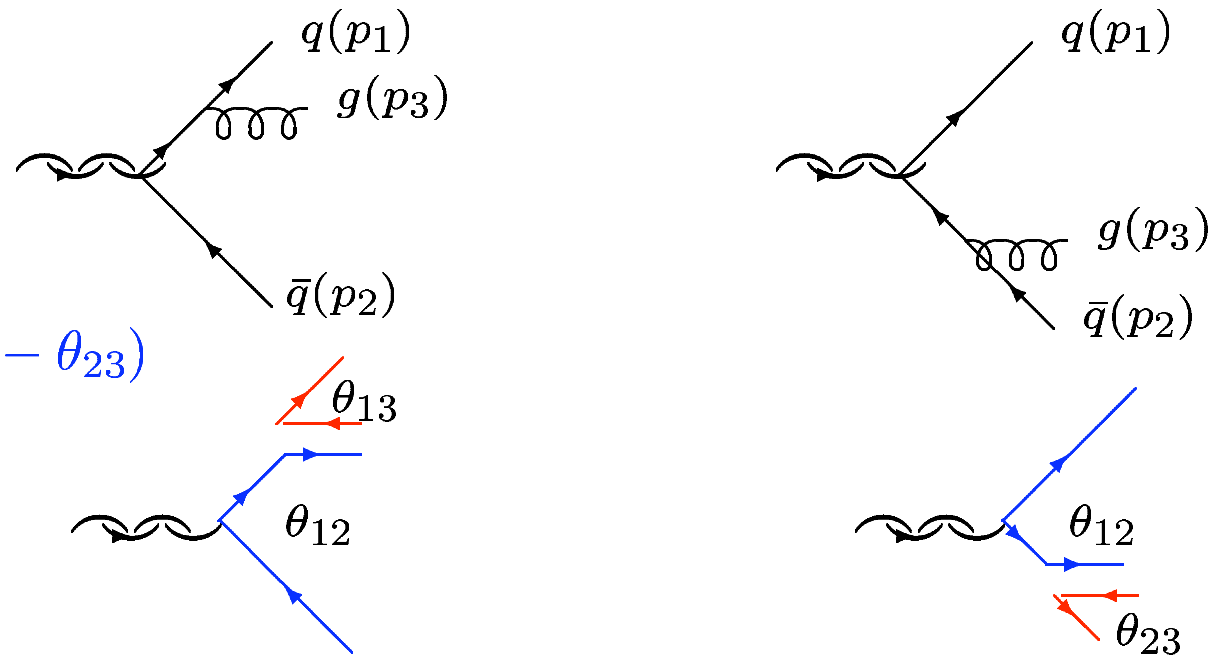
Angular ordering



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Monte Carlo event generators are often tuned to non-global observables

Angular ordering catches a relevant part of non-global logarithms

HERWIG : $Q^2 = E^2(1-\cos\theta) \simeq E^2\theta^2/2$ **Soft limit: angular ordering**

PYTHIA (up to 6.2 version): $Q^2 = p^2$

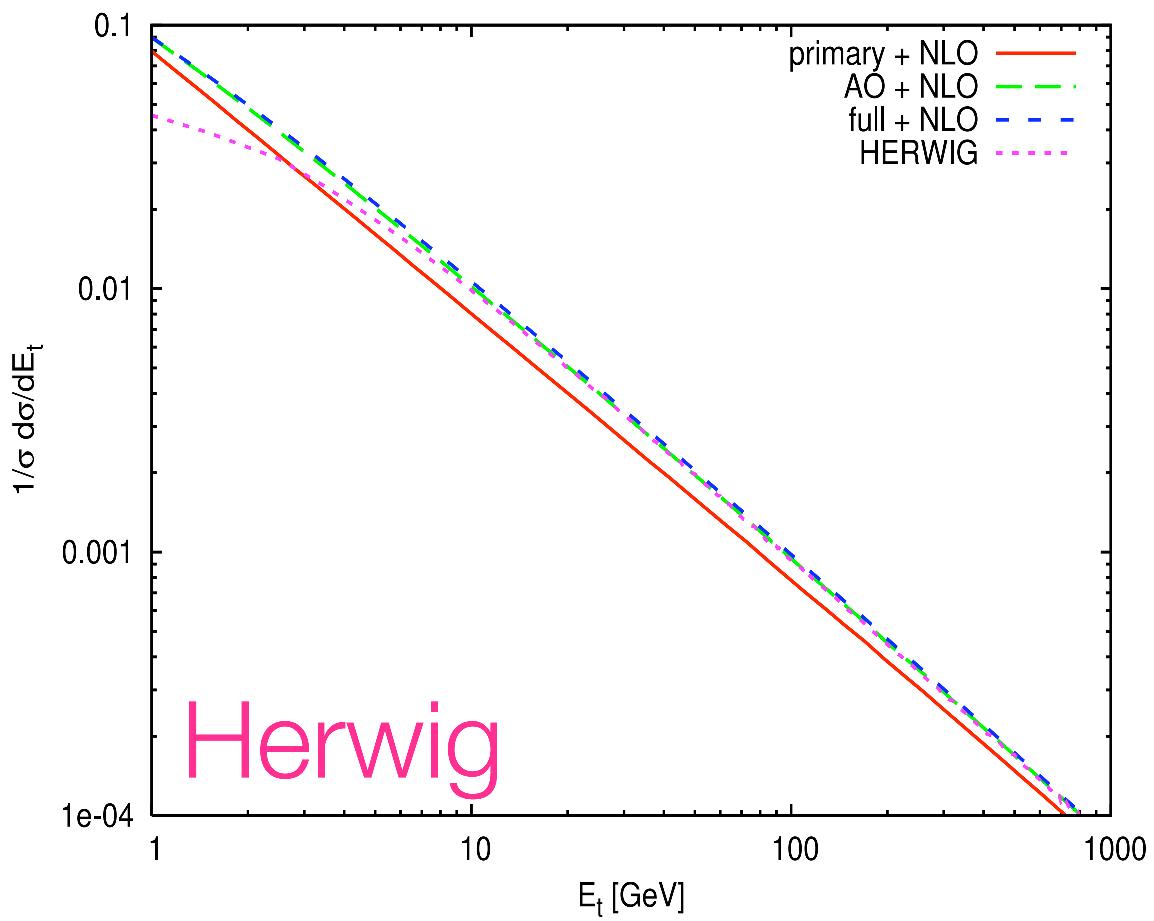
It includes angular ordering via an additional veto

