Plan for 4^{th} lecture

This lecture will focus on

- parton showers and Monte Carlo methods
- matching parton showers and fixed order calculations
- jets

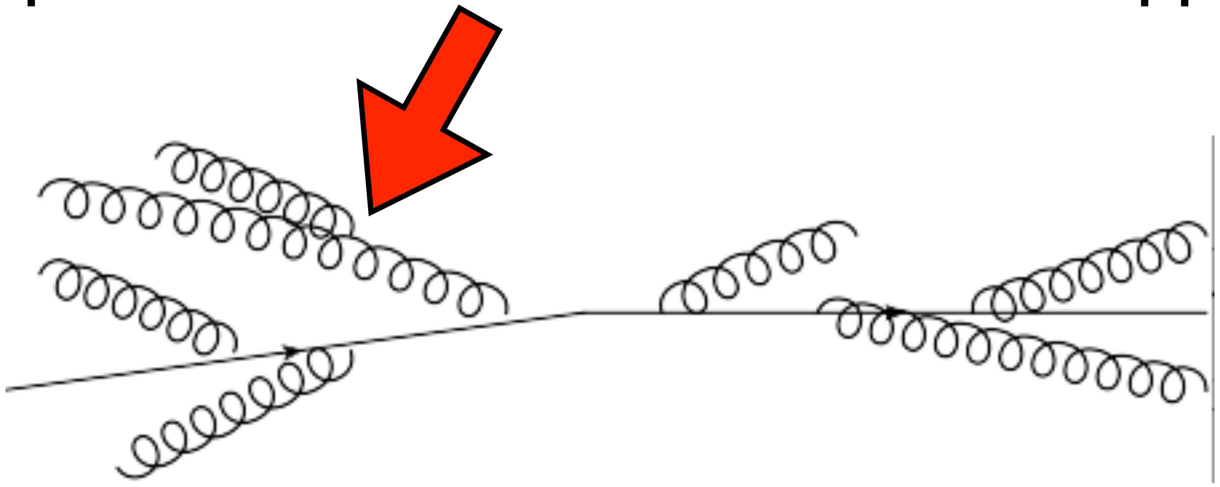
Parton shower & Monte Carlo methods

- today at the frontier of NLO calculations are processes with 4 or 5 particles in the final state. Difficult to expect much more in the coming years. However, typical LHC processes have much larger multiplicity
- we have also seen that large logarithms can spoil the convergence of PT, NLO results become unreliable
- now we adopt a different approach: we seek for an approximate result such that soft and collinear enhanced terms are taken into account to all orders
- this will lead to a 'parton shower' picture, which can be implemented in computer simulations, usually called Monte Carlo programs or event generators

Monte Carlos enter any experimental study at current colliders

Parton shower & Monte Carlo methods

- rather than aiming at an exact, fixed order result, parton showers describe multiple radiation in the soft-collinear approximation



- they are based on a probabilistic picture

- the probability for emitting a gluon above k_t can be computed in perturbation theory

- however want to shower to emit also from previously emitted gluons

Parton shower & Monte Carlo methods

- the probability for emitting a gluon above k_t is given by

$$P(\text{emission above } k_t) \sim \frac{2\alpha_s C_F}{\pi} \int \frac{dE}{E} \int \frac{d\theta}{\theta} \Theta(E\theta - k_t)$$

NB: based on soft-collinear approximation

- useful to look at the probability of not emitting a gluon

$$P(\text{no emission above } k_t) \sim 1 - \frac{2\alpha_s C_F}{\pi} \int \frac{dE}{E} \int \frac{d\theta}{\theta} \Theta(E\theta - k_t)$$

- the probability of nothing happening to all orders is the exponential of the first order result -- this is called Sudakov form factor

$$\Delta(k_t, Q) \sim exp\left\{ -\frac{2\alpha_s C_F}{\pi} \int \frac{dE}{E} \int \frac{d\theta}{\theta} \Theta(E\theta - k_t) \right\}$$

Done properly: α_s in the integration and use full splitting function

First branching

Then the probability for emitting a gluon satisfies $\frac{dP}{dk_{t1}} = \frac{d\Delta(k_{t1}, Q)}{dk_{t1}}$

1. generate the emission by generating a flat random number r_1 and solving $r_1 = \Delta(k_{t1},Q)$

2. Generate momentum fraction $z = x_2/x_1$ with $\text{Prob.} \sim \frac{\alpha_s}{2\pi} P(z)$

$$\int_{\epsilon}^{x_2/x_1} dz \frac{\alpha_s}{2\pi} P(z) = r' \int_{\epsilon}^{1-\epsilon} dz \frac{\alpha_s}{2\pi} P(z)$$

ε: IR cut-off for resolvable branching

3. Azimuthal angles: generated uniformly in $(0,2\pi)$ (or taking into account polarization correlations)

Multiple branchings

- once a gluon is emitted work out a Sudakov from a qqg system
- solve the equation for radiating a second gluon with $k_{t2} < k_{t1}$ from the qqg system using solving $r_2 = \Delta(k_{t2}, k_{t1})$
- iterate till $k_{t,n+1} < Q_0$ where Q_0 is a cut-off of the Monte Carlo
- the emissions $k_1 \ldots k_n$ are the parton-shower event
- in this example k_t is called ordering variable. Parton showers use angle, virtuality or transverse momentum as ordering variable

Angular ordering

When a soft gluon is radiated from a ($p_i p_j$) dipole one gets a universal eikonal factor

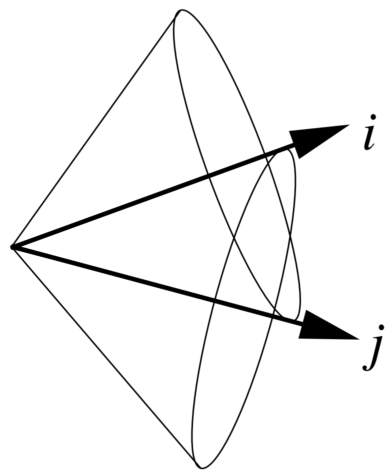
$$\omega_{ij} = \frac{p_i p_j}{p_i k \, p_j k} = \frac{1 - v_i v_j \cos\theta_{ij}}{\omega_k^2 (1 - v_i \cos\theta_{ik})(1 - v_j \cos\theta_{jk})}$$

Massless emitting lines $v_i = v_j = 1$, then

$$\omega_{ij} = \omega_{ij}^{[i]} + \omega_{ij}^{[j]} \qquad \omega_{ij}^{[i]} = \frac{1}{2}\left(\omega_{ij} + \frac{1}{1-\cos\theta_{ik}} - \frac{1}{1-\cos\theta_{jk}}\right)$$

Angular ordering

$$\int_0^{2\pi} \frac{d\phi}{2\pi} \omega_{ij}^{[i]} = \begin{cases} \frac{1}{\omega_k^2 (1-\cos\theta_{ik})} & \theta_{ik} < \theta_{ij} \\ 0 & \theta_{ik} > \theta_{ij} \end{cases}$$



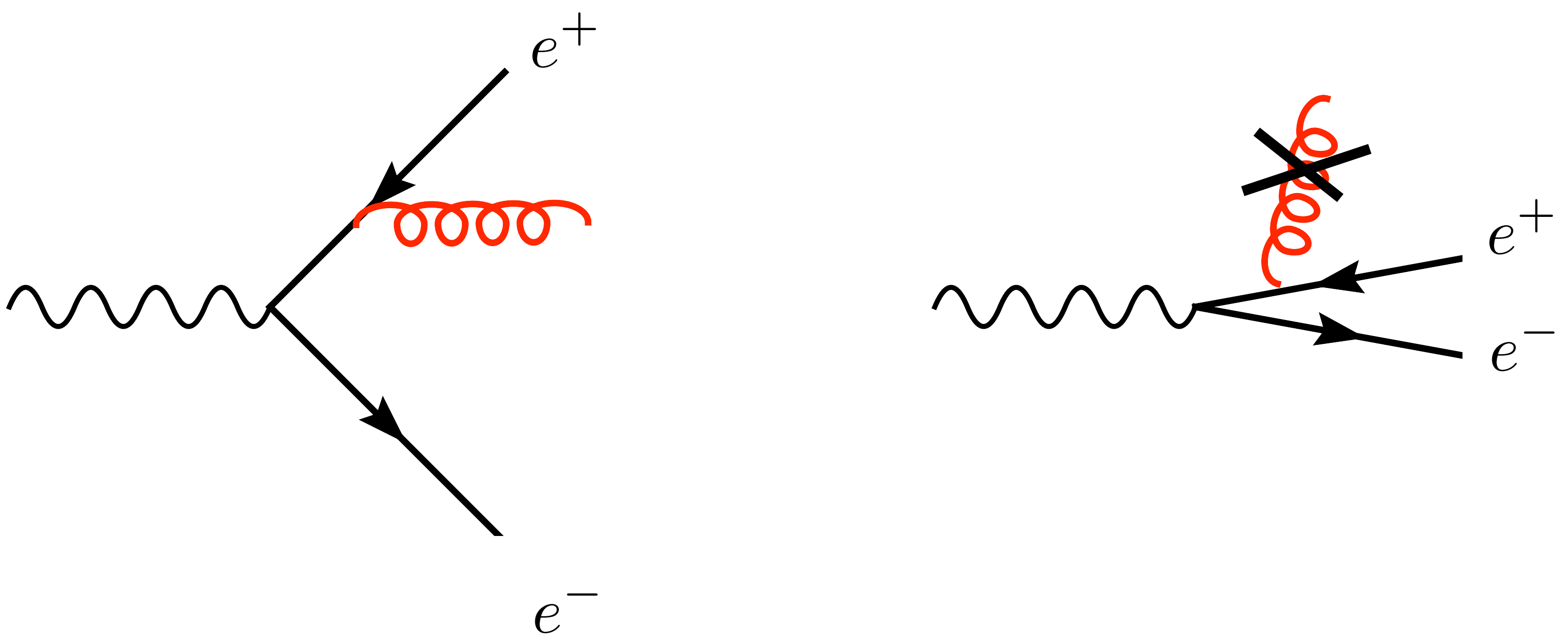
Proof: see e.g. QCD and collider physics, Ellis, Stirling, Webber

Angular ordering & coherence

A. O. is a manifestation of coherence of radiation in gauge theories

<u>In QED</u>

suppression of soft bremsstrahlung from an e+e- pair (Chudakov effect)
At large angles the e^+e^- pair is seen coherently as a system without total charge ⇒ radiation is suppressed



Herwig use the angle as an evolution variable, therefore has coherence built in. Other PS force angular ordering in the evolution.

An example with Herwig

Select the initial state, e.g. pp collisiosn at 14 TeV

---INITIAL STATE---

IHEP	ID	IDPDG	IST	MO1	MO2	DA1	DA2	P-X	P-Y	P-Z	ENERGY	MASS
1	P	2212	101	0	0	0	0	0.00	0.00	7000.0	7000.0	0.94
2	P	2212	102	0	0	0	0	0.00	0.00	-7000.0	7000.0	0.94
3	CMF	0	103	1	2	0	0	0.00	0.00	0.0	14000.0	14000.0

An example with Herwig

Select the hard process of interest, e.g. Z+ jet production

---HARD SUBPROCESS---

IHEP	ID	IDPDG	IST	MO1	MO2	DA1	DA2	P-X	P-Y	P-Z	ENERGY	MASS
4	UQRK	2	121	6	8	9	5	0.00	0.00	590.8	590.8	0.32
5	GLUON	21	122	6	4	17	8	0.00	0.00	-232.1	232.1	0.75
6	HARD	0	120	4	5	7	8	0.40	-9.40	358.7	823.0	740.63
7	Z0/GAMA*	23	123	6	7	22	7	-261.59	-217.31	329.3	481.6	88.56
8	UQRK	2	124	6	5	23	4	261.59	217.31	29.4	341.3	0.32

An example with Herwig

Then Herwig dresses the process for you, both with initial state and final state shower

---PARTON SHOWERS---

IHEP	ID	IDPDG	IST	MO1	MO2	DA1	DA2	P-X	P-Y	P-Z	ENERGY	MASS
9	UQRK	94	141	4	6	11	16	2.64	-9.83	592.2	590.2	-49.07
10	CONE	0	100	4	5	0	0	-0.27	0.96	0.1	1.0	0.00
11	GLUON	21	2	9	12	32	33	-1.02	3.59	5.6	6.7	0.75-
12	GLUON	21	2	9	13	34	35	0.25	1.46	3.6	4.0	0.75-
13	GLUON	21	2	9	14	36	37	-0.87	1.62	4.7	5.1	0.75-
14	GLUON	21	2	9	15	38	39	-0.81	4.17	3611.7	3611.7	0.75-
15	GLUON	21	2	9	16	40	41	-0.19	-1.01	1727.7	1727.7	0.75-
16	UD	2101	2	9	25	42	41	0.00	0.00	1054.6	1054.6	0.32-
17	GLUON	94	142	5	6	19	21	-2.23	0.44	-233.5	232.8	-18.36
18	CONE	0	100	5	8	0	0	0.77	0.64	0.2	1.0	0.00
19	GLUON	21	2	17	20	43	44	1.60	0.58	-2.1	2.8	0.75
20	UD	2101	2	17	21	45	44	0.00	0.00	-2687.6	2687.6	0.32
21	UQRK	2	2	17	32	46	45	0.63	-1.02	-4076.9	4076.9	0.32
22	Z0/GAMA*	23	195	7	22	251	252	-257.66	-219.68	324.8	477.5	88.56
23	UQRK	94	144	8	6	25	31	258.06	210.29	33.9	345.5	86.10
24	CONE	0	100	8	5	0	0	0.21	0.17	-1.0	1.0	0.00
25	UQRK	2	2	23	26	47	42	26.82	24.33	23.7	43.3	0.32
26	GLUON	21	2	23	27	48	49	8.50	8.18	6.0	13.3	0.75
27	GLUON	21	2	23	28	50	51	73.27	61.24	12.0	96.2	0.75
28	GLUON	21	2	23	29	52	53	73.66	58.54	-6.3	94.3	0.75
29	GLUON	21	2	23	30	54	55	67.58	52.13	-7.3	85.7	0.75
30	GLUON	21	2	23	31	56	57	6.98	4.60	2.3	8.7	0.75
31	GLUON	21	2	23	43	58	59	1.24	1.26	3.6	4.1	0.75

Add hadronization + U.E. then perform your desired physics study

Available Monte Carlos

Standard Monte Carlo:

[Ariadne, Pythia, Herwig, Isajet ...]

