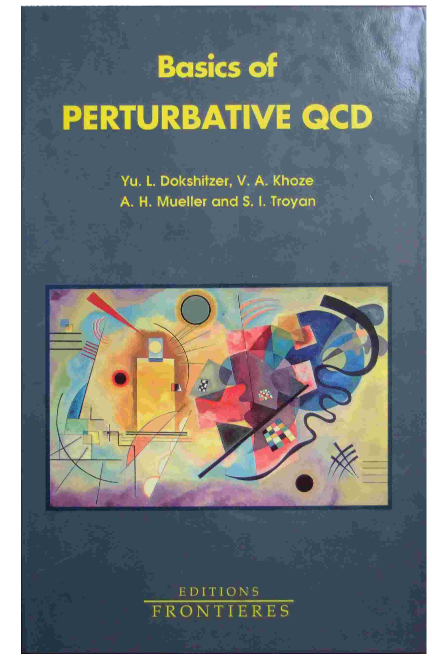
From event shapes to jets



Giulia Zanderighi
CERN, Oxford, ERC

Yuri's Fest, 18th October 2016, Paris

Event shapes and jet rates

Collinear and Infrared Safe (CIS) observables describing energy & momentum flow of particles in hard scatterings

$$\left.\begin{array}{c} e^+e^- \\ p\bar{p} \\ \gamma p \end{array}\right\} \rightarrow \text{(hadronic) jets}$$

- ✘ CIS $\Rightarrow$ computed with high accuracy in QCD $\Rightarrow$ good measurement of α_s
- ✘ infrared sensitive $\Rightarrow$ way to study NP physics

➥ way to test *our* understanding of strong interactions

Year 2000

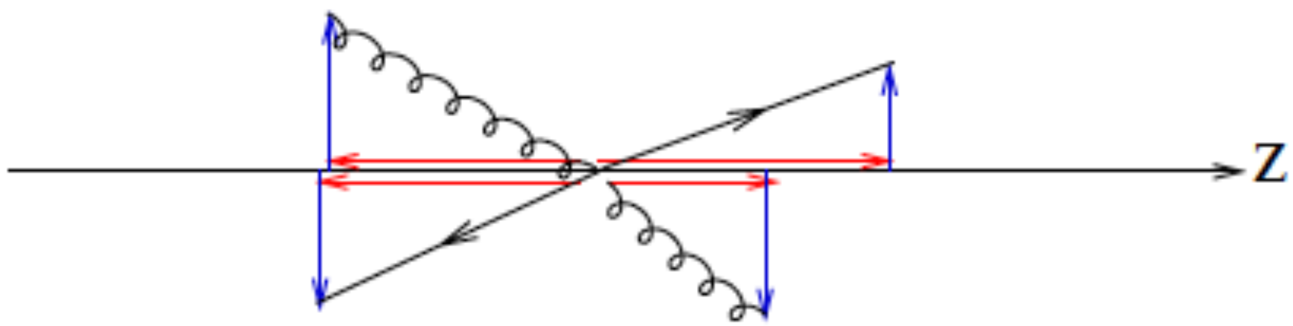
Most known examples

✗ Thrust: longitudinal particle alignment

$$✍\ T \equiv \frac{1}{Q} \max_{\vec{n}_T} \sum_i |\vec{p}_i \cdot \vec{n}_T| = \frac{1}{Q} \sum_i |p_{iz}|$$

✗ Broadening: transverse size of jets

$$✍\ B \equiv \frac{1}{2Q} \sum_i |\vec{p}_i \times \vec{n}_T| = \frac{1}{2Q} \sum_i |\vec{p}_{it}|$$