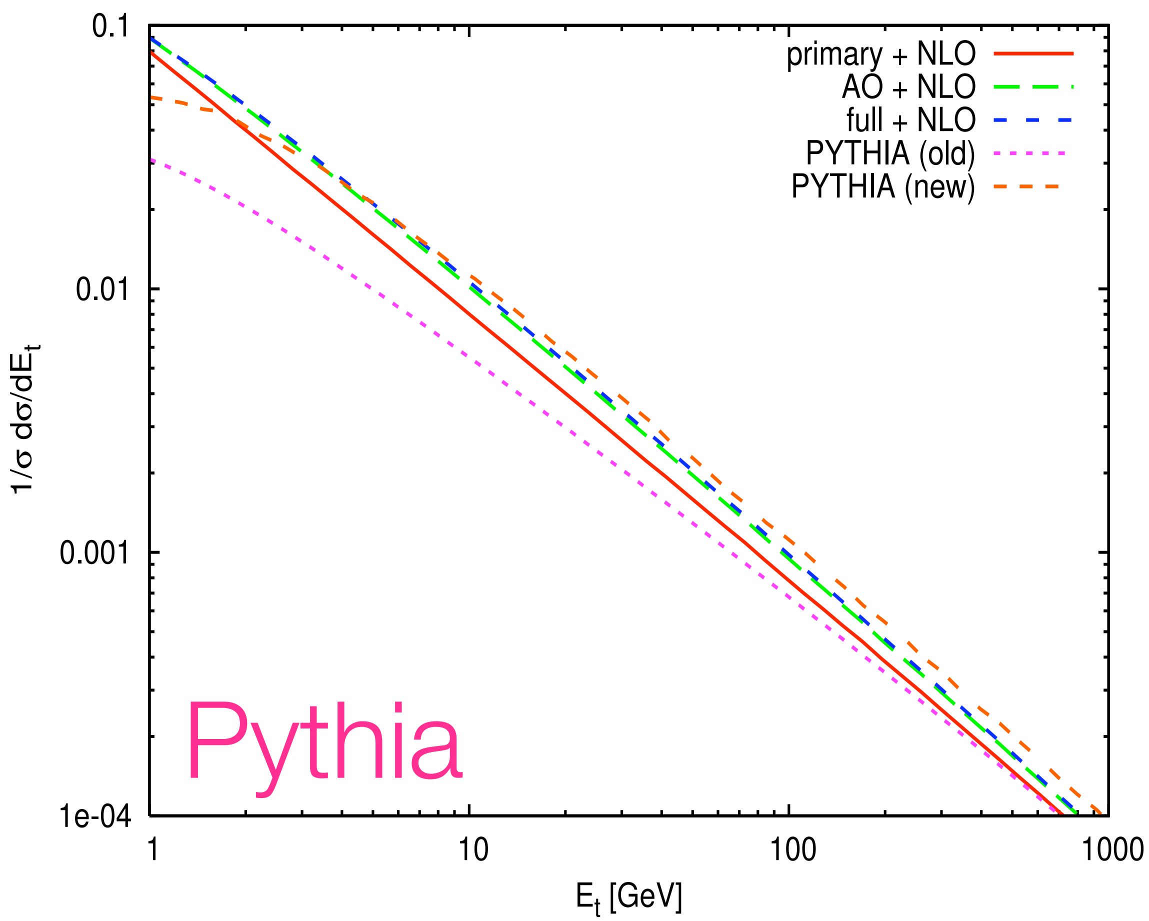
PYTHIA 6.3: $Q^2 = k_T^2$ **(better treatment of angular ordering)**

All orders and non-global observables

Comparing resummation and parton showers *Gennaro Corcella*

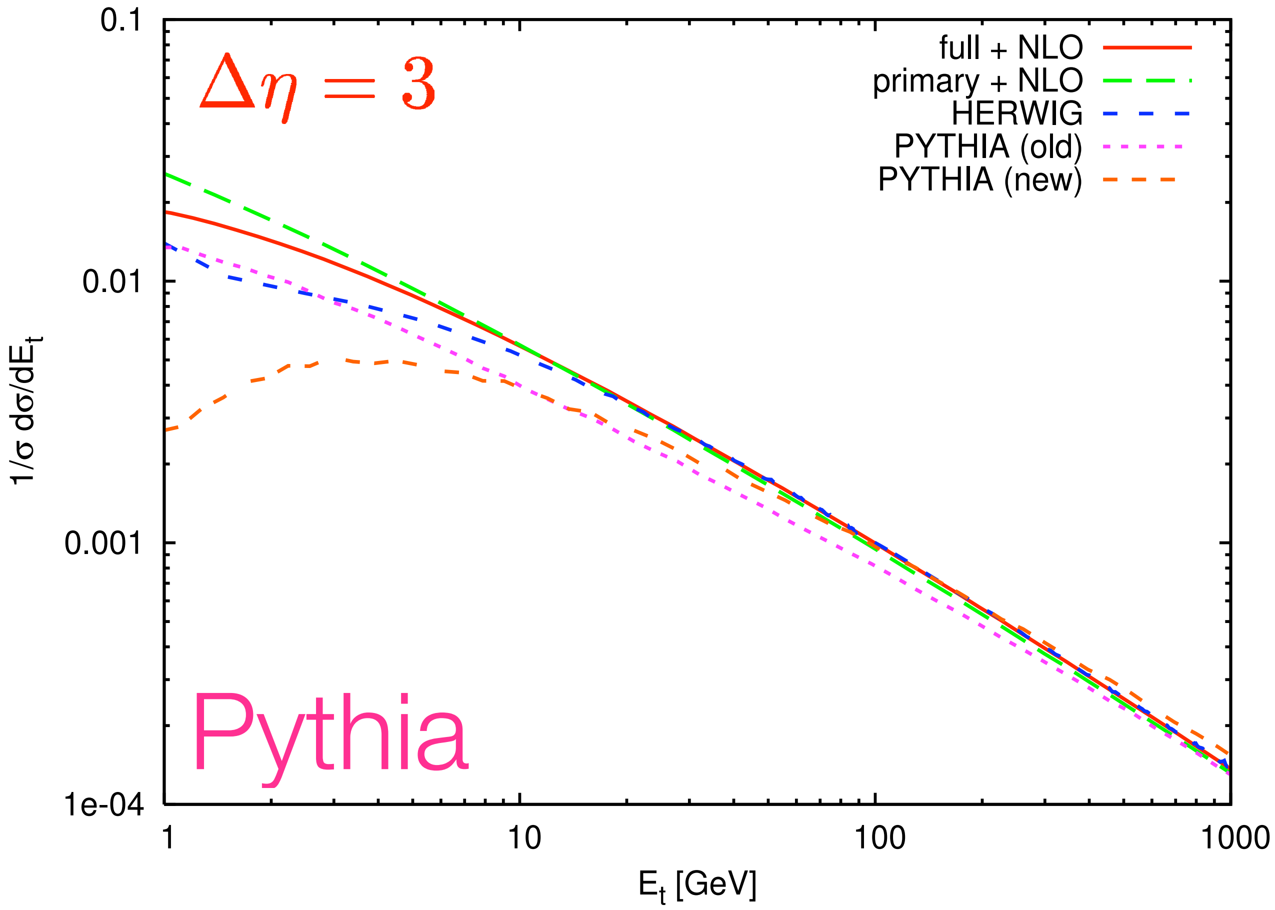
$Q = 10^5$ **GeV to neglect subleading effects** $\mathcal{O}(\alpha_S(Q))$ **and quark masses**





