QCD — theory part

Livio Fano', Iacopo Vivarelli & Giulia Zanderighi

Quinto Workshop sulla fisica pp ad LHC

Outline

This talk:

20'+5' ⇒ no complete overview of recent theory progress in QCD!

➟ see talk by G. Altarelli

Instead: discuss some selected* topics

- jets (some definitions, concepts & new ideas)
- various level of perturbative (bottleneck, techniques, status & update)
- event shapes and resummation
- not covered: all the rest (apologies)

* Selected
1. because of the fair amount of recent progress
2. as a reflection of knowledge and taste of the speaker

Jets: true or false?

Cones are IR unsafe!

The Cone is too rigid!

IR unsafety affects jet cross-sections by less than 1%, so don't need to care!

kt collects too much soft radiation!

Cones has a well-defined circular area!

Jet area not well defined in kt: U.E. and pile-up subtraction too difficult!

What about dark towers??

After all, if D=1.35 R Cone and kt are practically the same thing....

Jet algorithms

Jet algorithms provide a way of projecting away the multiparticle dynamics of an event so as to leave a simple quasi-partonic picture of the underlying hard scattering. This projection is however fundamentally ambiguous, reflecting the divergent and quantum mechanical nature of QCD. Consequently, jet physics is a rich subject. *[Salam, ISMD-proc'07]*

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Jet algorithms

Cone type

(UA1,JetCLU, Midpoint, SISCone..)

top down approach: cluster particles according to distance in coordinate-space

Sequential

(kt-type, Jade, Cambridge/ Aachen...)

bottom up approach: cluster particles according to distance in momentum-space

Easier said than done?

Snowmass accord

FERMILAB-Conf-90/249-E
[E-741/CDF]

Toward a Standardization of Jet Definitions

Several important properties that should be met by a jet definition are [3]:

1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields finite cross section at any order of perturbation theory;
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- flexibility
- transparency
- few parameters
- fast algorithm
- jet flavour $\sim$ flavour of origination hard parton
- ...

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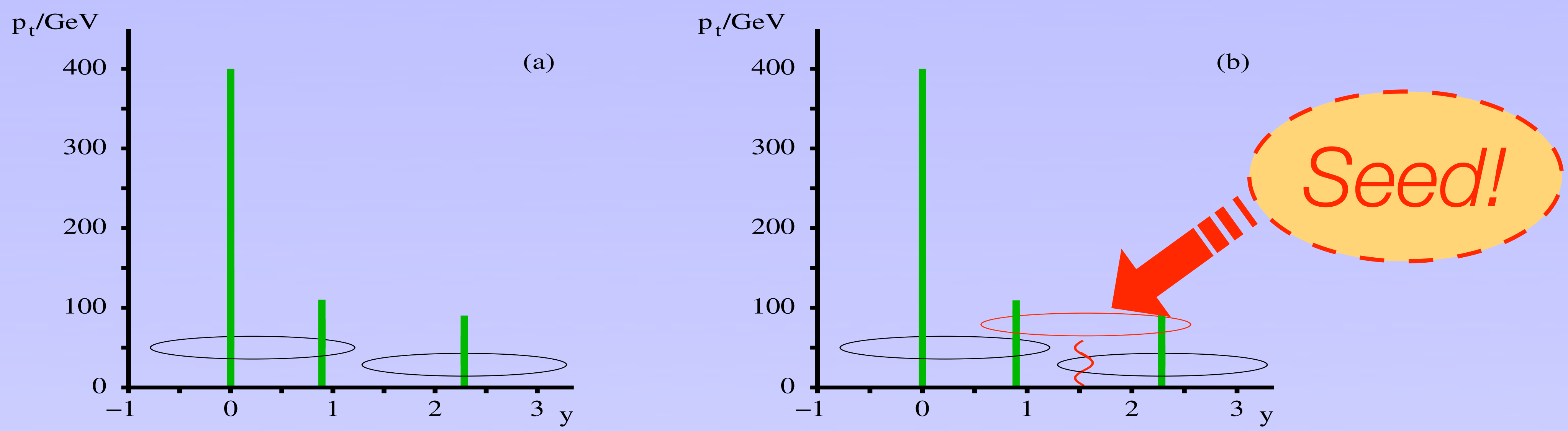
Despite this:

- cone algorithms used at Tevatron are IR unsafe
- often additional parameters or patches to fix IR unsafety
- some theory/exp. comparison carried out with different algorithms
- no systematic study of hadronization effects/U.E.

Infrared unsafety of seeded cone algorithms



3 h ⇒ 2 stable cones   3 h + 1 s ⇒ 3 stable cones

Soft emission changes the structure of the jets ⇒ algorithm is IR unsafe

	Last meaningful order	
	It. cone	MidPoint
Inclusive jets	LO	NLO *
$W/Z + 1$ jet	LO	NLO
3 jets	**none**	LO
$W/Z + 2$ jets	**none**	LO
m_{jet} in $2j + X$	**none**	**none**

IR-safety more important at the LHC

* e.g.: observed discrepancy between IR safe/unsafe only O(1%) because in inclusive case the violation appears first at relative O(α_s^2), in other cases it will be a O(1)

Seedless cone algorithm

<u>Seedless algorithm:</u> consider all possible enclosures of the N particles in the event. IR safe, but clustering time growths as $N \cdot 2^N$, i.e. 100 particles: 10^{17} years ⇒ prohibitive beyond PT (N~4,5,...).

[Blazey at al.'00]

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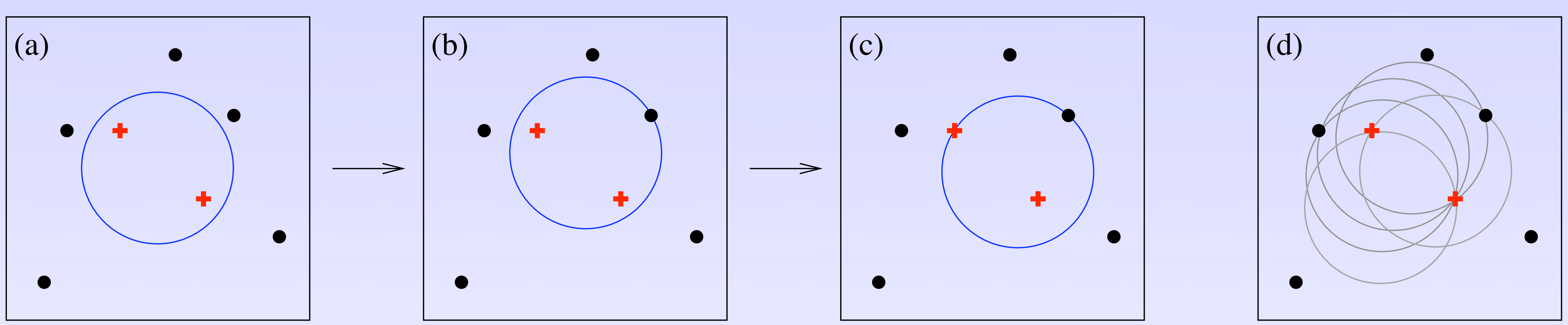
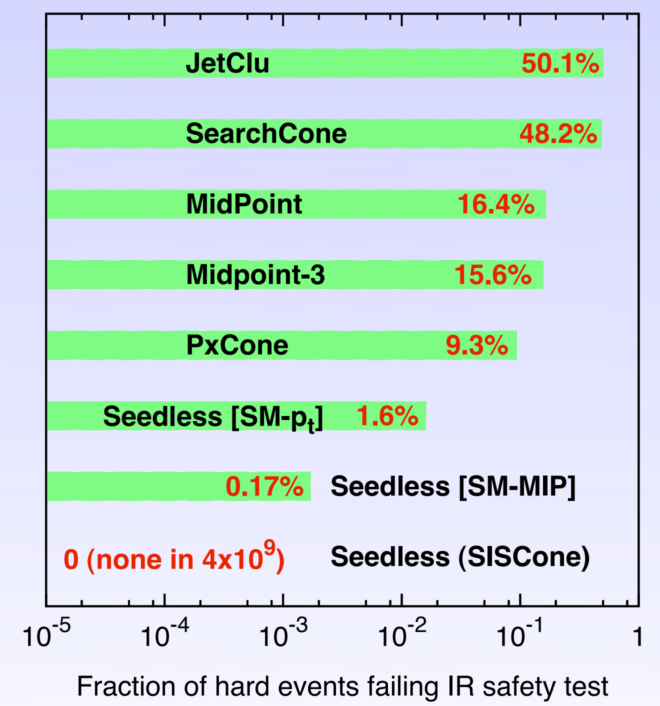
SISCone: recast the problem as a computational geometry problem, the identification of all distinct circular enclosures for points in 2D and find a solution to that (+ minor fixes) ⇒ $N^2 \ln N$ time IR safe algorithm

[Salam, Soyez '07]