- hard ($2 \rightarrow 2$) scattering
- parton shower
- hadronization model + underlying event model [we will not discuss this]

❖ Different Monte Carlos differ in the ordering variable of the shower (e.g. angle Herwig, transverse momentum Ariadne and Pythia (new), virtuality Pythia (old)), in U.E. model, in the hadronization model

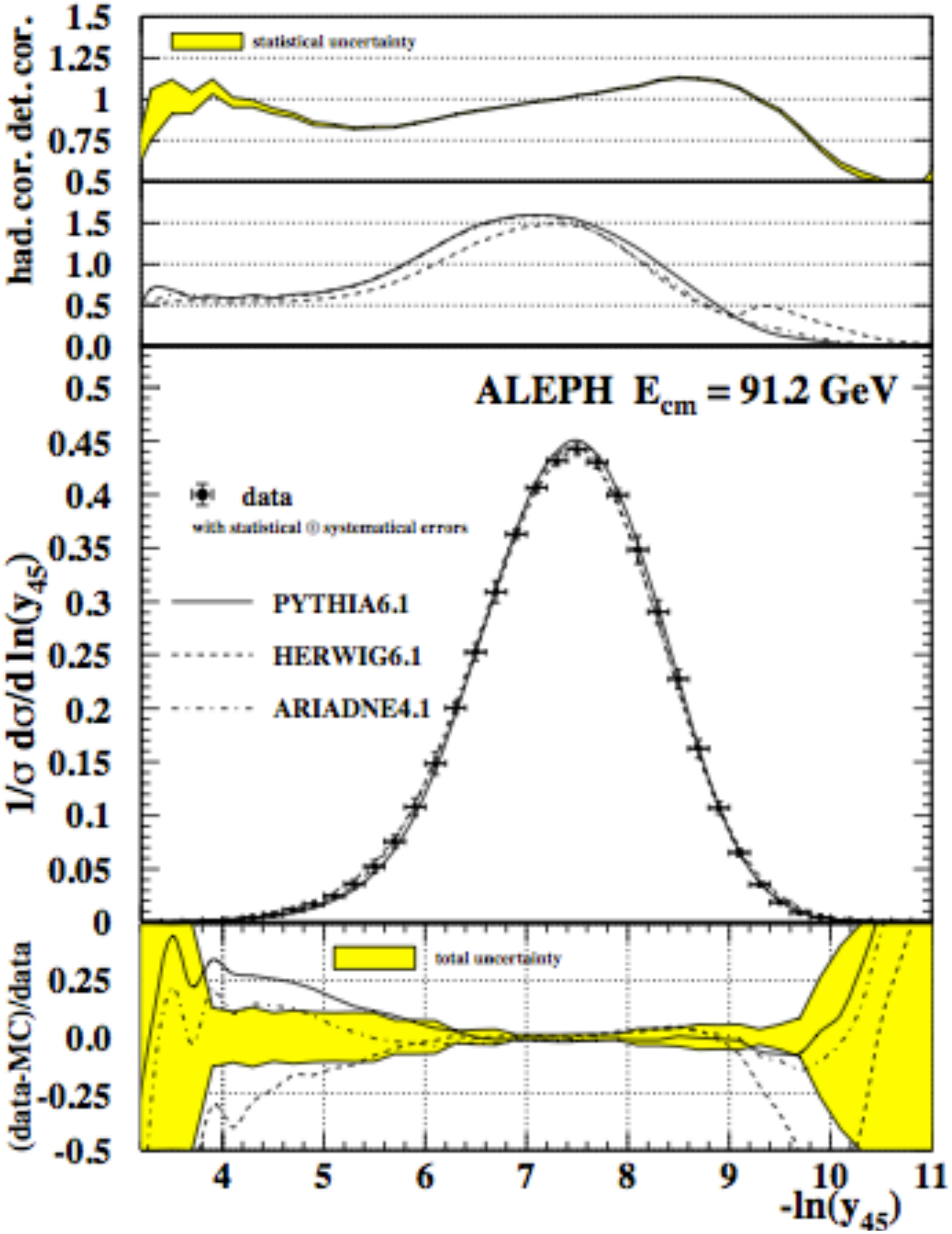
❖ Comparison between different MC is often the only way to estimate uncertainties

All fail to describe high multiplicity final states

Monte Carlos vs data

Example:
five-jet resolution parameter y_{45}

- Agreement over 3 orders of magnitudes for a variable that describes a multi-jet final state
- Surprising since MCs rely on the soft-collinear approximation + a model for hadronization
- Note however that MCs have been tuned to LEP data



Accuracy of Monte Carlos

Formally, Monte Carlos are Leading Logarithmic (LL) showers

- because they don't include any higher order corrections to the $1\to2$ splitting
- because they don't have any $1\to3$ splittings
- ....

However, they fare better than analytic Leading Log calculations, because

- they have energy conservation (NLO effect) implemented
- they have coherence
- they have optimized choices for the coupling
- they provide an exclusive description of the final state

So, despite not guaranteeing NLL accuracy, they fare better than LL analytic calculations

The real issue is that we are not able to estimate the uncertainty

NLO + parton shower

Combine best features:

Get correct rates (NLO) and hadron-level description of events (PS)
Difficult because need to avoid double counting

Two working examples:

- MC@NLO
  Frixione&Webber '02 and later refs.
- POWHEG (POWHEG-BOX)
  Nason '04 and later refs.

Processes implemented:

- W/Z boson production
- WW, WZ, ZZ production
- inclusive Higgs production
- heavy quark production
- single-top
- dijets
- W^+W^+ + dijets ...
- ....

Other progress: shower with quantum interference [Nagy, Soper], Geneve (SCET) [Bauer et al.], Vincia (antenna factorization) [Giele et al.], Dipole factorization [Schumann]

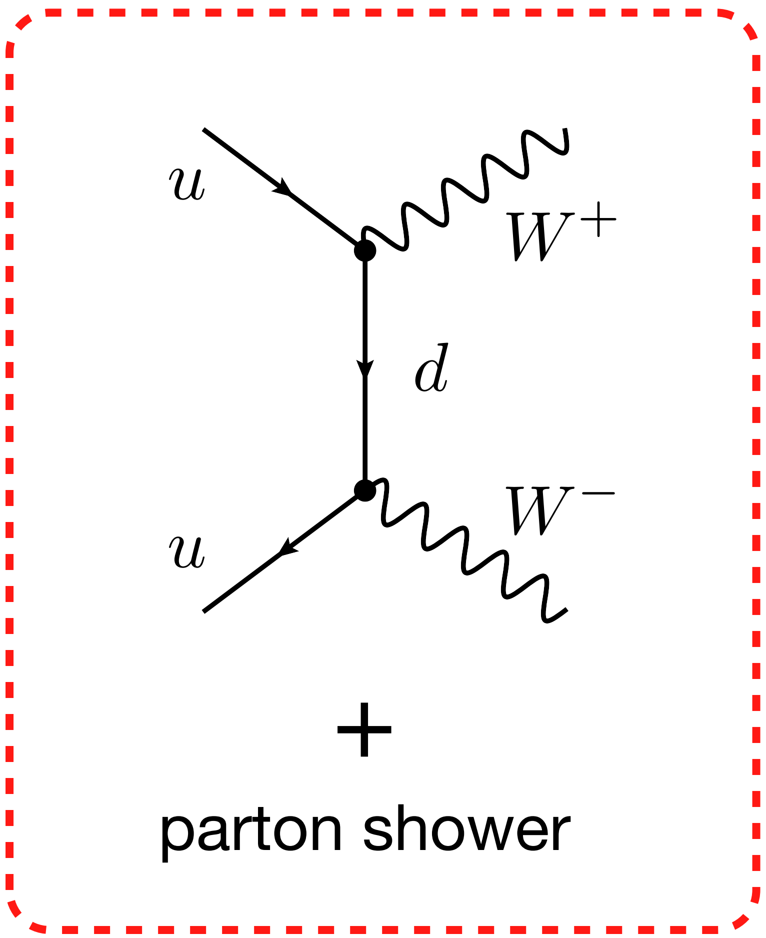
MC@NLO

IPROC	IV	IL_1	IL_2	Spin	Process
–1350–IL				✓	$H_1H_2 \to (Z/\gamma^* \to) l_{IL}\bar{l}_{IL} + X$
–1360–IL				✓	$H_1H_2 \to (Z \to) l_{IL}\bar{l}_{IL} + X$
–1370–IL				✓	$H_1H_2 \to (\gamma^* \to) l_{IL}\bar{l}_{IL} + X$
–1460–IL				✓	$H_1H_2 \to (W^+ \to) l^+_{IL}\nu_{IL} + X$
–1470–IL				✓	$H_1H_2 \to (W^- \to) l^-_{IL}\bar{\nu}_{IL} + X$
–1396				×	$H_1H_2 \to \gamma^*(\to \sum_i f_i\bar{f}_i) + X$
–1397				×	$H_1H_2 \to Z^0 + X$
–1497				×	$H_1H_2 \to W^+ + X$
–1498				×	$H_1H_2 \to W^- + X$
–1600–ID					$H_1H_2 \to H^0 + X$
–1705					$H_1H_2 \to b\bar{b} + X$
–1706		7	7	×	$H_1H_2 \to t\bar{t} + X$
–2000–IC		7		×	$H_1H_2 \to t/\bar{t} + X$
–2001–IC		7		×	$H_1H_2 \to \bar{t} + X$
–2004–IC		7		×	$H_1H_2 \to t + X$
–2030		7	7	×	$H_1H_2 \to tW^-/\bar{t}W^+ + X$
–2031		7	7	×	$H_1H_2 \to \bar{t}W^+ + X$
–2034		7	7	×	$H_1H_2 \to tW^- + X$
–2600–ID	1	7		×	$H_1H_2 \to H^0W^+ + X$
–2600–ID	1	i		✓	$H_1H_2 \to H^0(W^+ \to) l^+_i\nu_i + X$
–2600–ID	-1	7		×	$H_1H_2 \to H^0W^- + X$
–2600–ID	-1	i		✓	$H_1H_2 \to H^0(W^- \to) l^-_i\bar{\nu}_i + X$
–2700–ID	0	7		×	$H_1H_2 \to H^0Z + X$
–2700–ID	0	i		✓	$H_1H_2 \to H^0(Z \to) l_i\bar{l}_i + X$
–2850		7	7	×	$H_1H_2 \to W^+W^- + X$
–2860		7	7	×	$H_1H_2 \to Z^0Z^0 + X$
–2870		7	7	×	$H_1H_2 \to W^+Z^0 + X$
–2880		7	7	×	$H_1H_2 \to W^-Z^0 + X$

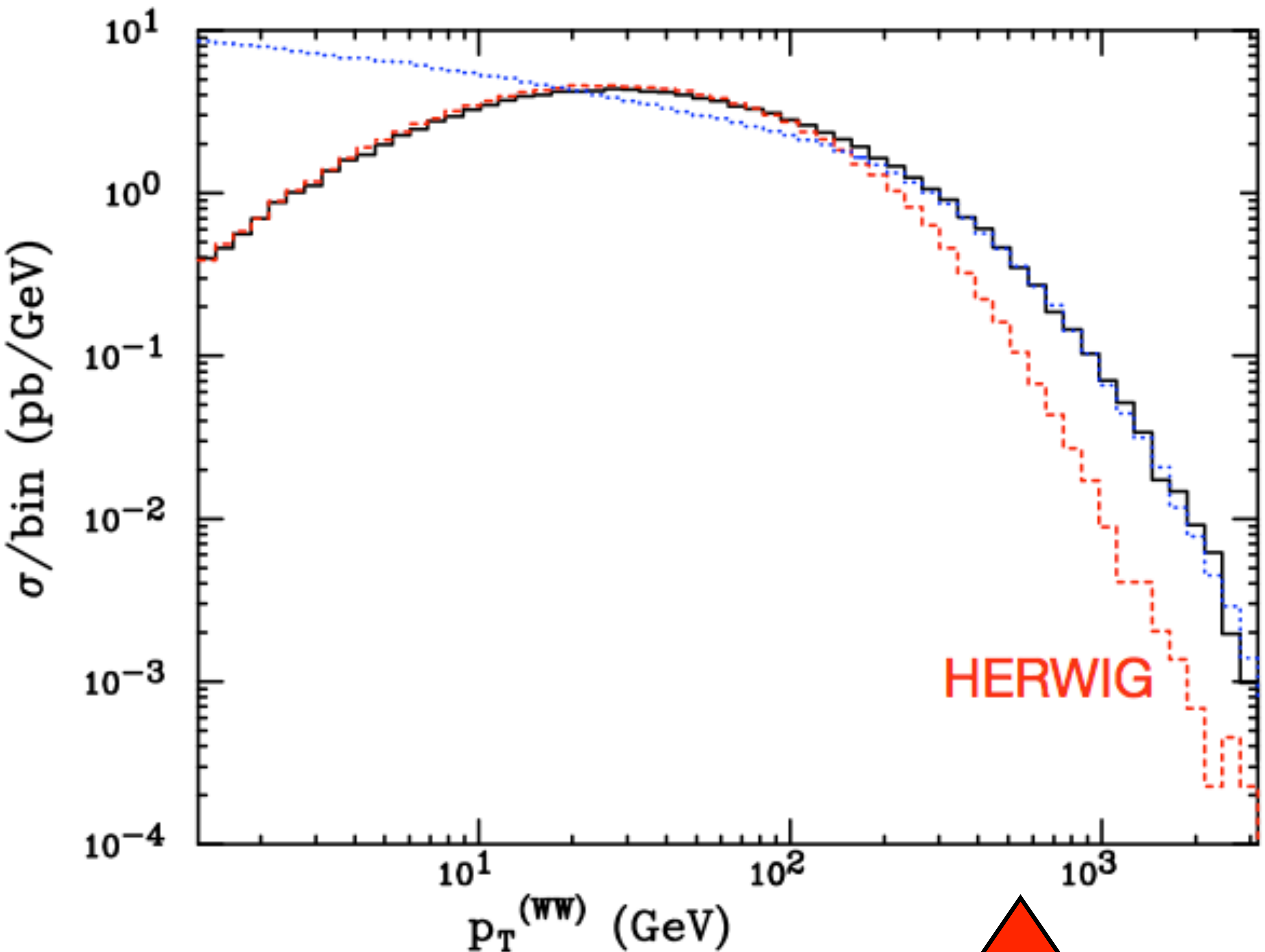
- $H_{1,2}$ denote nucleon and antinucleon
- The "Spin" indicates whether spin correlations in vector boson fusion or top decays are included (✓), neglected (×) or absent (void entry)
- The values of IV, IL, IL_1, and IL_2 control the identities of vector bosons and leptons

