Very high precision theoretical challenges

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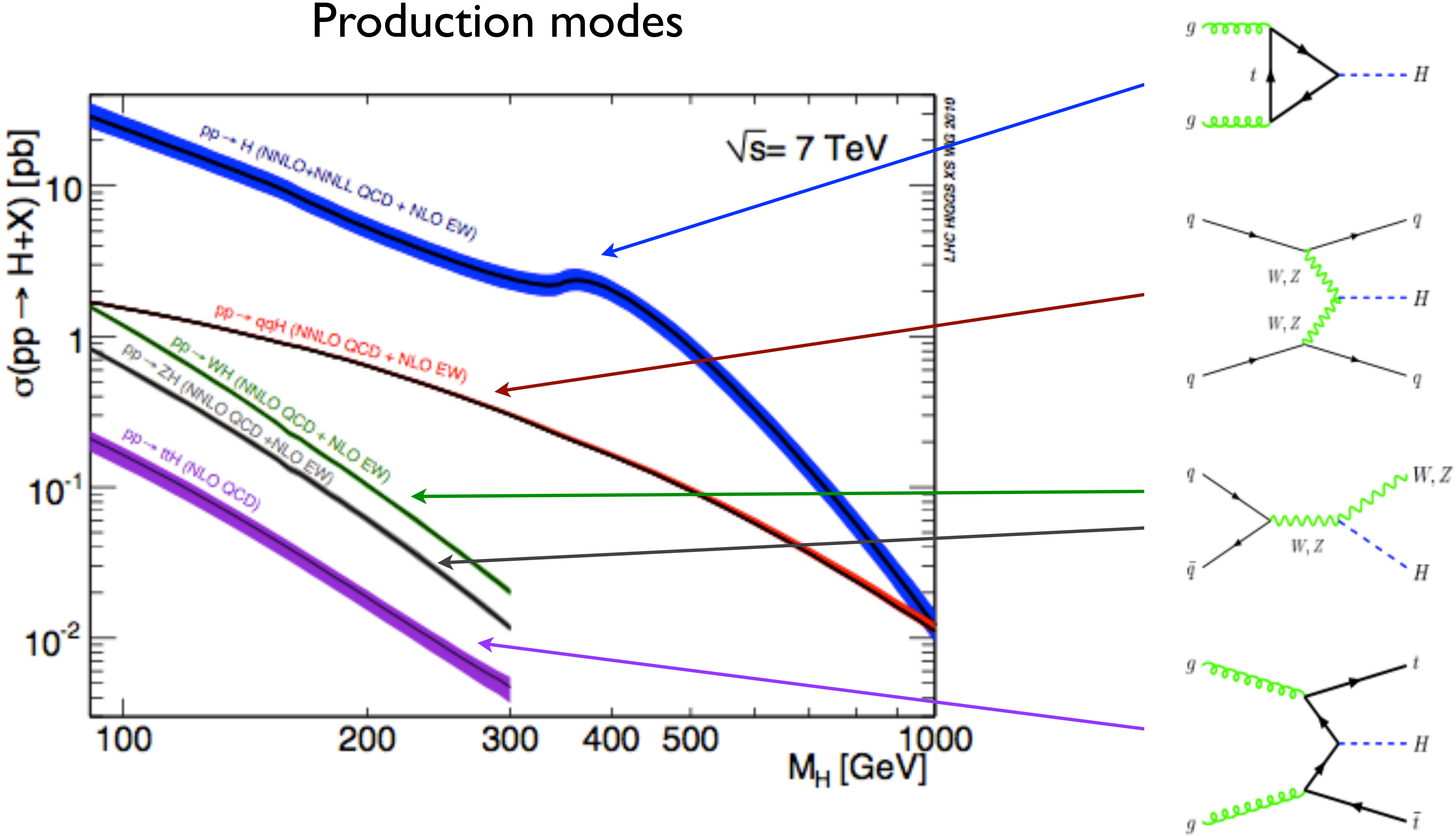
3rd Lecture

Cargese Summer School — July 2014

Multi-TeV Probes of Standard Model Physics with the LHC

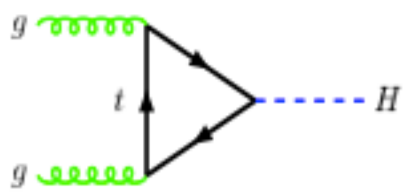
SM Higgs production at the LHC

Production modes

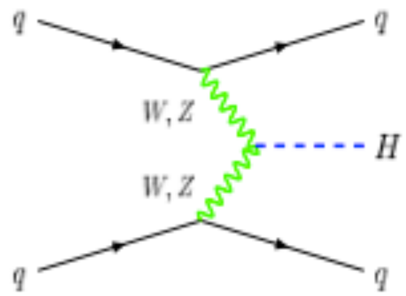


SM Higgs production at the LHC

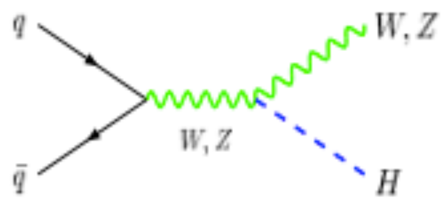
- largest mode
- most studied (NNLO,NLO+EW, NNLL ...)
- accuracy 20% ?



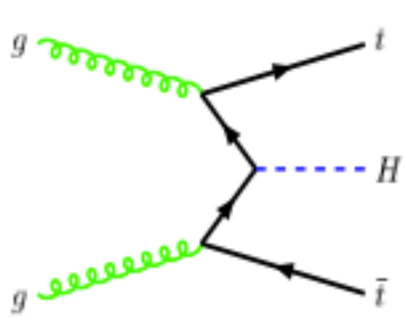
- distinctive tagging jets (apply VBF cuts)
- possibility to measure Higgs couplings
- NLO, partial NNLO. Accuracy 2-3% ?



- large background. Resurrected using boosted studies
- possibility to measure HWW and HZZ couplings
- NNLO production. Accuracy 2-5% ?



- re-analyzed using boosted studies
- would allow to measure Htt coupling
- difficult final state, large backgrounds (ttbb,ttjj)



see Handbook for LHC cross-sections: 1101.0593 and 1201.3084

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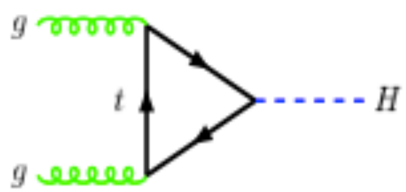

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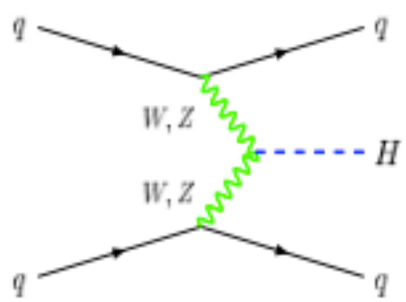

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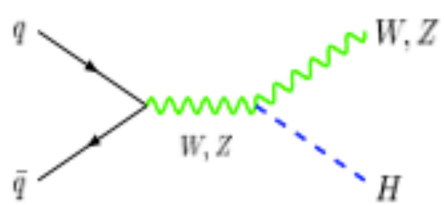

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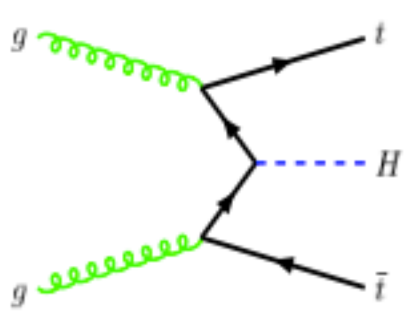

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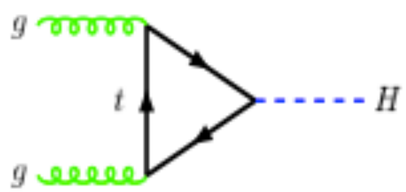

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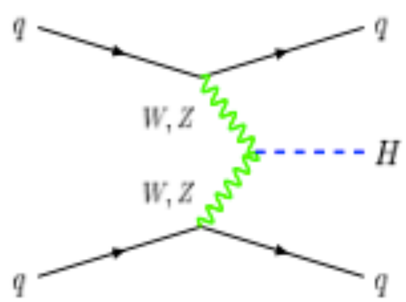

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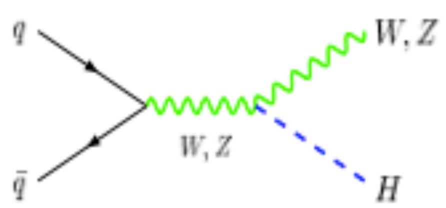

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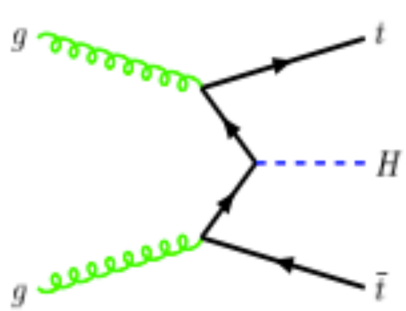

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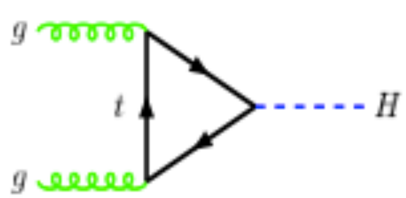

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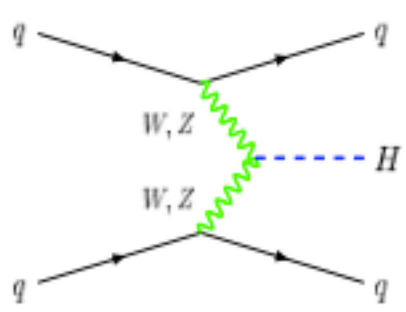

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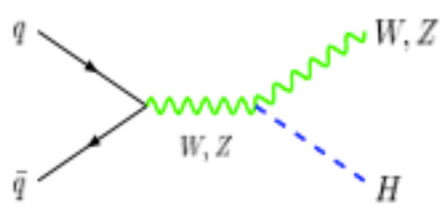

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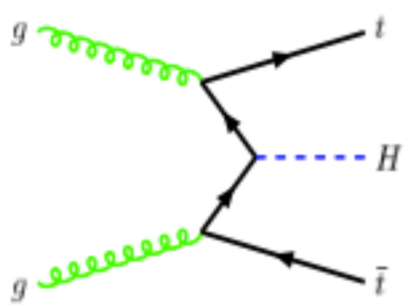