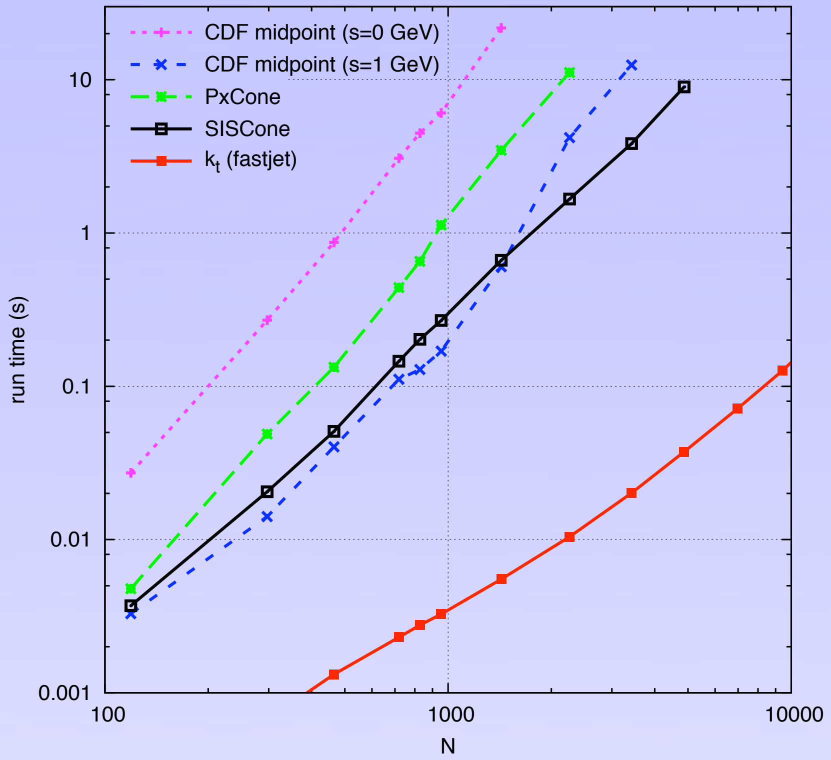


http://projects.hepforge.org/siscone/

Jet issues & applications

1. speed: no longer an issue

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



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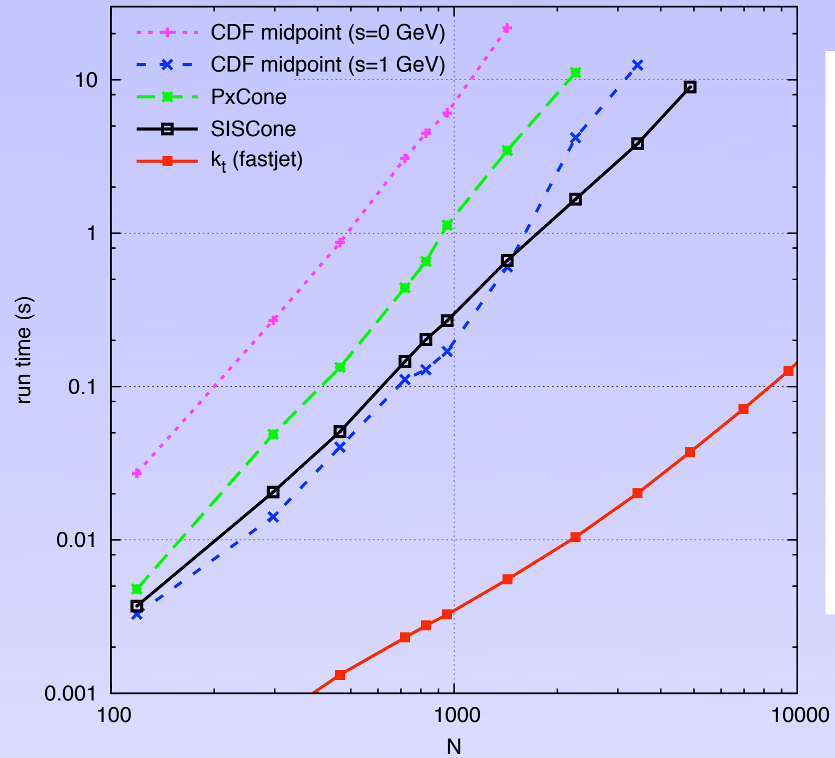
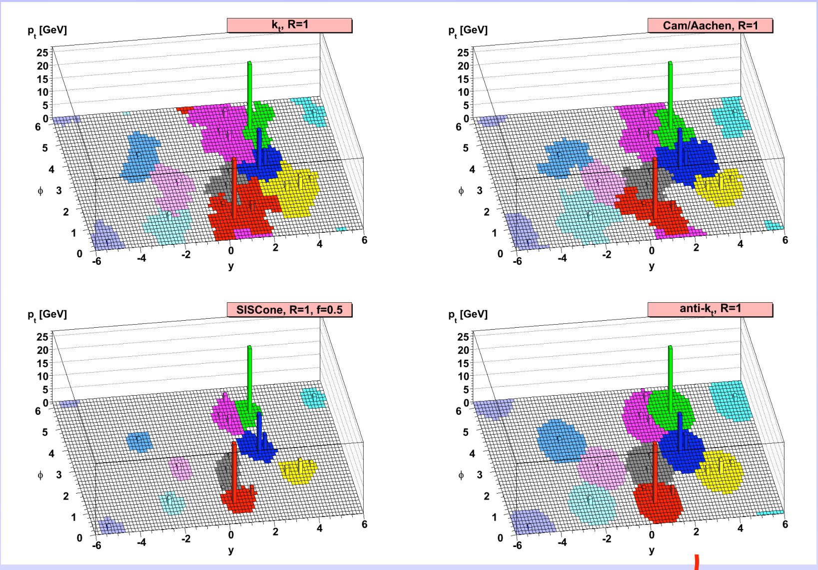
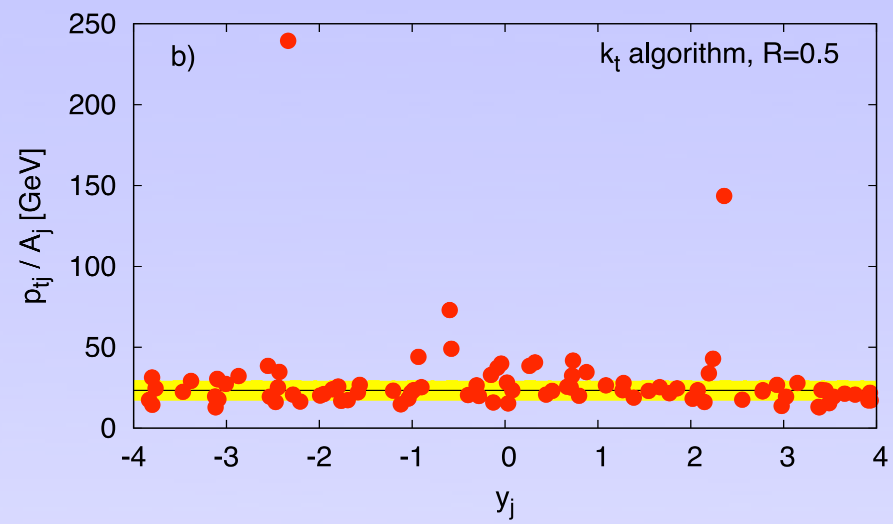
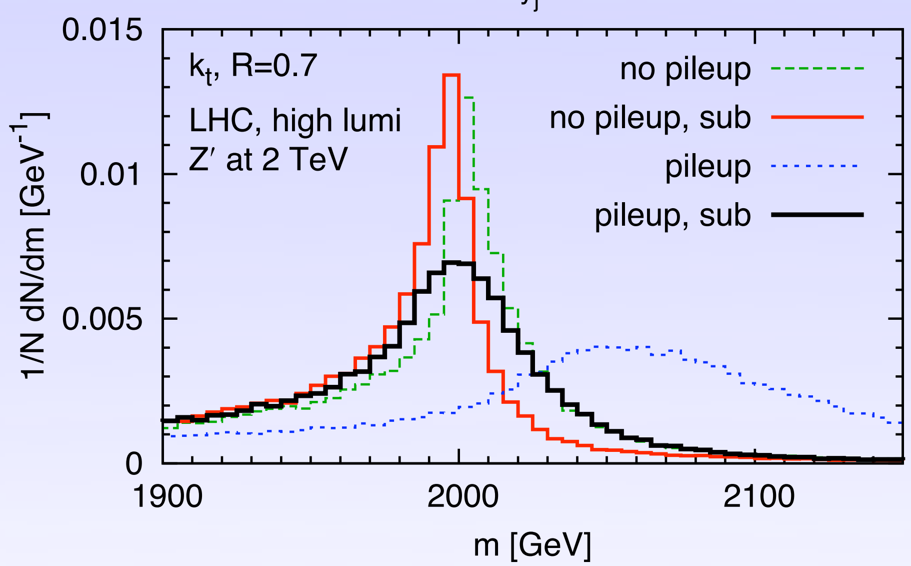




NB: anti-kt





2. jet-area ≡ catching area of the jet when adding uniformly infinitely soft emissions

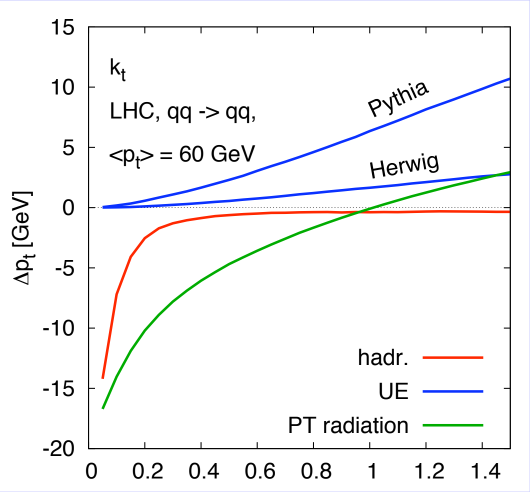
⇒ simple area based subtraction for a variety of algorithms: $p_j^{\rm sub} = p_j - A_j \rho$
(NB: area of cones < πR^2 !)

[Cacciari, Salam '07]

More sophistication

Different effects on the transverse momentum of jets:

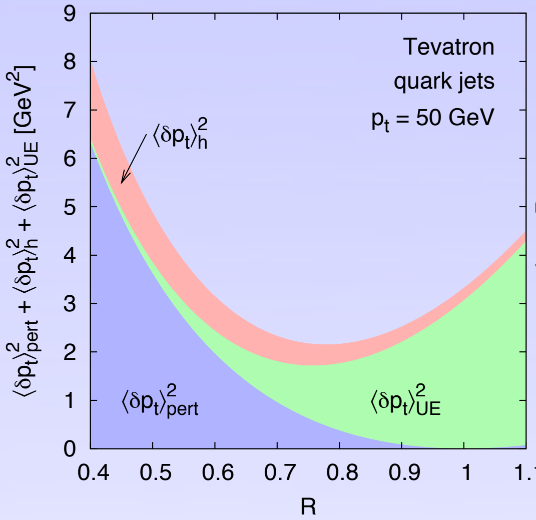
	Jet $\langle \delta p_t \rangle$ given by product of dependence on			
	scale	colour factor	R	$\sqrt{s}$
perturbative radiation	$\sim \frac{\alpha_s(p_t)}{\pi} p_t$	C_i	$\ln R + \mathcal{O}(1)$	–
hadronisation	Λ_{h}	C_i	$-1/R + \mathcal{O}(R)$	–
underlying event	Λ_{UE}	–	$R^2/2 + \mathcal{O}(R^4)$	s^{ω}

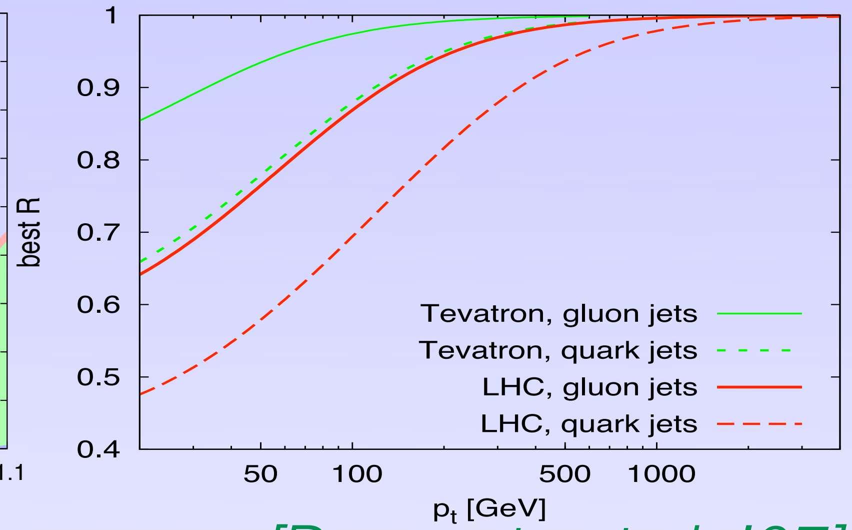


⇒ Different R dependence:

a) disentagle different effects

b) choose an optimal R minimizing some (or all) effects

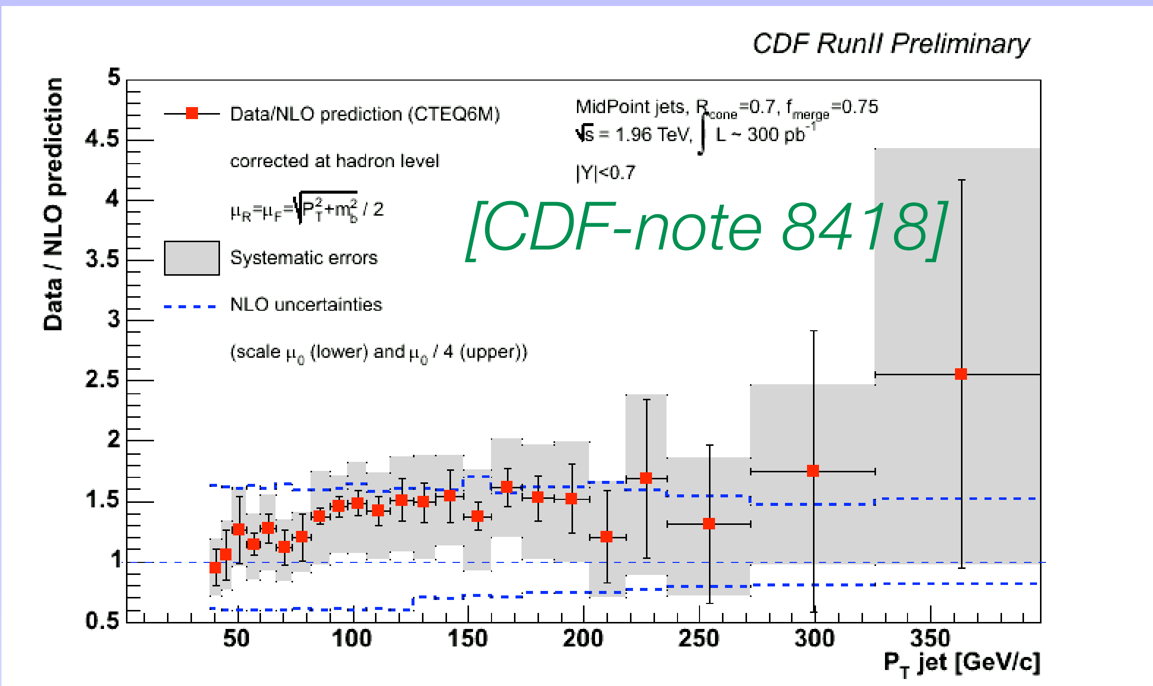




[Dasgupta et al. '07]

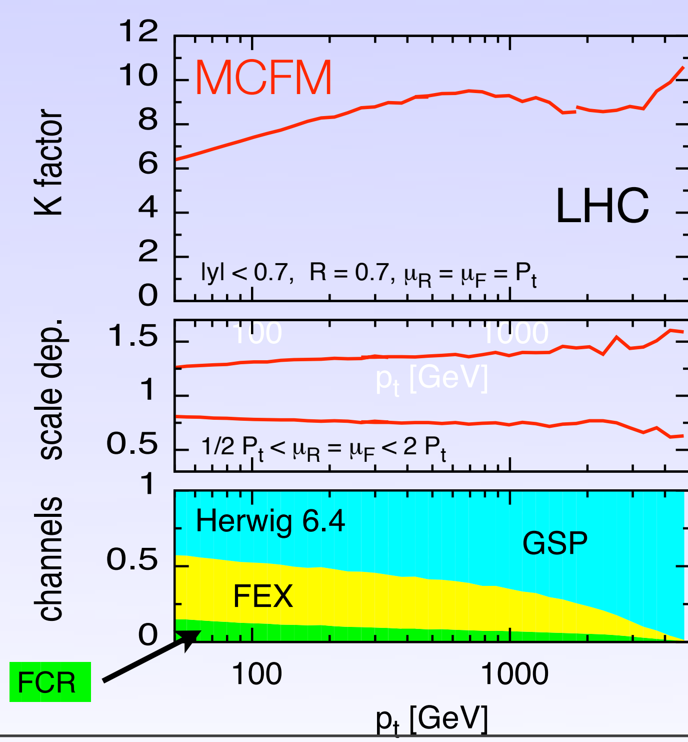
Take advantage of flexibility offered by modern jet tools: make flexible choices of jet-definitions and parameters!