IPROC	IV	IL_1	IL_2	Spin	Process
–1706		i	j	✓	$H_1H_2 \to (t \to) b_k f_i f'_i (\bar{t} \to) \bar{b}_l f_j f'_j + X$
–2000–IC		i		✓	$H_1H_2 \to (t \to) b_k f_i f'_i / (\bar{t} \to) \bar{b}_k f_i f'_i + X$
–2001–IC		i		✓	$H_1H_2 \to (\bar{t} \to) \bar{b}_k f_i f'_i + X$
–2004–IC		i		✓	$H_1H_2 \to (t \to) b_k f_i f'_i + X$
–2030		i	j	✓	$H_1H_2 \to (t \to) b_k f_i f'_i (W^- \to) f_j f'_j /$ $(\bar{t} \to) \bar{b}_k f_i f'_i (W^+ \to) f_j f'_j + X$
–2031		i	j	✓	$H_1H_2 \to (\bar{t} \to) \bar{b}_k f_i f'_i (W^+ \to) f_j f'_j + X$
–2034		i	j	✓	$H_1H_2 \to (t \to) b_k f_i f'_i (W^- \to) f_j f'_j + X$
–2850		i	j	✓	$H_1H_2 \to (W^+ \to) l^+_i \nu_i (W^- \to) l^-_j \bar{\nu}_j + X$

MC@NLO: W^+W^- production (LHC)

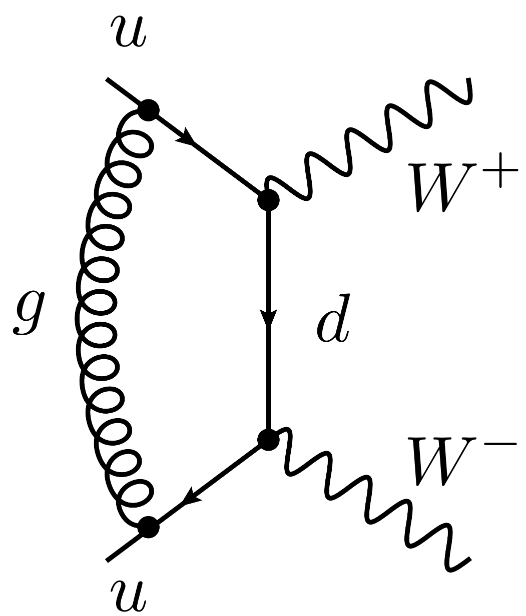


HERWIG

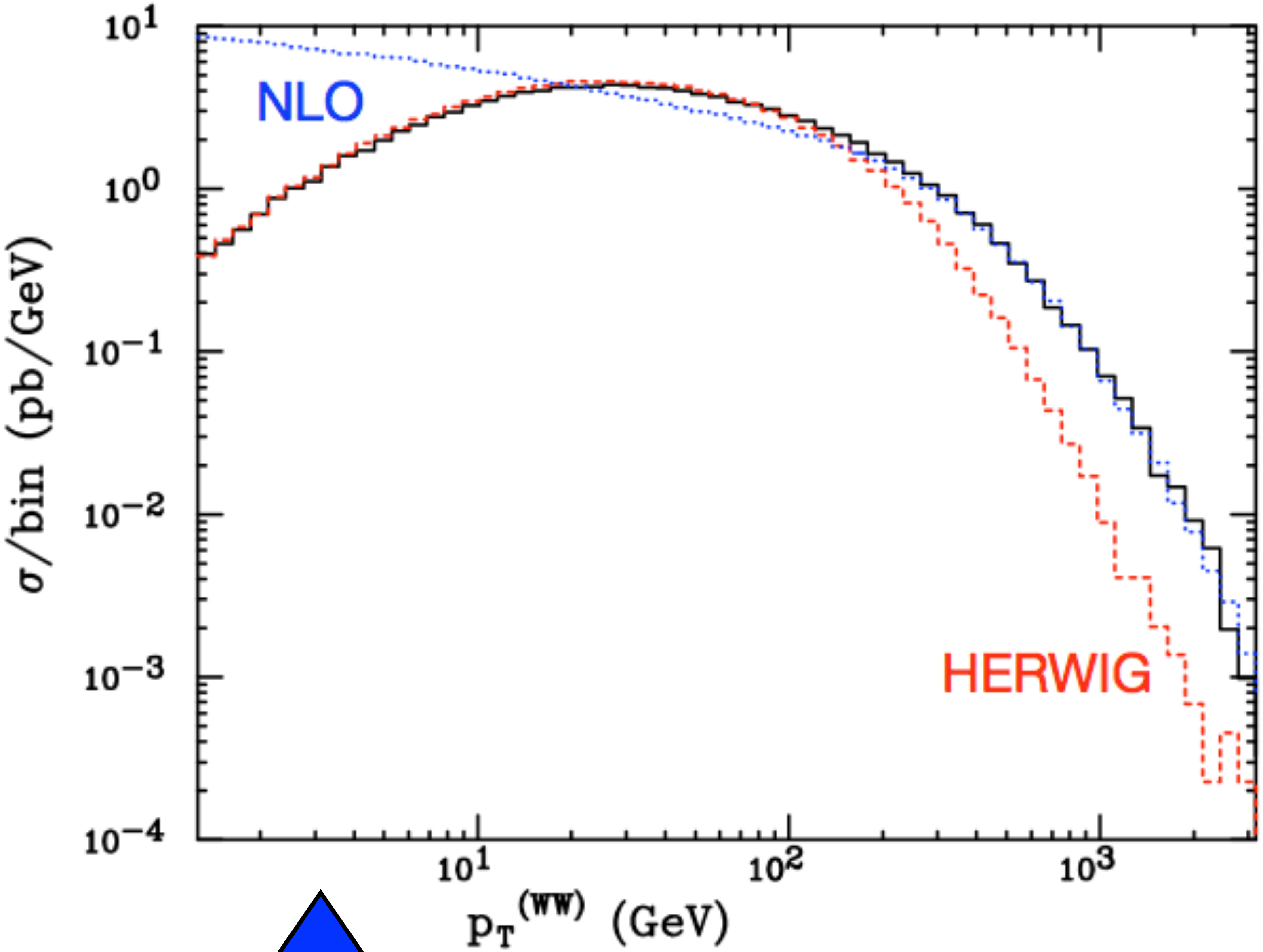


Herwig too soft in the high-p_t region

MC@NLO: W^+W^- production (LHC)

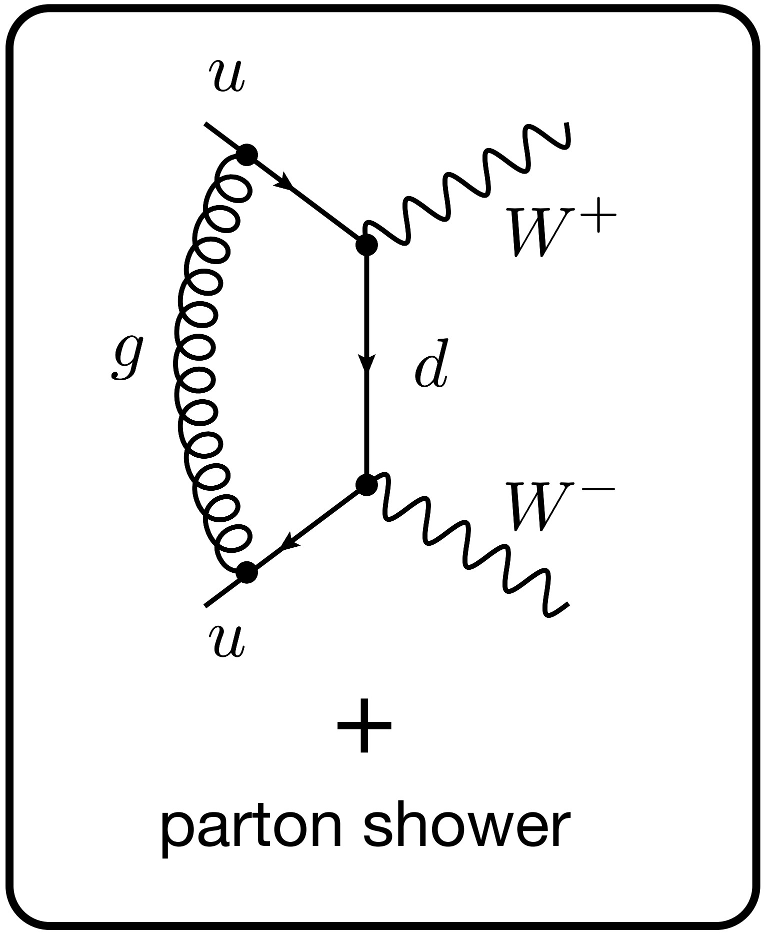


NLO

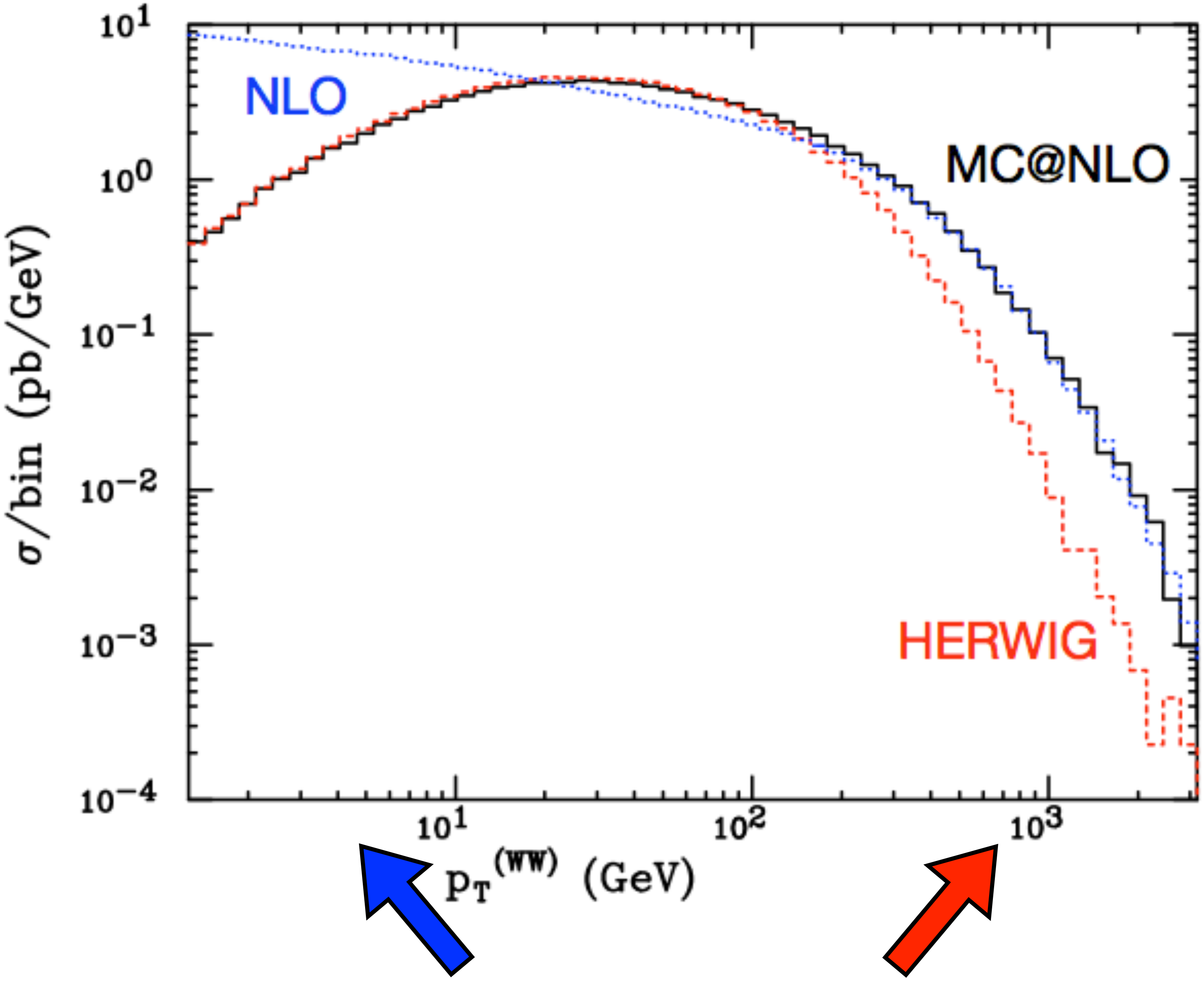


NLO divergent
in the soft region

MC@NLO: W^+W^- production (LHC)



MC@NLO



MC@NLO correctly interpolates between the two regimes

Jets: before 2006

Where do jets enter ?

Essentially everywhere at colliders!