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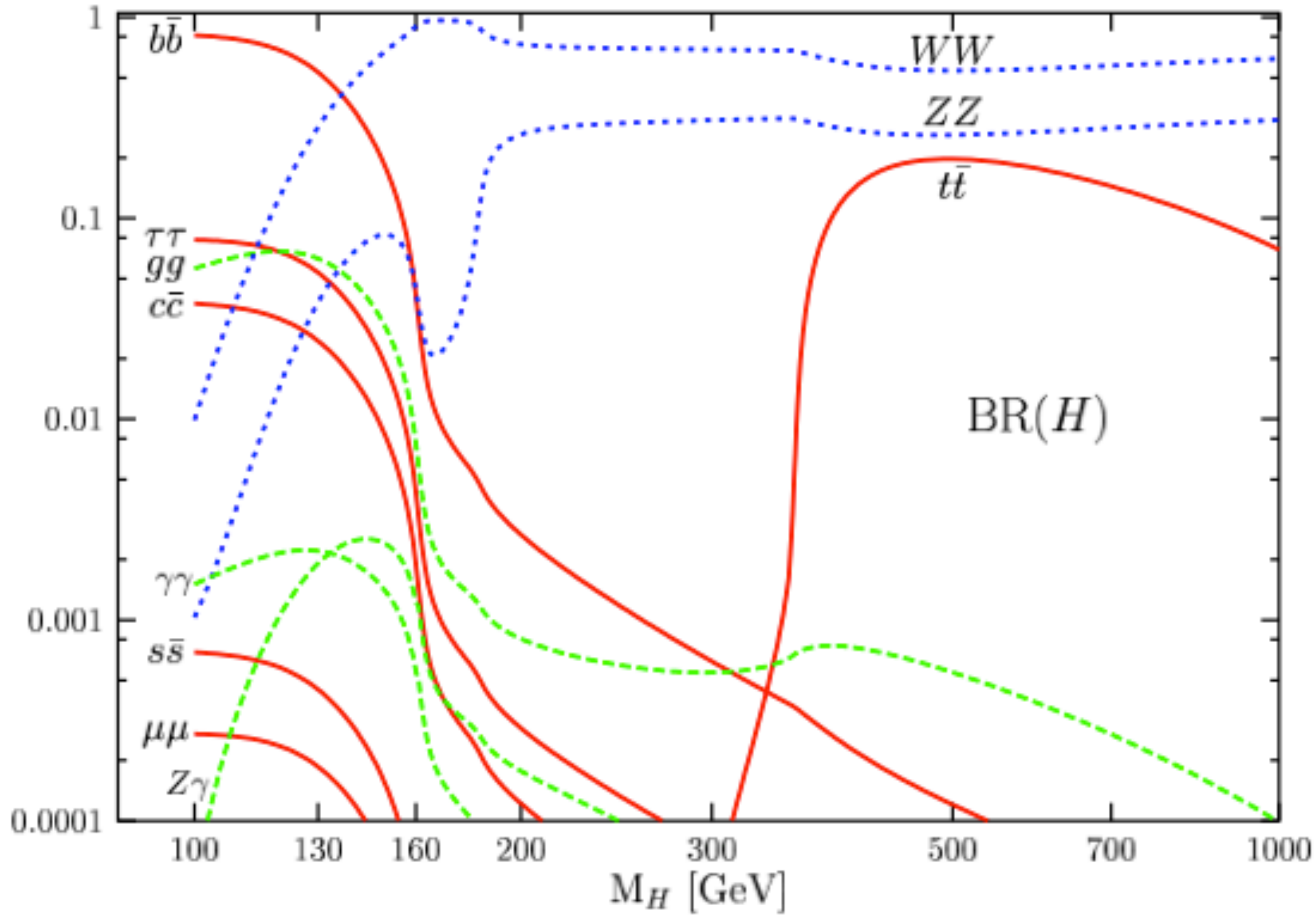
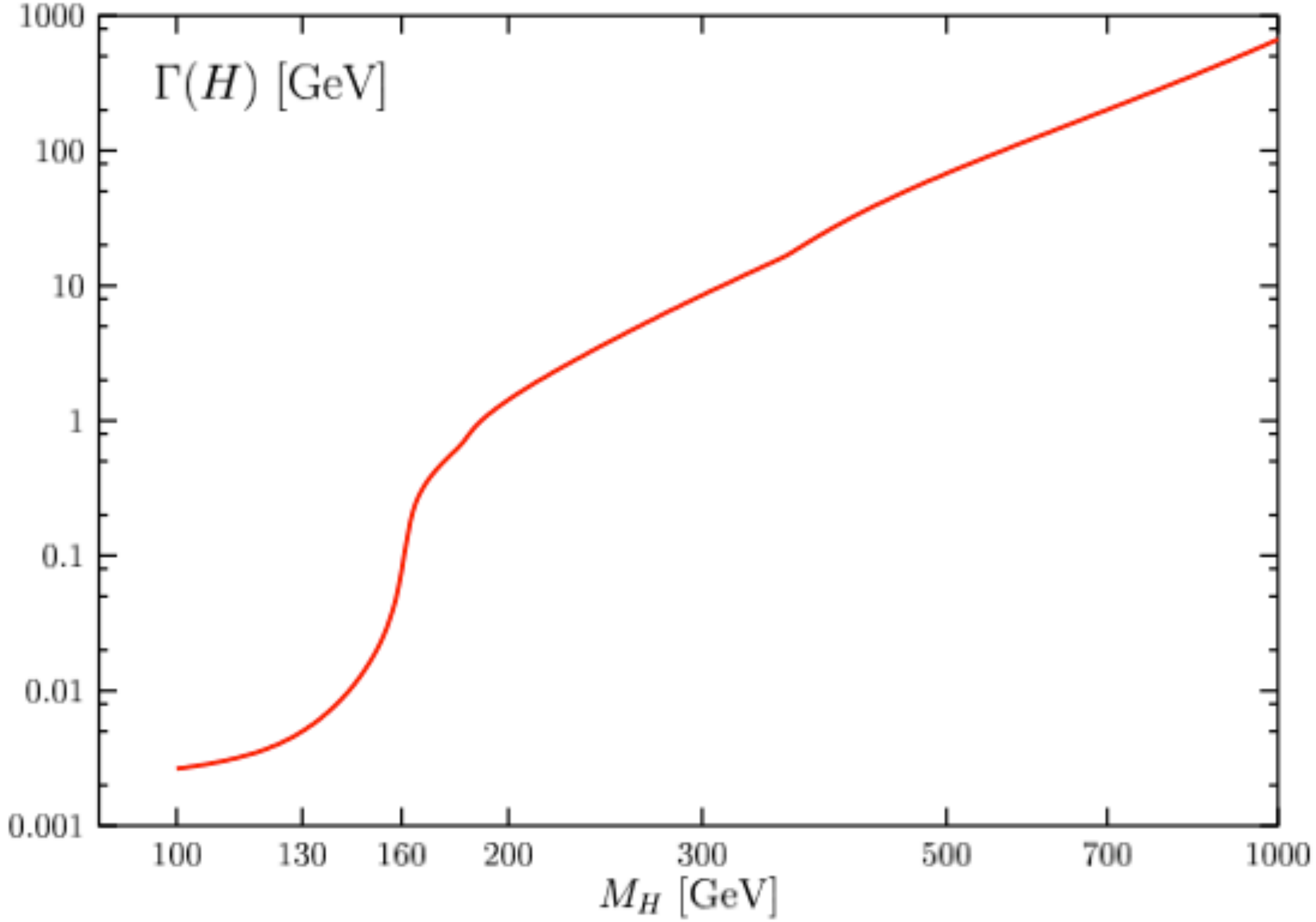
SM Higgs decay modes and branching ratios



Dominant decay into
- WW/ZZ for $M_H > 130$ GeV
- bb for $M_H < 130$ GeV (but difficult background, while γγ is very small but much cleaner)

SM Higgs total width



- heavy Higgs (M_H>500 GeV) has a width comparable to its mass
- unclear how to represent a Higgs propagator
- also unclear how legitimate it is to think of the Higgs as particle

Couplings to the SM Higgs boson

The SM Higgs boson mechanism is testable at the LHC since given the Higgs mass, all couplings to the Higgs boson are known

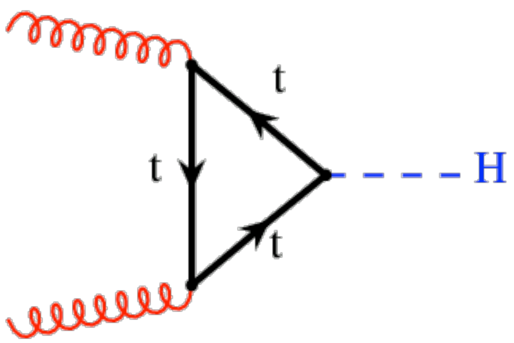
$$g_{ffH} \propto m_f/v \qquad \text{(fermions)}$$
$$g_{VVH} \propto M_V^2/v \qquad \text{(gauge bosons)}$$

Therefore the Higgs properties (production modes, decay modes and branching ratios, and lifetime) are fully determined by it's mass

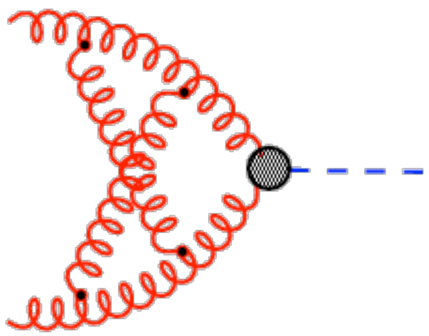
Extended Higgs models have a more complicated structure

Inclusive NNLO Higgs production

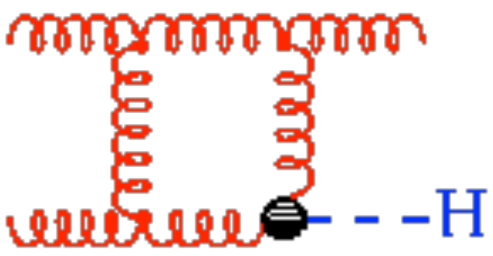
Inclusive Higgs production via gluon-gluon fusion in the large m_t-limit:



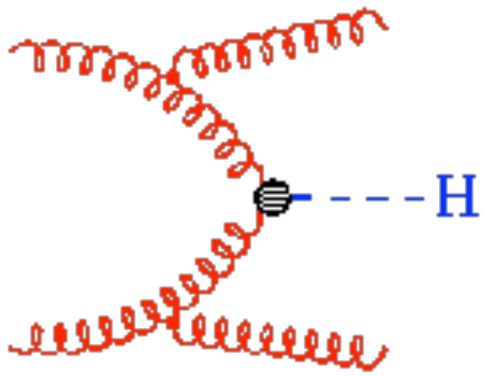
NNLO corrections known since many years now:



virtual-virtual

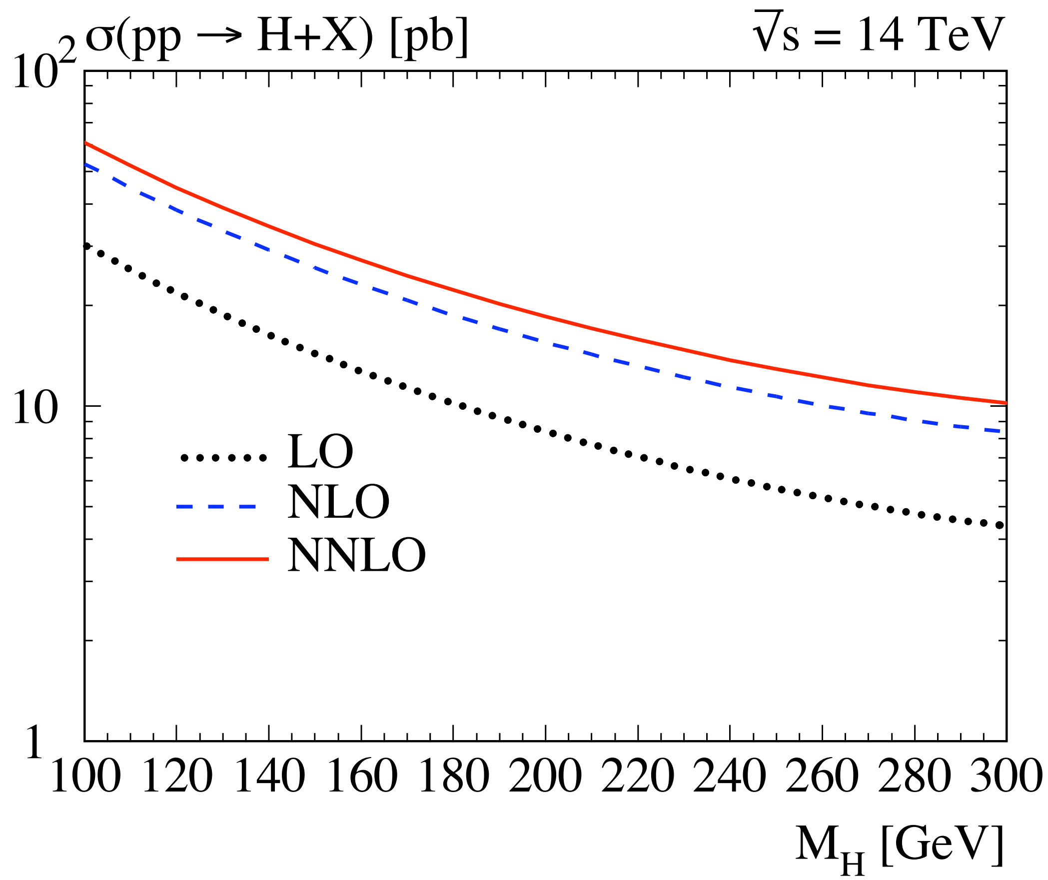


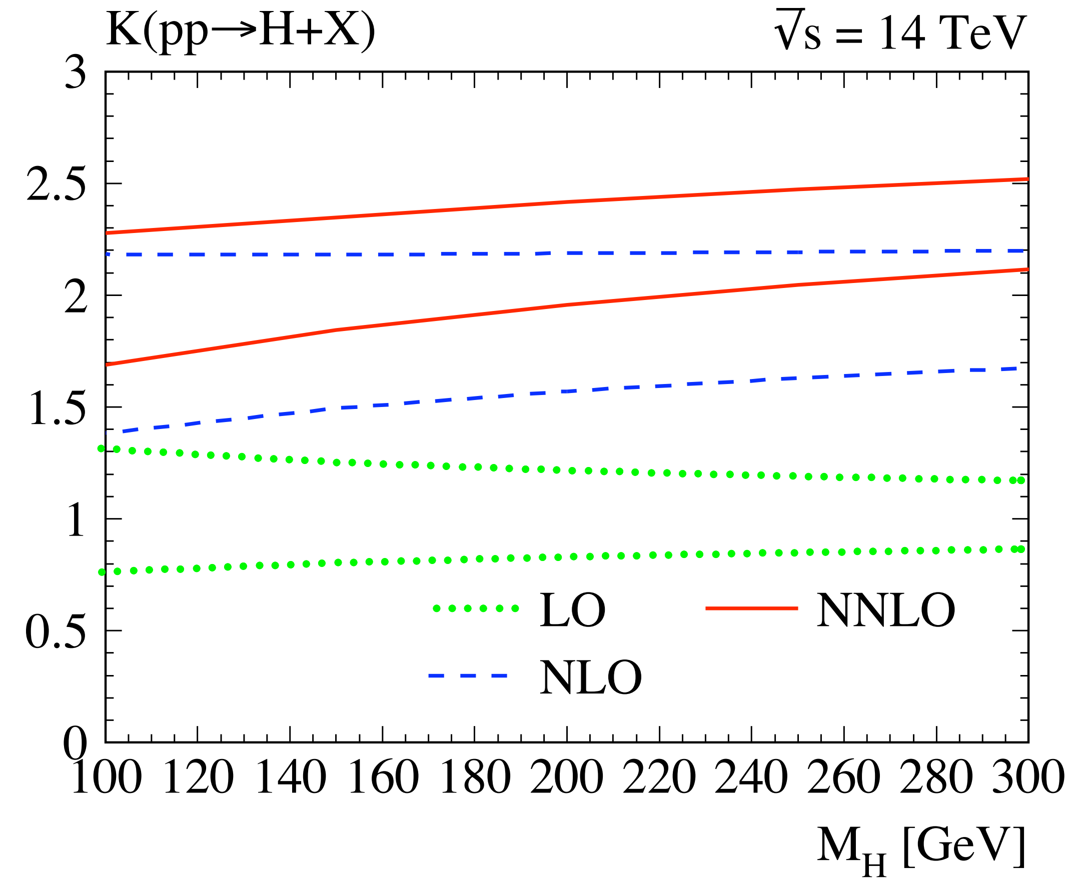
real-virtual



real-real

Inclusive NNLO Higgs production





Kilgore, Harlander '02
Anastasiou, Melnikov '02

Further improvement on gg → H

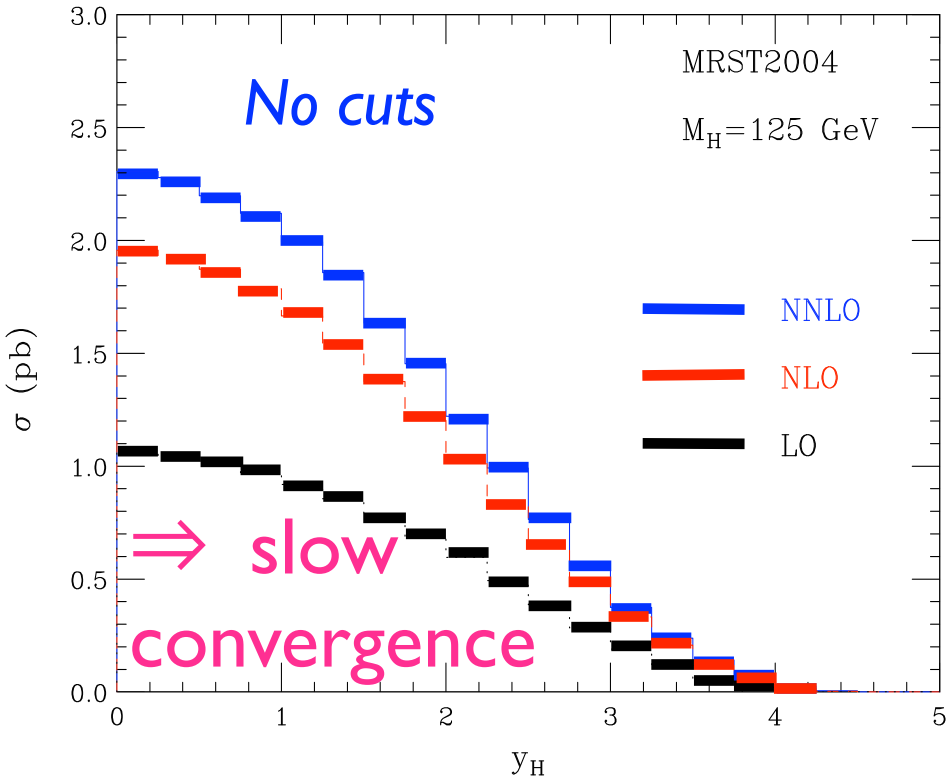
The urge to understand EW symmetry breaking led to most advanced theoretical predictions, for instance, we know the main gg → H production mechanism in the SM including

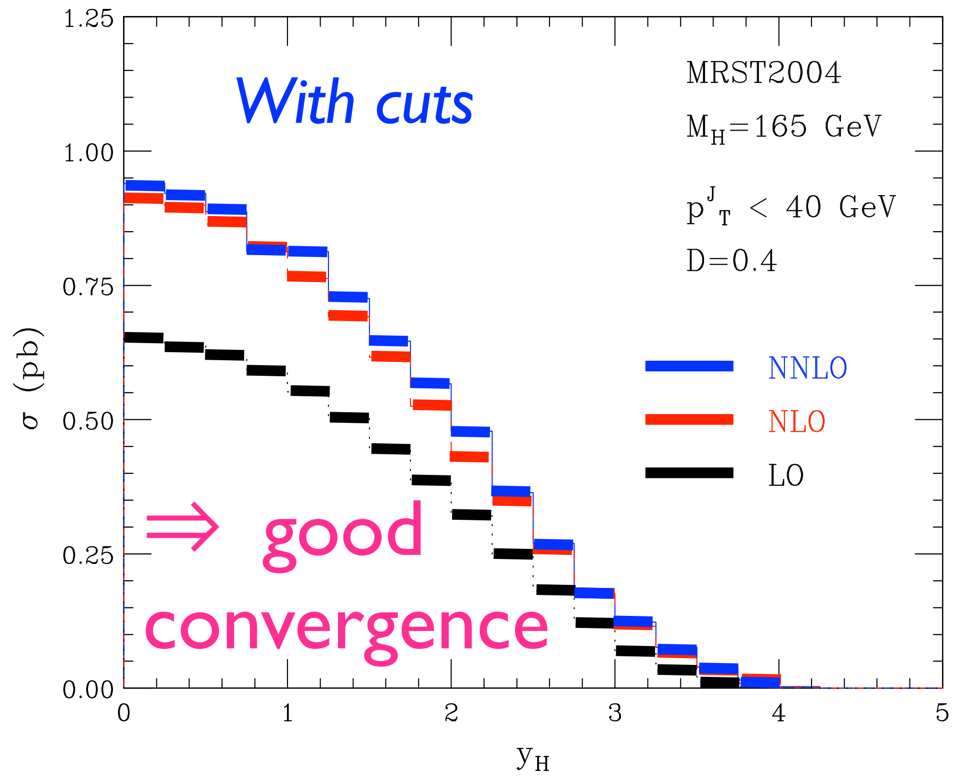
- NLO with exact top and bottom loop — Djouadi, Graudenz, Spira, Zerwas '93,'95
- electroweak corrections — Actis, Passarino, Sturm, Uccirati '08
- mixed QCD - EW corrections — Anastasiou, Boughezal, Petriello '09
- resummation and/or N^3LO soft — Catani, De Florian, Grazzini, Nason '03; Moch and Vogt '05; Laenen, Magnea '06; Ahrens, Becher, Neubert, Yang '08
- fully exclusive decays to $\gamma\gamma$, WW → $l^+l^- \nu\nu$ and ZZ → 4l — Catani and Grazzini '08; Anastasiou, Melnikov Petriello '05; Anastasiou, Dissertori, Stoeckli '07
- also exclusive NNLO VH(→bb) — Ferrera, Grazzini, Tramontano '11
- first approx N^3LO terms — Anastasiou et al '14