Heavy flavoured jets



b-jet ≡ any jet containing at least a b-quark

⇒ NLO calculation (MC@NLO) has ∼40-60% theoretical uncertainty



- LO (FC) < NLO (FEX+GSP)
- higher orders enhanced by $\log(m_b/p_t)$
- despite $m_b \ll p_t$ need massive calculation

Flavour jet-algorithm

Flavour kt-distance measure:

$$d^F_{ij} = \frac{\Delta y^2_{ij} + \Delta\phi^2_{ij}}{R^2} \times \begin{cases} \max(k^2_{ti}, k^2_{tj}) & \text{softer of } i,j \text{ is b} \\ \min(k^2_{ti}, k^2_{tj}) & \text{softer of } i,j \text{ is } \not{b} \end{cases}$$

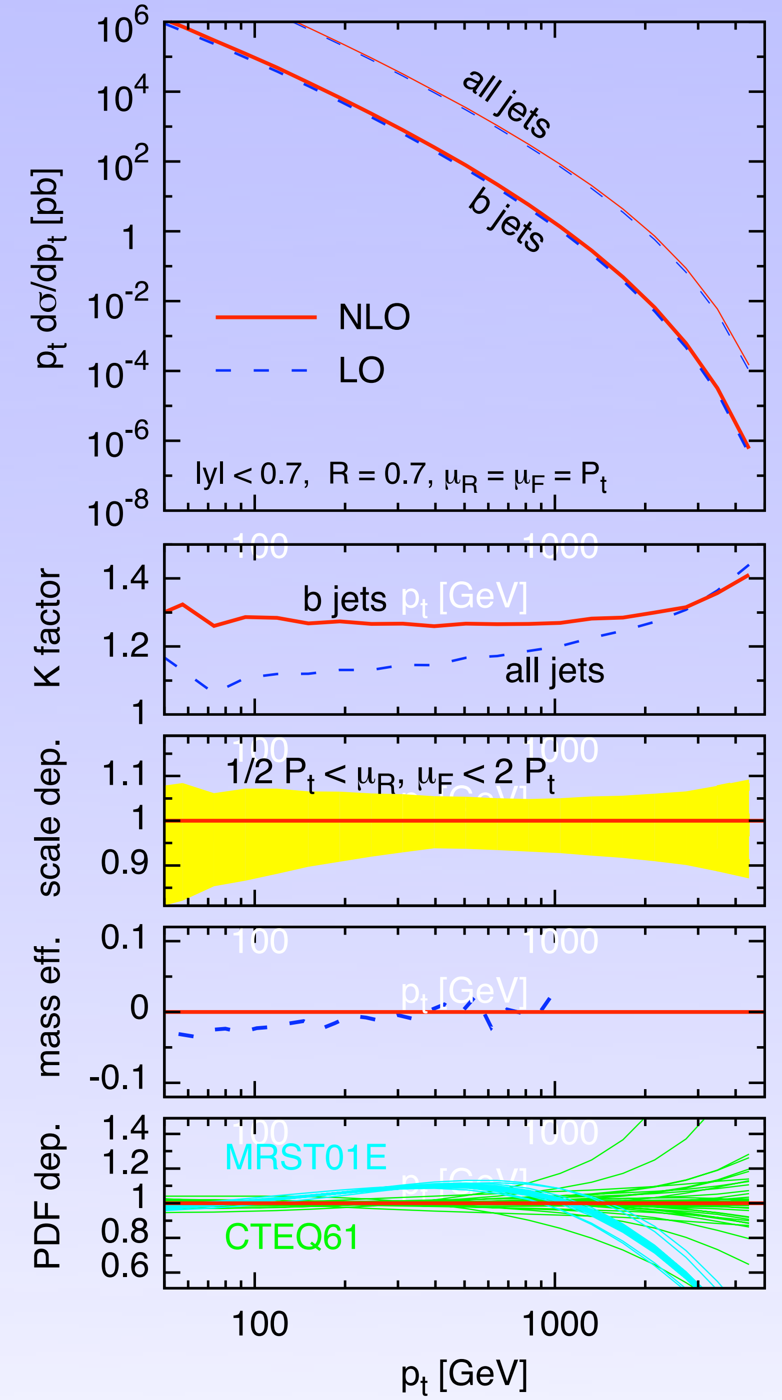
Reflects different (q,g) divergences of QCD

⇒ undo splittings occurred in the branching

1. jet with b and $\bar{b}$ = gluon jet (not trivial experimentally)
2. resume FEX logs in p-PDFs (collinear factorization)

1. + 2. ⇒ no large logs left take m_b=0 limit

➡ As a result: th. uncertainty goes down from 40-60% to 10-20% (~ light jets)



[Banfi et al. '07]

Perturbative: various levels of approximations

- Parton showers (Ariadne, Herwig, Pythia,...)
- LO matrix elements (ALPGEN, Madgraph...)
- LO matrix elements + parton shower (ALPGEN, Madgraph...)
- NLO matrix elements (MCFM, NLOjet,...)
- NLO matrix elements + parton shower (MC@NLO, POWHEG)
- NNLO matrix elements (e.g. Higgs, DY, ee $\longrightarrow$ 3jets)

Performance of LO techniques

- Helicity amplitudes & LO recursions → BG *[Berends, Giele '88]*
- from twistors: onshell-recursion / MHV vertices → BCF / CSW
  [Britto, Cachazo, Feng '04, Cachazo, Svrcek, Witten '04]
- other methods [HELAS, ALPHA, HELAC...]
  [Hagiwara et al.'92, Caravaglios & M. Moretti '95; Kanaki & Papadopoulos'00]

☛ Various automated methods: limiting factor is computer time

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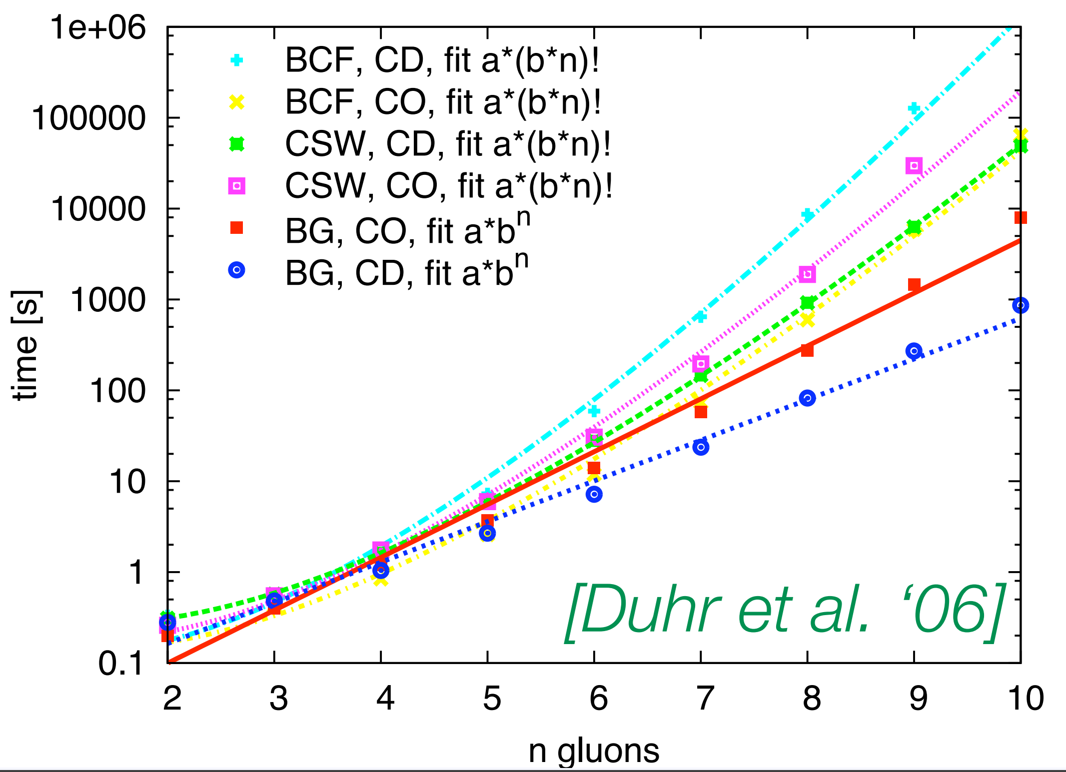
Pure gluon amplitudes (theorists favourite playground):



- CO: Color Ordered (partial)
- CD: Color Dressed (full)

➡ BCF/CSW: compact, but factorial growth

➡ BG: power-like algorithm
→ much faster at large n

LO matrix elements + parton shower

Matching: improve ME in soft-collinear regions (using Sudakov) and parton shower at large angles (using ME)

Procedures:

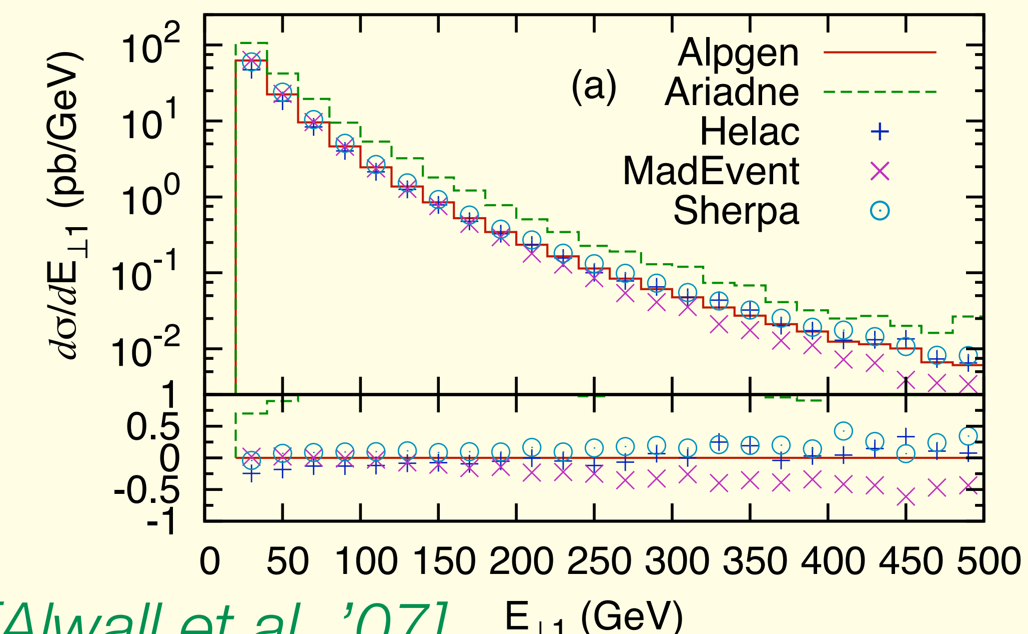
- CKKW: separate ME&PS domain using a clustering variable
  [Catani et al. '01]
- MLM: match parton to jet, no modification to the shower (simple)
  [Mangano '02]
- others (CKKW-L, Pseudo-shower...)

⇒ Different showers, ME and matching procedures

➡ reasonable good agreement

➡ systematics at Tevatron $\sim$ LHC

☛ tune codes to Tevatron and give consistent predictions for LHC



[Alwall et al. '07]

ME + parton shower: back to basics

[Lavesson & Lonnblad '07]

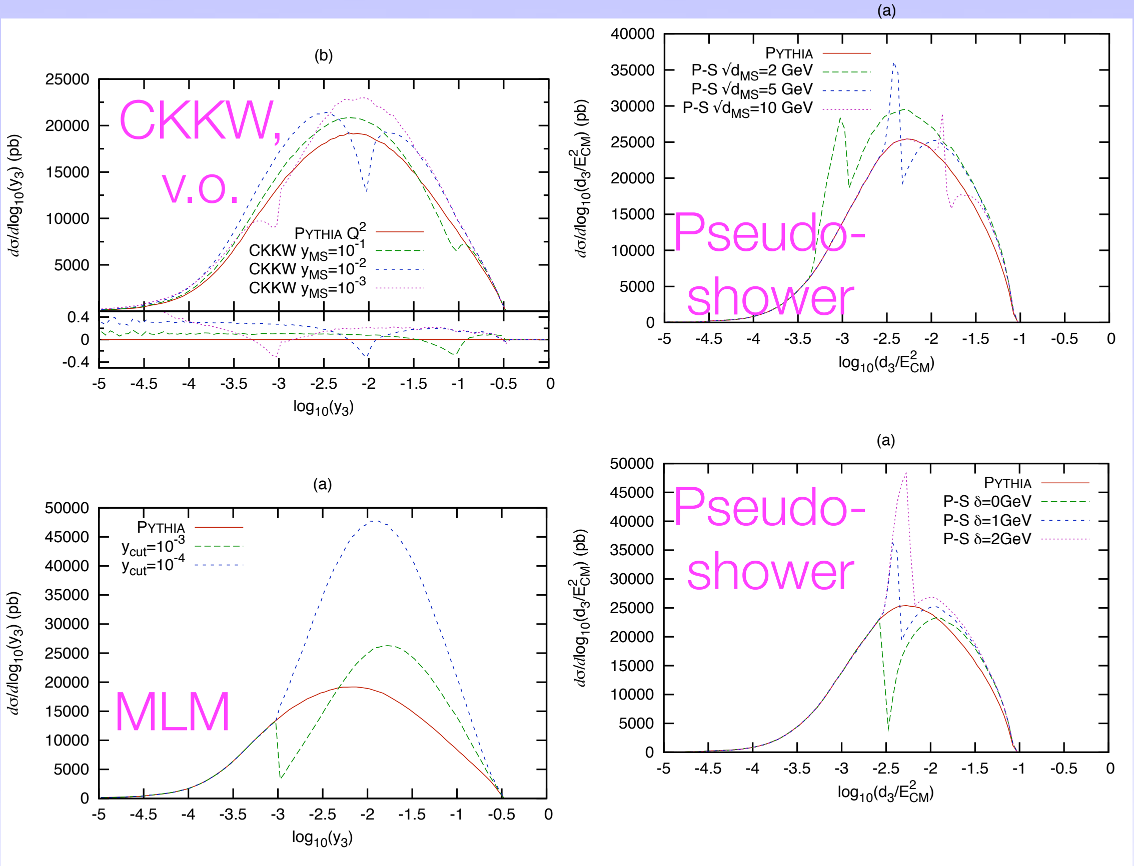
Similar study in simplest environment $e^+e^- \rightarrow q\bar{q}$ at Z pole

Aim: check whether various schemes meet their goals

NB: correct answer known (reweight hardest emission of the PS)

Outcome: various problems, e.g.