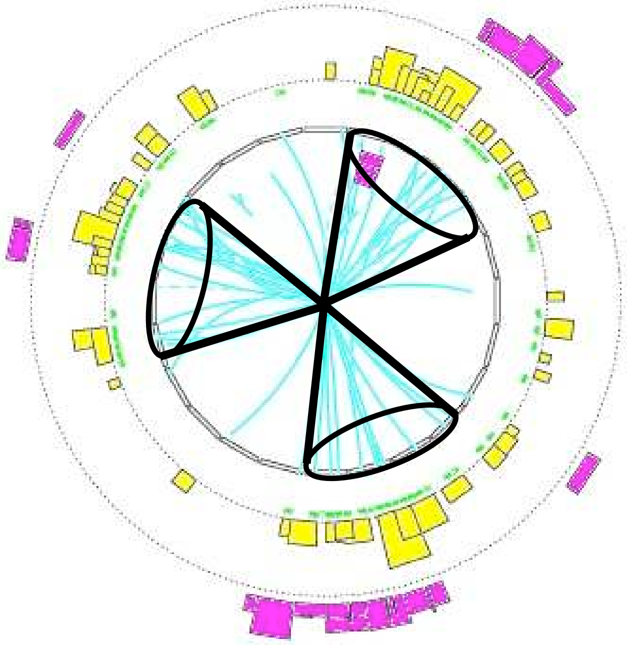
Jets are an essential tool for a variety of studies:

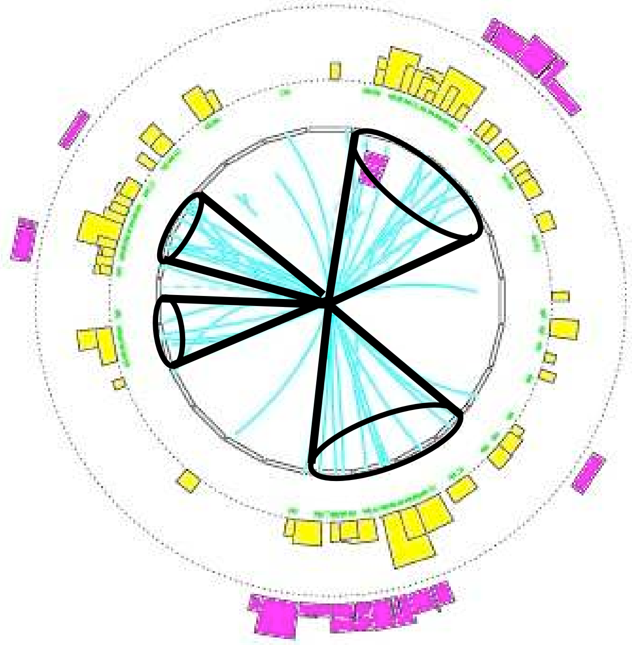
- top reconstruction
- mass measurements
- most Higgs and NP searches
- general tool to attribute structure to an event
- instrumental for QCD studies, e.g. inclusive-jet measurements
  $\Rightarrow$ important input for PDF determinations

Jets

Jets provide a way of projecting away the multiparticle dynamics of an event ⇒ leave a simple quasi-partonic picture of the hard scattering

The projection is fundamentally ambiguous ⇒ jet physics is a rich subject



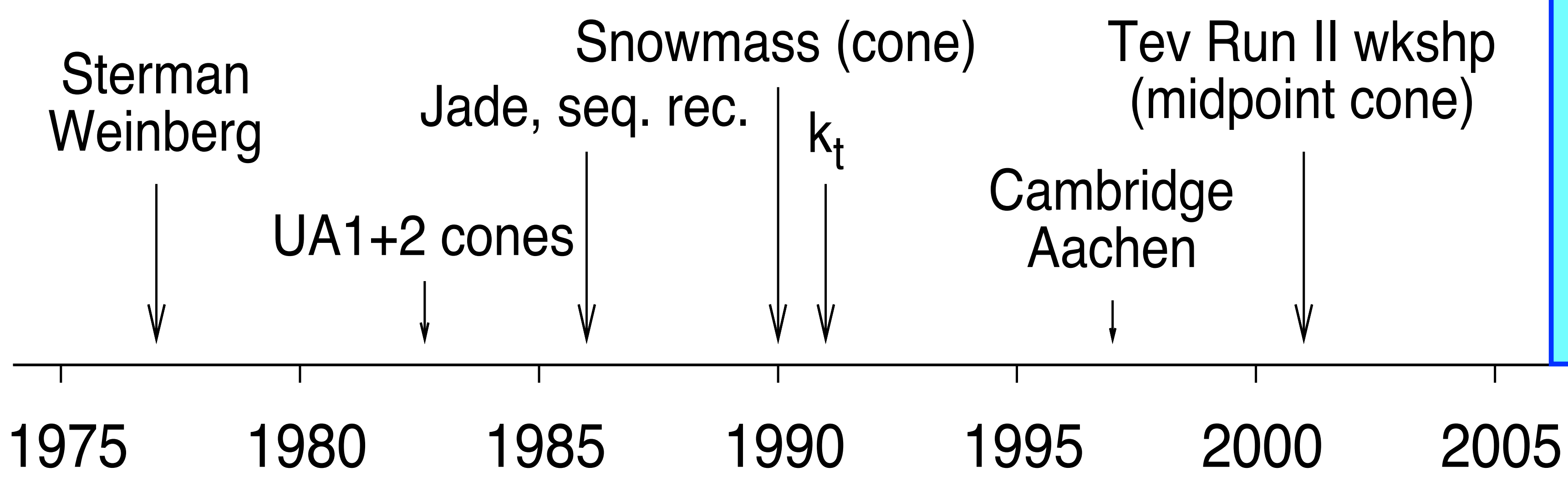


Ambiguities:

1) Which particles should belong to a same jet ?

2) How does recombine the particle momenta to give the jet-momentum?

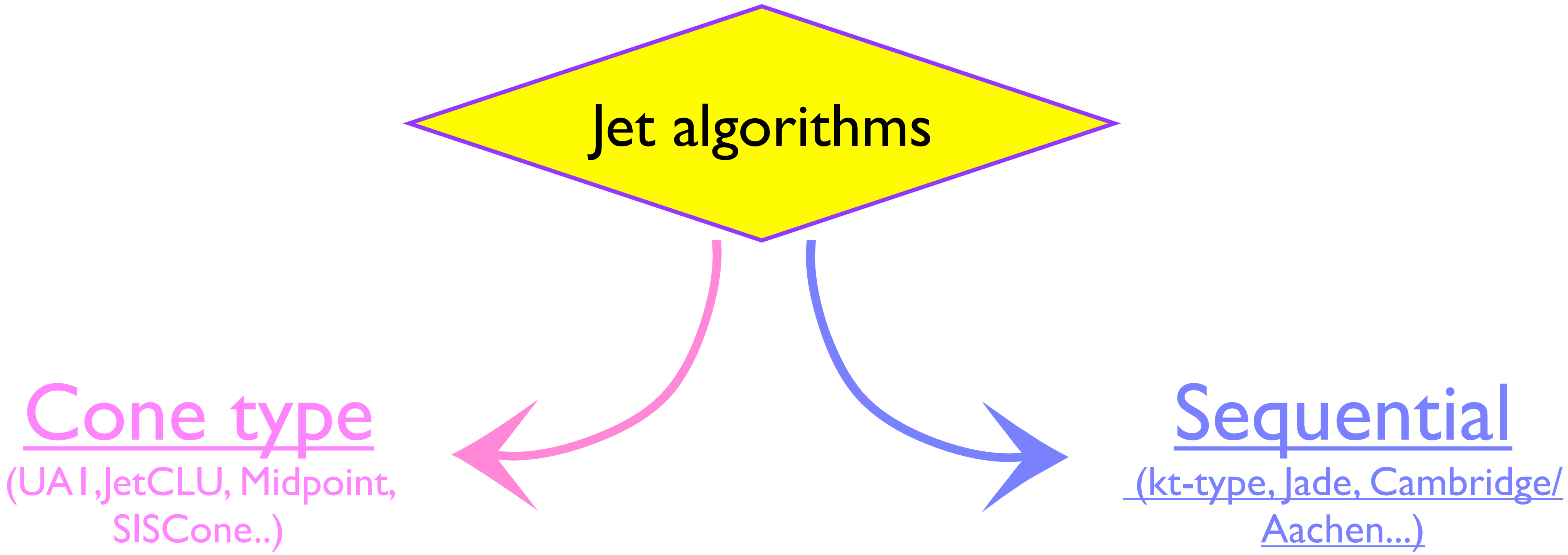
Jet developments



fast-kt, SISCone, anti-kt, jet-areas, jet-flavour, non-perturbative effects, quality measures, jet-substructure ...

Two broad classes of jet algorithms

Today many extensions of the original Sterman-Weinberg jets.
Modern jet-algorithms divided into two broad classes



top down approach: cluster particles according to distance in coordinate-space
Idea: put cones along dominant direction of energy flow

bottom up approach: cluster particles according to distance in momentum-space
Idea: undo branchings occurred in the PT evolution

Jet requirements

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;
5. Yields a cross section that is relatively insensitive to hadronization.

Other desirable properties:

- flexibility
- few parameters
- fast algorithms
- transparency
- ...

Inclusive k_t/Durham-algorithm

Catani et. al '92-'93; Ellis&Soper '93

Inclusive algorithm:

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

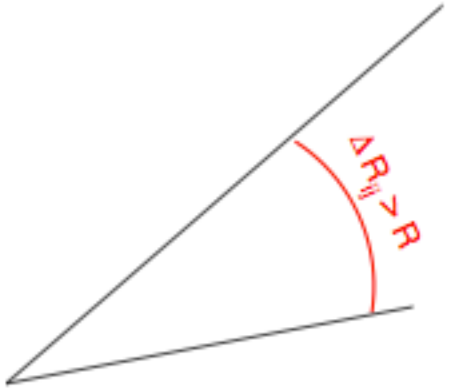
$$d_{ij} = \frac{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}{R^2} \min\{k_{ti}^2, k_{tj}^2\}$$

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 ($\Longrightarrow$ recombination scheme); if it is d_{iB} declare i to be a jet and remove it from the list of particles

   NB: if $\Delta R_{ij} \equiv \Delta y_{ij}^2 + \Delta\phi_{ij}^2 < R$ then partons (ij) are always recombined, so R sets the minimal interjet angle



4. repeat the procedure until no particles are left

Exclusive k_t/Durham-algorithm

Inclusive algorithm gives a variable number of jets per event, according to the specific event topology

Exclusive version: run the inclusive algorithm but stop when either

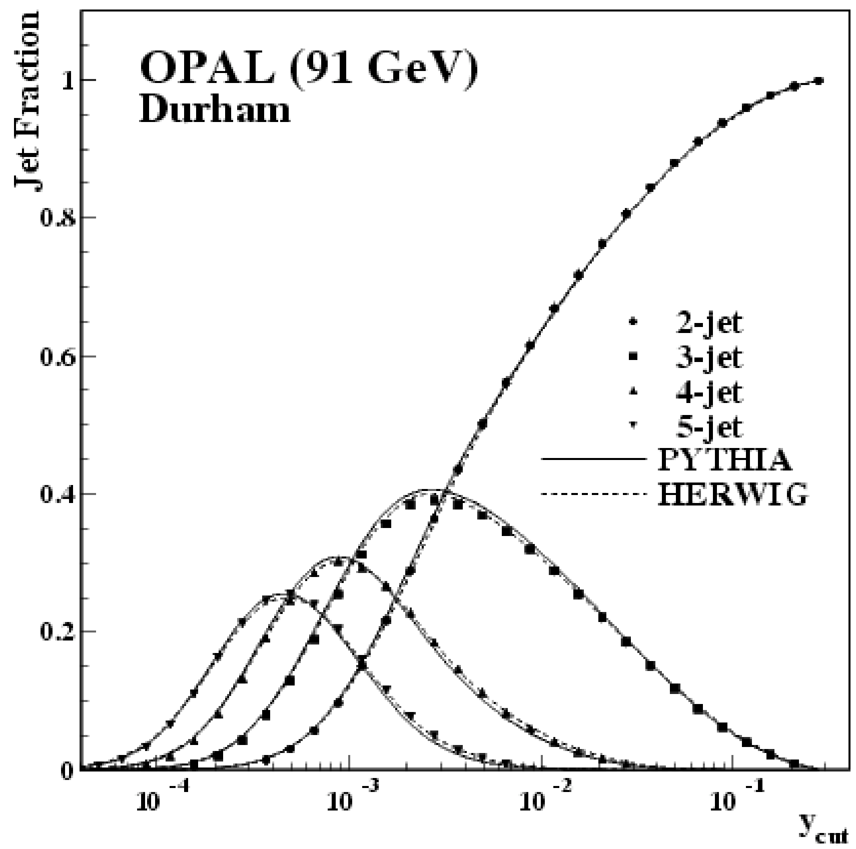
- all d_{ij}, d_{iB} > d_{cut} or
- when reaching the desired number of jets n

k_t/Durham-algorithm in e^+e^-

k_t originally designed in e^+e^-, most widely used algorithm in e^+e^- (LEP)

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

- can classify events using y_{23}, y_{34}, y_{45}, y_{56} ...
- resolution parameter related to minimum transverse momentum between jets



Satisfies fundamental requirements:

1. Collinear safe: collinear particles recombine early on
2. Infrared safe: soft particles do not influence the clustering sequence

⇒ collinear + infrared safety important: it means that cross-sections can be computed at higher order in pQCD (no divergences)!

The CA and the anti-k_t algorithm

The Cambridge/Aachen: sequential algorithm like k_t, but uses only angular properties to define the distance parameters

$$d_{ij} = \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = 1 \qquad \Delta R_{ij}^2 = (\phi_i - \phi_j)^2 + (y_i - y_j)^2$$

Dotshitzer et. al '97; Wobisch & Wengler '99

The anti-kt algorithm: designed not to recombine soft particles together

$$d_{ij} = \min\{1/k_{ti}^2, 1/k_{tj}^2\}\Delta R_{ij}^2/R^2 \qquad d_{iB} = 1/k_{ti}^2$$

Cacciari, Salam, Soyez '08

anti-kt is the default algorithm for ATLAS and CMS

Recombination schemes in e^+e^-

Given two massless momenta p_i and p_j how does one recombine them to build p_{ij} ? Several choices are possible.

Most common ones:

1. E-scheme $p_{ij} = p_i + p_j$
2. E_0-scheme $\vec{p}_{ij} = \vec{p}_i + \vec{p}_j$ $\quad E_{ij} = |\vec{p}_{ij}|$
3. P_0-scheme $E_{ij} = E_i + E_j$ $\quad \vec{p}_{ij} = \dfrac{E_{ij}}{|\vec{p}_i + \vec{p}_j|}(\vec{p}_i + \vec{p}_j)$

E_0/P_0-schemes give massless jets, along with the idea that the hard parton underlying the jet is massless

E-scheme give massive jets. Most used in recent analysis.