Exclusive NNLO Higgs production

First fully exclusive NNLO calculation of $H \to WW \to 2l\ 2\nu$

FEHIP, Anastasiou, Dissertori, Stoeckli '07
also: HNNLO Catani, Grazzini '08





⇒ impact of NNLO dramatically reduced by cuts.
[But is this really true? ...]

Very important to include cuts and decays in realistic studies

Uncertainty on gg → H

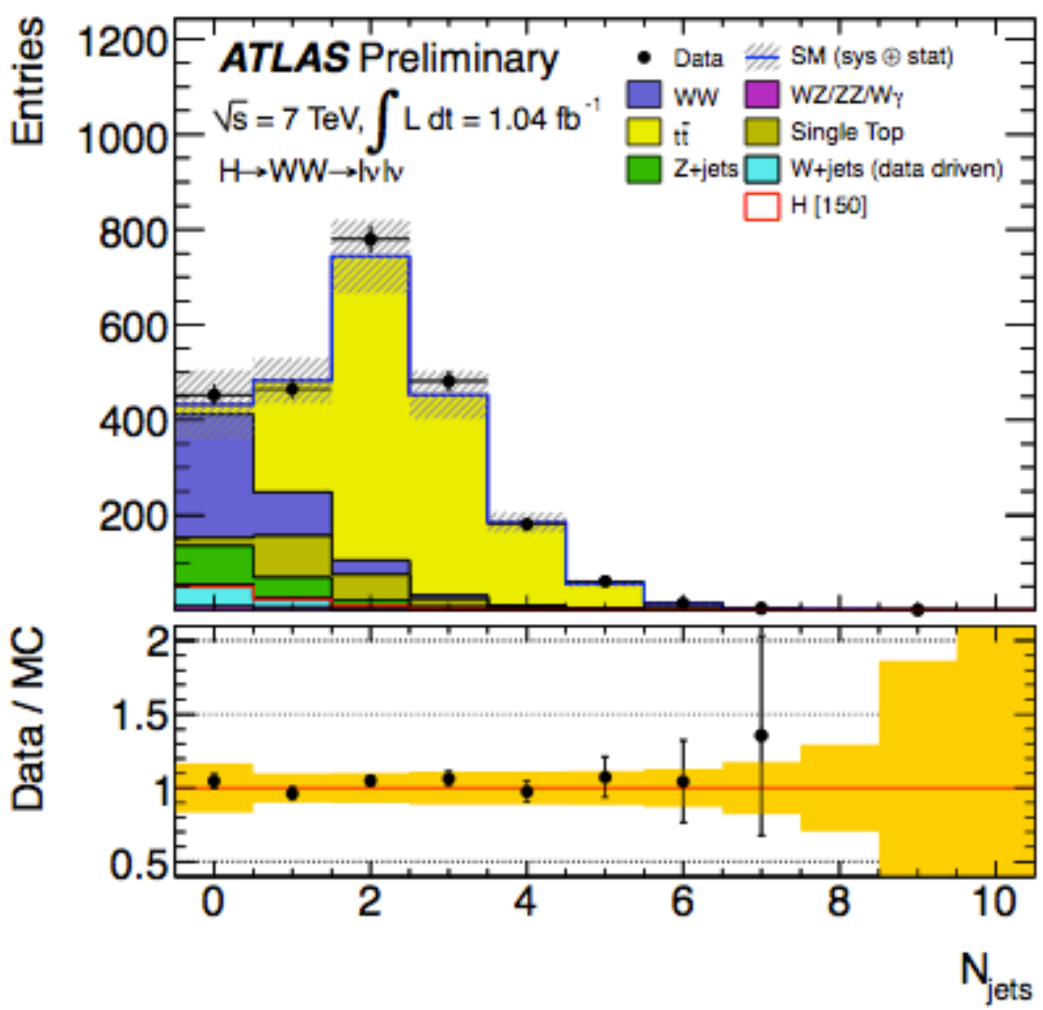
So, how well do we know this process?
What is the theory error on it ?

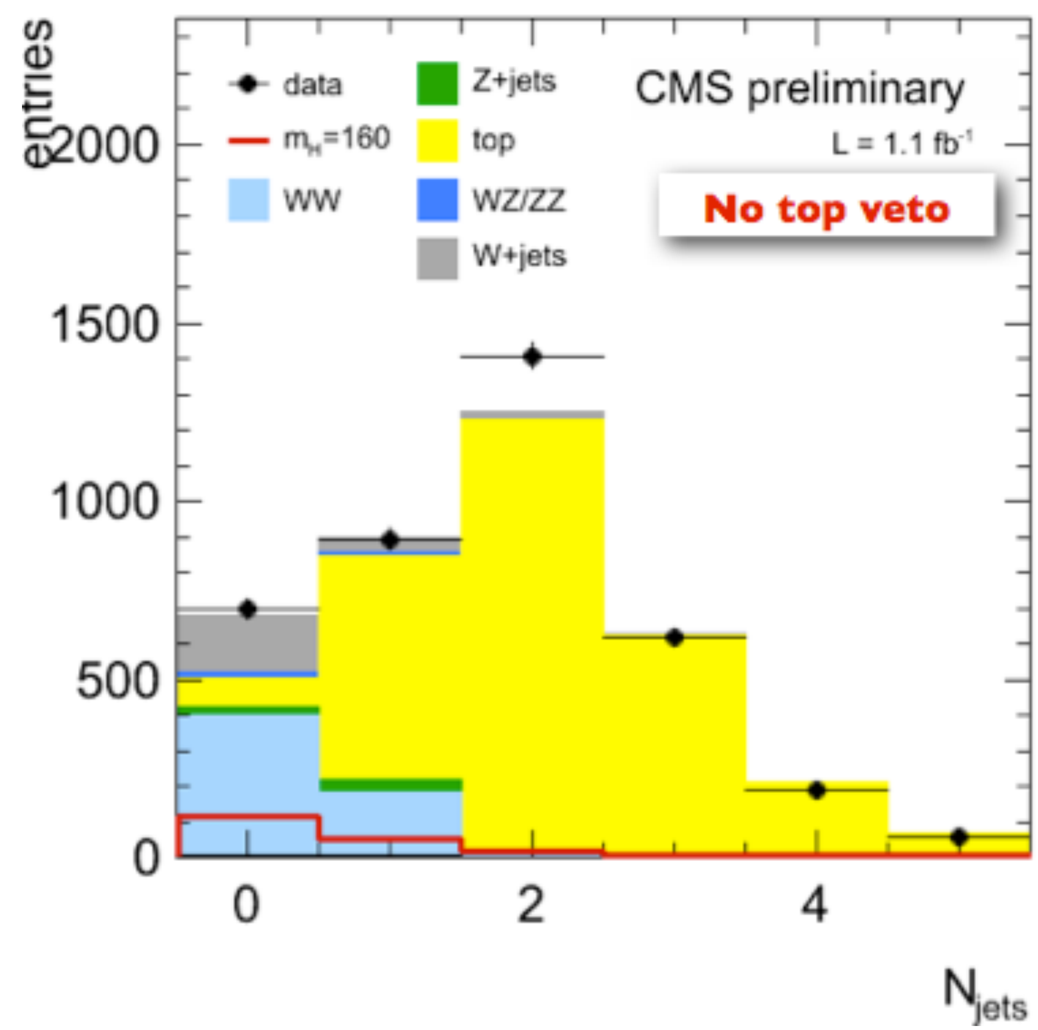
Assigning a theoretical error very important to claim exclusion/excess, and for measurements of couplings. Yet, even for the main Higgs production channel there are still controversies. I will illustrate here one of them.