Difference with respect to the full resummed result for $E_t = 10$ GeV:
– 10% (HERWIG); + 7.5% (PYTHIA new); – 50% (PYTHIA old)

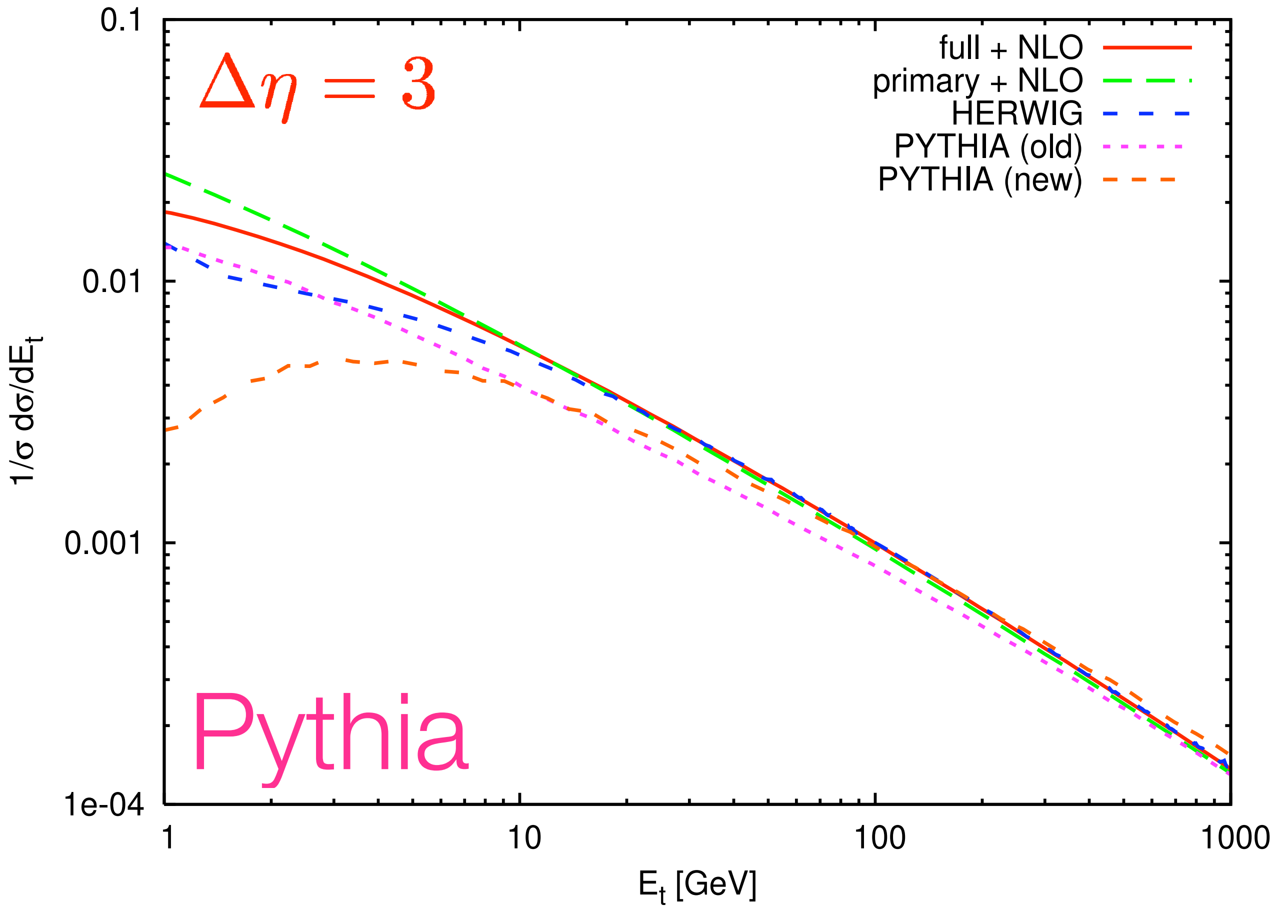
All orders for non-global observables



Gennaro Corcella

⇒ remarkable discrepancy between new PYTHIA model and resummation at large rapidity slices.
Further investigation needed.

All orders for non-global observables



Gennaro Corcella

⇒ remarkable discrepancy between new PYTHIA model and resummation at large rapidity slices.
Further investigation needed.

Need care when fitting event generators to non-global observables!
In MC tuning may incorporate in the underlying event or in NP parameters effects which are calculable in PT.

Do we have the necessary tools/measurements for best tuned MCs?
Need to clarify the above discrepancies!