Recombination schemes in hh

Most common schemes:

- E-scheme (as in e+e-)
- p_t, p_t^2, E_t, E_t^2 schemes
  - first preprocessing, i.e. make particles massless, rescaling the 3-momentum in the E_t, E_t^2 schemes or the energy in the p_t, p_t^2 schemes
  - then define

$$p_{t,ij} = p_{t,i} + p_{t,j}$$

$$\phi_{ij} = (w_i \phi_i + w_j \phi_j) / (w_i + w_j)$$

$$y_{ij} = (w_i y_i + w_j y_j) / (w_i + w_j)$$

  where the weights w_i are p_{ti} for the p_t, E_t schemes and p_{ti}^2 for the p_t^2 and E_t^2 schemes

NB: *a jet-algorithm is fully specified only once all parameters and the recombination scheme is specified too*

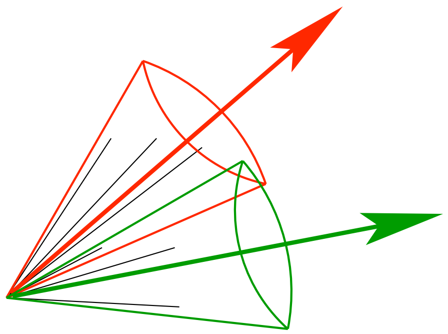
Cone algorithms

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

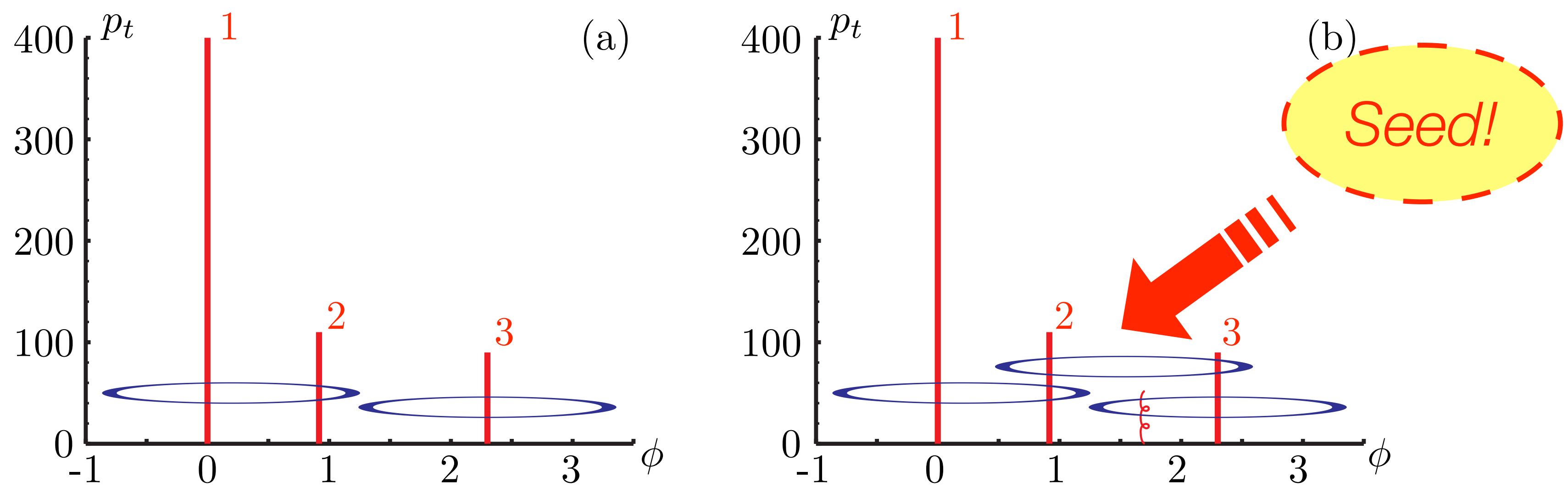
4. Stable cones can overlap. Run a split-merge on overlapping jets: merge jets if they share more than an energy fraction f, else split them and assign the shared particles to the cone whose axis they are closer to.
Remark: too small f (<0.5) creates hugh jets, not recommended

Cone algorithms

- The question is where does one start looking for stable cone ?
- The direction of these trial cones are called seeds
- Ideally, place seeds everywhere, so as not to miss any stable cone
- Practically, this is unfeasible. Speed of recombination grows fast with the number of seeds. So place only some seeds, e.g. at the (y, Φ)-location of particles.

Seeds make cone algorithms infrared unsafe

Jets: infrared unsafety of cones



3 hard ⇒ 2 stable cones   3 hard + 1 soft ⇒ 3 stable cones

Soft emission changes the hard jets ⇒ algorithm is IR unsafe

Midpoint algorithm: take as seed position of emissions and midpoint between two emissions (postpones the infrared satefy problem)

Seedless cones

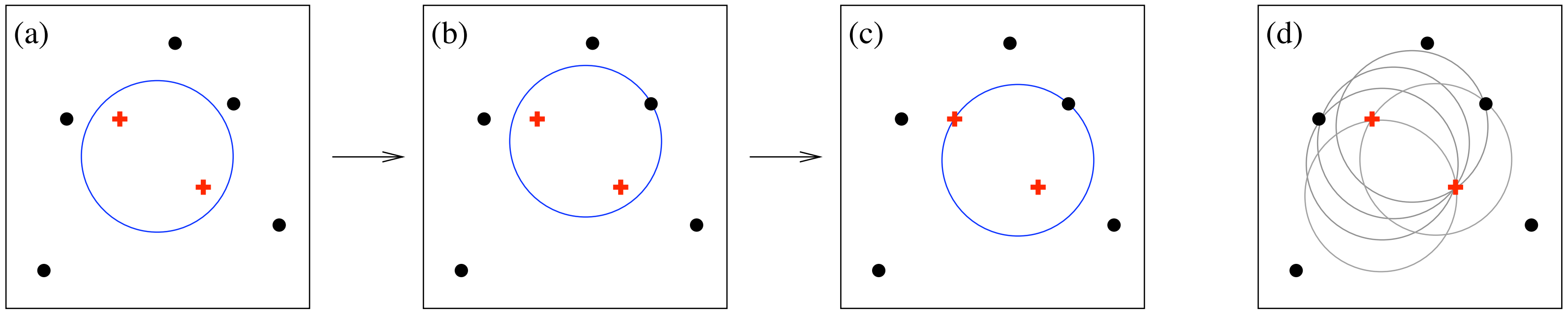
Solution:
use a seedless algorithm, i.e. consider all possible combinations of particles as candidate cones, so find all stable cones [⇒ jets]

Blazey '00

The problem:
clustering time growth as $N2^N$. So for an event with 100 particles need 10^{17} ys to cluster the event ⇒ prohibitive beyond PT (N=4,5)

Better solution:

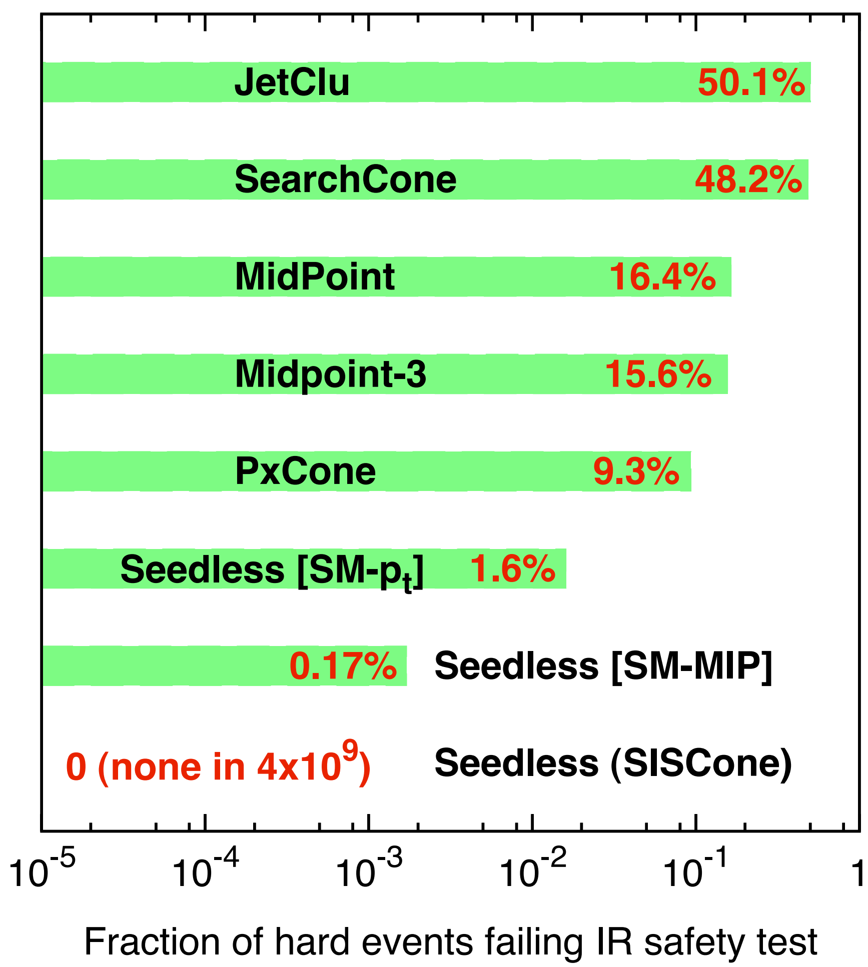
SISCone recasts the problem as a computational geometry problem, the identification of all distinct circular enclosures for points in 2D and finds a solution to that ⇒ $N^2 \ln N$ time IR safe algorithm

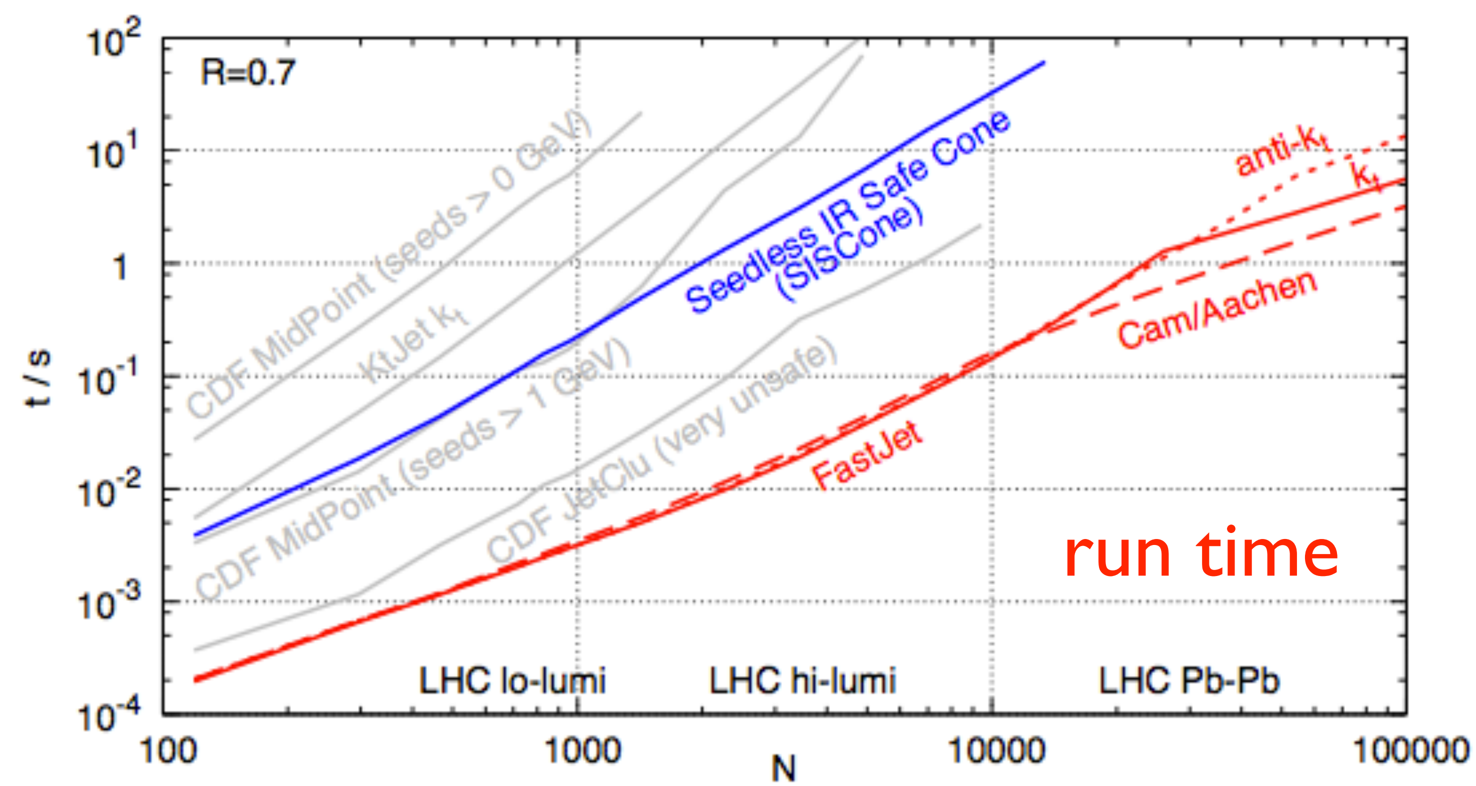


Salam, Soyez '07

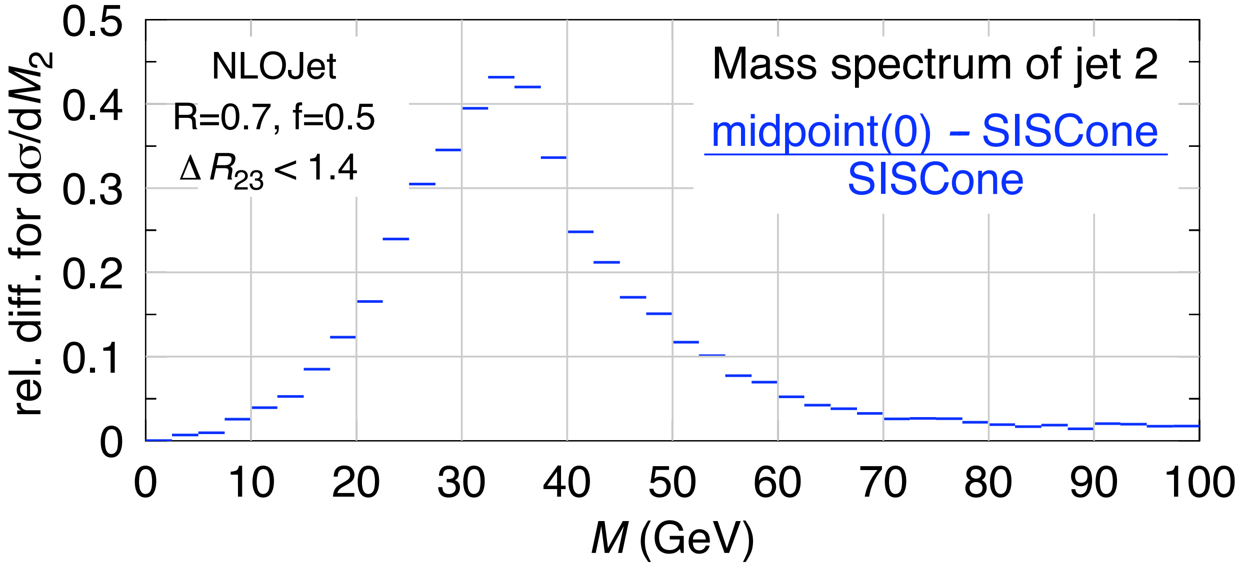
IR safety test & time comparisons

IR safety test: take a random hard event, add very soft emissions, count the number of times the hard jets change due to soft emissions