Many issues, discussions, recommendations can be found in the Handbook of LHC cross-sections (Vol I and II) 1101.0593 and 1201.3084

Jet veto

Need jet veto to kill large top background, ideally $p_T^{veto} \approx 25$ GeV

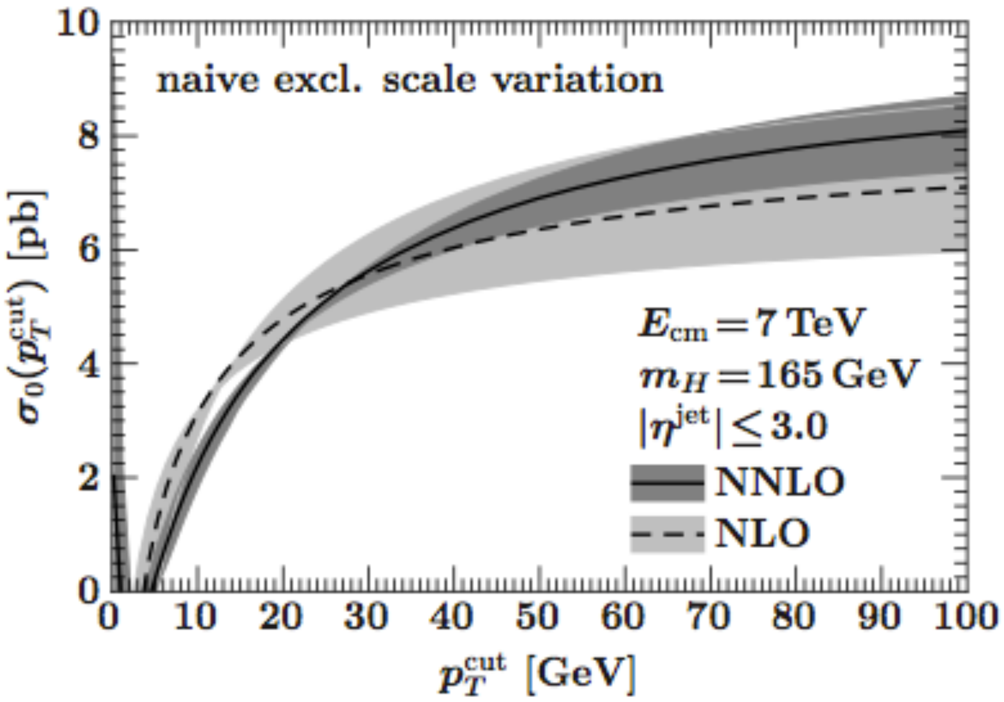


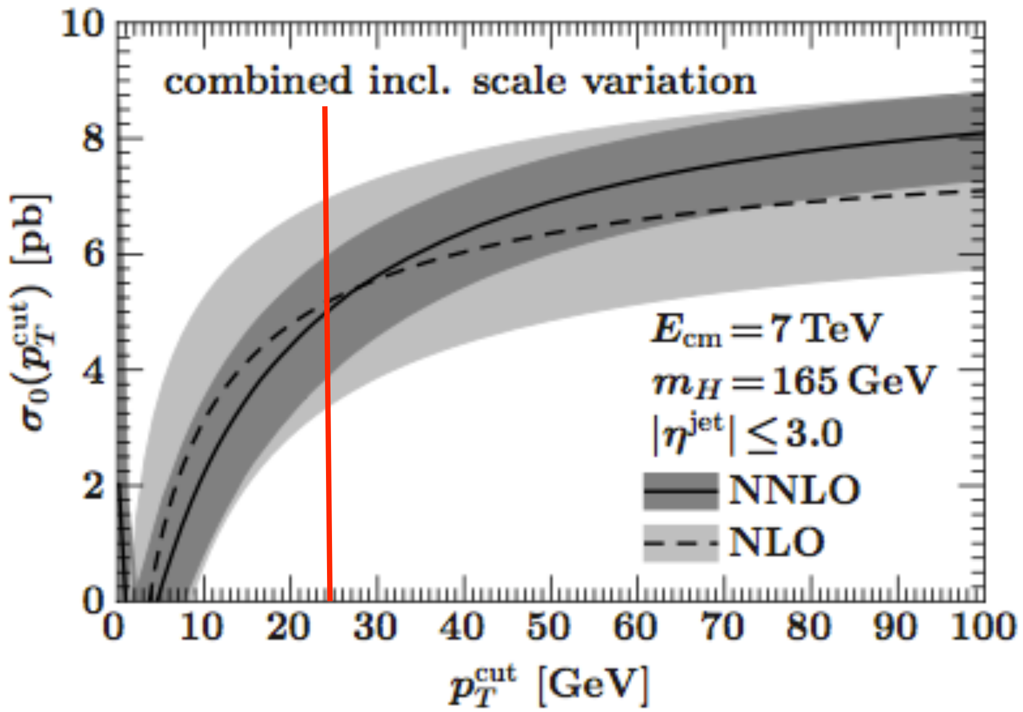


Higgs production studied in 0-,1-,2-jet bin separately to maximize sensitivity

Jet veto uncertainties

Stewart and Tackman '11





- with p_T^{veto} much smaller error
- large positive correction (K-fact) and large negative logarithms

$$-\frac{2C_A\alpha_s}{\pi}\ln^2\frac{M_H}{p_T^{veto}}$$

Scale variation alone underestimates uncertainties

- full correlations between jet bins

large K *large logarithms*

$$\sigma_{0\,\text{jets}} = \sigma_{\text{tot}} - \sigma_{\geq 1\,\text{jet}}$$

$$\Delta^2\sigma_{0\,\text{jets}} = \Delta^2\sigma_{\text{tot}} + \Delta^2\sigma_{\geq 1\,\text{jet}}$$

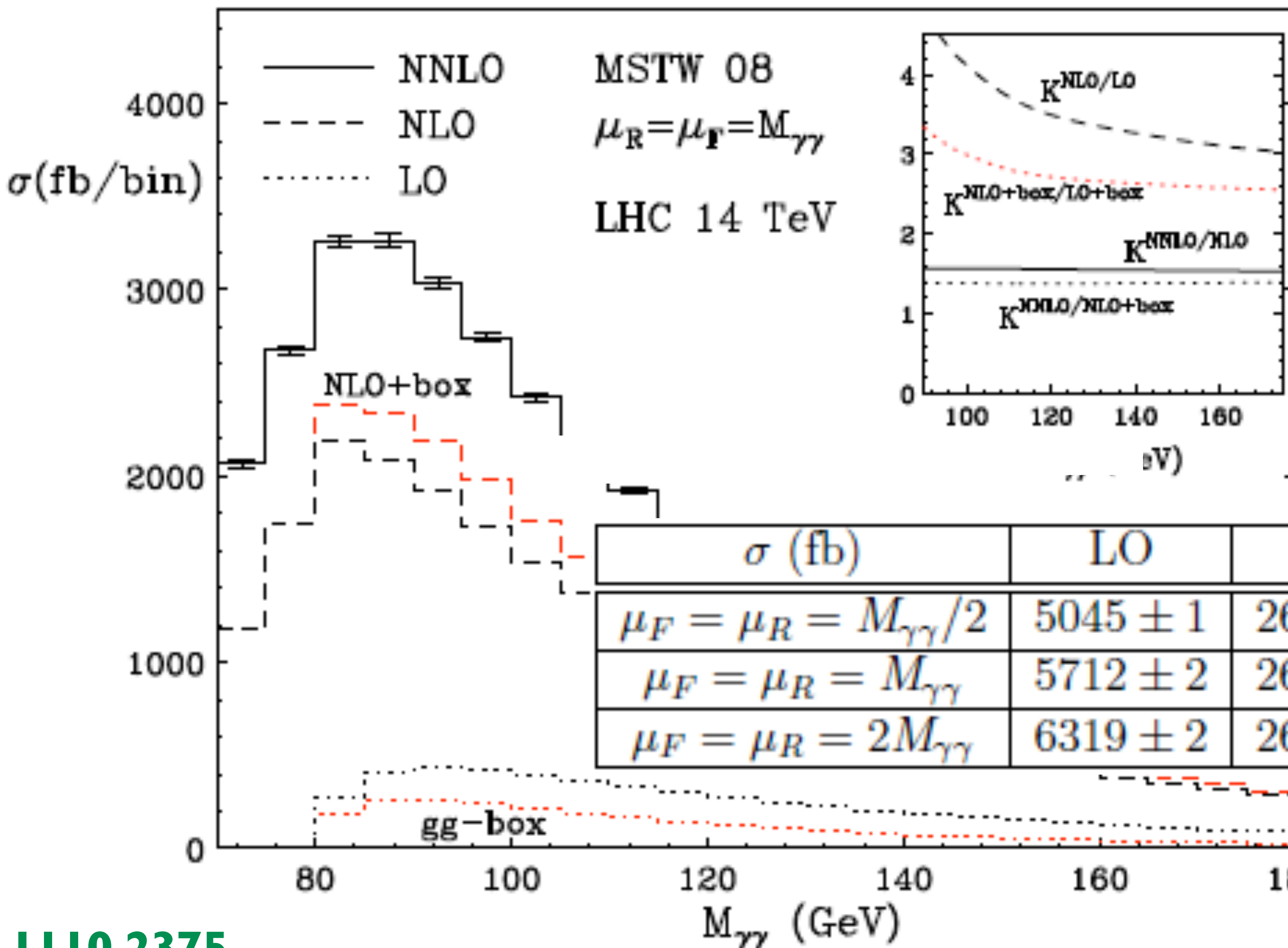
Uncertainties overestimated?

Higgs

Despite the high degree of sophistication in Higgs cross-section calculations an assessment of the theoretical uncertainties is still controversial today.

Focus in the next years will be on these kind of issues.

Recent NNLO highlights:γγ



σ (fb)	LO	NLO	NNLO
$\mu_F=\mu_R=M_{\gamma\gamma}/2$	5045 ± 1	26581 ± 23	45588 ± 97
$\mu_F=\mu_R=M_{\gamma\gamma}$	5712 ± 2	26402 ± 25	43315 ± 54
$\mu_F=\mu_R=2M_{\gamma\gamma}$	6319 ± 2	26045 ± 24	41794 ± 77

Catani et al. 1110.2375

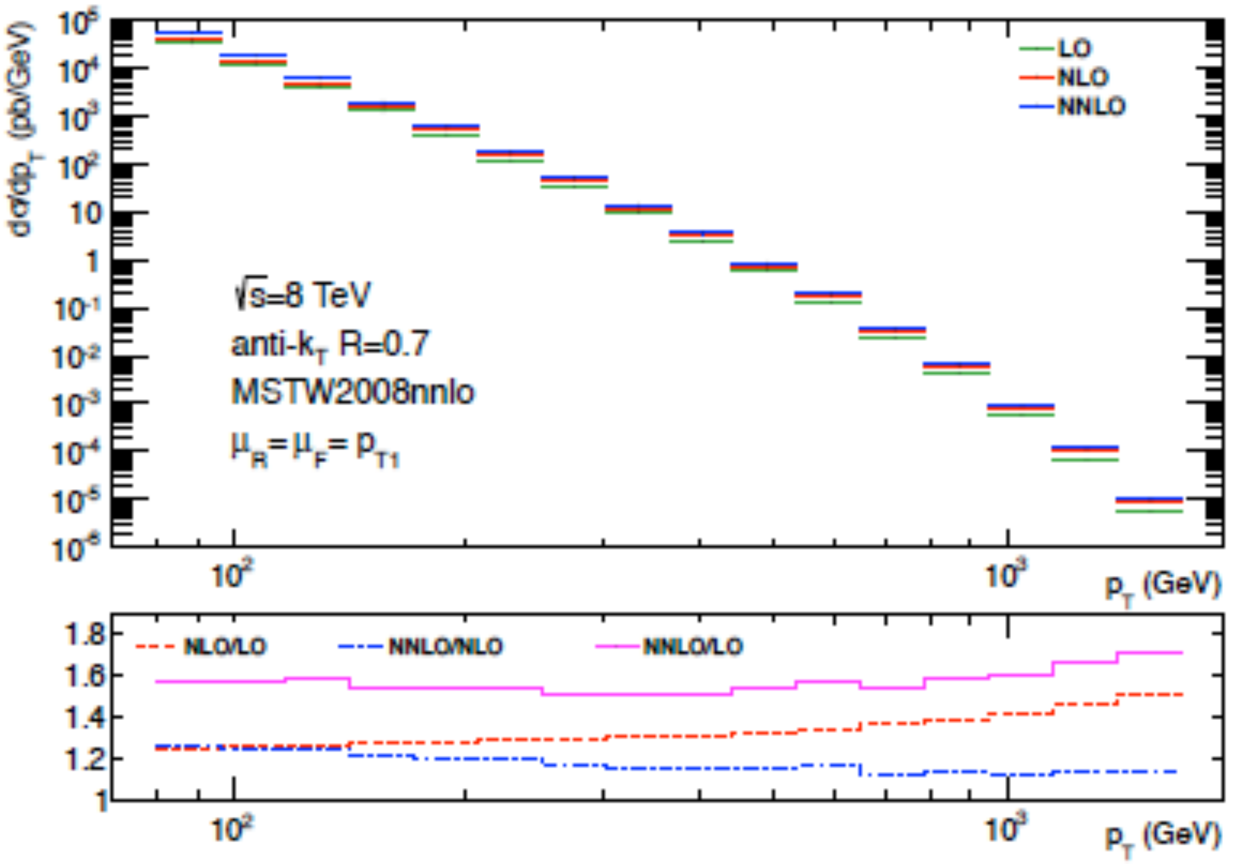
⇒ no good convergence of PT (asymmetric cuts + new channels)