SISCone:seedless infrared safe cone jet-finder

Gregory Soyez

Usual seeded method to search stable cones: midpoint cone algorithm

- For an initial seed
  1. sum the momenta of all particles within the cone centred on the seed
  2. use the direction of that momentum as new seed
  3. repeat 1 & 2 until stable state cone reached
- Sets of seeds:
  1. All particles (above a p_t threshold s)
  2. Midpoints between stable cones found in 1.

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Problems:

- the p_t threshold s is collinear unsafe
- seeded approach $\Rightarrow$ stable cones missed $\Rightarrow$ infrared unsafety

SISCone:seedless infrared safe cone jet-finder

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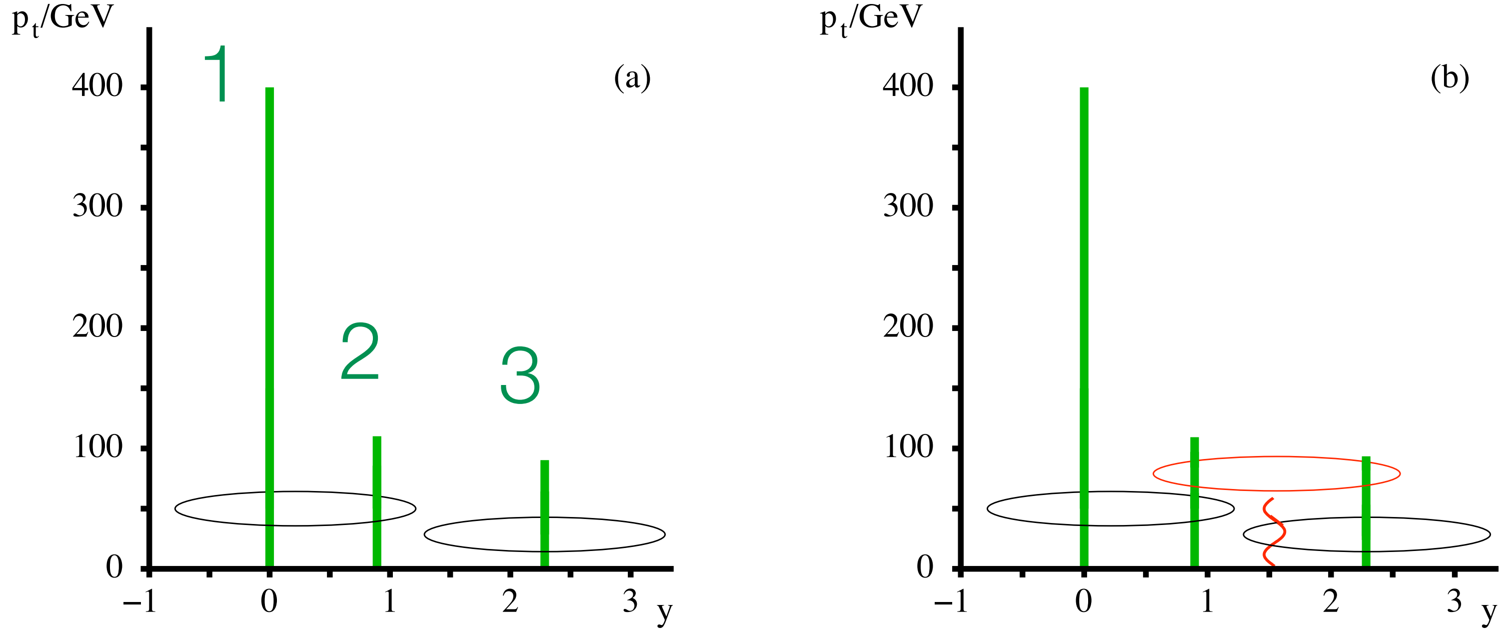
Hard event — Hard+soft event



	Hard event	Hard+soft event	
Stable cones:			
Midpoint:	{1,2} & {3}	{1,2} & {3} & {2,3}	Overlapping cones
Seedless:	{1,2} & {3} & {2,3}	{1,2} & {3} & {2,3}	⇒ run split merge
Jets: ($f = 0.5$)			
Midpoint:	{1,2} & {3}	{1,2,3}	
Seedless:	{1,2,3}	{1,2,3}	⇒ get one big cone!

⟶ **IR unsafety of the midpoint algorithm**

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SISCone finds provably all stable cones, without introducing seeds

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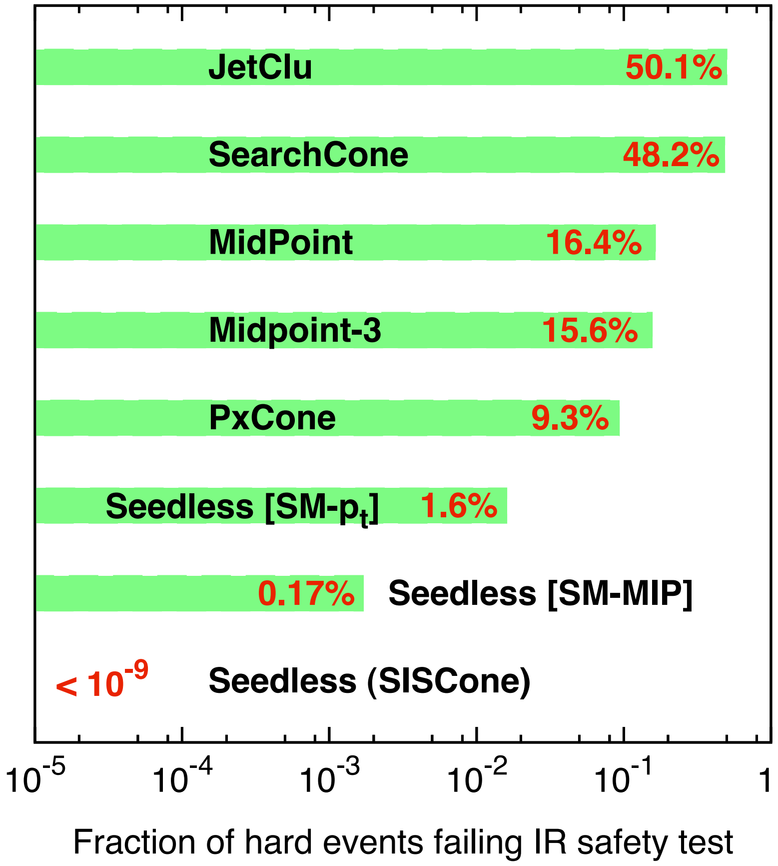
Test of IR-safety



With currently used cones important fraction of events fails IR-safety test.