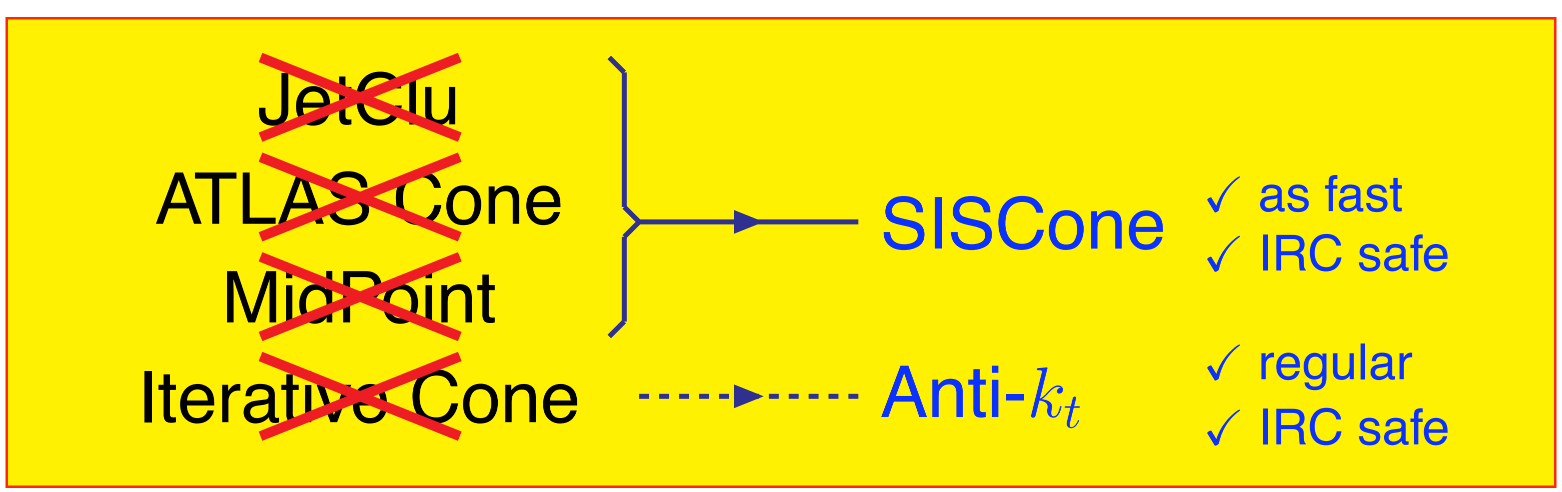
Physical impact of infrared unsafety



Up to 40% difference
in mass spectrum

IR-unsafety is an
issue at the LHC

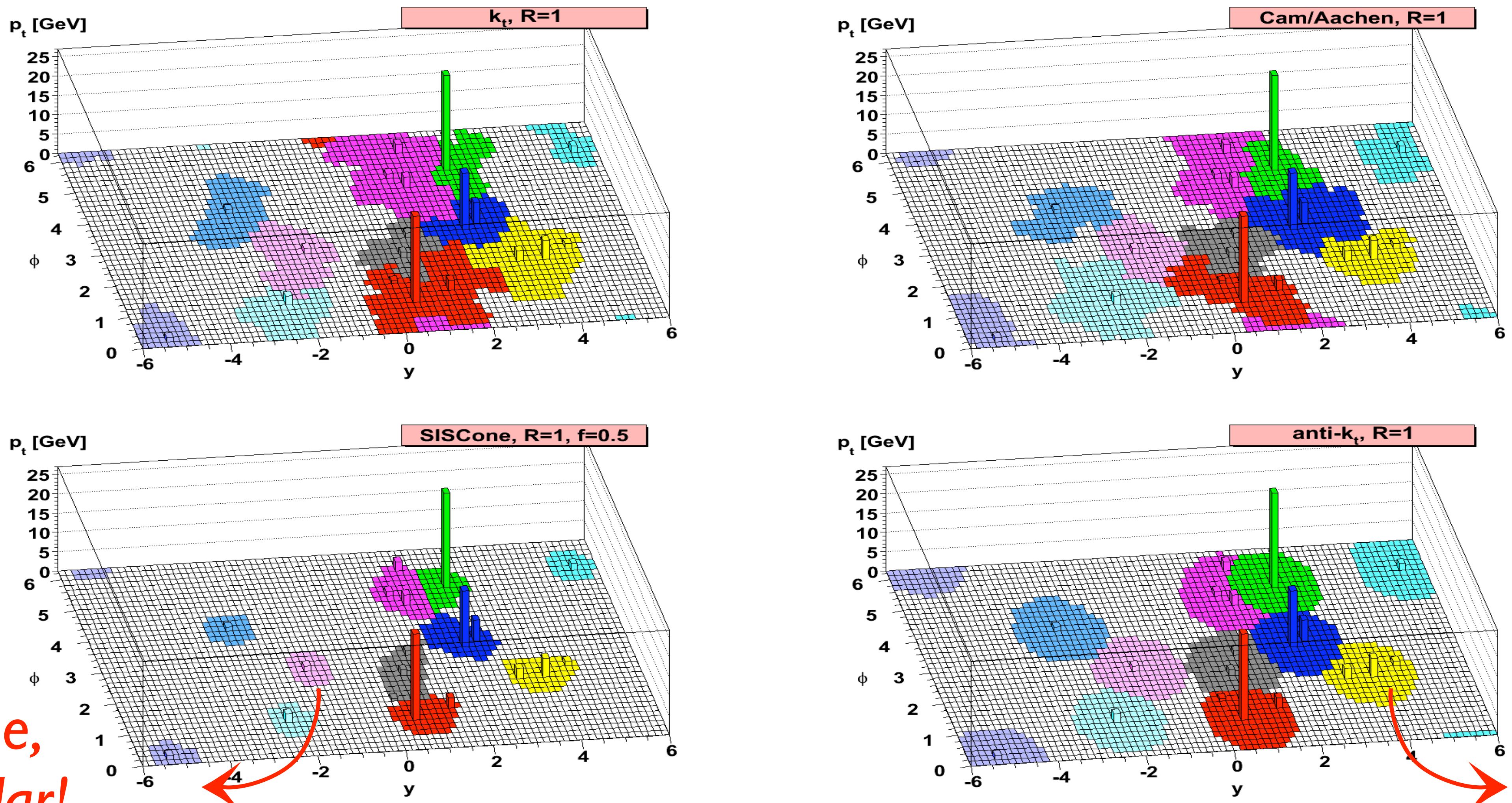
Observable	1st miss cones at	Last meaningful order
Inclusive jet cross section	NNLO	NLO
3 jet cross section	NLO	LO (NLO in NLOJet)
$W/Z/H$ + 2 jet cross sect.	NLO	LO (NLO in MCFM)
jet masses in 3 jets	LO	none (LO in NLOJet)



If you don't want
theoretical efforts
to be wasted!

Jet area

Given an infrared safe, fast jet-algorithm, can define the jet area A as follows: fill the event with an infinite number of infinitely soft emissions uniformly distributed in η-φ and make A proportional to the # of emissions clustered in the jet



NB: cone, not circular!

NB: new anti-kt

What jet areas are good for

jet-area ≡ catching area of the jet when adding soft emissions

⇒ use the jet area to formulate a simple area based subtraction of pile-up events

1. cluster particle with an IR safe jet algorithm
2. from *all jets* (most are pile-up ones) in the event define the median

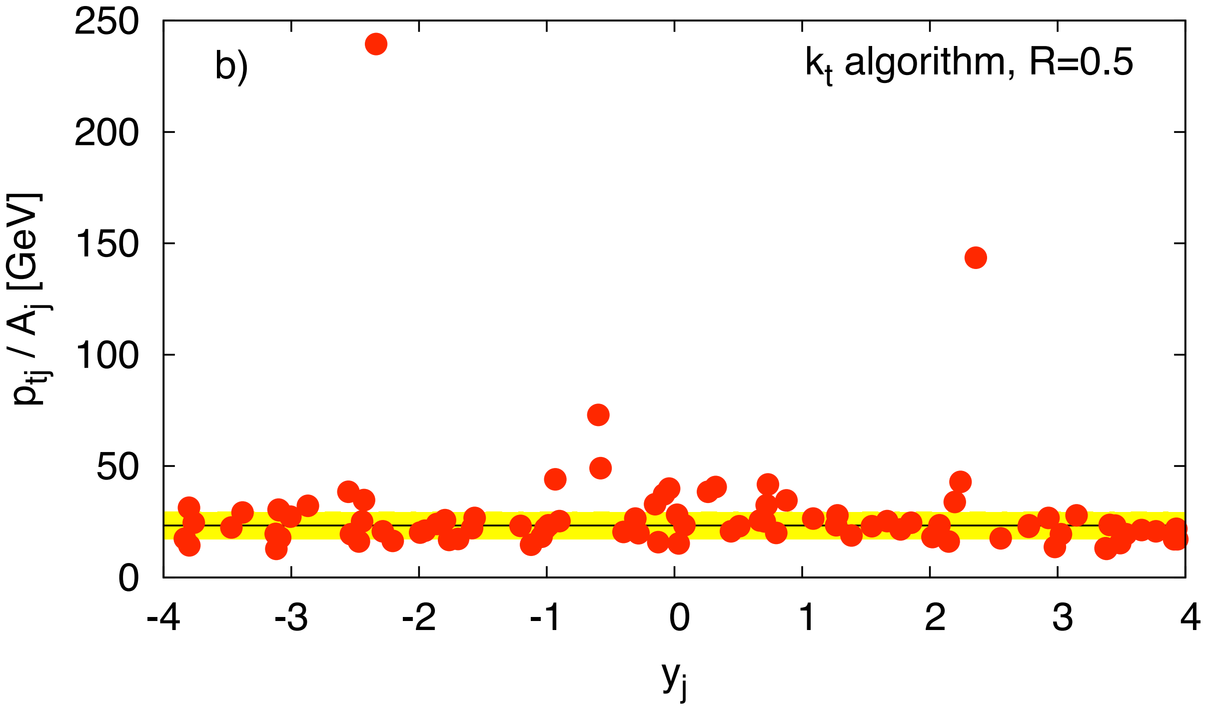
$$\rho = \frac{p_{t,j}}{A_j}$$

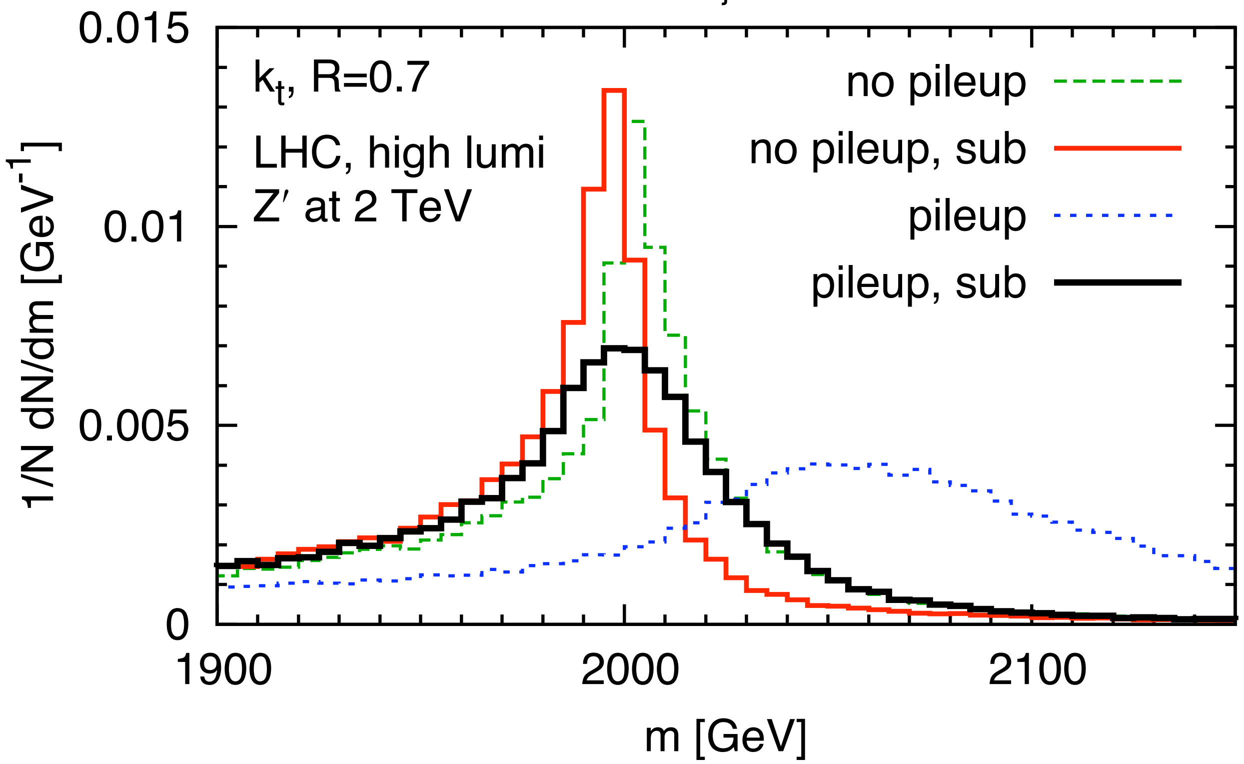
3. the median gives the typical p_t/A_j for a given event
4. use the median to subtract off dynamically the soft part of the soft events

$$p_j^{\mathrm{sub}} = p_j - A_j \rho$$

Pileup = generic p-p interaction (hard, soft, single-diffractive...) overlapping with hard scattering

Sample 2 TeV mass reconstruction





Cacciari et al. '07

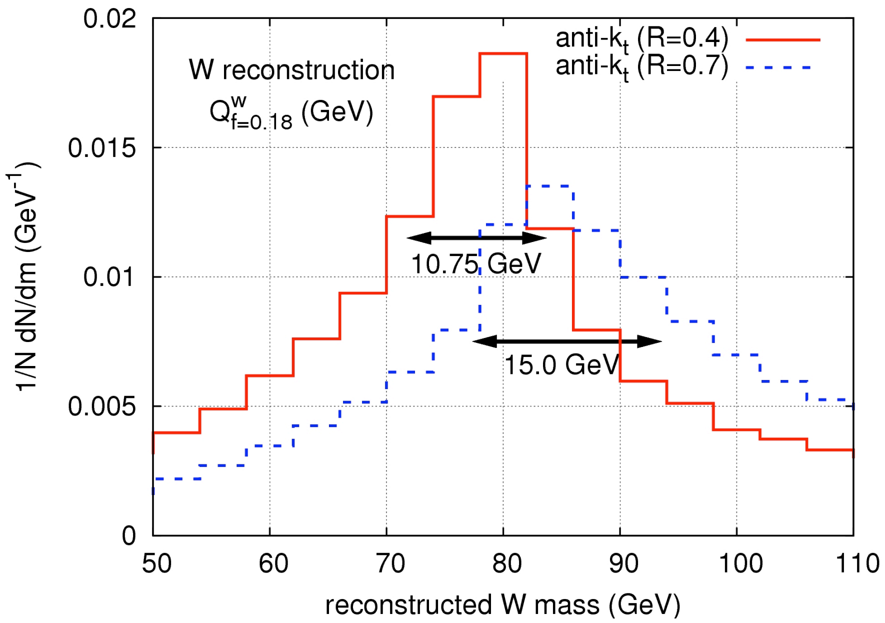
Quality measures of jets

Suppose you are searching for a heavy state ($H \rightarrow gg$, $Z' \rightarrow qq$, ...)