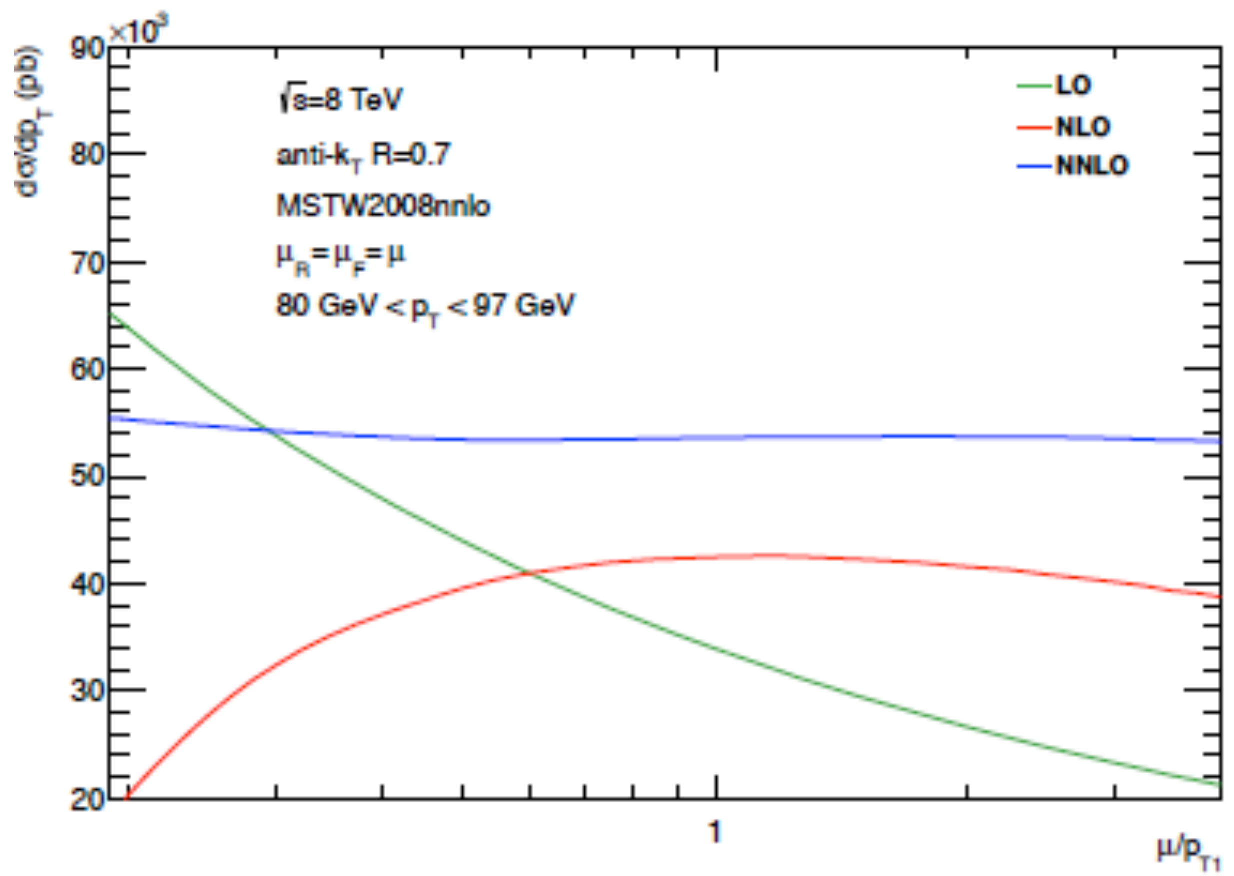
[similar to gg → H]

Recent NNLO highlights: dijets

gluon only contribution

Gehrmann et al. 1301.7310



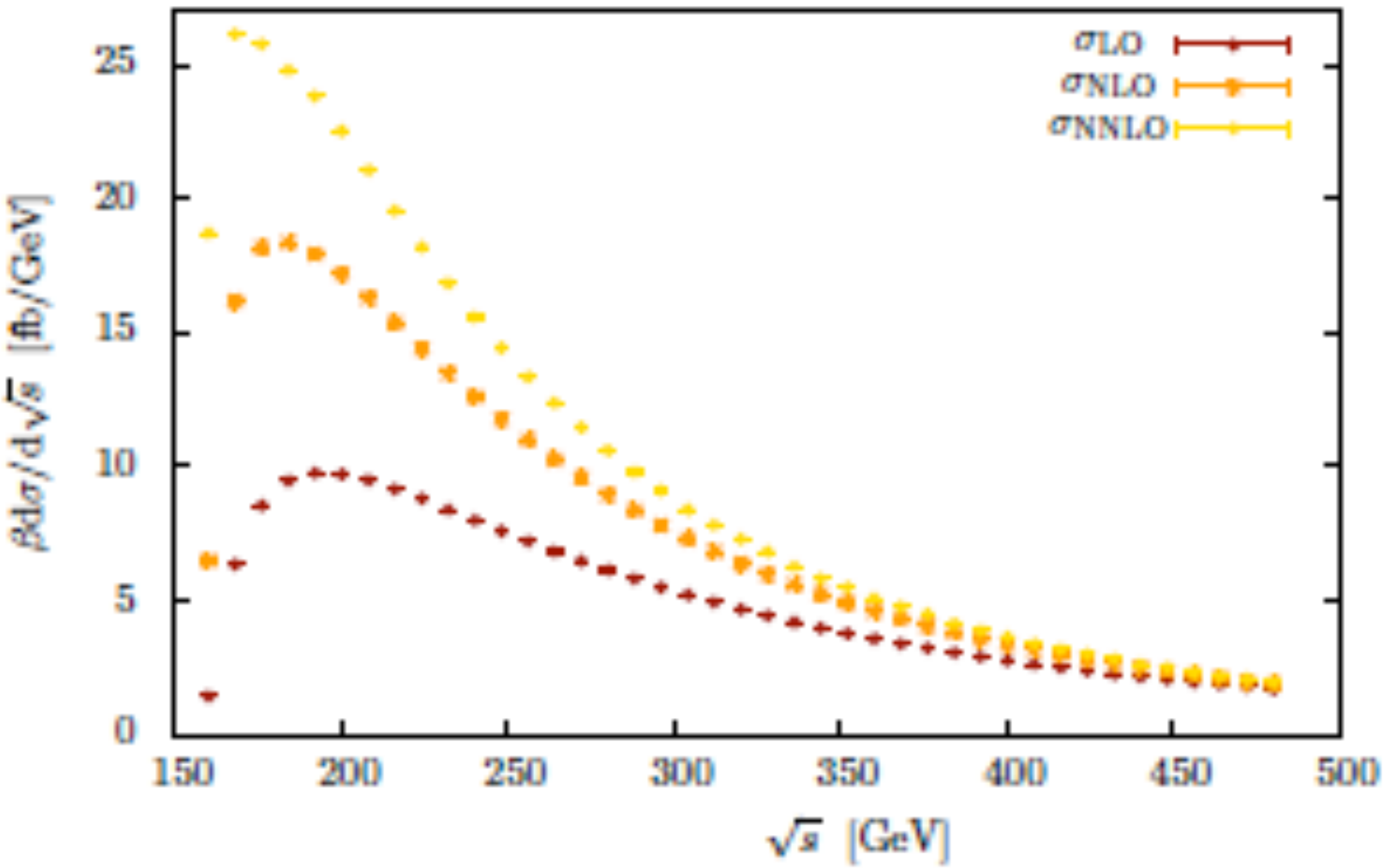


⇒ no good convergence of PT [similar to gg → H, pp → γγ]

Does this pattern survive once the full NNLO calculation is completed?