- inconsistent results with SHERPA
- problems with CKKM and virtuality ordered shower
- poor cancellation of merging-scale & fudge factor in pseudo-shower
- MLM: no convergence lowering ME cutoff



Conclusion: extra parameters need to be tuned (different for different processes, scales, observables?) ⇒ *predictability of models reduced*

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- LO predictions only qualitative, due to poor convergence of perturbative expansion ($\alpha_s \sim 0.1$) ⇒ NLO can be 30-100% !

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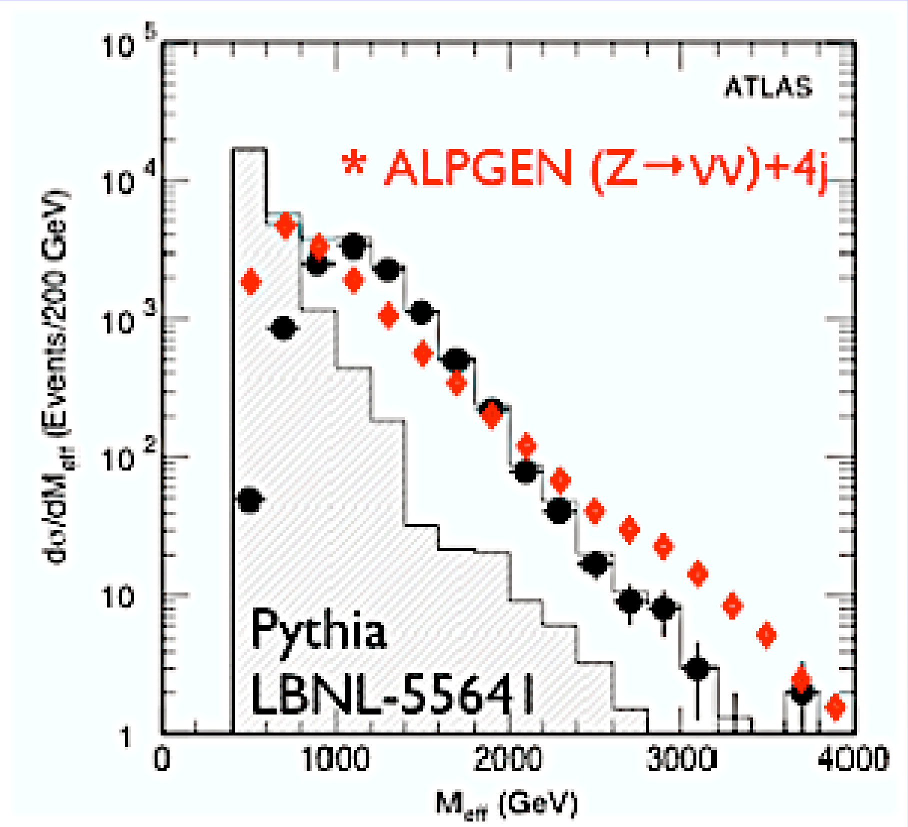
⇒ gain confidence that cross sections are under control for precision measurements

LHC example: SUSY search

- SUSY signature: missing E_T + jets

$$M_{\rm eff} = E_{\rm T,Mis} + \sum_{j=1}^{4} E_{\rm T,j}$$



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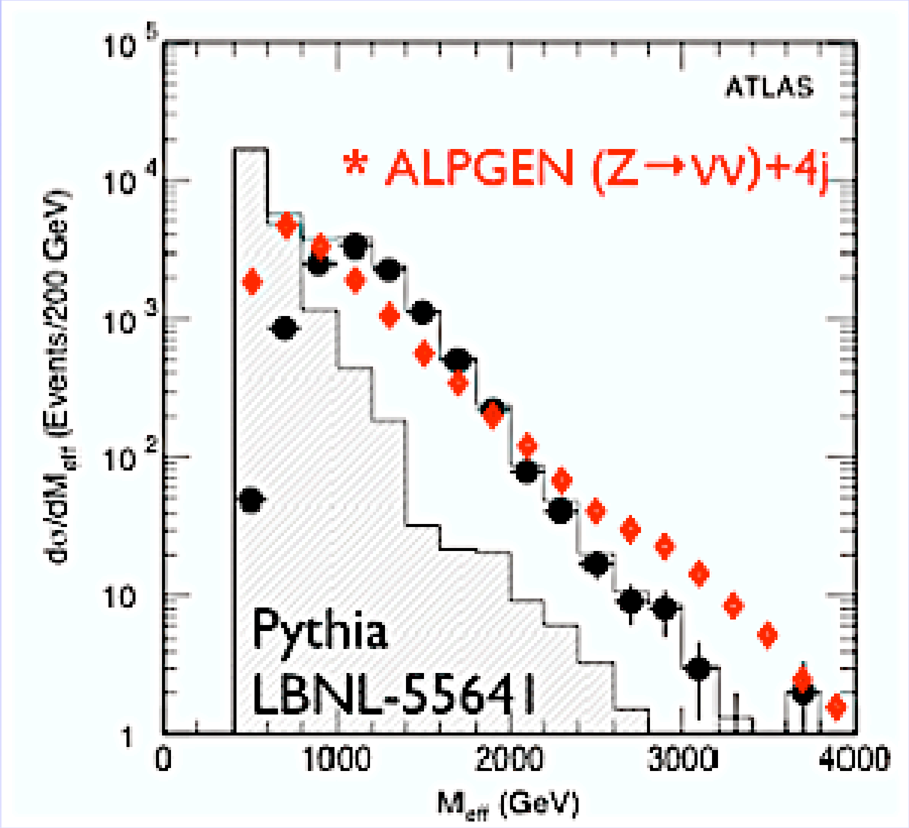

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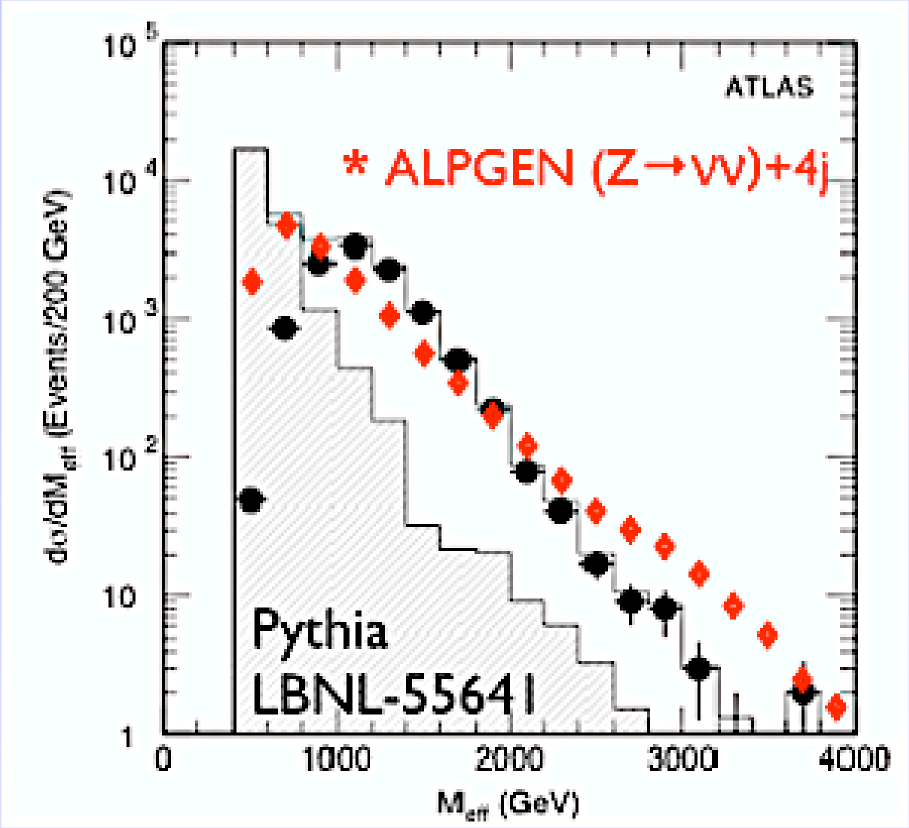

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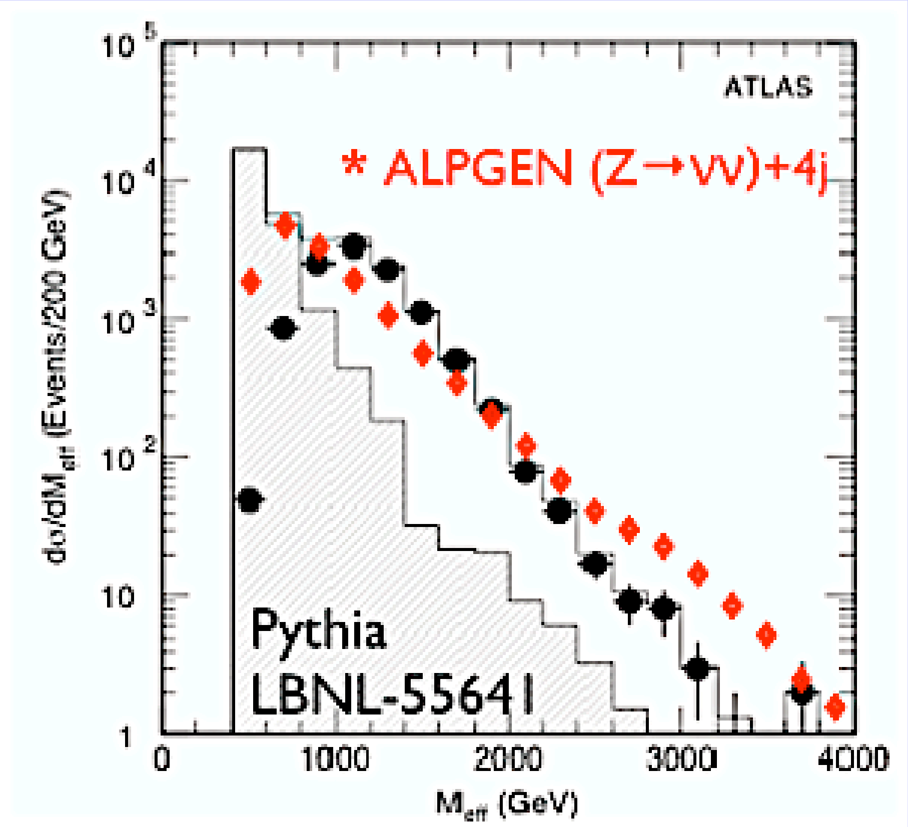

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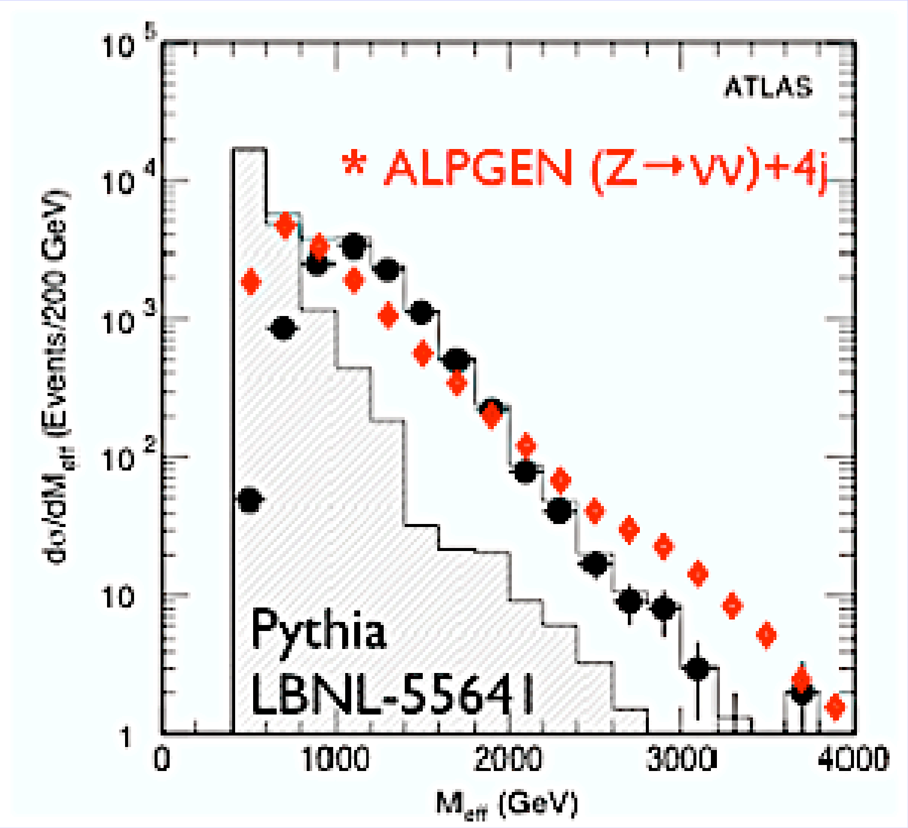