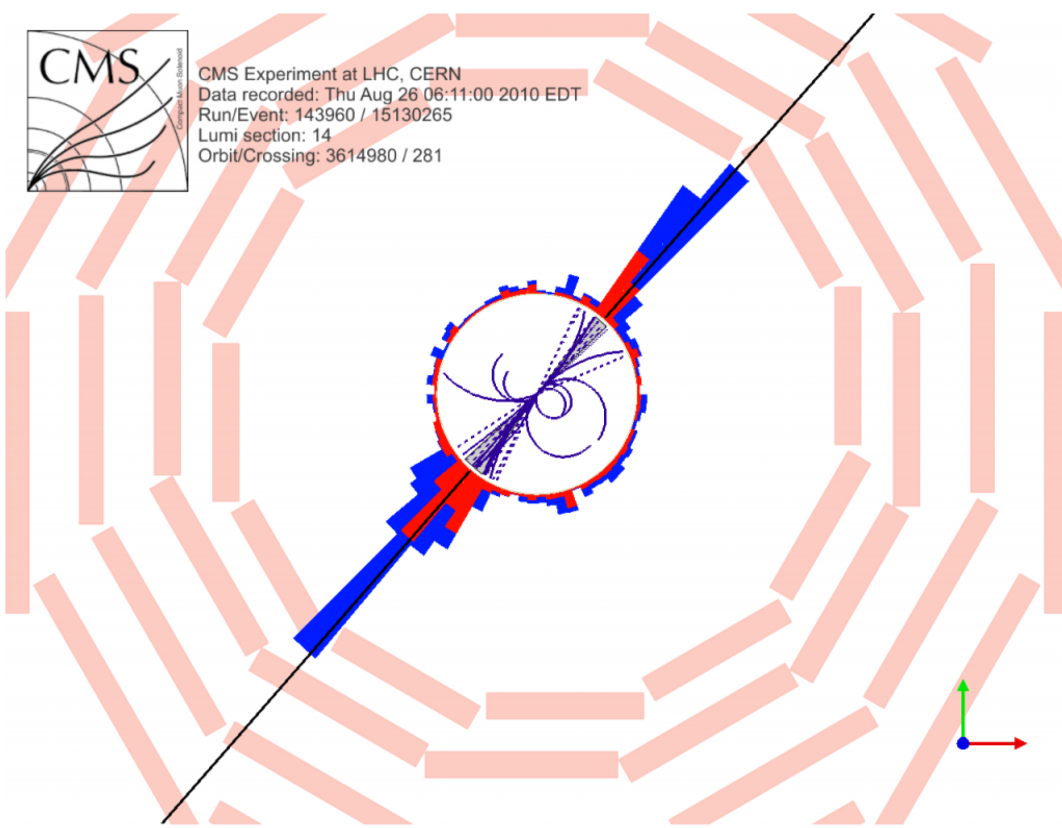
p_z : Thrust

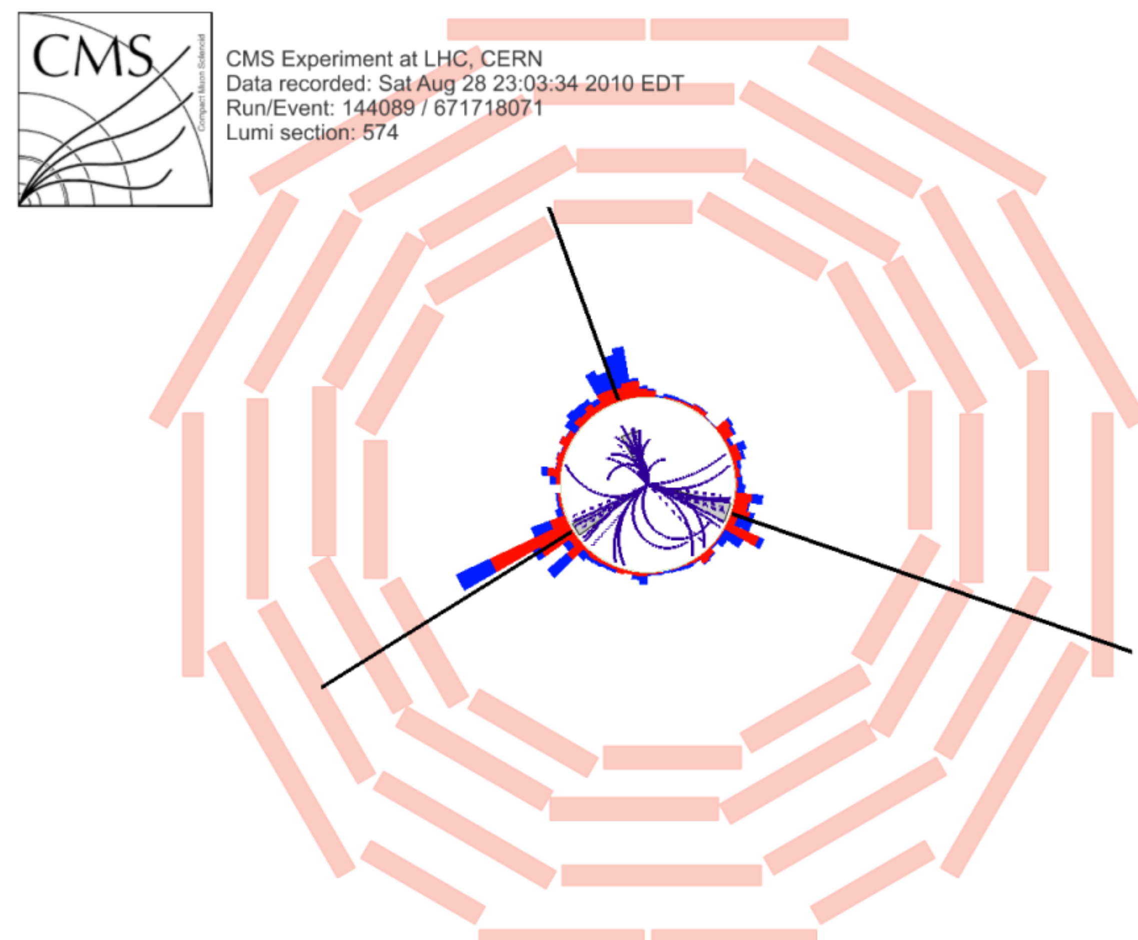
p_t : Broadening

Year 2000

Event shapes measure shapes of events

Example: thrust(*), standard to define $\tau \equiv 1 - T$





$\tau \ll 1$ $\tau \sim 1$

(*) images refer to transverse thrust as measured today at the LHC

✗ $\tau \sim \mathcal{O}(1)$ inclusive region

observable sensitive to the total energy & momentum flow, not to the destiny of single partons

✗ $\tau \to 0$: less inclusive region

the mismatch between R-V emphasised, IR divergences cancel, but large *log*-enhanced contributions appear
$\Rightarrow$ the expansion parameter is not $\alpha_s \ll 1$, but $\alpha_s \ln \tau \sim 1$
$\Rightarrow$ one must resum all terms $(\alpha_s \ln \tau)^n$ at any order

☛ In spite of $\alpha_s \ll 1$ quarks and gluons willingly multiply giving rise to a bulk of soft and collinear emissions!

Year 2000

Resummation achieved via factorization of

- ✗ Matrix element and phase space $\Rightarrow$ Independent emission (OK for global CIS quantities only!)

NB: use of an independent emission approximation at single-logarithmic order not trivial

$$dw_n = \frac{1}{n!}\prod_i [dk_i]w(k_i) \qquad w(k) = \frac{\alpha_s(k_t^2)}{\pi k_t^2} \text{ (2-loop)}$$

- ✗ Observable $\Rightarrow$ Mellin transform $\left(\theta(x) = \int \frac{d\nu}{2\pi i\nu}e^{\nu x}\right)$

$$\theta(V - f_v) = \int \frac{d\nu}{2\pi i\nu}e^{\nu V}\prod_i \underbrace{e^{-\nu v(k_i)}}_{\substack{u(k_i)\\ \text{source function}\\ \text{(obs. dependent)}}}$$

Year 2000

Event shapes exponentiate $\Leftrightarrow \ln \Sigma$ is free of $\alpha_s^n L^m$ with $n+1 < m \leq 2n$ (while they appear in Σ)

$$\boxed{\Sigma(V) = e^{Lg_1(\alpha_s L)+g_2(\alpha_s L)+\alpha_s g_3(\alpha_s L)+\ldots} \quad L = \ln \frac{1}{V}}$$

✗ LL approximation: $g_1 \Leftrightarrow \alpha_s^n L^{n+1}$ in $\ln \Sigma$.

- soft and collinear emissions
- leading running of the coupling effects (β_0)

✗ NLL approximation: Includes $g_2 \Leftrightarrow \alpha_s^n L^n$ in $\ln \Sigma$)

- soft, large angle emissions
- hard, collinear radiation
- subleading running of the coupling effects (β_1)
- multiple emission effects (recoil, Mellin transform)

Year 2000

Year 2001

- ✘ till recently this accuracy reached only in 2-jet event shapes, since they constitute the bulk of events ($\Rightarrow$ rich phenomenology!)

- ✘ but in multi-jet events the real essence of QCD is probed more deeply $\Leftrightarrow$ coherence effects become crucial

Yuri's vision of the importance of multi jet events

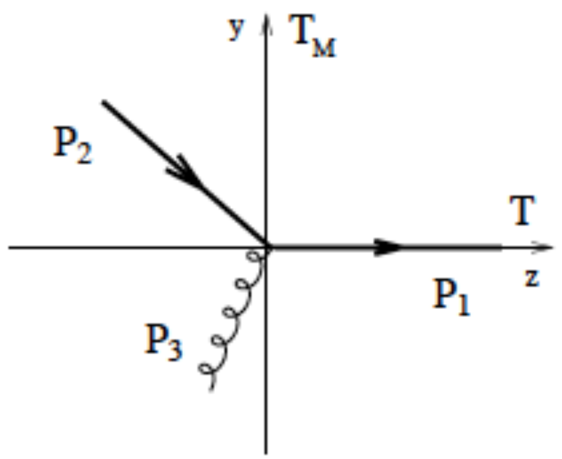
AIM: Extend the state-of-the-art to 3-jet event shapes