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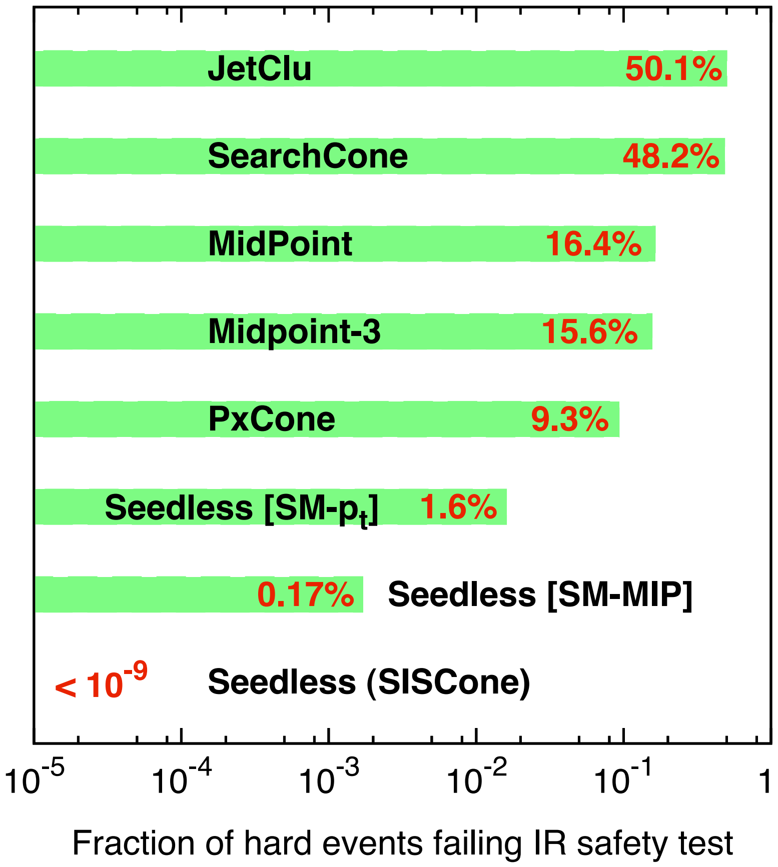

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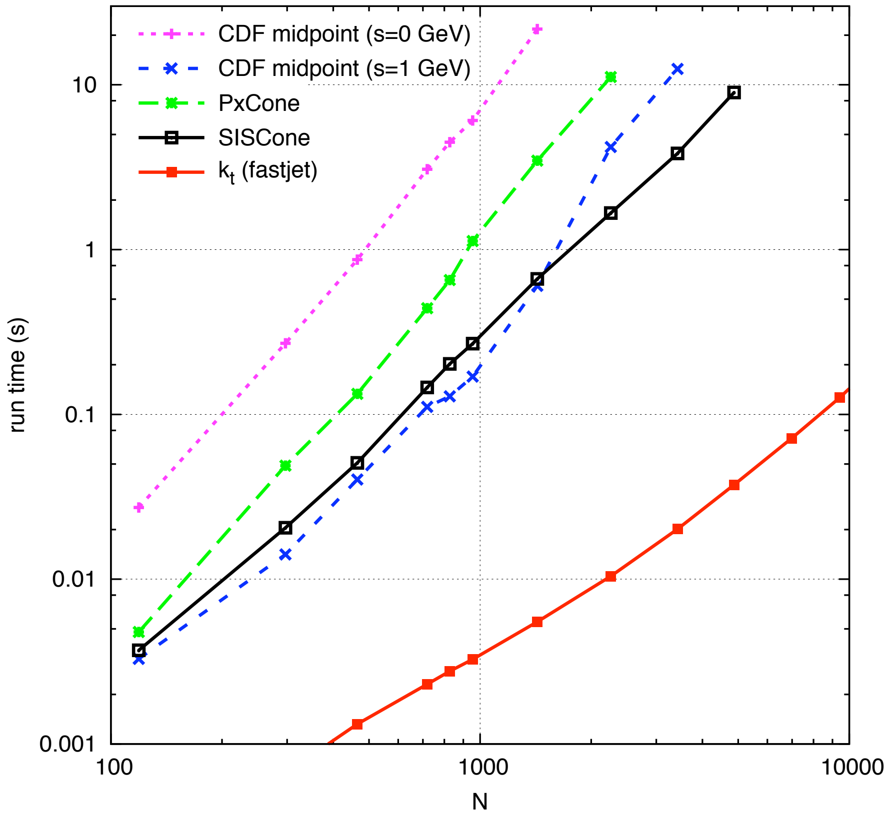
Speed issue



NB: speed IS an issue! With a naive implementation of seedless cone need 10^{17} years to cluster 100 particles!