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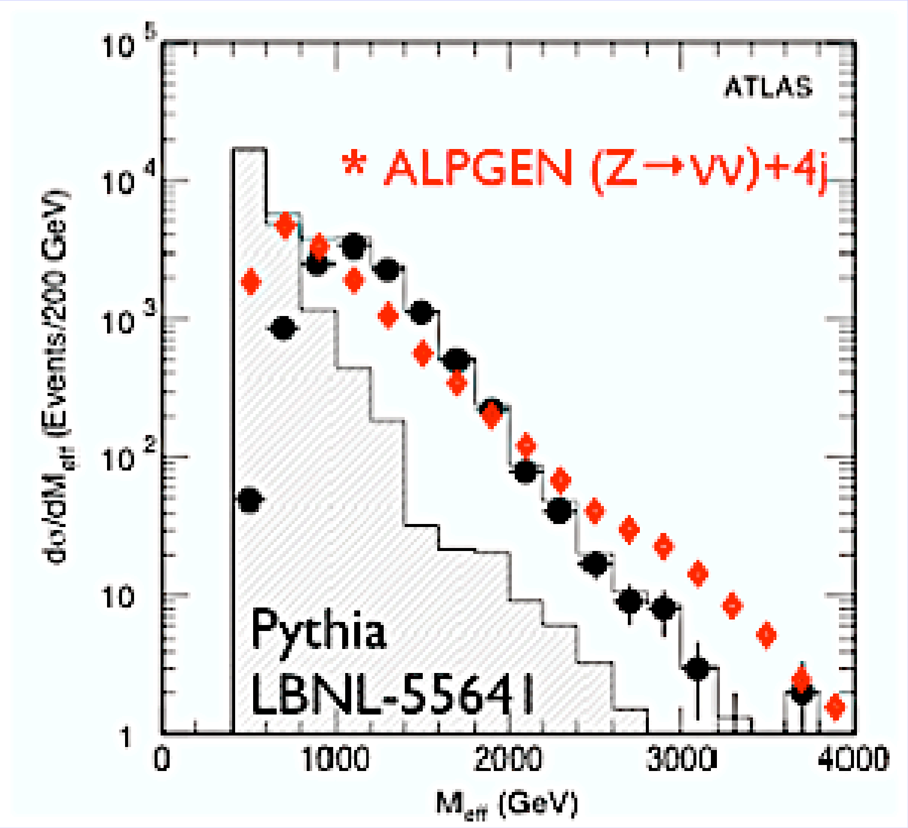

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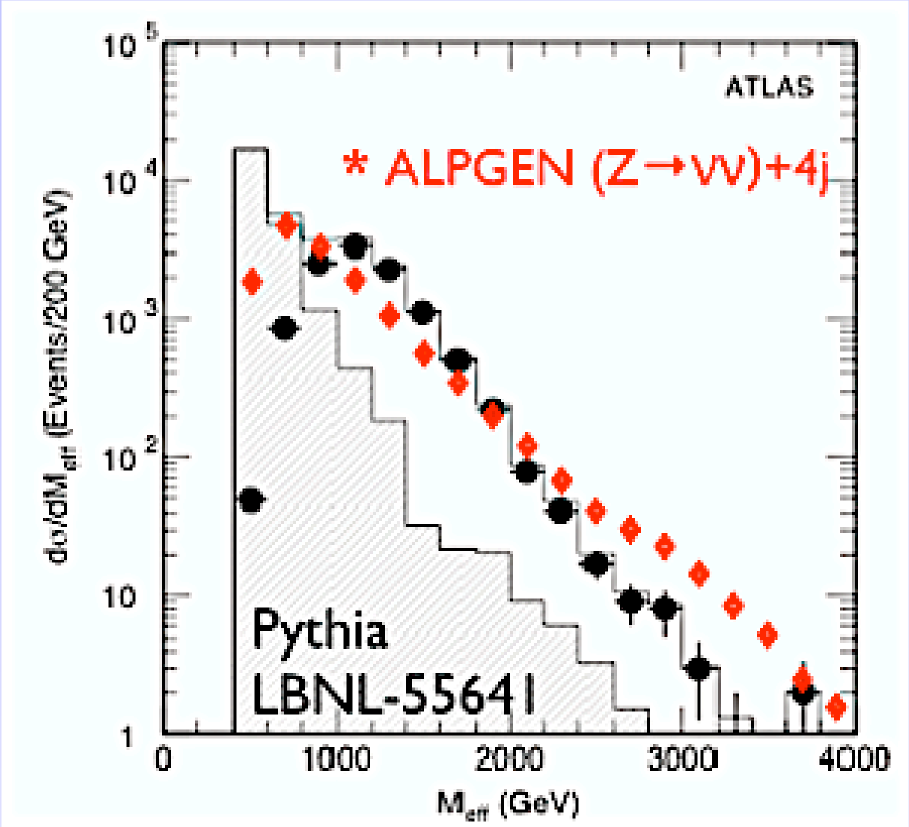

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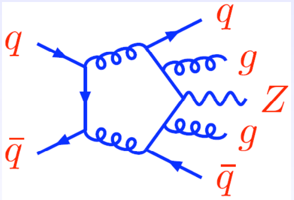
⇒ need Z+4 jets at NLO



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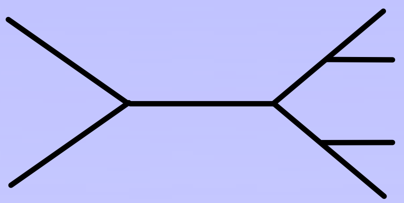

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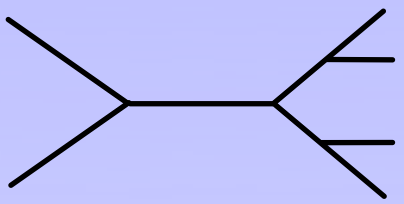
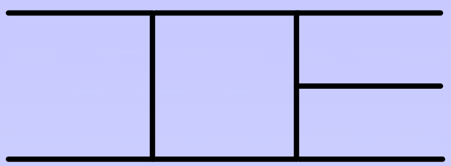


- virtual correction to N-leg process
  ➔ divergence from loop integration



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An N-particle NLO calculation requires:

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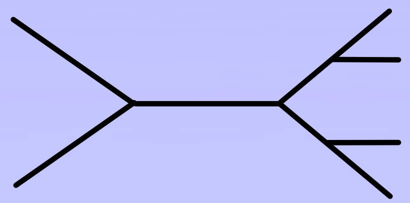
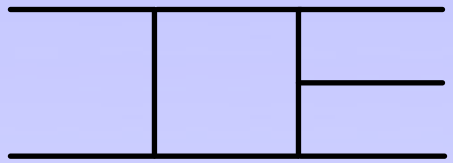
- virtual correction to N-leg process
  → divergence from loop integration
- set of subtraction terms





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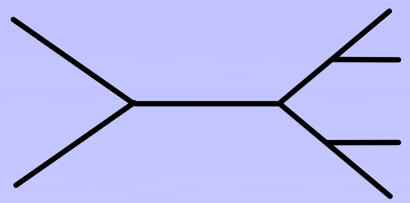
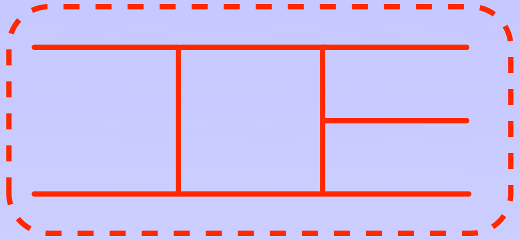
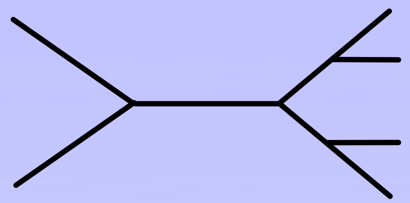




bottleneck

NLO: elements of the calculation & status

An N-particle NLO calculation requires:



- ☑ tree graph rates with N+1 partons
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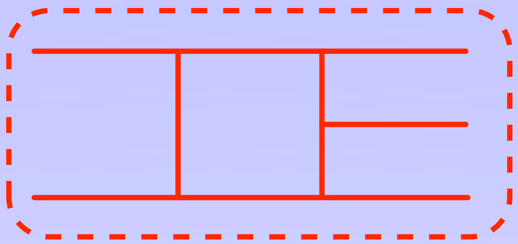

bottleneck

Status:

- ☑ 2⇒2: well established in SM and MSSM
- ☑ 2⇒3: some SM processes known, some missing
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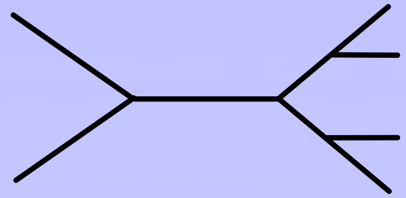

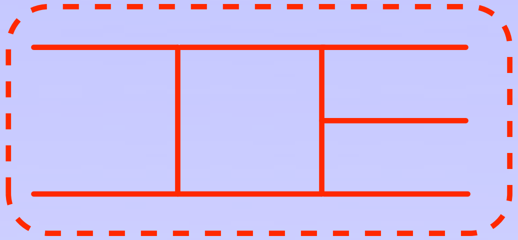

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Problem as most new-physics signatures involve high multiplicity final states ⇒ huge effort devoted to NLO multi-leg calculations

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Traditionally: Feynman diagrams, agonizing pain for each calculation.
NLO programs available at: http://www.cedar.ac.uk./hepcode

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‘Numerical unitarity formalism for evaluating one-loop amplitudes’
‘Full one-loop amplitudes from tree amplitudes’

[Ellis, Giele, Kunszt ’07; Giele, Kunszt, Melnikov ‘08]

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Final aim: $\sim$ ALPGEN at NLO (power-like algorithm). In 3-5 years?

NLO progress in '06-'07

- $qq \to qqVV$ (VBF, no decays) *[Bozzi, Jaeger, Oleari, Zeppenfeld '06]*
- $H \to 4f$ *[Bredenstein, Denner, Dittmaier, Uwer '06]*
- $gg \to HH(H)$ *[Binoth, Karg, Kauer, Rueckl '06]*
- $gg \to WW$ *[Binoth, Ciccolini, Kauer, Kramer '06]*
- $pp \to H + 2j$ via gg-fusion (no decay) *[Ellis, Campbell, Zanderighi '06]*
- $pp \to t\bar{t}j$ (no decays) *[Dittmaier, Uwer, Weinzierl '06]*
- $pp \to ZZZ$ (no decays) *[Lazopoulos, Petriello, Melnichov '07]*
- $pp \to H + 2j(VBF) \times pp \to H + 2j(ggf)$ *[Andersen, Binoth, Heinrich, Smillie '07]*
- $pp \to t\bar{t}Z$ (gluon induced part, no decay) *[Lazopoulos et al. '07]*
- $pp \to WWj$ *[Dittmaier, Kallweit, Uwer; Campbell, Ellis, Zanderighi '07]*
- $gg \to gggg$ (amplitude only) *[N:Campbell et al. '06; A: finished by Xiao et al.'06]*
- $\gamma\gamma \to \gamma\gamma\gamma\gamma$ (amplitude only) *[Nagy et al. '07, Binoth et al. '07, Ossola et al. '07]*
- various other multi-parton helicity amplitudes, 1 to 2, 2 to 2 in BSM *[....]*

Beyond NLO: NLO+PS

Combine best features:

Get correct rates (NLO) and hadron-level description of events (PS)
Difficult because need exact NLO subtraction and remove it from PS

Working (LHC) examples:

- MC@NLO: do NLO, add PS without MC NLO, negative weights, Herwig only (DY, Higgs, QQ, VV, H+V, single top)

  [Frixione&Webber '02 and later refs.]

- POWHEG: generate the hardest emission first at NLO, add then any parton shower, positive weights but truncated shower (ZZ, QQ)

  [Nason '04 and later refs.]