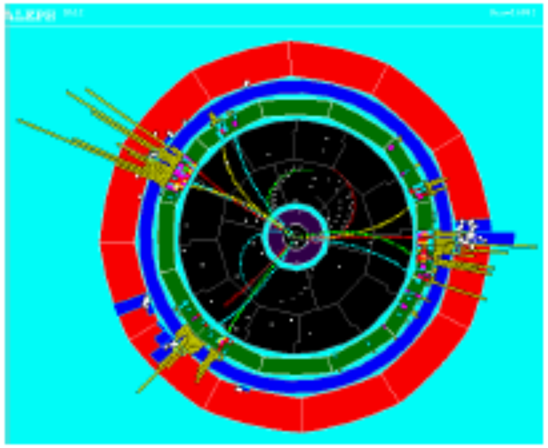
- ✗ 3-jet in e^+e^-: thrust-minor and D-parameter ✓
- ✗ 3-jet events in pp and DIS: out-of-plane radiation ✓

Born level:

Year 2001

$e^+e^- \to q\bar{q}g$





$$e^+e^- \to \underbrace{q\bar{q}g}\ \underbrace{k_1 \dots k_n} \quad (\Rightarrow \text{hadrons})$$

✗ D-parameter: determinant of the momentum tensor $\theta_{\alpha\beta}$

$$D \equiv 27 \det\theta \simeq 27\lambda_1\lambda_2 \sum_i \frac{k_{ix}^2}{\omega_i Q}$$

damped in rapidity

Banfi, Dokshitzer Marchesini, GZ, hep-ph/0104162

✗ Thrust-minor: out-of-event-plane momenta

$$T_m Q \equiv \sum_h |p_{hx}| \equiv K_{\text{out}}$$

uniform in rapidity

BDMZ, hep-ph/0004027, hep-ph/0010267, hep-ph/0101205

PT results for the thrust-minor

$$\Sigma(K_{\text{out}}) = \underbrace{e^{-R(K_{\text{out}})}}_{DL} \cdot \underbrace{\mathcal{F}\,(K_{\text{out}})}_{SL}$$

✗ DL-contributions: $R\,(K_{\text{out}}) = \sum_{a=1}^{3} C_a r(K_{\text{out}}, Q_a)$

$$r(K_{\text{out}}) = \int_{K_{\text{out}}}^{Q_a} \frac{dk_x}{k_x} \frac{\alpha_s(2k_x)}{\pi} \ln \frac{Q_a^2}{k_x^2} \qquad Q_a^2 = \frac{{p_{ta}}^2 e^{-g_a}}{4}$$

$C_a = C_F, C_A$: colour charge of parton $\#a$

➥ contribution from each parton singled out

Year 2001

$\boldsymbol{PT}$ *results for the thrust-minor*

✗ SL-corrections:

- argument of the coupling $\alpha_s(2k_x)$
- hard part of the splitting functions $g_a = -3/2, -\beta_0/2N_C$
- geometry dependence in hard momentum scales p_{ta}
- hard parton recoil in SL-function $\mathcal{F}$

$\mathcal{F}$ to first order in α_s (one gluon emission):

$$\mathcal{F}(K_{\text{out}}) = 1 - \frac{2\alpha_s}{\pi} \ln \frac{Q}{K_{\text{out}}} (2\,C_1 + C_2 + C_3) \ln 2$$

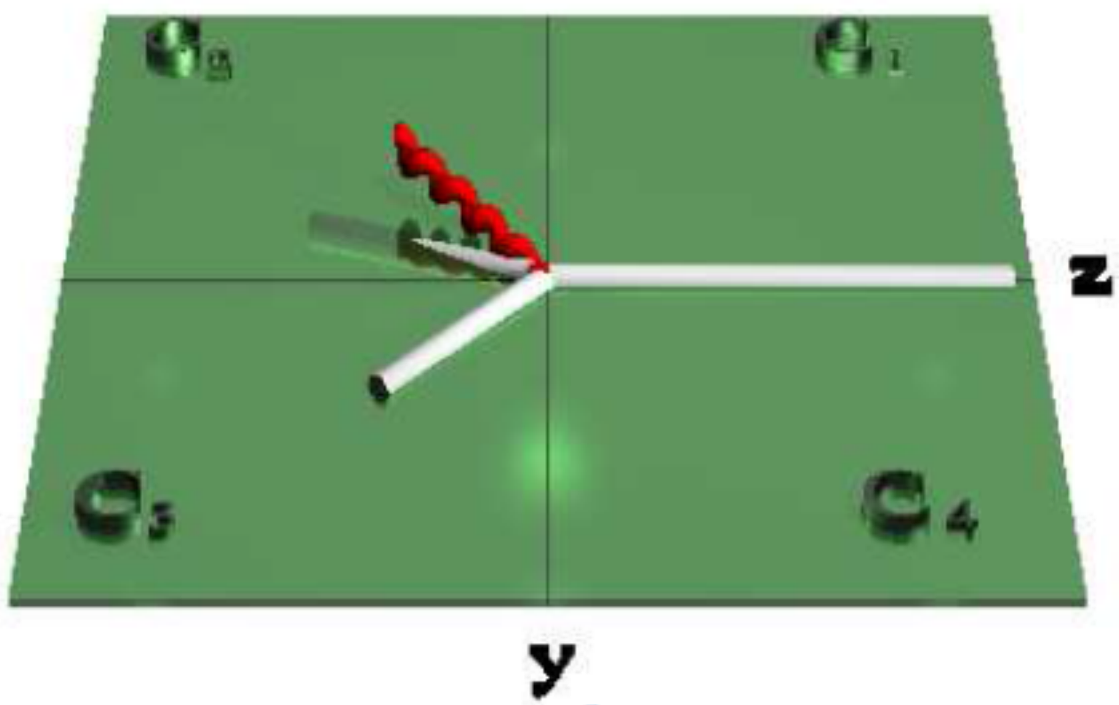
➡ contribution from the parton $\#1$ along $\vec{n}_T$ is doubled.

Why???

$\mathcal{F}$ depends crucially on the kinematics

Year 2001

Event plane kinematics & constraints



Emission from parton #2:
(Similar for parton #3)