Recent NNLO highlights: H+1jet

Gluon fusion contribution to H+1jet

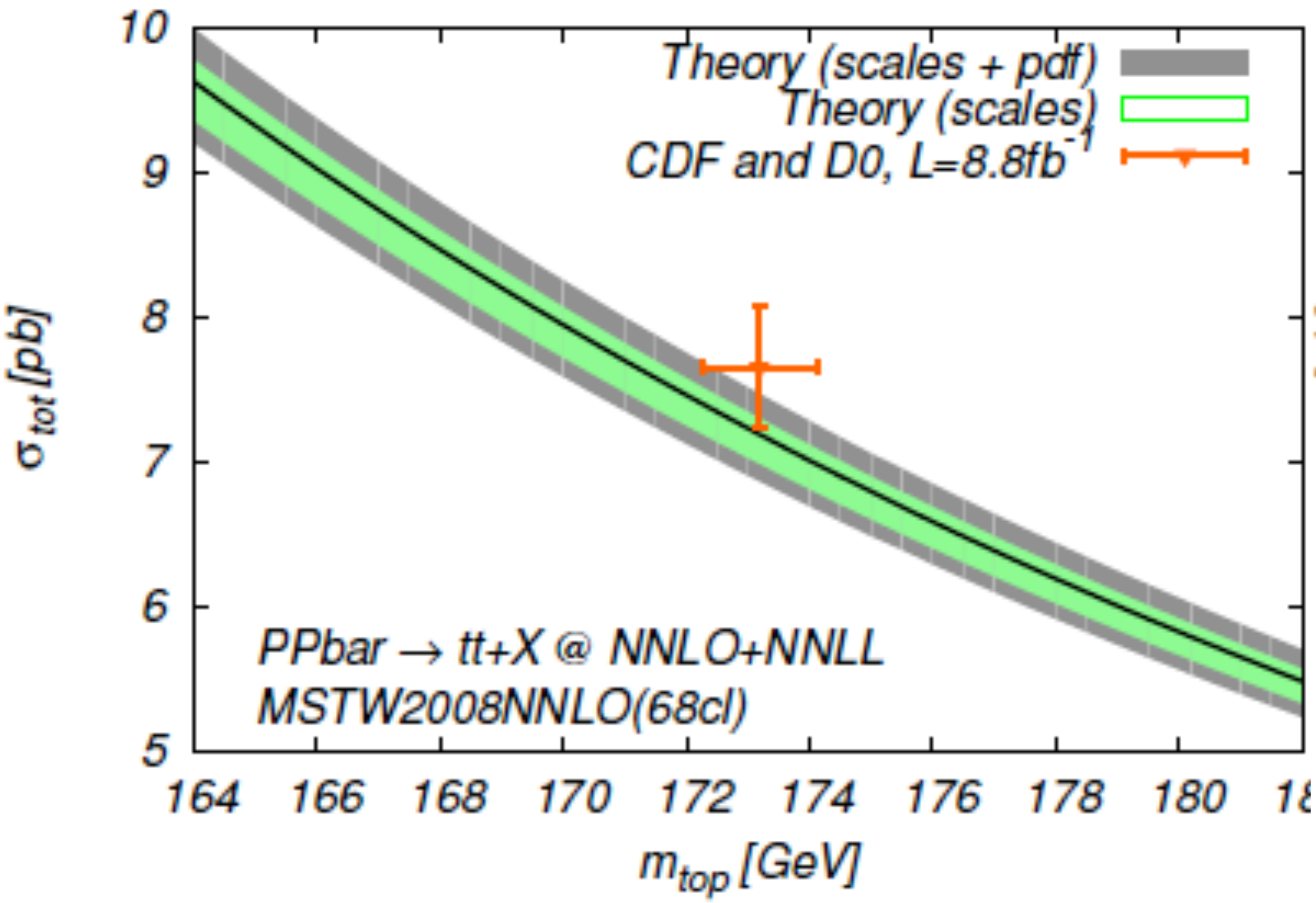


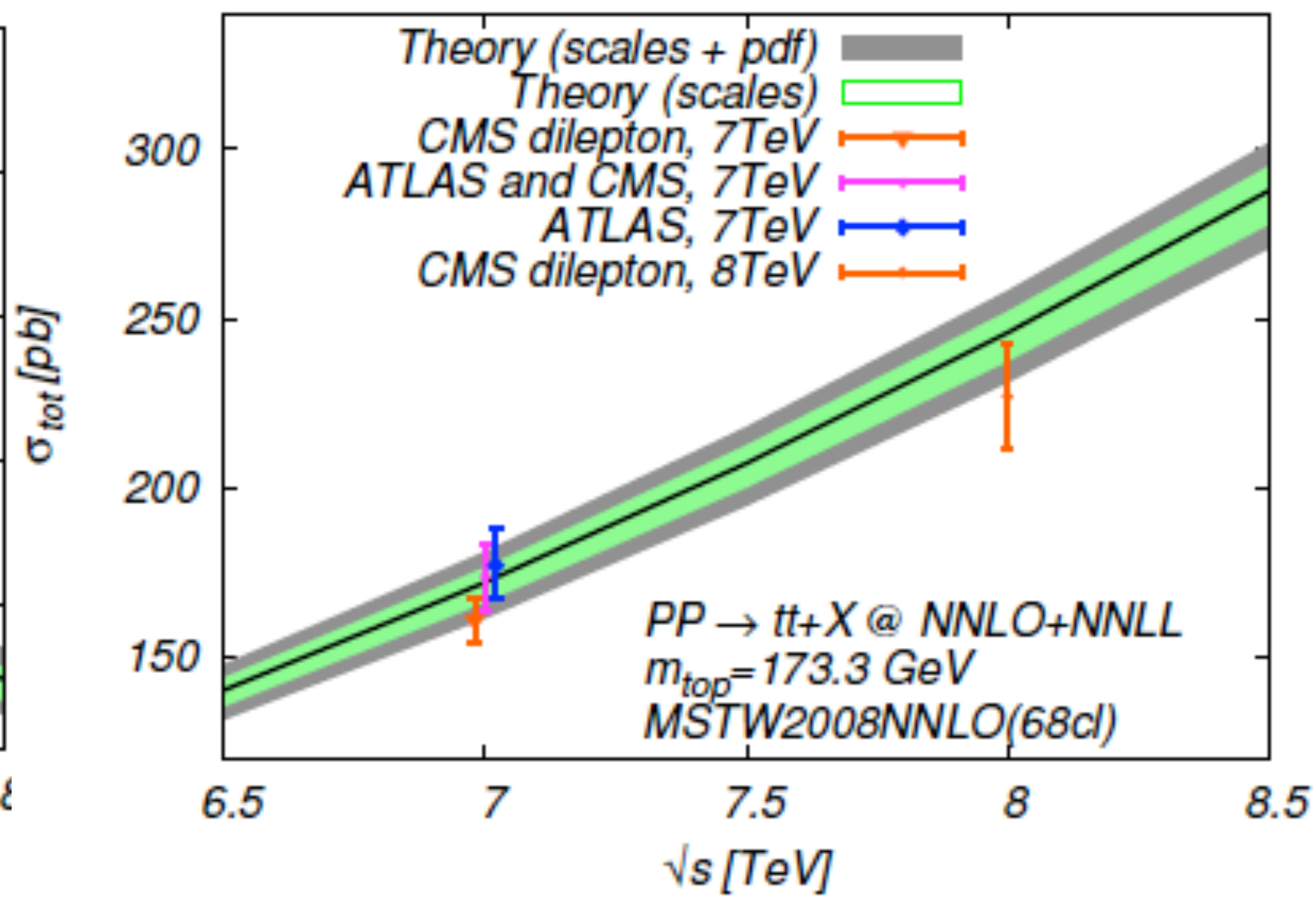
⇒ no good convergence of PT [similar to gg → H, pp → γγ, pp → dijets]

Does this pattern survive once the full NNLO calculation is completed?

Recent NNLO highlights: tt

First full NNLO calculation with colored particles in the initial and final state. Paves the way to a number of other calculations

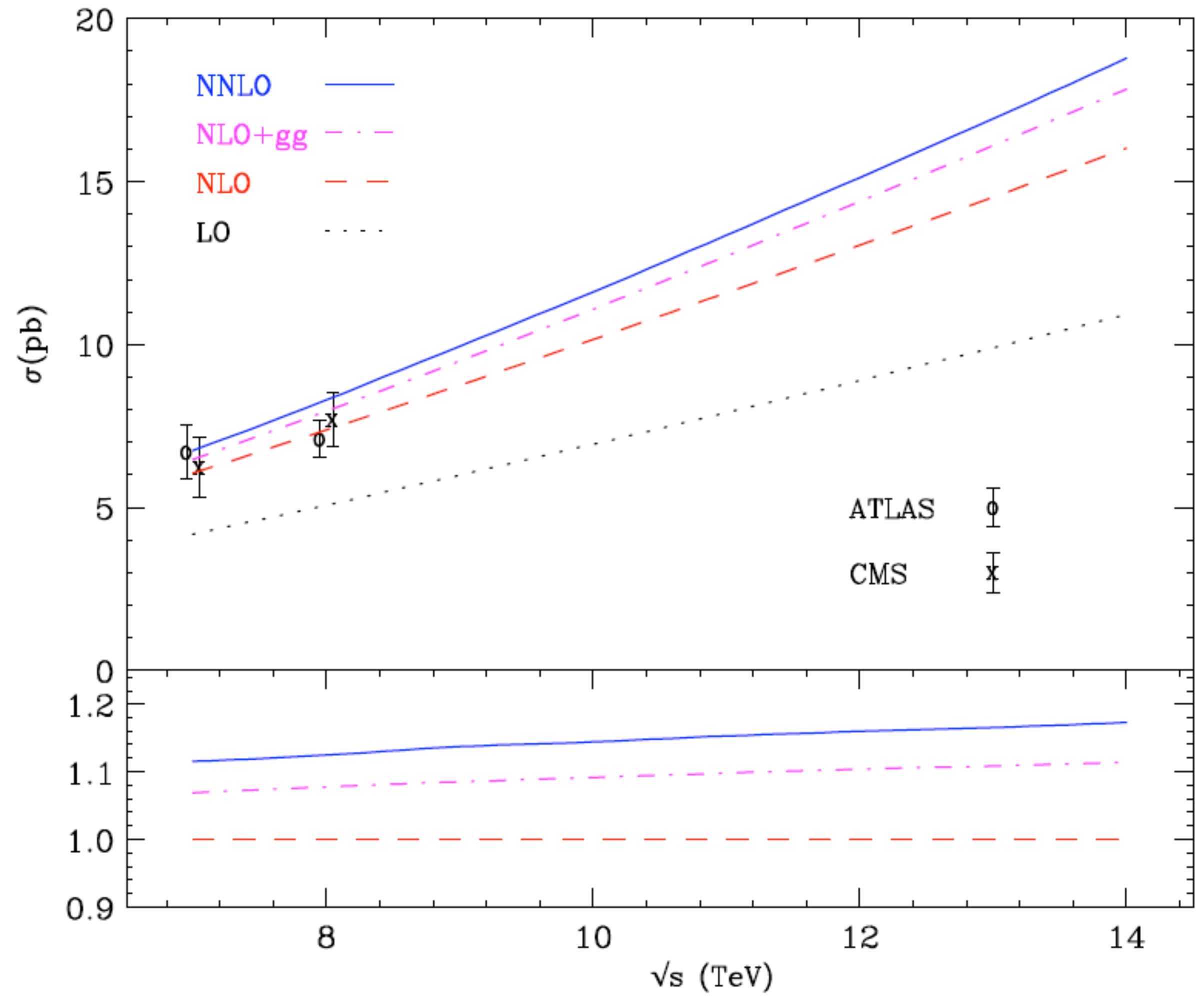




Czakon et al. 1303.6254
[+ previous refs...]