Other recent progress:

Shower with quantum inteference *[Nagy, Soper]*, SCET *[Bauer, Schwartz]*, Vincia (antenna factorization) *[Giele et al.]*, Dipole factorization *[Schumann]*

Beyond NLO: NNLO

Collider processes known at NNLO today:

(a) Higgs ➟ see talk by G. Bozzi

(b) Drell-Yan (Z,W) ➟ see talk by C. Carloni Calame

(c) 3-jets in e+e-

Motivation: error on α_s from jet-observables

$$\alpha_s(M_Z) = 0.121 \pm 0.001(\mathrm{exp.}) \pm 0.005(\mathrm{th.})$$

[Bethke '06]

➥ dominated by theoretical uncertainty

After several years, NNLO 3-jet calculation in e^+e^- completed in 2007

[Gehrmann, Gehrmann-DeRidder, Glover, Heinrich '07]

Method: developed antenna subtraction at NNLO

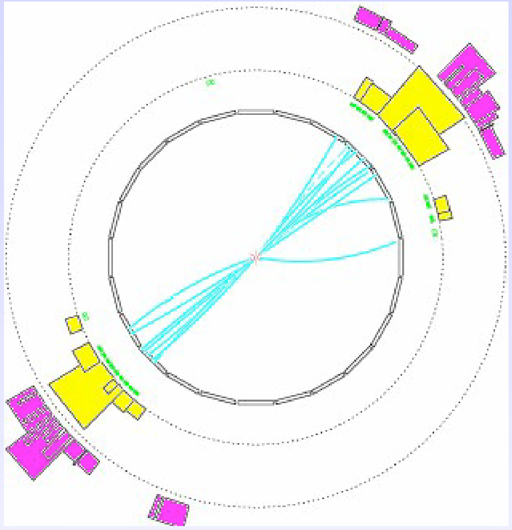
First application: NNLO fit of α_s from event-shapes

Event shapes

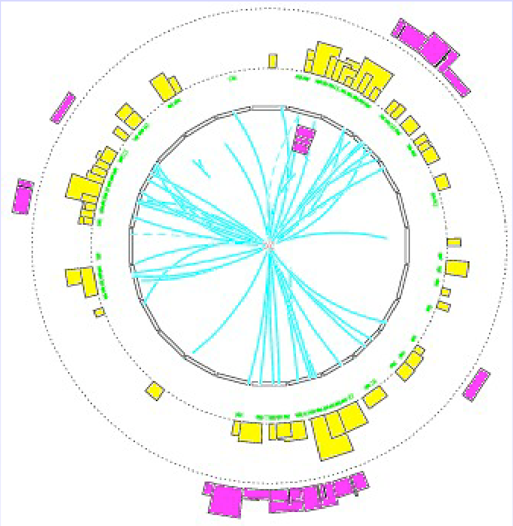
Event-shapes and jet-rates: infrared safe observables describing the energy and momentum flow of the final state.

Candle example in e^+e^-: The thrust $T = \max_{\vec{n}} \frac{\sum_i \vec{p}_i \cdot \vec{n}}{\sum_i |\vec{p}_i|}$

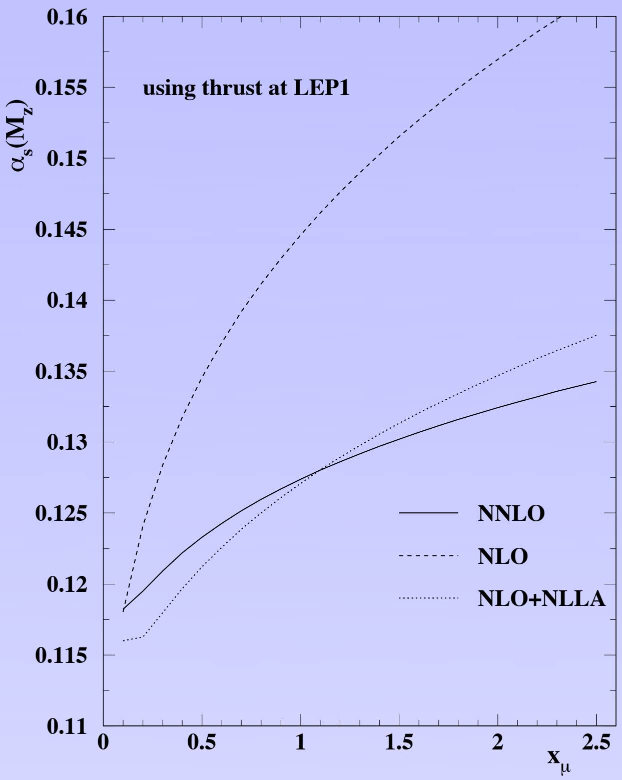
Pencil-like event: $1 - T \ll 1$



Planar event: $1 - T \sim 1$



α_s from NNLO event shapes



- scale variation reduced by a factor 2 at NNLO

[Dissertori et al. 0712.0327]

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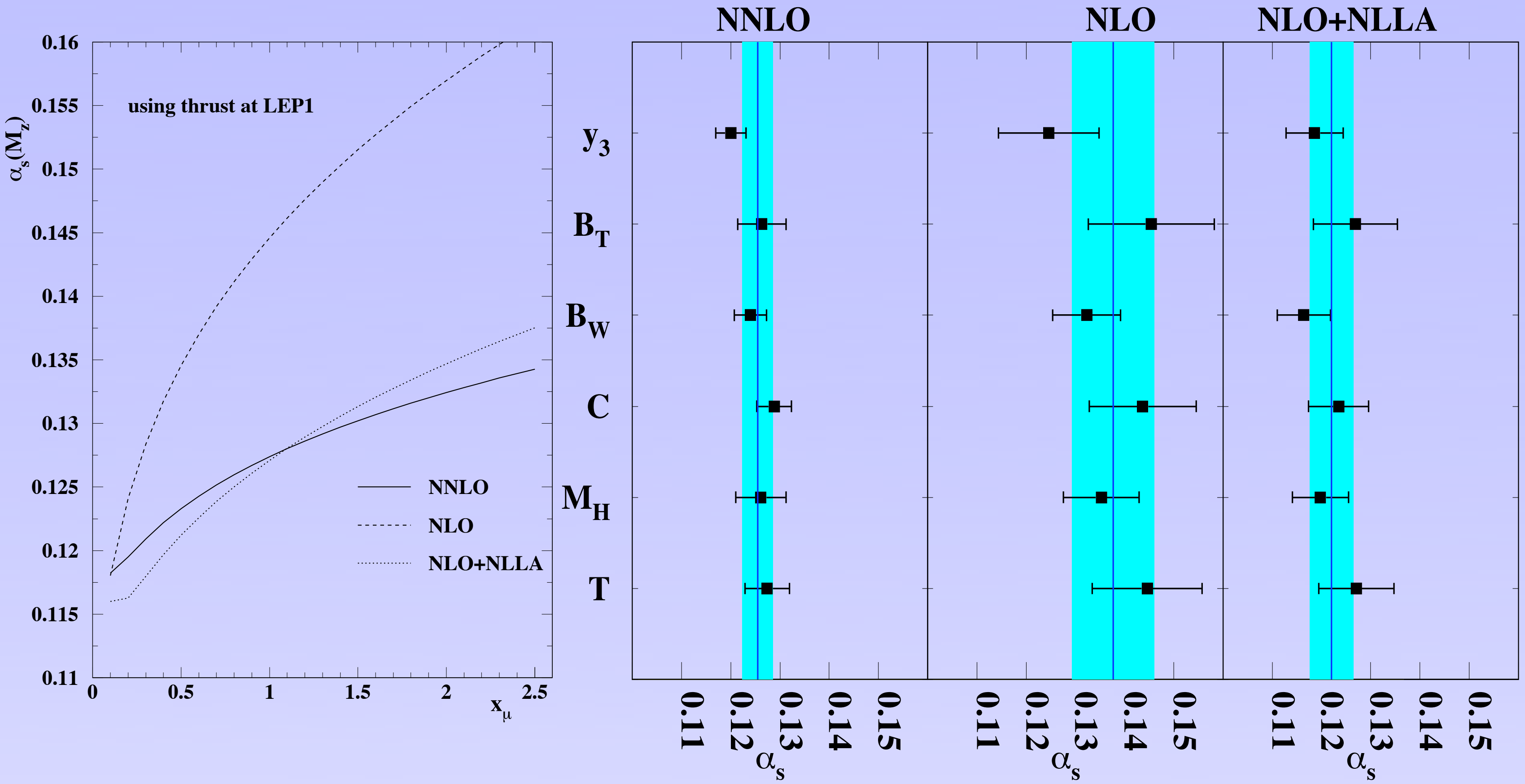

- scale variation reduced by a factor 2 at NNLO
- scatter between α_s from different event-shape reduced

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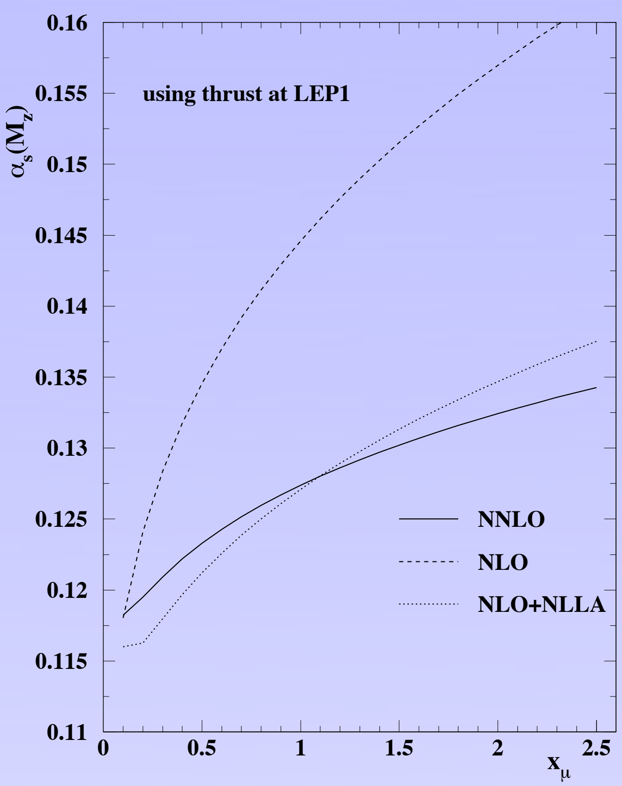