$$|q_{2x}| = |k_x|$$

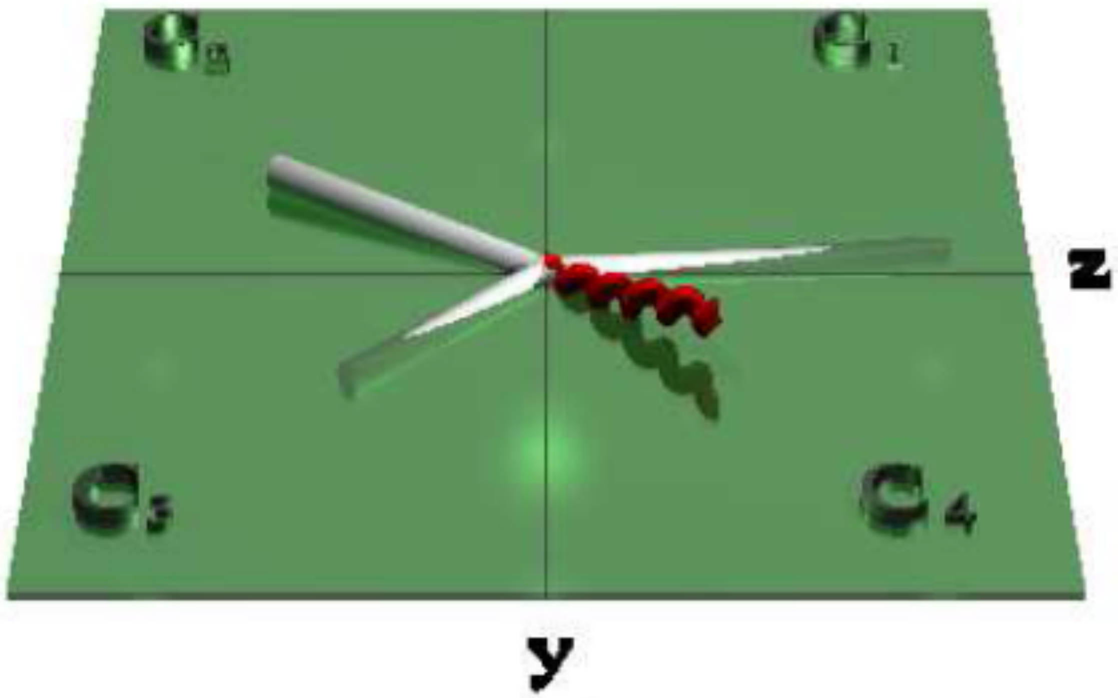
$$|q_{1x}| = |q_{3x}| = 0$$

$$K_{\mathrm{out}} = 2 \cdot |k_x|$$

➥ $$\frac{d\sigma}{\sigma d \ln K_{\mathrm{out}}} \sim C_2 \frac{\alpha_{\mathrm{s}}}{\pi} \ln \frac{Q}{|k_x|} \sim C_2 \frac{\alpha_{\mathrm{s}}}{\pi} \ln \frac{2Q}{K_{\mathrm{out}}}$$

Year 2001

Event plane kinematics & constraints



Emission from parton #1:

$|q_{1x}| = |q_{2x}| = |q_{3x}| = |k_x|$

$K_{\text{out}} = 4 \cdot |k_x|$

$$\frac{d\sigma}{\sigma\, d\ln K_{\text{out}}} \sim C_1 \frac{\alpha_{\text{s}}}{\pi} \ln \frac{Q}{|k_x|} \sim C_1 \frac{\alpha_{\text{s}}}{\pi} \ln \frac{4Q}{K_{\text{out}}}$$

Year 2001

Follow-up of work with Yuri

Understanding the structure of single logarithmic corrections in a generic way allowed us to formulate a semi-numerical method to resum generic event-shapes and jet-rates at NLL

IDEA: Banfi, Salam, GZ *JHEP* 01 **018** (2002)

relate SL effects due to multiple emissions to the given observable V the resummation of a 'simple' reference observable V_s which

- ✘ has the same DL structure
- ✘ factorizes trivially

Natural choice:

$$V = \sum_i V(k_i) \quad \Rightarrow \quad V_s = \max[V(k_1), \ldots V(k_n)]$$

Year 2002

Follow-up of work with Yuri

$$\boxed{\Sigma(v) = \Sigma_s(v)\mathcal{F}(R')}$$

All non trivial multiple effects embodied in $\mathcal{F}$!

Since $\mathcal{F}$ depends on the kinematics, exploit the fact that doing the kinematics numerically is much easier than analytically

---

Extension to full numerical resummation.

`CAESER` (Computer Automated Expert Semi-Numerical Resummer)

- determines basic properties of the observable, in particular whether it can be resummed
- determines the input to the master resummation formula
- evaluation of formula

Banfi, Salam, GZ '04

Follow-up of work with Yuri

For the observable to be resummed automatically it should

- ✗ be infrared and collinear safe
- ✗ vanish in the Born limit
- ✗ exponentiate (JADE excluded)
- ✗ be continuously global ($a_\ell = a \;\forall$ hard legs ℓ)
- ✗ behave as $V(k) \simeq d_\ell \left(\frac{k_t}{Q}\right)^{a_\ell} e^{-b_\ell \eta} g_\ell(\phi)$ for 1 SC gluon along leg ℓ
- ✗ satisfy minor (technical) requirements

While this might seem a long list

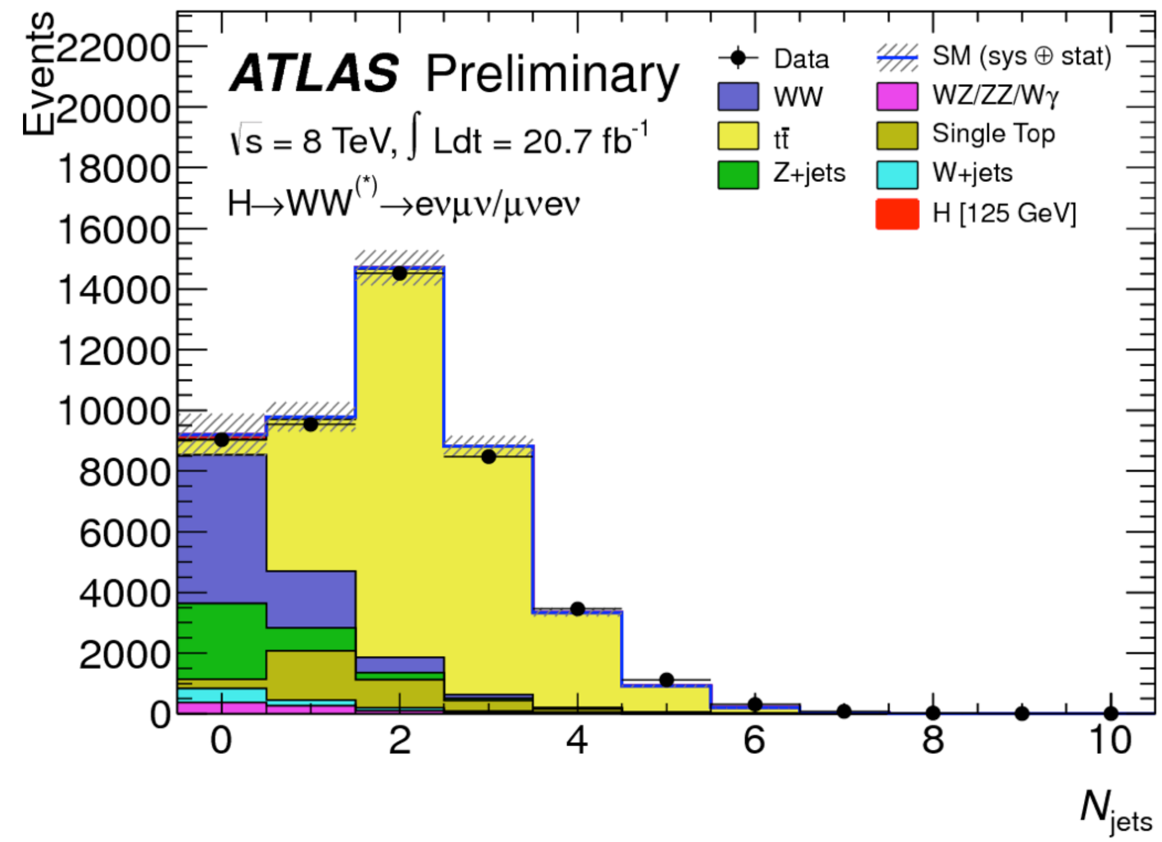
- ☛ practically the limiting condition is the requirement of globalness (all other conditions are satisfied by all observables resummed so far)
- ☛ an essential feature of the program is the ability to perform all checks automatically and to resum the observable only if correctness of the result is guaranteed at NLL

➡ Observables beyond the scope of the program are outwith our current understanding!