The object is reconstructed through its decay products
$\Rightarrow$ *Which jet algorithm (JA) is best ? Does the choice of R matter?*

Define: Q_f^w*(JA, R)* $\equiv$ *width of the smallest mass window that contains a fraction f of the generated massive objects*

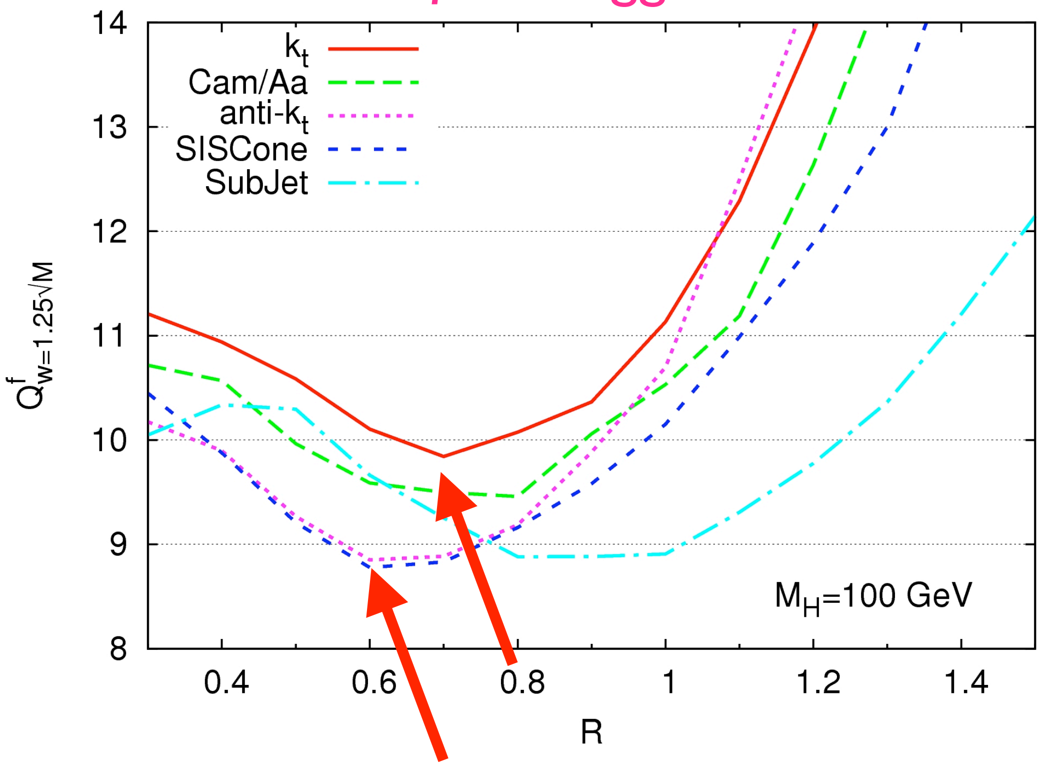
- good algo $\Leftrightarrow$ small Q_f^w(JA, R)
- ratios of Q_f^w(JA,R): mapped to ratios of effective luminosity (with same $S/\sqrt{B}$)

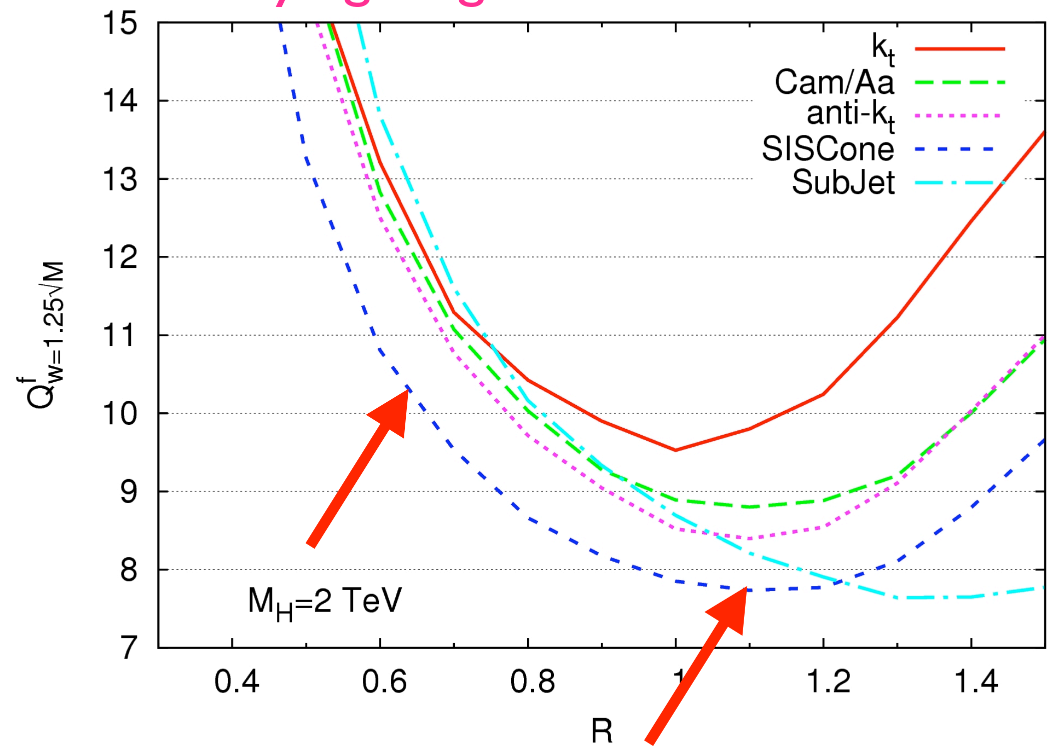


$$\mathcal{L}_2 = \rho_{\mathcal{L}} \mathcal{L}_1 \qquad \rho_{\mathcal{L}} = \frac{Q_z^f(JA_2, R_2)}{Q_z^f(JA_1, R_1)}$$

Quality measures: sample results

NB: Here "fake Higgs" = narrow resonance decaying to gluons

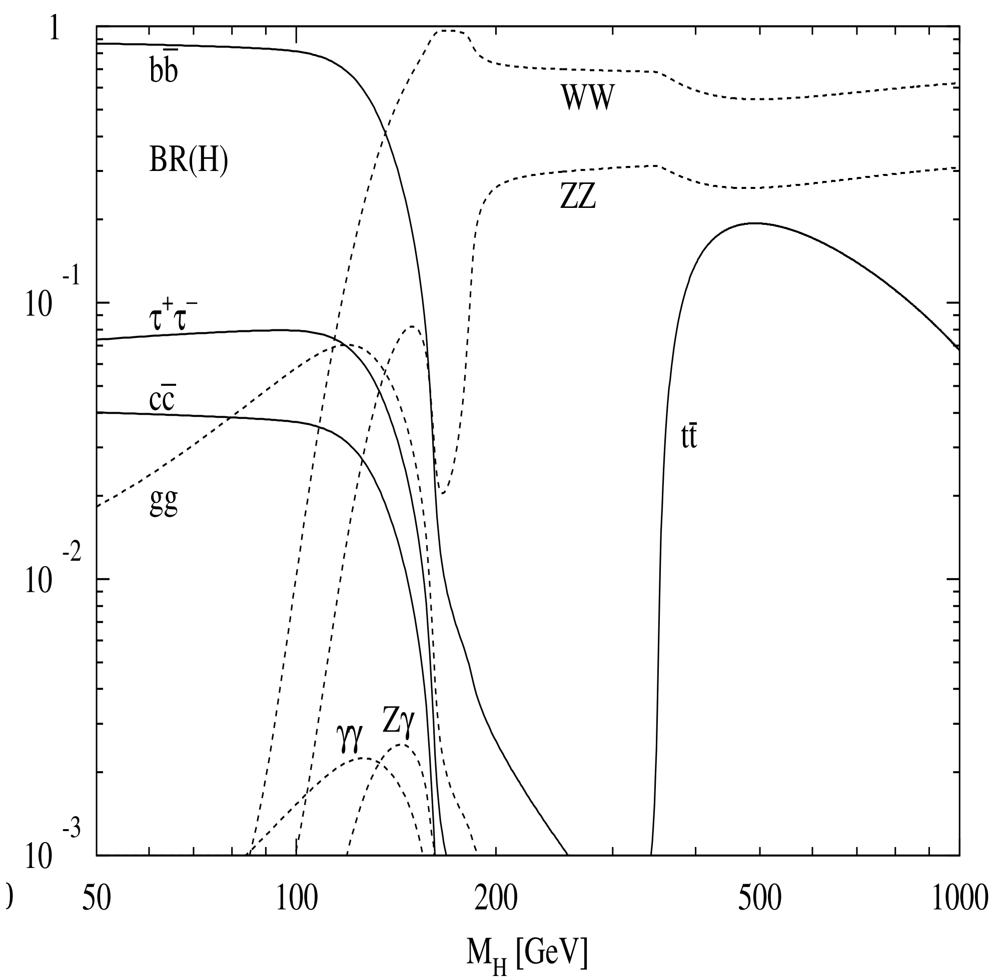


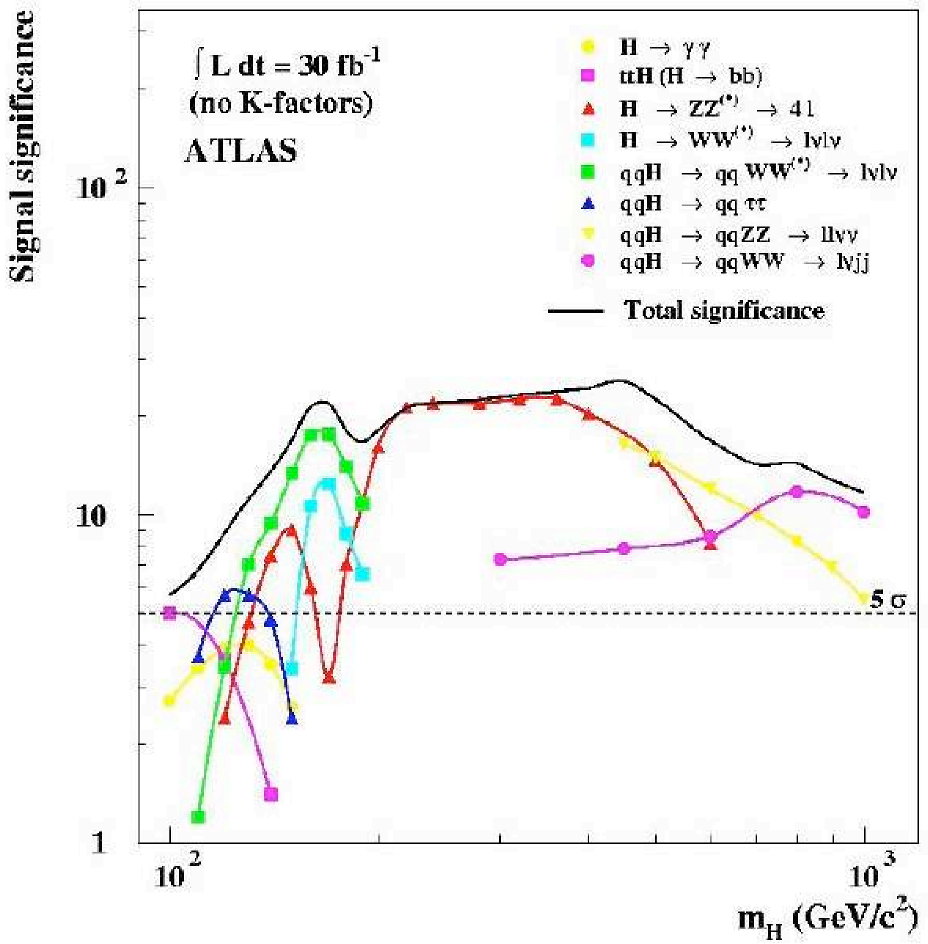


- At 100GeV: use a Tevatron standard algo (k_t, R=0.7) instead of best choice (SISCone, R=0.6 $\Rightarrow$ lose $\rho_{\mathcal{L}} = 0.8$ in effective luminosity
- At 2 TeV: use $M_{Z'}$=100GeV best choice (or k_t) instead SIScone, R=1.1 $\Rightarrow$ lose $\rho_{\mathcal{L}} = 0.6$ in effective luminosity

A good choice of jet-algorithm does matter!
Bad choice of algo $\Leftrightarrow$ lost in discrimination power!

Z/W+ H (→bb) rescued ?





⇒ Light Higgs hard: Higgs mainly produced in association with Z/W, decay H→bb is dominant, but overwhelmed by QCD backgrounds

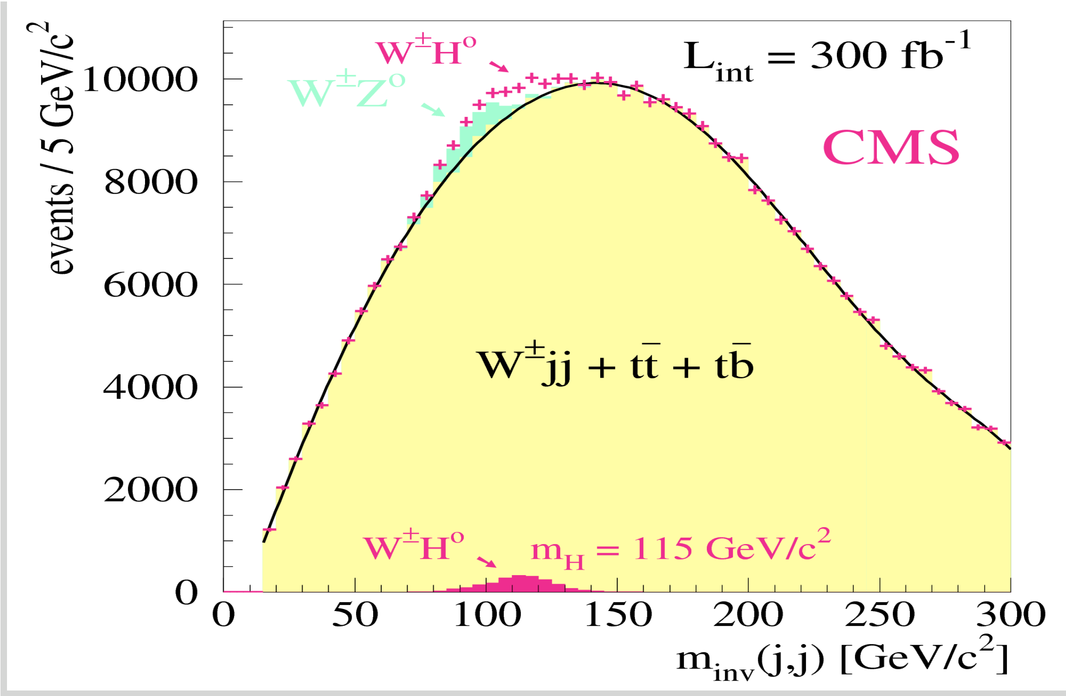
Z/W+ H (→bb) rescued ?