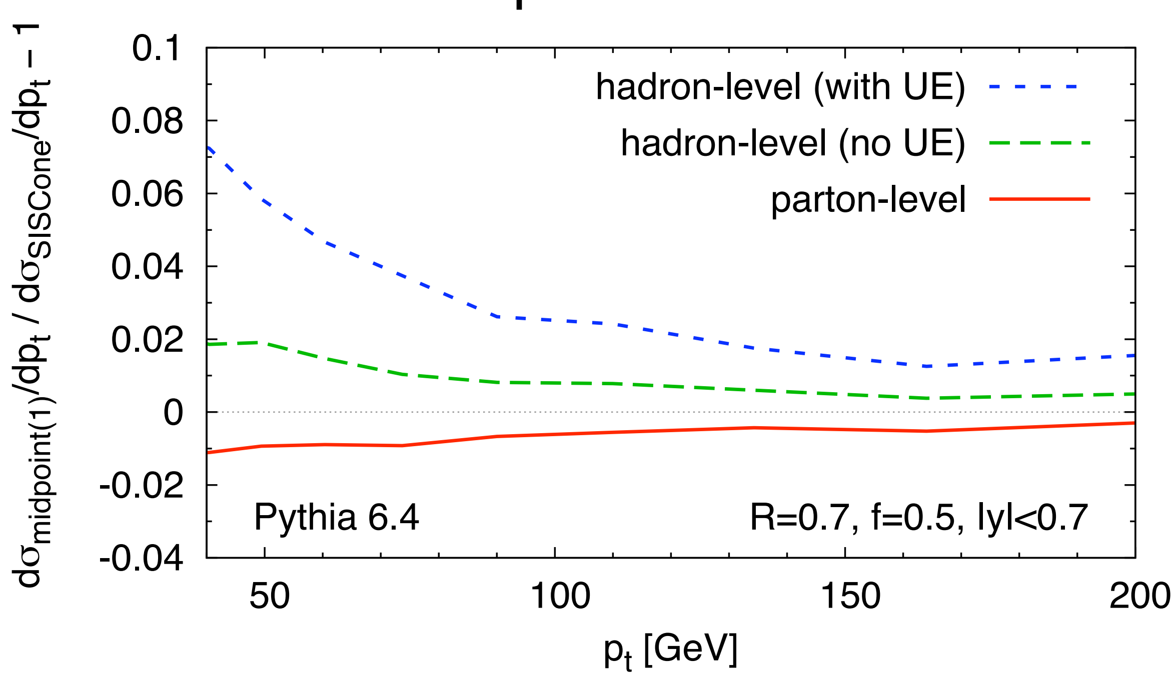
SISCone:seedless infrared safe cone jet-finder

Impact of SISCone:

Gregory Soyez

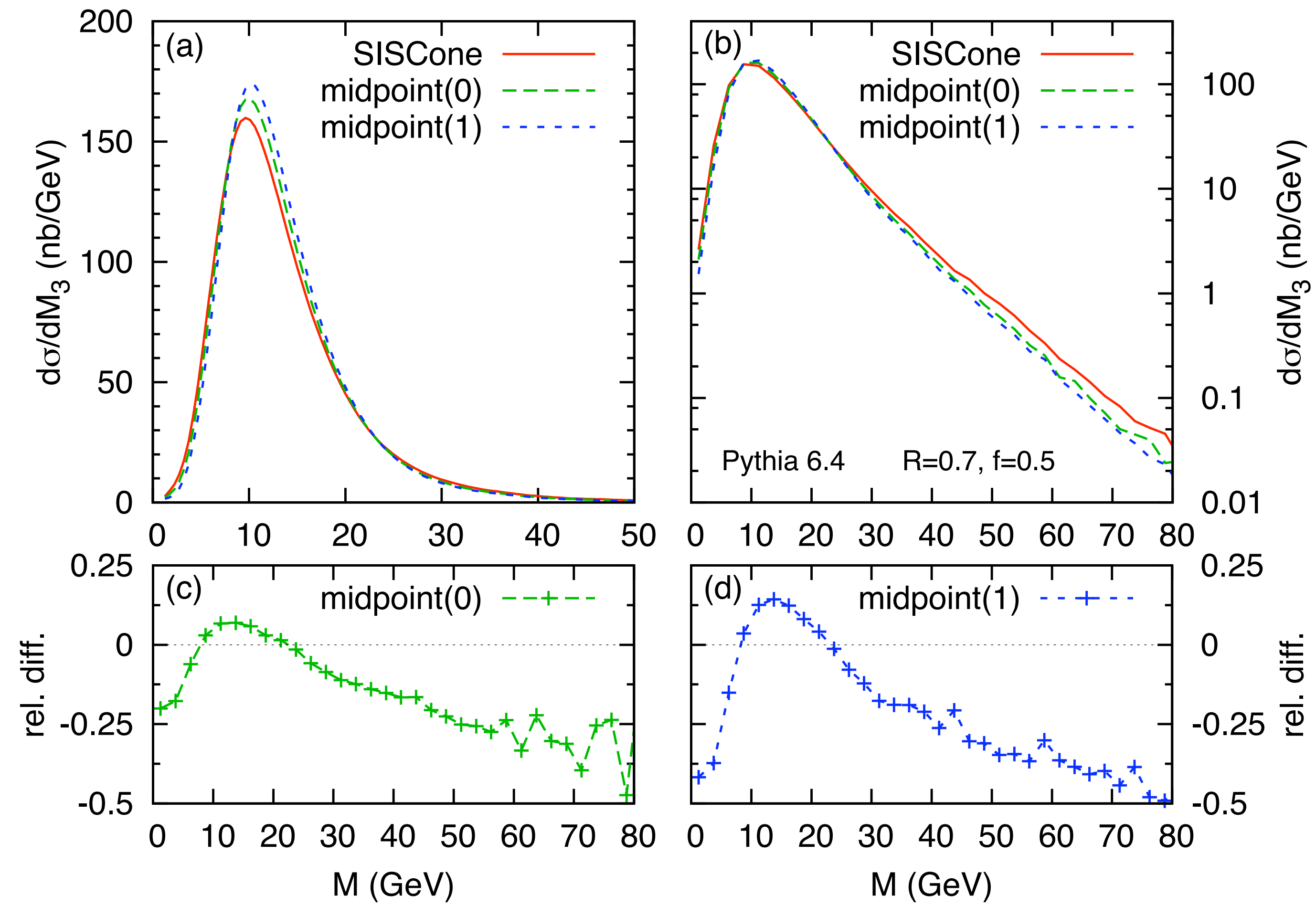
Inclusive jet spectrum

Ratio midpoint/SISCone:



- Differences up to 6 %
- Less effect from underlying event in SISCone

Jet mass spectrum



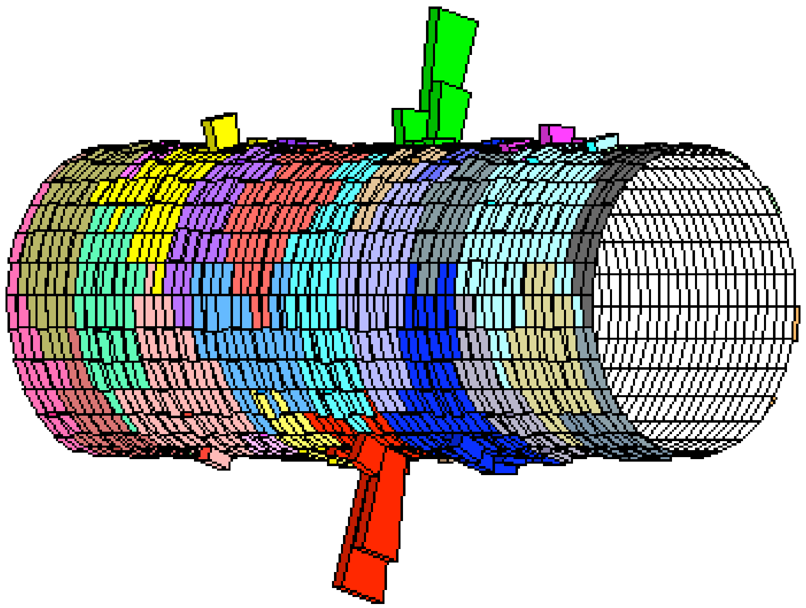
▷ Differences of order 10 %

▷ Larger effects in the tail

Jet areas and what they are good for

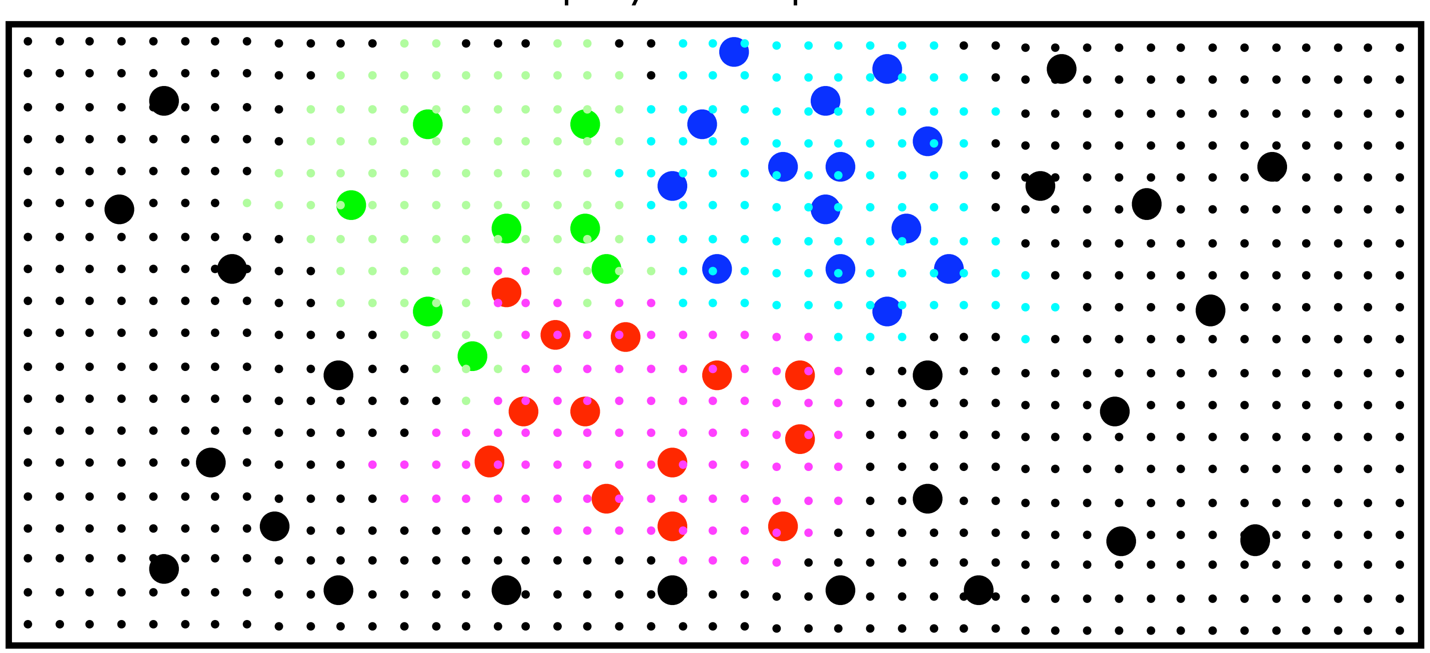
Matteo Cacciari

The 'active area' of a jet is (proportional to) the number of uniformly distributed infinitely soft particles that get clustered in it



After the clustering, a given set of ghosts belong to each jet

Their number (times the average area of a single ghost) defines the **catchment area** of the jet