Year 2004

Resummation for the jet-veto

Maybe most important application of CAESAR framework today: resummation for jet-veto in Higgs production
NB: jet-veto critical in Higgs production to remove large background from top production that gives rise to many jets



- The NLL difference between V and V_s comes from the region where emissions are well-separated in rapidity (angular ordering)
- In this limit, each emission leads to a jet, so, for the jet-veto, $V = V_s$
- This implies that there are no multiple emission effects, i.e. that the resummation for the jet veto at NLL is a pure Sudakov form factor

Banfi, Salam, GZ ’12

Year 2012

Resummation for the jet-veto

The NLL resummed result takes the very simple form

$$\Sigma_{\rm NLL} = \mathcal{L}_{\rm pp}(p_{\rm t,veto})|M_{\rm Born}|^2 e^{-R(p_{\rm t,veto})}$$

Drell Yan:

$$\mathcal{R}_Z \propto C_F \alpha_s \ln^2 \frac{M_Z}{p_{\rm t,veto}}$$

Higgs production

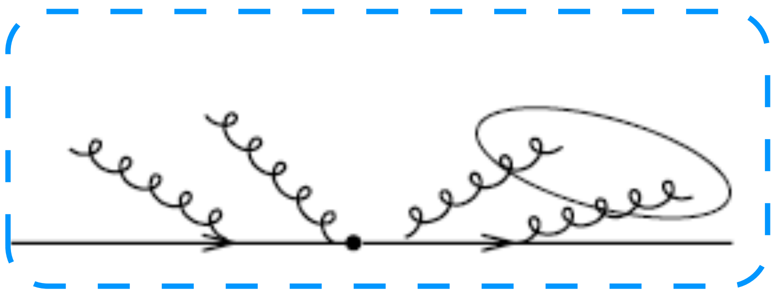
$$\mathcal{R}_Z \propto C_A \alpha_s \ln^2 \frac{M_H}{p_{\rm t,veto}}$$

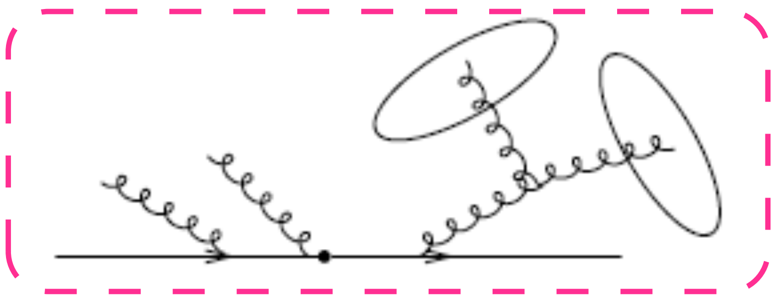
Since the NLL result is so simple, natural to wonder about NNLL

Year 2012

Resummation for the jet-veto

NNLL dependence on jet-radius has only two sources: clustering of independent emissions that are clustered together or correlated emissions that end up in different jets





$$\Sigma^{(J)}(p_{\mathrm{t,veto}} = \mathcal{L}_{gg}(p_{\mathrm{t,veto}})|\mathcal{M}_B|^2 e^{-R(p_{\mathrm{t,veto}})}\delta\mathcal{F}$$

Sudakov form-factor and parton luminosities: identical to boson pt resummation

Multiple soft-collinear real emissions: includes the dependence on jet-radius

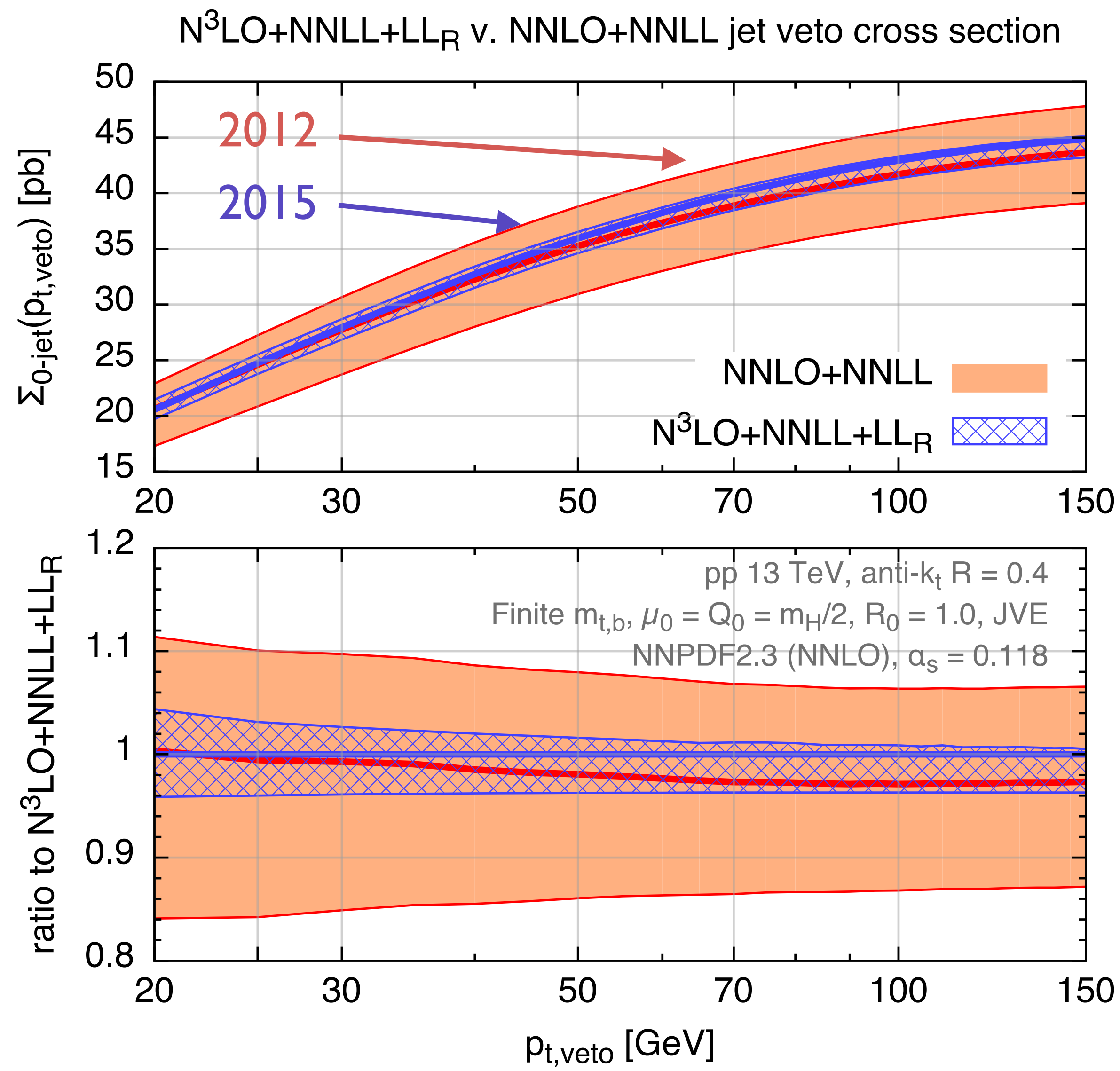
Banfi, Monni, Salam, GZ '12

Year 2015

JetVeto: latest results

Jet-veto predictions including

- ✓ N^3LO corrections to inclusive cross-section
  Anastasiou et al ’15
- ✓ NNLO corrections to H + 1 jet
  Caola et al ’15
- ✓ mass corrections
  Banfi, Monni, GZ et al ’13
- ✓ resummation of logarithms of (small) jet-radius
  Dreyer et al ’14