Recall why searching for pp →WH(bb) is hard:

$\sigma(\mathrm{pp} \to WH(bb)) \sim \text{few pb}$ $\quad \sigma(\mathrm{pp} \to Wbb) \sim \text{few pb}$

$\sigma(\mathrm{pp} \to tt) \sim 800\text{pb}$ $\quad \sigma(\mathrm{pp} \to Wjj) \sim \text{few } 10^4\text{pb}$ $\quad \sigma(\mathrm{pp} \to bb) \sim 400\text{pb}$

⇒ signal extraction very difficult



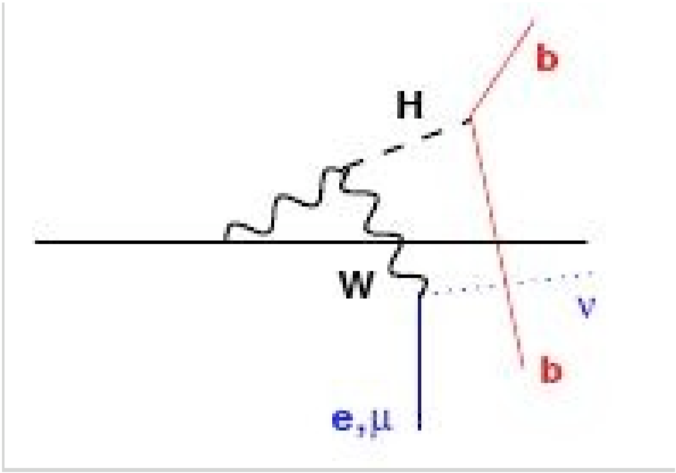
<u>Conclusion [ATLAS TDR]:</u>
The extraction of a signal from H → bb decays in the WH channel will be very difficult at the LHC even under the most optimistic assumptions [...]

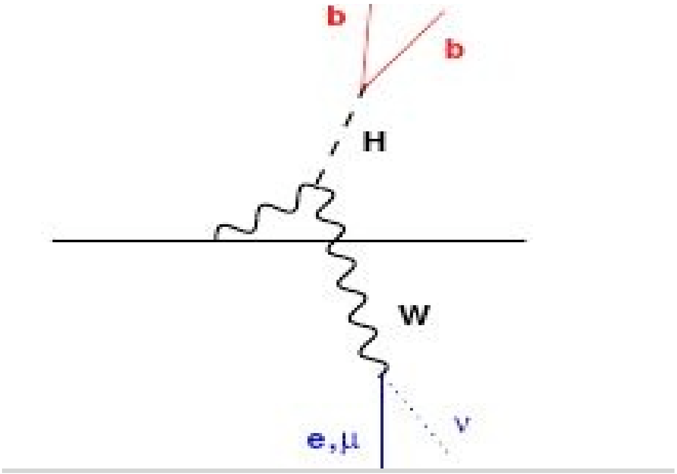
Z/W+ H (→bb) rescued ?

But ingenious suggestions open up to window of opportunity

Central idea: require high-p_T W and Higgs boson in the event

- leads to back-to-back events where two b-quarks are contained within the same jet
- high p_T reduces the signal but reduces the background much more
- improve acceptance and kinematic resolution

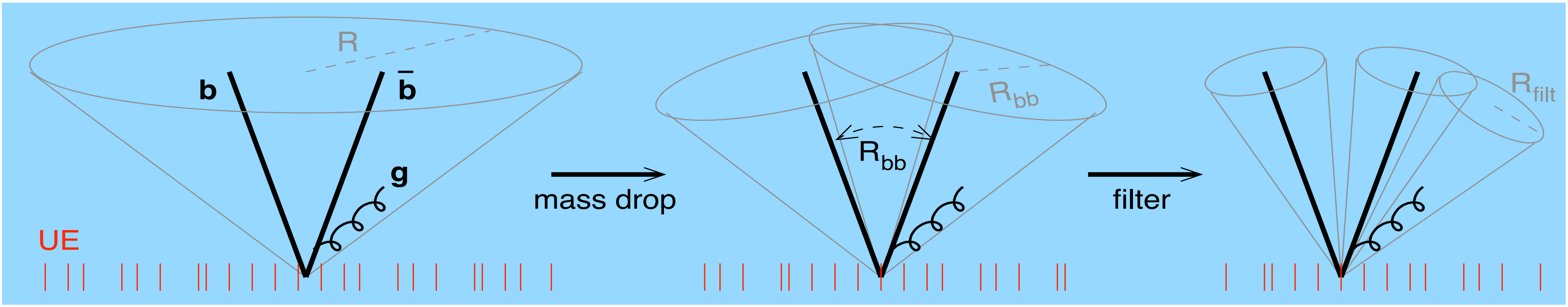




Z/W+ H (→bb) rescued ?

Then use a jet-algorithm geared to exploit the specific pattern of H → bb vs g → gg, q → gg

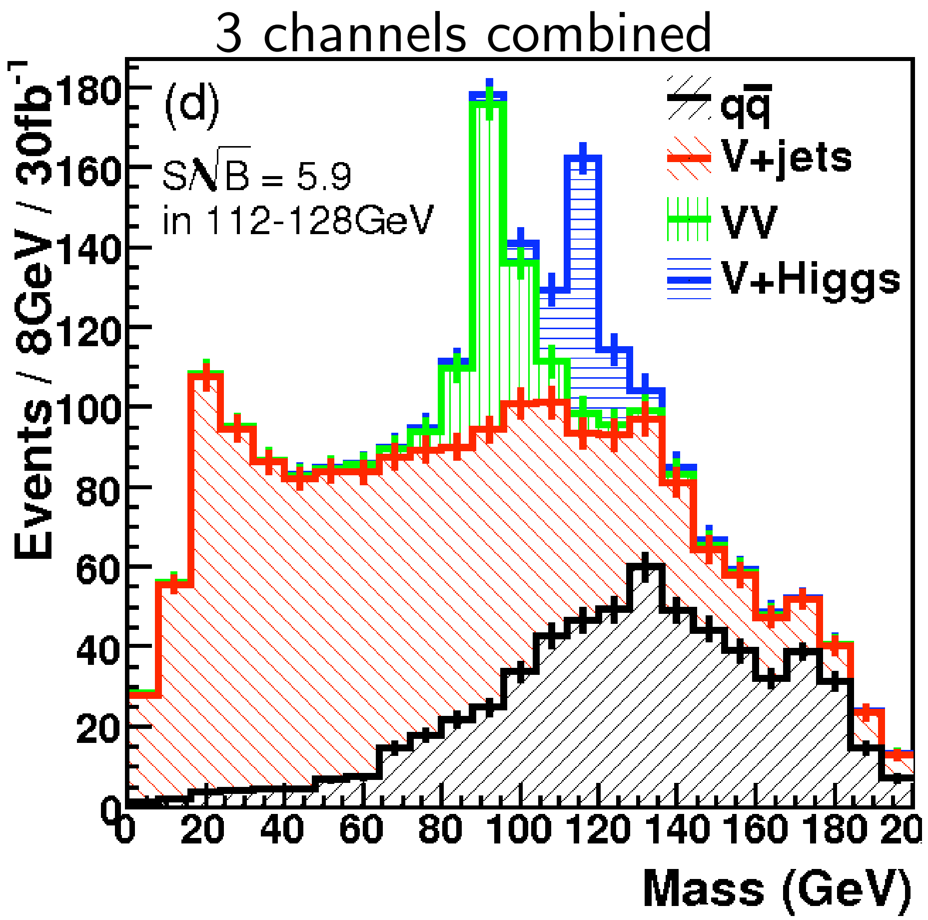
- QCD partons prefer soft emissions (hard → hard + soft)
- Higgs decay prefers symmetric splitting
- try to beat down contamination from underlying event
- try to capture most of the perturbative QCD radiation



1. cluster the event with e.g. CA algo and large-ish R
2. undo last recomb: large mass drop + symmetric + b tags
3. filter away the UE: take only the 3 hardest sub-jets

Z/W+ H (→bb) rescued ?

Mass of the three hardest sub-jets:



- with common & channel specific cuts: p_{tV}, p_{tH} > 200GeV , ...
- real/fake b-tag rate: 0.7/0.01
- NB: very neat peak for WZ (Z →bb) Important for calibration

Butterworth, Davison, Rubin, Salam '08

5.9σ at 30 fb^{-1}:VH with H → bb recovered as one of the best discovery channels for light Higgs

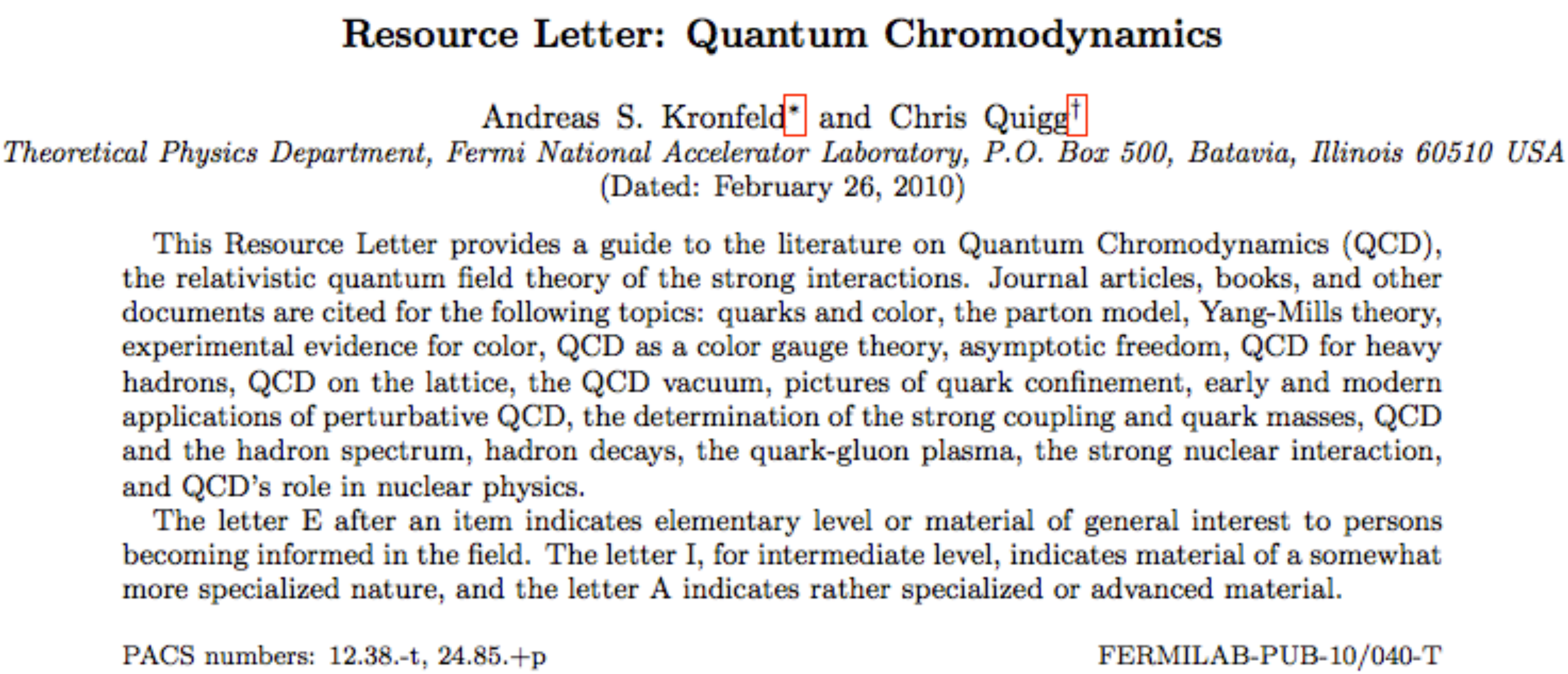
Recap on jets

- Two major jet classes: sequential (k_t, CA, ...) and cones (UA1, midpoint, ...)
- Jet algo is fully specified by: clustering + recombination + split merge or removal procedure + all parameters
- Standard cones based on seeds are IR unsafe
- SISCone is new IR safe cone algorithm (no seeds) and anti-kt a new sequential algorithm
- Using IRunsafe algos you can not use perturbative QCD calculations
- With IRsafe algo: sophisticated studies e.g. jet-area for pile-up subtraction
- Not all algos fare the same for BSM/Higgs searches: quality measures
- Recent applications of jet substructure (Higgs example)

Some bibliography

- Text books
  - QCD and Collider physics, Ellis, Stirling, Webber (a.k.a. The pink book)
  - Basics of Perturbative QCD, Dokshitzer, Khoze, Mueller, Troyan
  - Foundations of Quantum Chromodynamics, Muta
  - Quantum Chromodynamics: High Energy Experiments and Theory, Dissertori, Knowles, Schmelling
- Summaries of recent research activity
  - Les Houches writeups
    - SM and NLO multi-leg working group: summary report [1003.1241]
    - Quantum Chromidynamics, PDG contribution, Dissertori & Salam [http://pdg.lbl.gov/2009/reviews/rpp2009-rev-qcd.pdf]
- Various papers cited on the way

More bibliography


Resource Letter: Quantum Chromodynamics

Andreas S. Kronfeld[*] and Chris Quigg[†]
Theoretical Physics Department, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510 USA
(Dated: February 26, 2010)

This Resource Letter provides a guide to the literature on Quantum Chromodynamics (QCD), the relativistic quantum field theory of the strong interactions. Journal articles, books, and other documents are cited for the following topics: quarks and color, the parton model, Yang-Mills theory, experimental evidence for color, QCD as a color gauge theory, asymptotic freedom, QCD for heavy hadrons, QCD on the lattice, the QCD vacuum, pictures of quark confinement, early and modern applications of perturbative QCD, the determination of the strong coupling and quark masses, QCD and the hadron spectrum, hadron decays, the quark-gluon plasma, the strong nuclear interaction, and QCD's role in nuclear physics.

The letter E after an item indicates elementary level or material of general interest to persons becoming informed in the field. The letter I, for intermediate level, indicates material of a somewhat more specialized nature, and the letter A indicates rather specialized or advanced material.

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