NB: without fastjet this work would not be feasible

Jet areas and what they are good for

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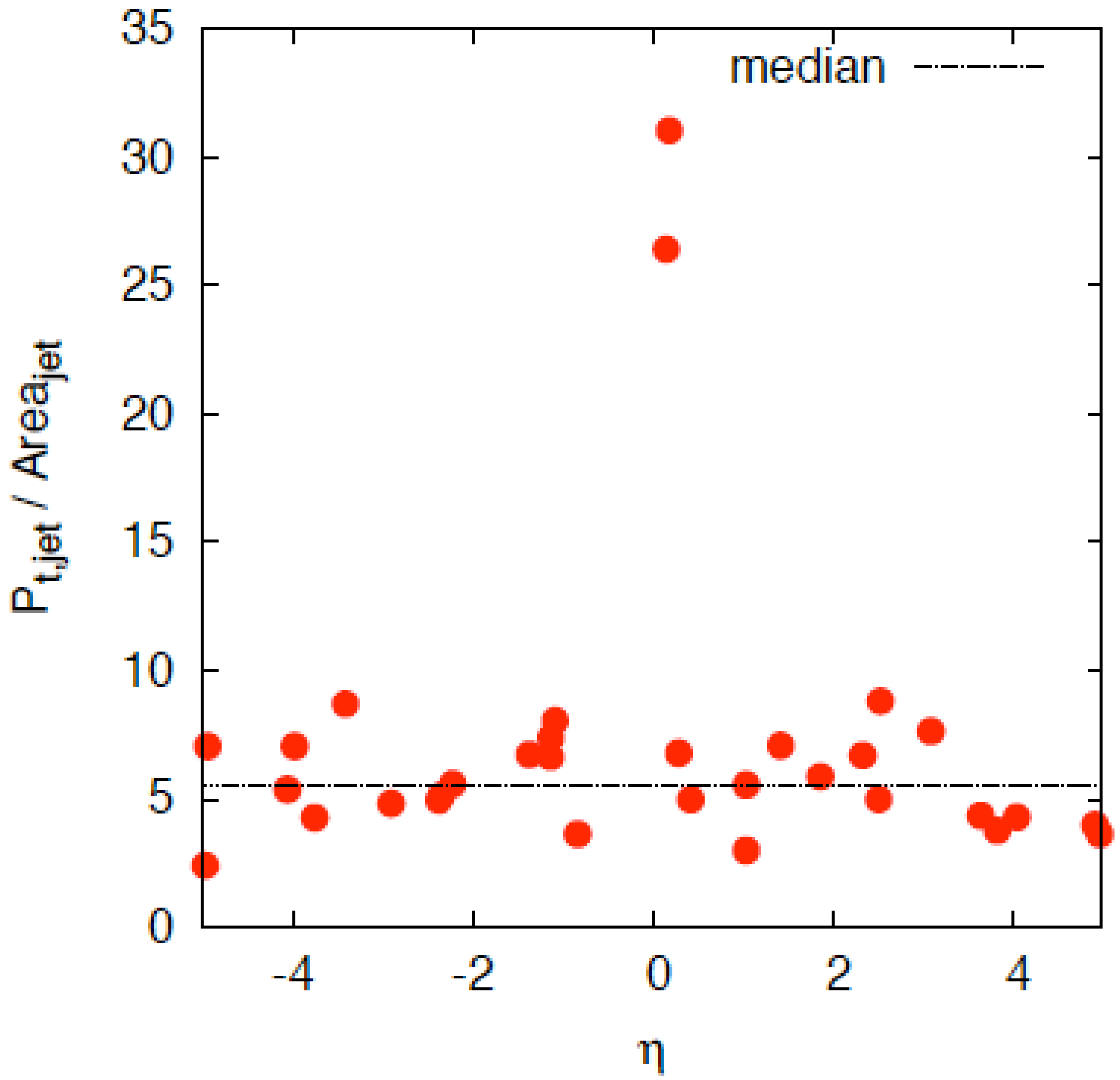
Applications:



The distribution of background jets establishes its own average momentum density

(NB. this is true on an event-by-event basis)

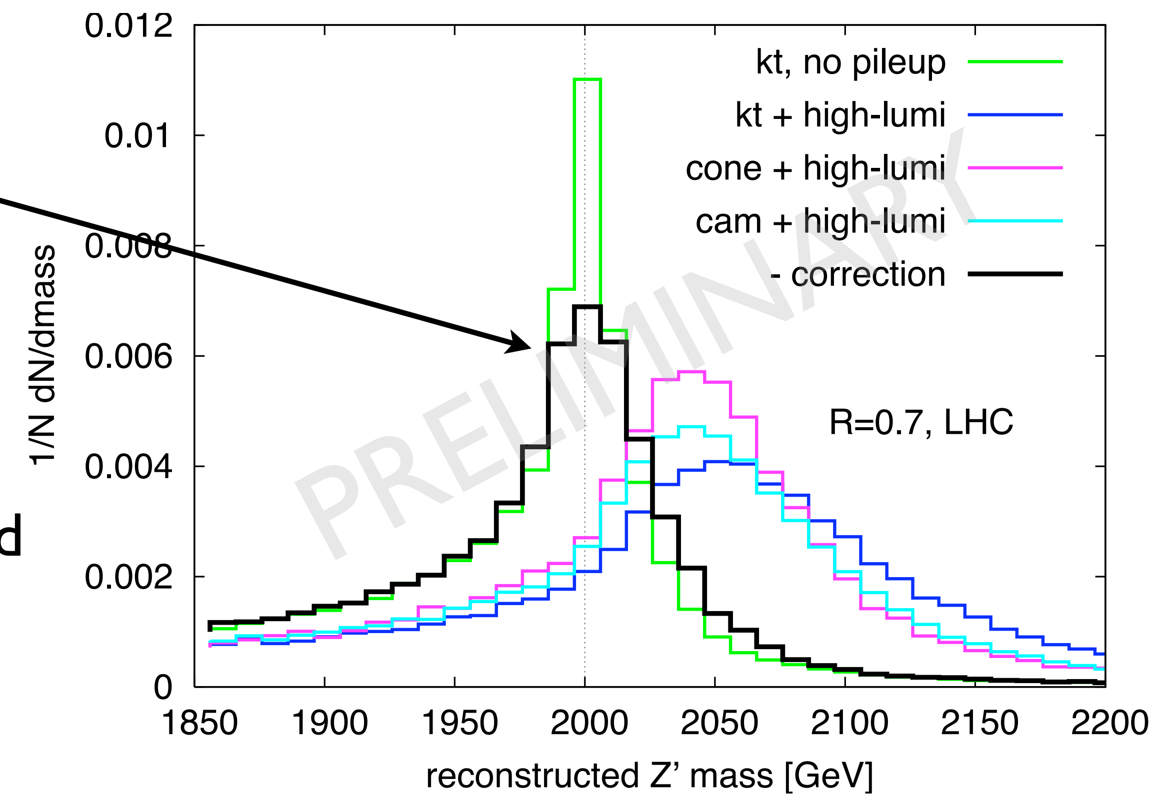
p_T/Area is fairly constant, except for the hard jets

Jet areas and what they are good for

Matteo Cacciari

When a hard event is superimposed on a **roughly uniformly distributed background**, study of **transverse momentum/area** of each jet allows one to determine the noise density **ρ** (and its fluctuation) on an event-by-event basis

After subtraction the correct mass is recovered with good resolution



- ☑ Given a proper jet-finder, jet areas can be defined
- ☑ They can be used to estimate the level of a uniformly distributed noise
- ☑ They can be used to subtract the background contribution from the hard jets

Jets: cone versus kt

We heard many rumours about the kt-algorithm being not well behaved in some contexts

Now that we have

- ✓ an efficient kt-algorithm
- ✓ an efficient, infrared-safe Cone algorithm
- ✓ methods to estimate noise/background/sensitivity to UE

We hope to see soon a systematic comparison between the two types of algos (e.g. sensitivity to underlying event, hadronization effects, etc.)

Part II: experimental summary by Claire Gwenlan