Few percent theory error (considerable reduction in the last years)

Banfi, Caola, Dreyer, Monni, Salam, GZ, Dulat ’15

Generic NNLL resummation?

Understanding that one can “correct” a NLL result (for the jet-veto) to include NNLL corrections lead us to think if one can compute generic NNLL resummations following the same spirit

ARES (Automated Resummation): a NNLL resummation for e+e- event shapes can be computed from a NLL one (from CAESAR) by including the following effects

- soft-collinear correction
- hard-collinear correction
- recoil correction
- soft wide-angle correction
- soft correlated correction

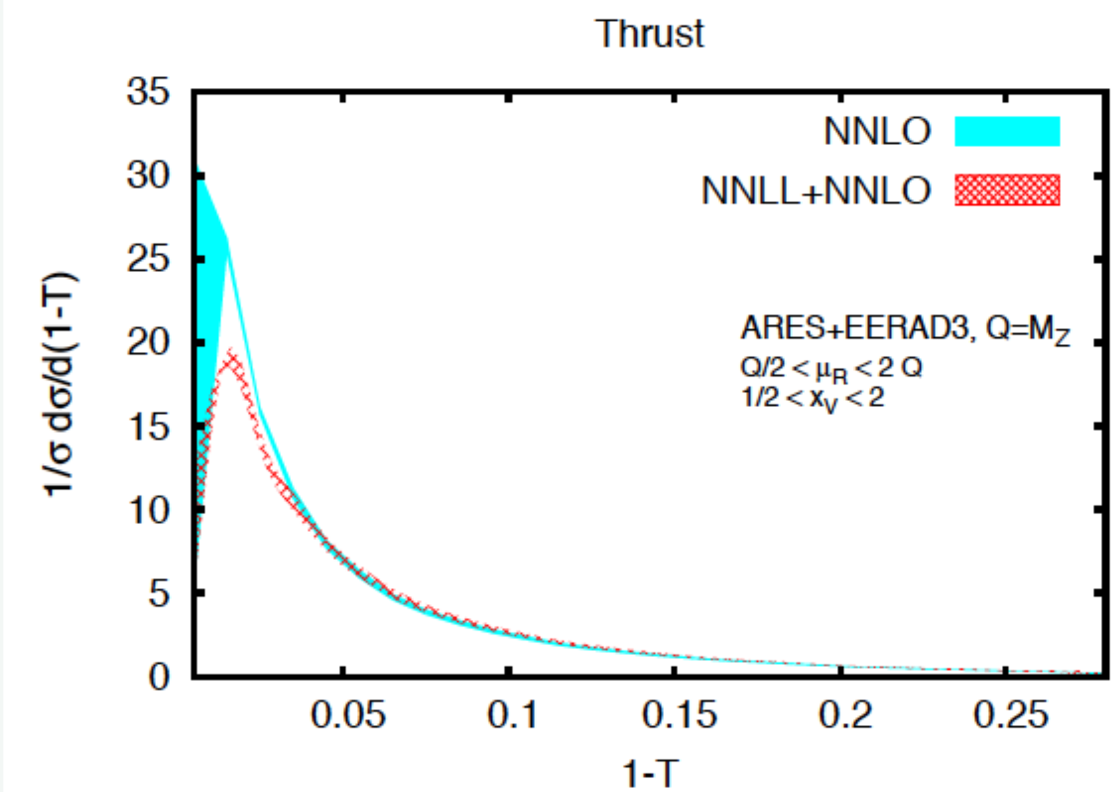
Banfi, McAslan, Monni, GZ ’14

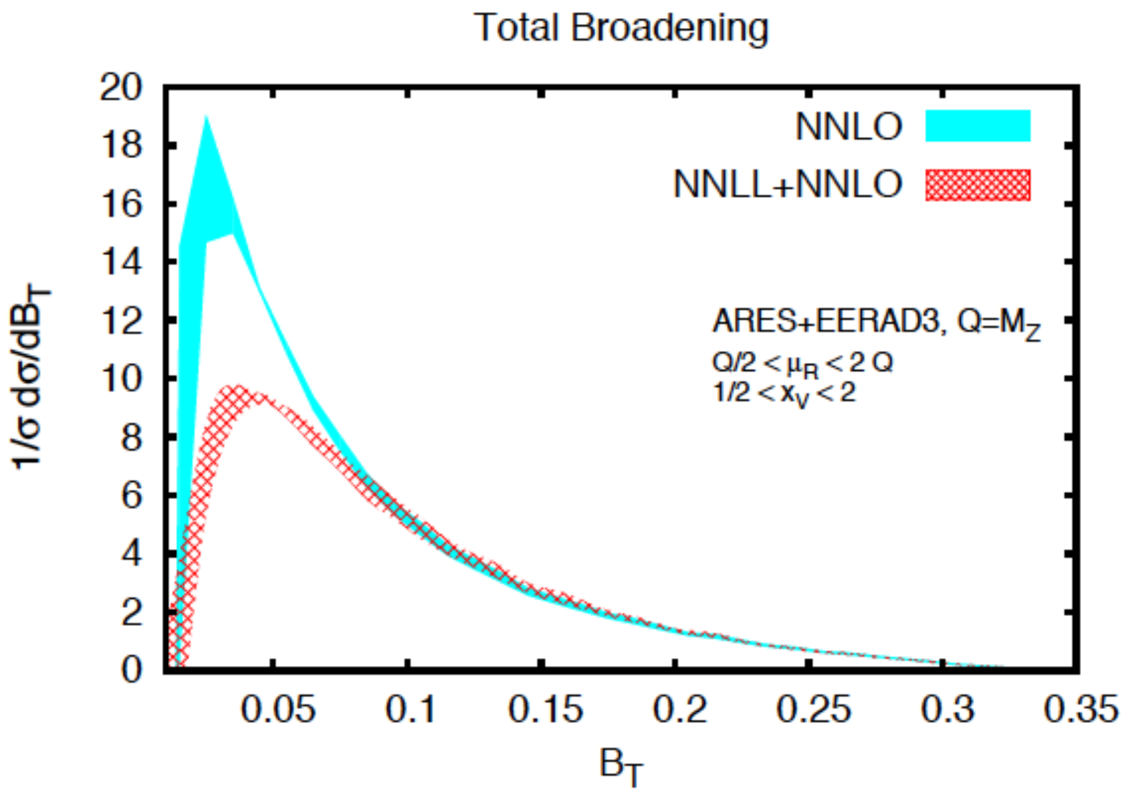
Each “corrections” lifts an approximation done at NLL, and is computed as a difference between the expression without approximation and the NLL approximated result, hence it is finite