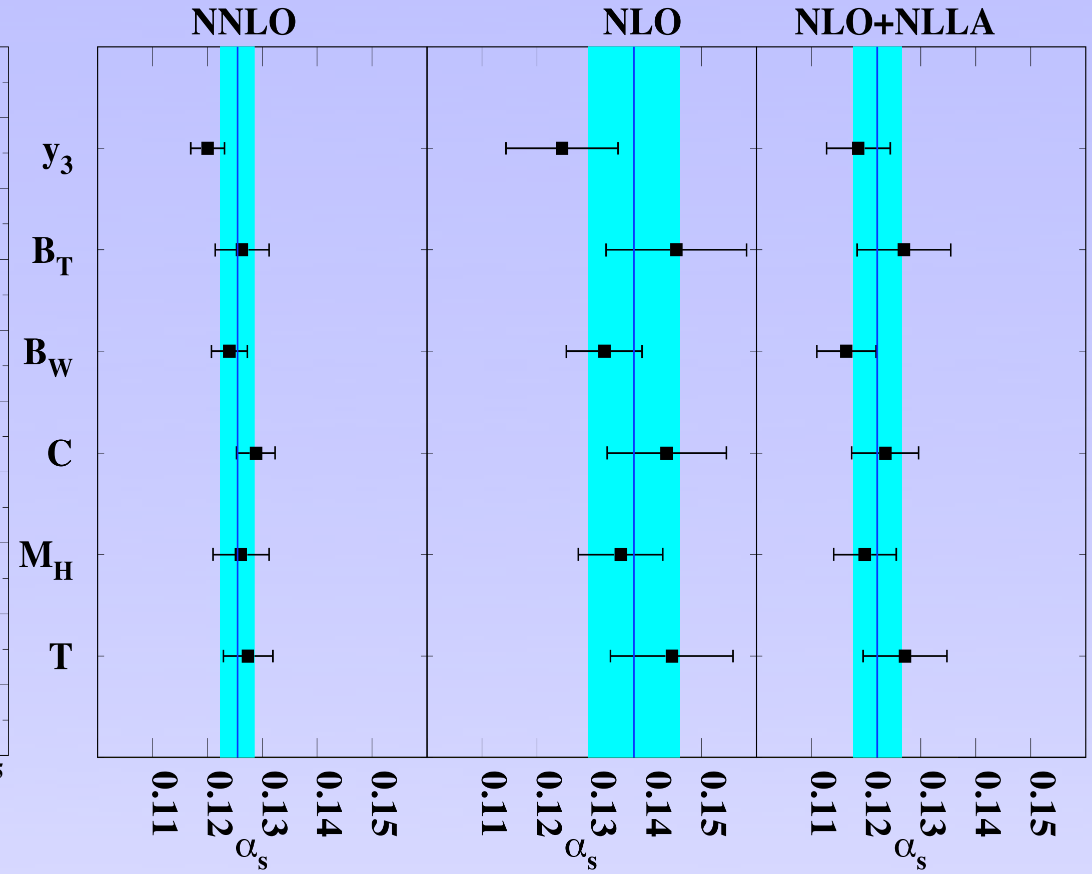

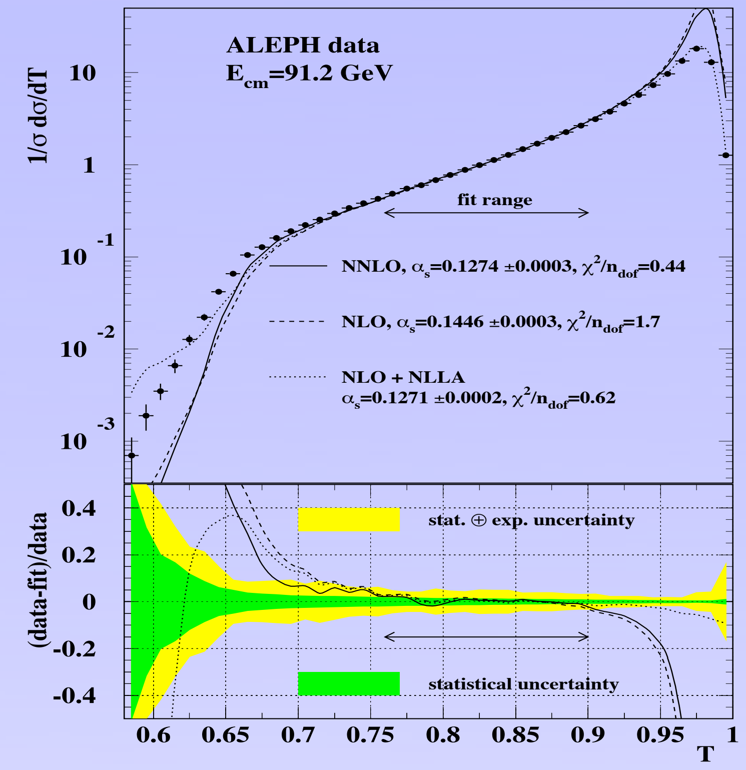

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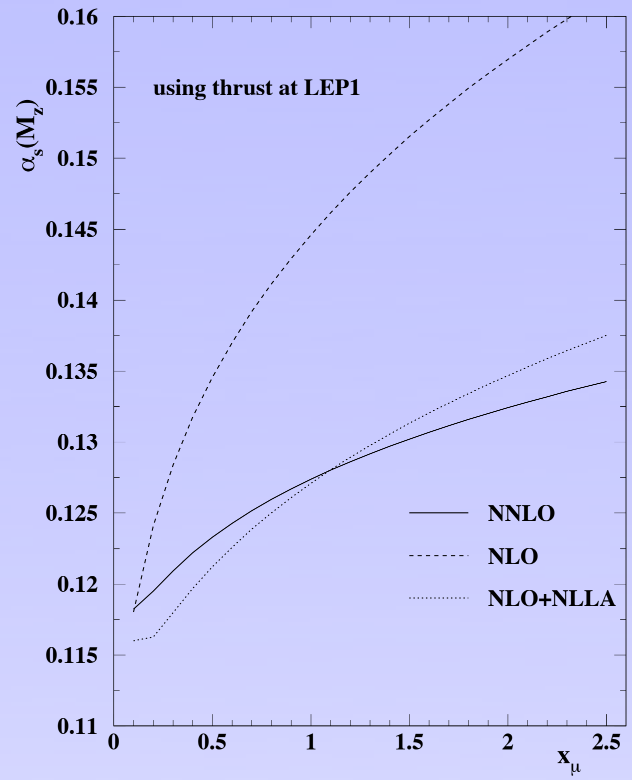

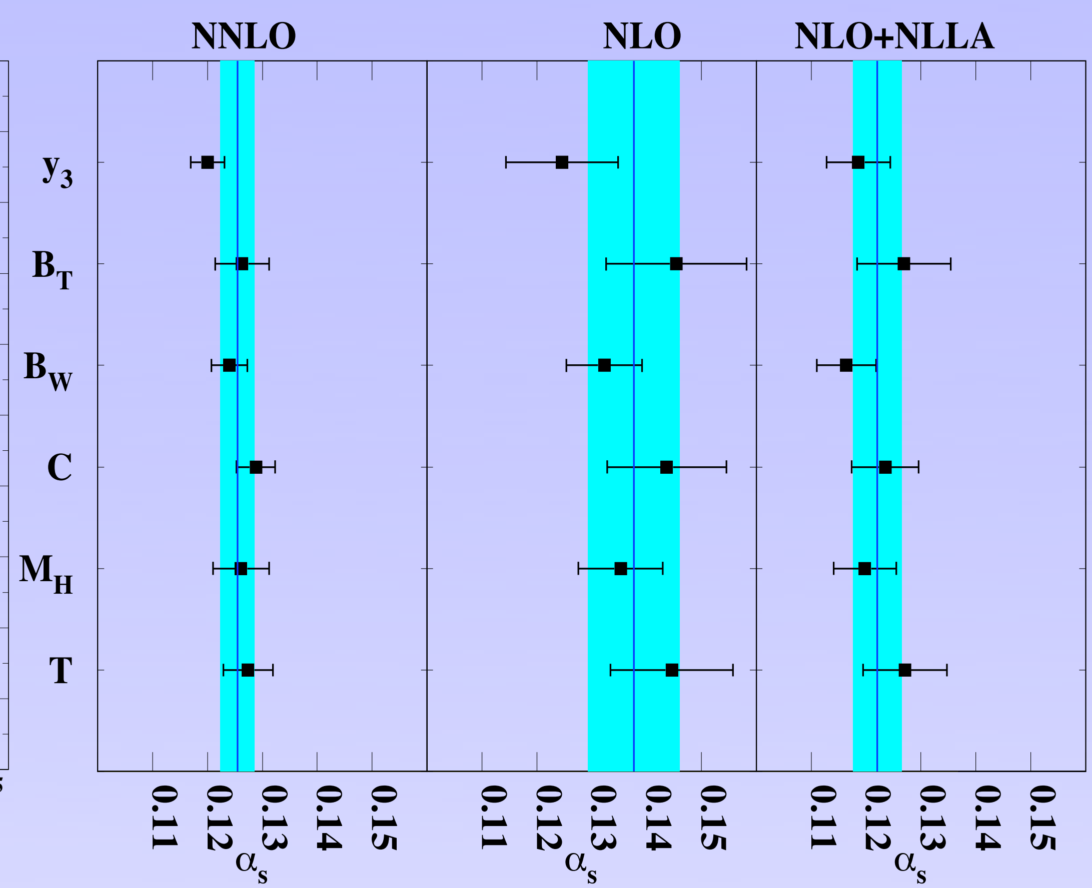

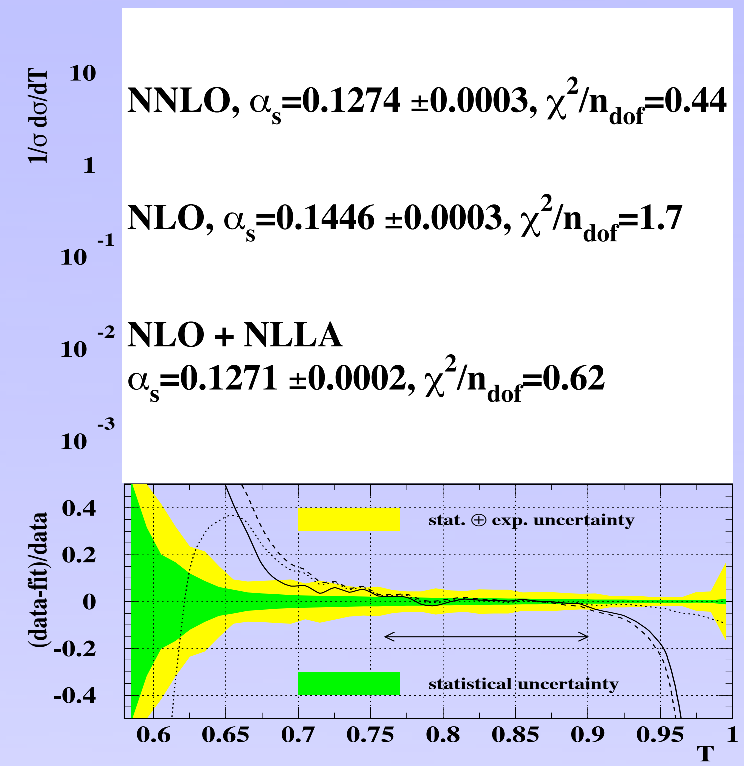

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$$\alpha_s(M_Z^2) = 0.1240 \ \pm\ 0.0008\,(\mathrm{stat}) \ \pm\ 0.0010\,(\mathrm{exp}) \ \pm\ 0.0011\,(\mathrm{had}) \ \pm\ 0.0029\,(\mathrm{theo})$$

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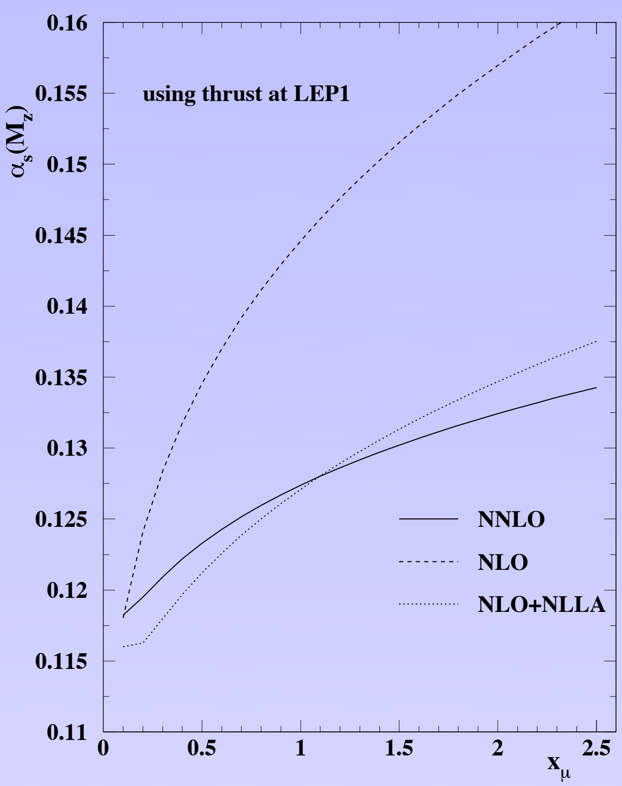