Year 2014

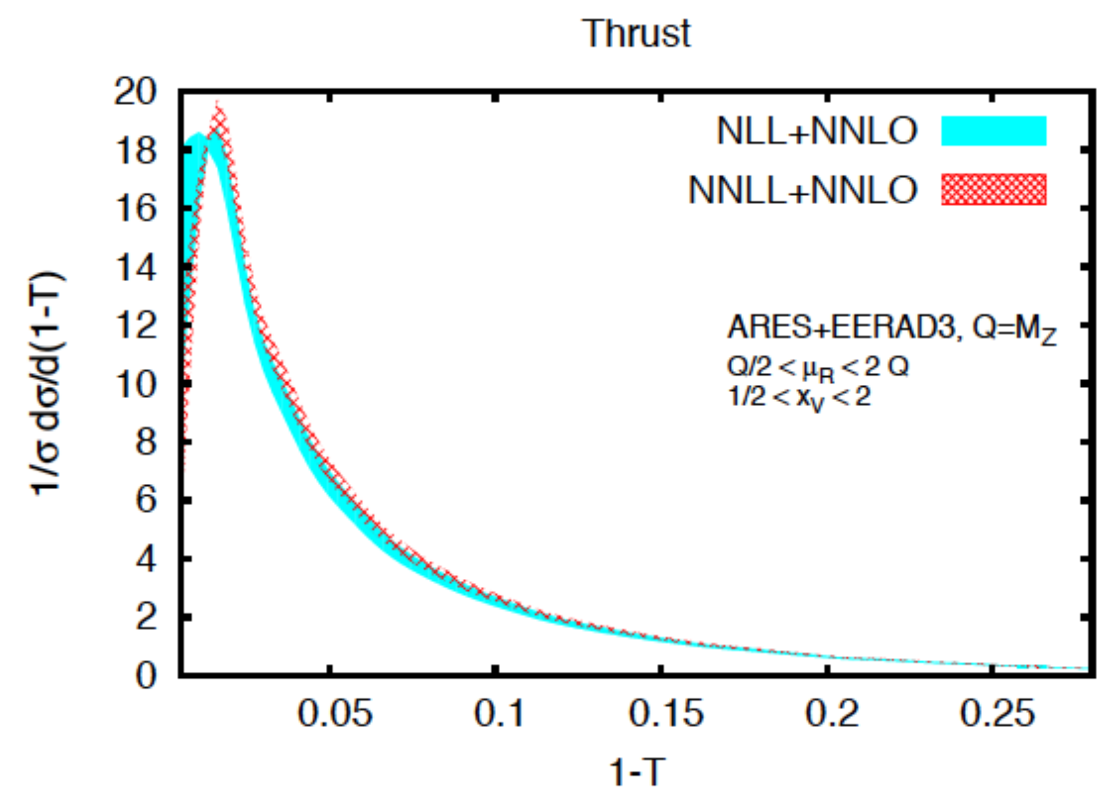
Sample results

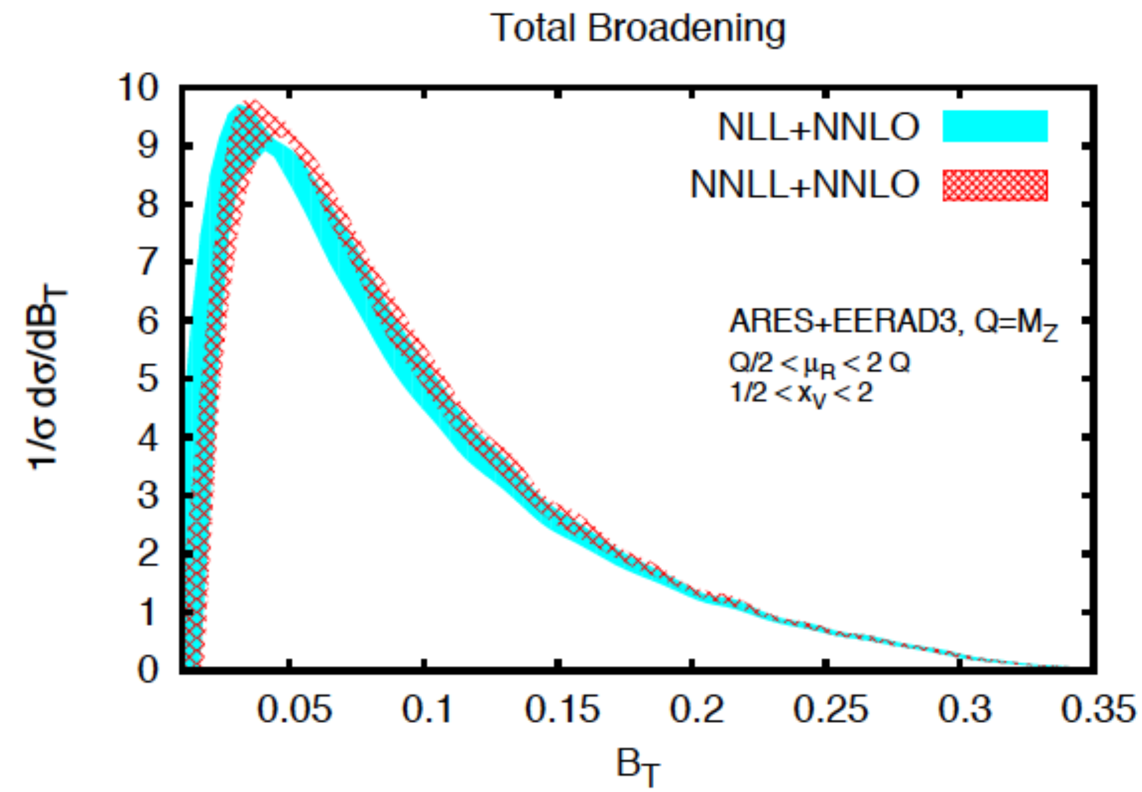
Comparison to NNLO





Comparison to NLL+NNLO





NNLL predictions for y_3

Two-jet rate defined through a clustering based on an angular distance v_{ij} and a test variable y_{ij}. For the Durham algorithm the two coincide

$$y_{ij}^{(D)} = v_{ij}^{(D)} = 2\frac{\min\{E_i, E_j\}^2}{Q^2}(1-\cos\theta_{ij})$$

Catani, Dokshitzer, Olsson, Turnock, Webber '91

In the Cambridge algorithm

$$y_{ij}^{(C)} = y_{ij}^{(D)}\,, \qquad v_{ij}^{(C)} = 2\,(1-\cos\theta_{ij})$$

Select the pair with the smallest v_{ij}. If $y_{ij} < y_{cut}$, then the two particles are recombined, otherwise the softer becomes a jet (soft freezing mechanism)

Dokshitzer, Leder, Moretti, Webber '97

NNLL predictions for y_3

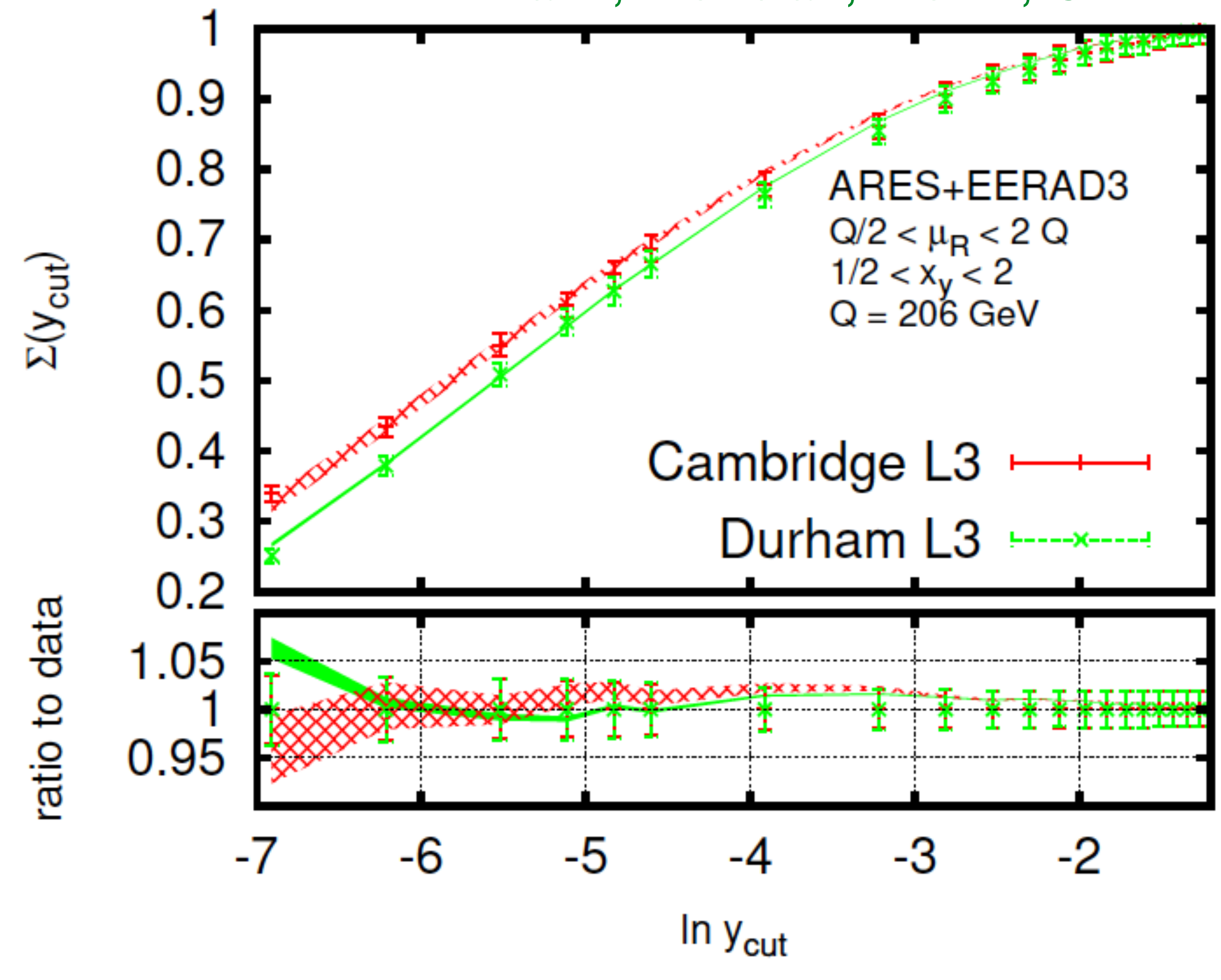
Jet-rates notably more difficult than even shapes: observable depends on whether emissions are with respect to each other

For jet rates a new element arises: two independent emissions can cluster into the same jet (new clustering corrections appear)

Comparison to LEP data

Next: new global fit of α_s based on NNLL+NNLO predictions from event shapes and jet rates

Banfi, McAslan, Monni, GZ '14



Conclusion

Work with Yuri left a profound imprint on my research. Many of Yuri's visionaries ideas affect my research today

- independent emission picture
- new jet-algorithm for which a accurate predictions are possible
- idea to exploit multi-jet events to explore region in between jets and to understand general patterns of QCD radiation in complicated environments

I sometimes think back of the years during my master/PhD when Pino, Yuri, Gavin and Andrea were in Milano. As a student, I entered a new world, and I assumed that that was a normal work environment. Only later I realised how lucky and privileged I was to come across such a remarkable combination of physicists

We are here to celebrate Yuri, Pino is here with us too, in our hearts

True synergy

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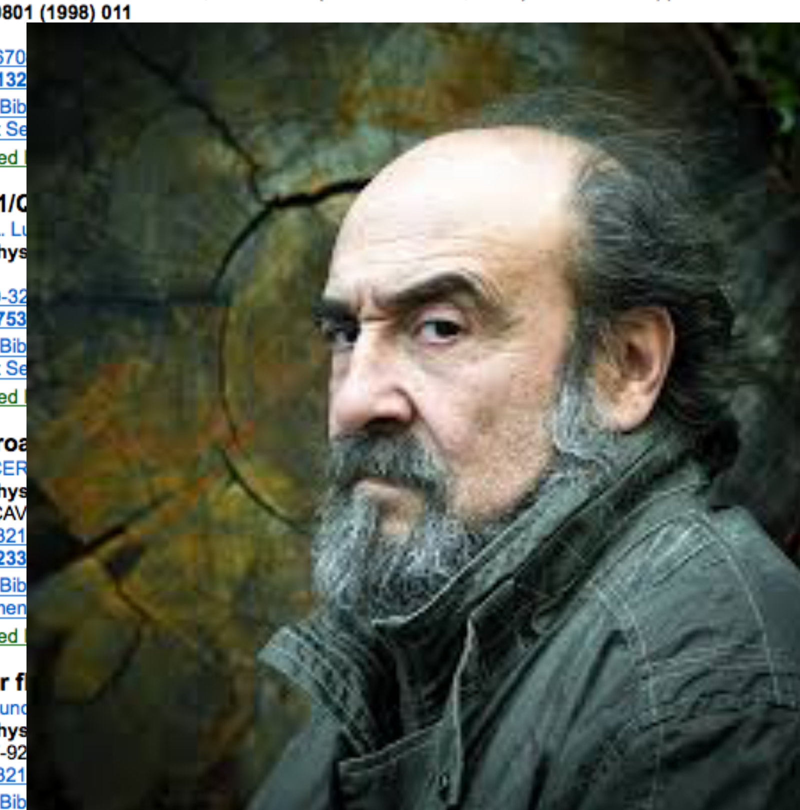

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