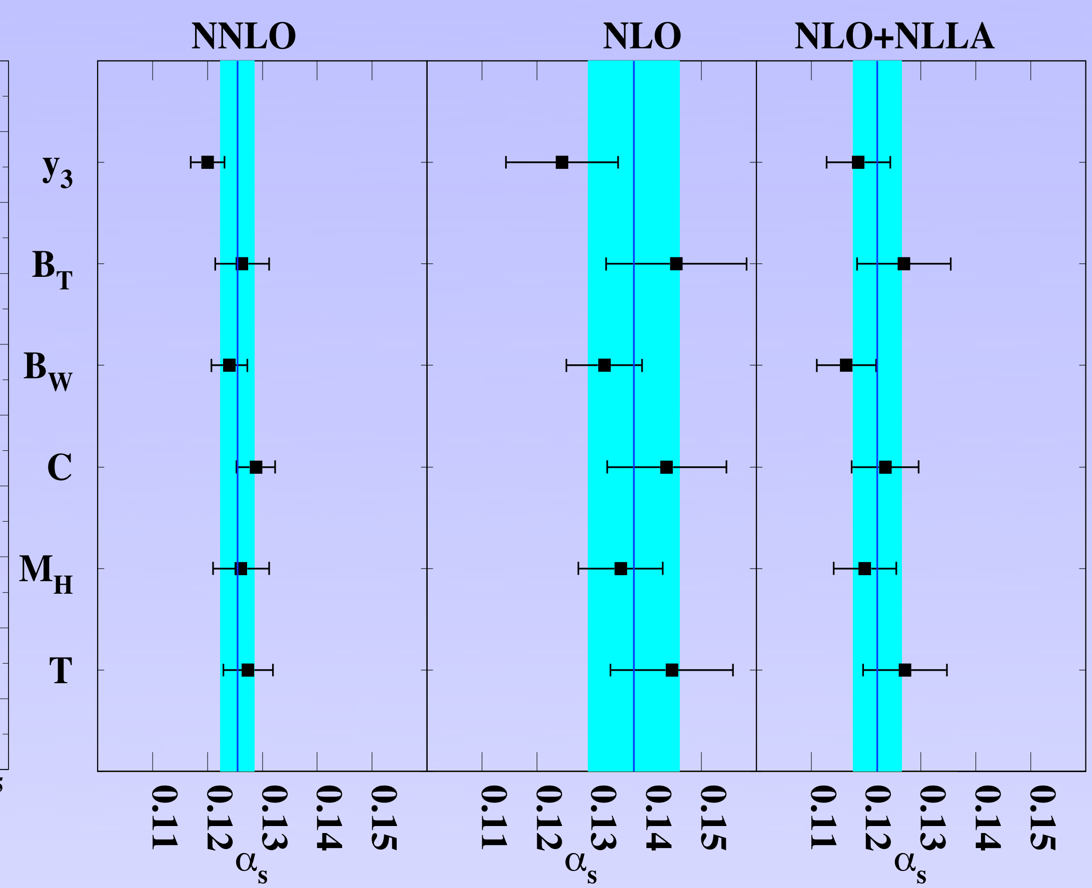

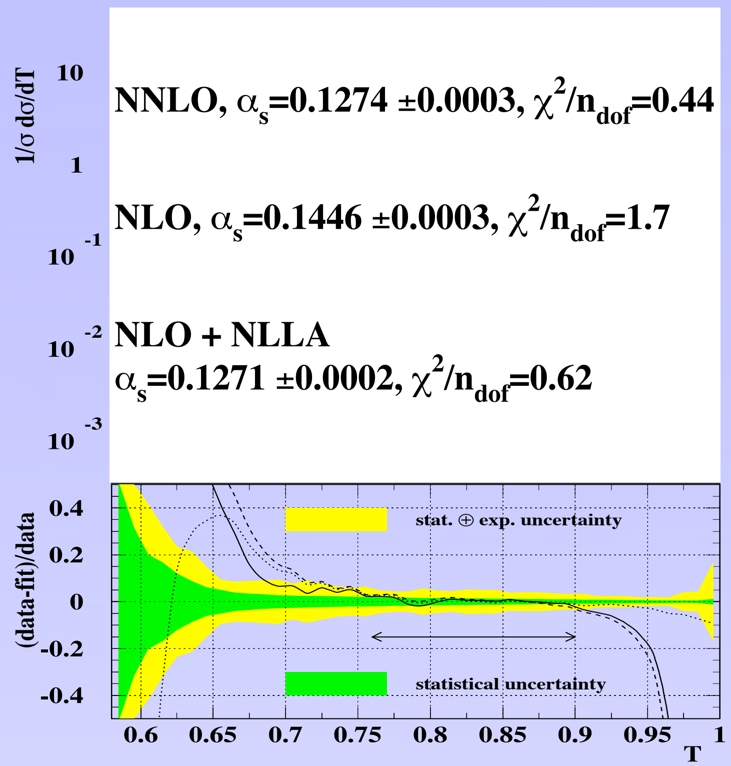

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➥ need NNLO + NLLA (in progress) [& EW ?]

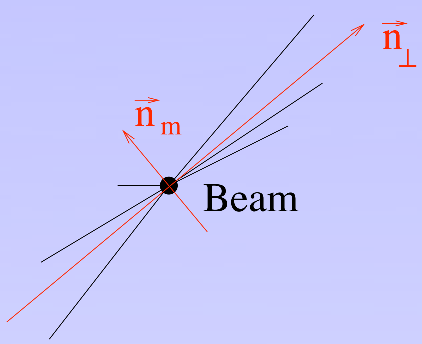
Event shapes at hadron colliders

So far event shapes largely neglected at hadron colliders because of difficulties associated to U.E.
Only (published) exceptions: measurement of the broadening by CDF in '91 and of a thrust by D0 in '02

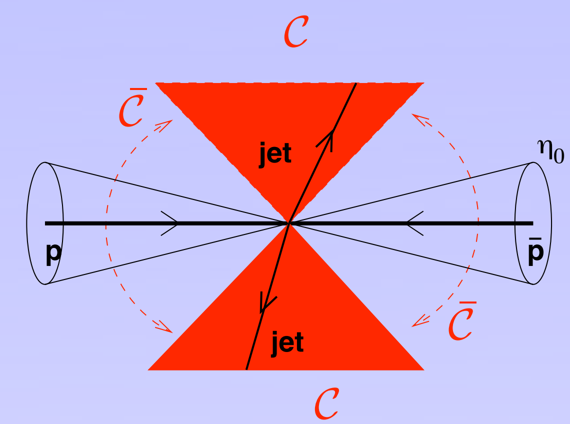
- ✗ U.E. and hadronization effects in shapes of distributions
  $\Rightarrow$ Monte-Carlo tuning
- ✗ event shapes distributions robust against jet-energy scale
  $\Rightarrow$ optimal for initial data analysis
- ✗ theoretically challenging but automated NLL resummation available for global event shapes (CAESAR)
- ✗ model independent New Physics searches: heavy states change shapes of distributions

Definition of event shapes at hadron colliders

Definition analogous to e+e- case, but use only transverse momenta, e.g. transverse thrust:



$$T_{\perp,\mathcal{R}} \equiv \max_{\vec{n}} \frac{\sum_{i\in\mathcal{R}} \vec{p}_{\perp,i}\cdot\vec{n}}{\sum_{i\in\mathcal{R}} |\vec{p}_{\perp,i}|}$$



Global: measure all particles, can be resummed automatically, but forward region experimentally inaccessible

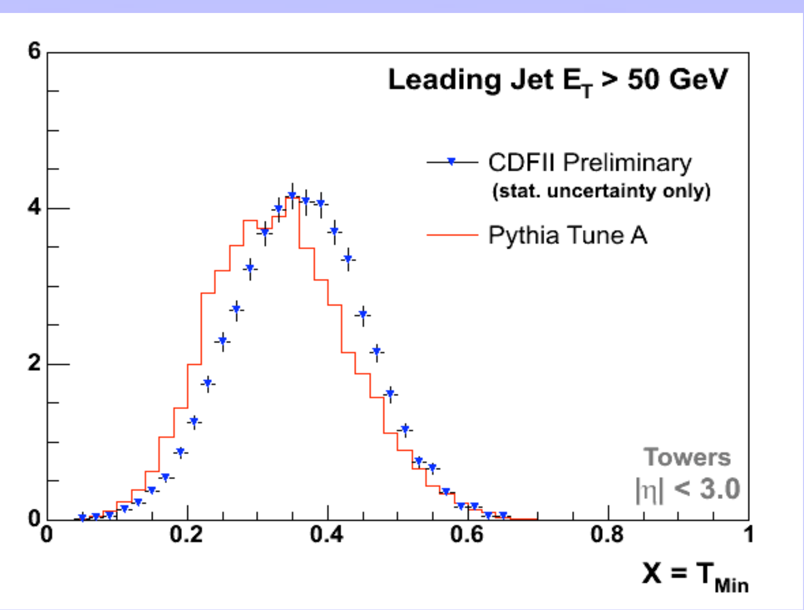
Non-global: $\mathcal{R} = \mathcal{C}$ sensitive only to subset (central) of the particles, but theoretically not so well understood

$\Rightarrow$ use tricks to make event-shapes global, e.g. exploit recoil effects, or add term exponentially suppressed at large rapidities

[Banfi et al. '04]

Ongoing activity

- Tevatron (CDF): first measurements
  MC shifted wrt data?



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  - ev. shapes robust under jet-energy scaling and jet energy resolution on generator level
  - complementary properties of different ev. shapes
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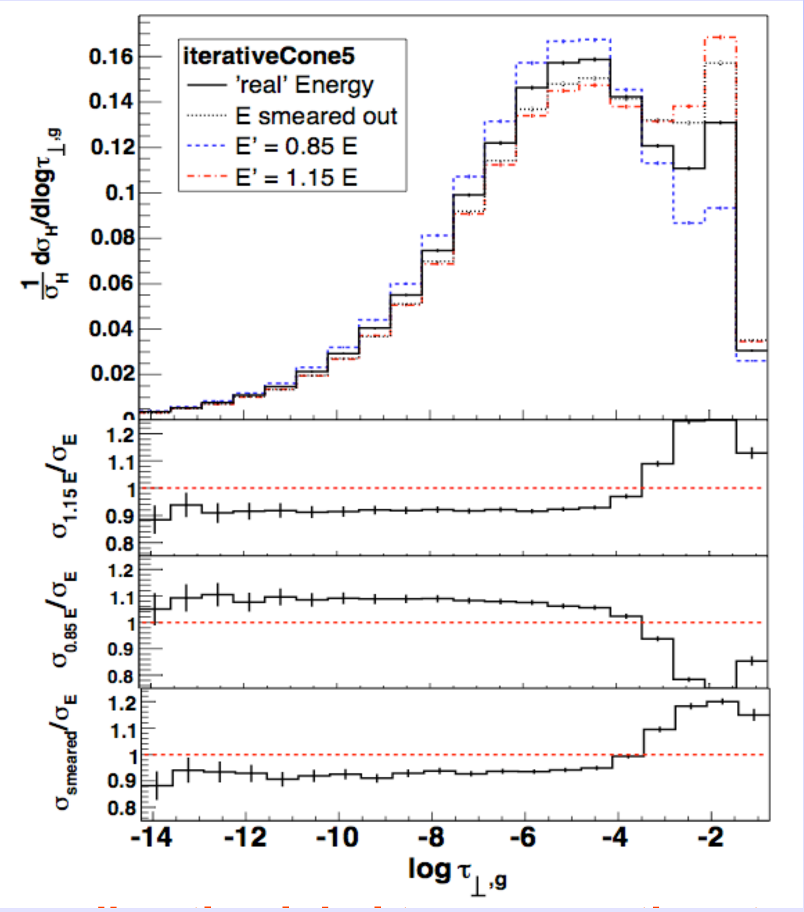

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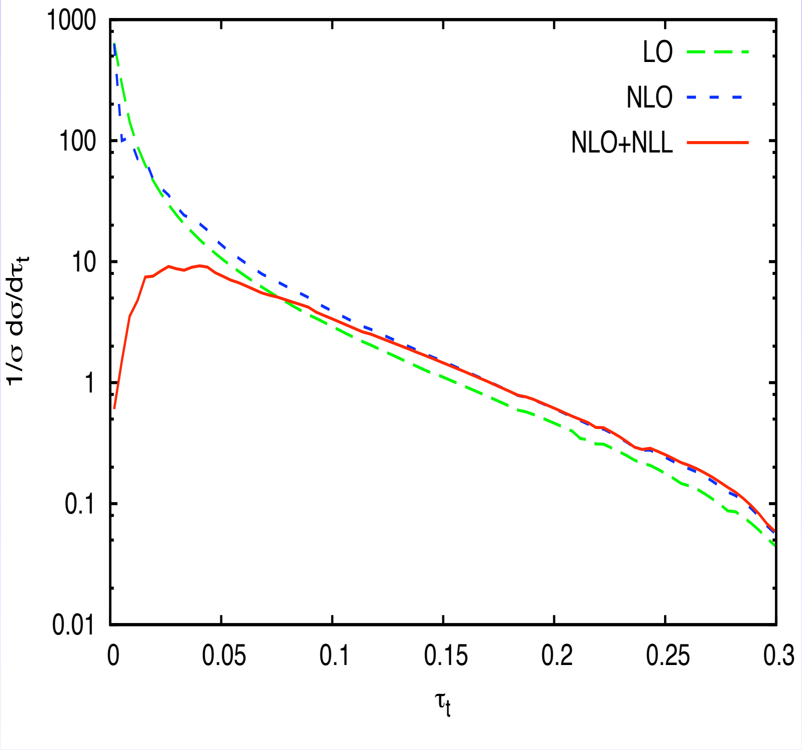
- <u>Theory:</u> NLL resummation with NLO matching for several event-shapes in progress



Backup slides

Iterative cone algorithms (Snowmass implementation)

1. A particle i at rapidity and azimuthal angle (y_i, ϕ_i) ⊂ cone C iff

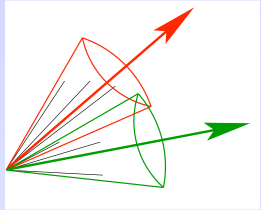
$$\sqrt{(y_i - y_C)^2 + (\phi_i - \phi_C)^2} \leq R_{\text{cone}}$$

2. Define

$$\bar{y}_C \equiv \frac{\sum_{i\in C} y_i \cdot p_{T,i}}{\sum_{i\in C} p_{T,i}} \qquad \bar{\phi}_C \equiv \frac{\sum_{i\in C} \phi_i \cdot p_{T,i}}{\sum_{i\in C} p_{T,i}}$$

3. If weighted and geometrical averages coincide $(y_C, \phi_C) = (\bar{y}_C, \bar{\phi}_C)$ a stable cone (⇒ jet) is found, otherwise set $(y_C, \phi_C) = (\bar{y}_C, \bar{\phi}_C)$ & iterate

4. Split-merge on overlapping jets (2nd par: overlap parameter f)



Ideally: place trial cones everywhere and find all stable cones

Practically (JetClu, MidPoint, PxCone..): introduce trial directions (seeds)

Seeds make cone algorithms infrared unsafe

Longitudinally invariant inclusive kt algorithm

[Catani et. al '92-'93, Ellis&Soper '93]

1. For any pair of final state particles i,j define the distance

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

2. For each particle i define a distance with respect to the beam

$$d_{iB} = k_{ti}^2$$

3. Find the smallest distance. If it is a d_{ij} recombine i and j into a new particle (⇒ recombintion scheme); if it is d_{iB} declare i to be a jet and remove it from the list of particles

4. repeat the procedure until no particles are left

Exclusive version: stop when all d_{ij}, $d_{iB} > d_{cut}$ or when reaching n-jets

Aachen/Cambridge: same with $d_{ij} = (\Delta_{ij}^2 + \Delta\phi_{ij}^2)/R^2$ and $d_{iB} = 1$

[Dotshitzer et. al '97, Wobisch &Wengler '99]