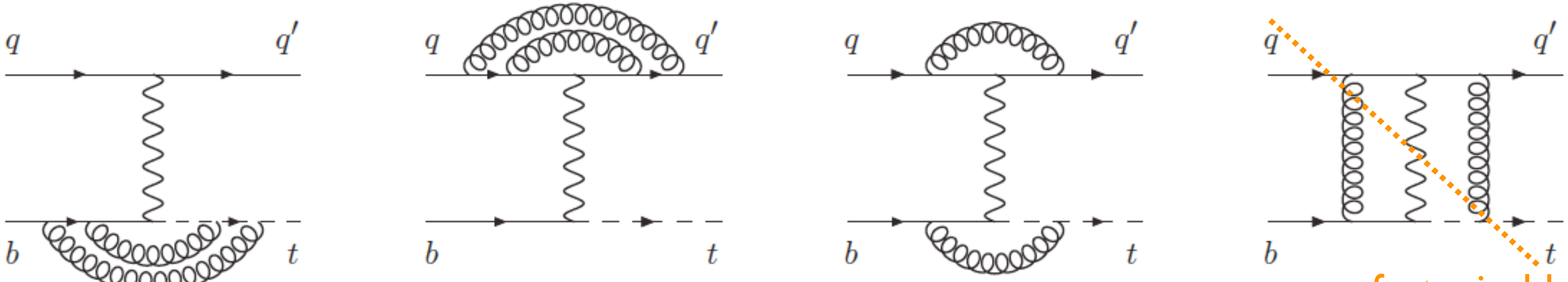
Recent NNLO highlights: ZZ

Cascioli et al. 1405.2219



- NNLO corrections reasonable (gg was known to be important because of gg luminosity)
- NNLO corrections to W^+W^- available soon? interesting because of persisting discrepancy of NLO with ATLAS/CMS data at 7 and 8 TeV

Recent NNLO highlights: single top



$p_\perp$	$\sigma_{\rm LO}$, pb	$\sigma_{\rm NLO}$, pb	$\delta_{\rm NLO}$	$\sigma_{\rm NNLO}$, pb	$\delta_{\rm NNLO}$
0 GeV	$53.8^{+3.0}_{-4.3}$	$55.1^{+1.6}_{-0.9}$	$+2.4\%$	$54.2^{+0.5}_{-0.2}$	-1.6%
20 GeV	$46.6^{+2.5}_{-3.7}$	$48.9^{+1.2}_{-0.5}$	$+4.9\%$	$48.3^{+0.3}_{-0.02}$	-1.2%
40 GeV	$33.4^{+1.7}_{-2.5}$	$36.5^{+0.6}_{-0.03}$	$+9.3\%$	$36.5^{+0.1}_{+0.1}$	-0.1%
60 GeV	$22.0^{+1.0}_{-1.5}$	$25.0^{+0.2}_{+0.3}$	$+13.6\%$	$25.4^{-0.1}_{+0.2}$	$+1.6\%$

- high precision reached and confirmed by NNLO, less of 1% theory error (like Drell Yan and top-pairs), but experimentally more difficult
- NLO correction depends on p_t, but NNLO very stable

NNLO: open questions ...

What is the pattern that emerges?

➡ sometimes NNLO well behaved

➡ sometimes NNLO corrections very large

Is it possible to find a generic pattern/lesson, or a way to improve convergence? or are we missing something important in some cases ..? i.e. what is the origin of the large corrections?

- new channels ?
- peculiarities of gluon-gluon fusion ... ?
- logs ... ?

Completion of partial calculations and new calculations in the next few years will help gain more experience and a better theoretical understanding. Useful insights also from analytical resummations.

Beyond NNLO

Anastasiou et al 1403.4616

First approximate N^{3}LO calculation of inclusive Higgs production

$$\hat{\sigma}_{ij}(\hat{s}, m_H) = \frac{\pi C(\mu^2)^2}{8v^2} \sum_{k=0}^{\infty} \left(\frac{\alpha_s}{\pi}\right)^k \eta_{ij}^{(k)}(z)$$

where $C(\mu^2)/(4v)$ is the effective Hgg coupling and $z = m_H^2/\hat{s}$

New! Result for delta and plus terms at N^{3}LO in the threshold expansion

$$\begin{aligned}
\hat{\eta}^{(3)}(z) \simeq\ & \delta(1-z)\, 1124.308887\ldots & (\to 5.1\%) \\
& + \left[\frac{1}{1-z}\right]_+ 1466.478272\ldots & (\to -5.85\%) \\
& - \left[\frac{\log(1-z)}{1-z}\right]_+ 6062.086738\ldots & (\to -22.88\%) \\
& + \left[\frac{\log^2(1-z)}{1-z}\right]_+ 7116.015302\ldots & (\to -52.45\%) \\
& - \left[\frac{\log^3(1-z)}{1-z}\right]_+ 1824.362531\ldots & (\to -39.90\%) \\
& - \left[\frac{\log^4(1-z)}{1-z}\right]_+ 230 & (\to 20.01\%) \\
& + \left[\frac{\log^5(1-z)}{1-z}\right]_+ 216\,. & (\to 93.72\%)
\end{aligned}$$

large cancellations between different terms lead to:

$$\hat{\eta}^{(3)}(z) \sim -2.2\%$$

Reminder:

$$\int_0^1 dz \left[\frac{g(z)}{1-z}\right]_+ f(z) \equiv \int_0^1 dz\, \frac{g(z)}{1-z}\, [f(z) - f(1)]$$

Beyond NNLO

Anastasiou et al 1403.4616

Problem threshold expansion ambiguous (can multiply and divide out by any function that goes to 1 for z → 1)

$$\int dx_1\, dx_2\, [f_i(x_1)\, f_j(x_2) z g(z)] \lim_{z\to 1} \left[\frac{\hat{\sigma}_{ij}(s,z)}{z g(z)}\right]$$

Take different form for g(z) and look at the N^3LO correction relative to the fixed order

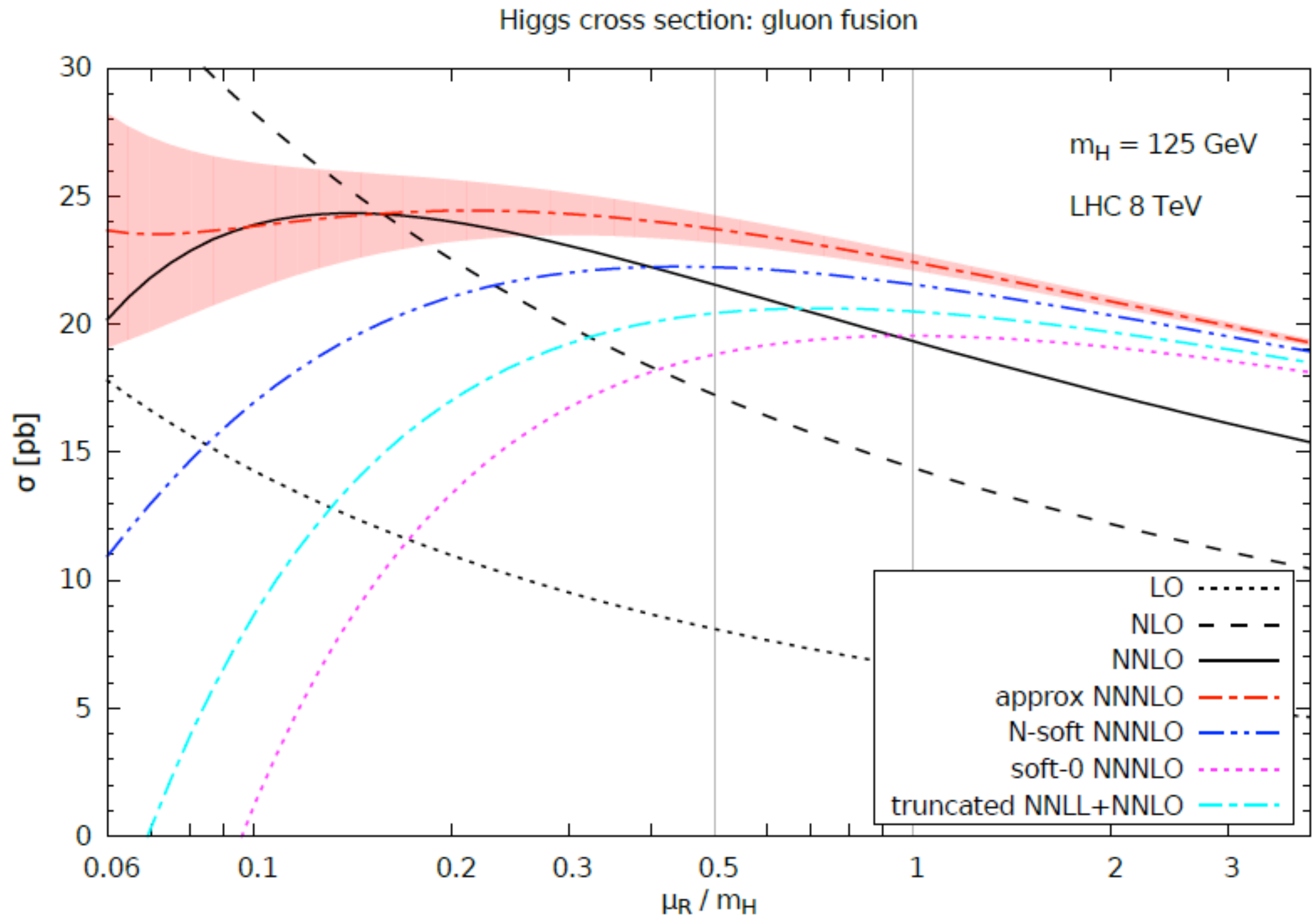
g(z)	1	z	z^2	1/z
$\delta N^3LO/LO$	-2.2%	8.2%	30.2%	7.7%

Too premature for phenomenology ... ?

Beyond NNLO

Bonvini et al 1404.3204

Comparison of several approximate N^3LO



Large N^3LO corrections + large spread in the predictions

Exact NNNLO may not be that far ...

Recap of fixed order

- Leading order
  - everything can be computed in principle today (practical edge: 8 particles in the final state), many public codes
  - techniques: standard Feynman diagrams or recursive methods (Berends-Giele, BCF, CSW, ...)
- Next-to-leading order
  - automation realized for QCD corrections
  - next: NLO EW corrections and NLO for BSM
- Next-to-next-to-leading order
  - $2 \to 1$ processes available since a while (Higgs, Drell-Yan)
  - a number of new results for $2 \to 2$ processes. More to come soon.
- Next-to-next-to-next-to-leading order
  - very first steps ...

Next

Next will focus on

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

Parton shower & Monte Carlo methods

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- 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

Parton shower & Monte Carlo methods

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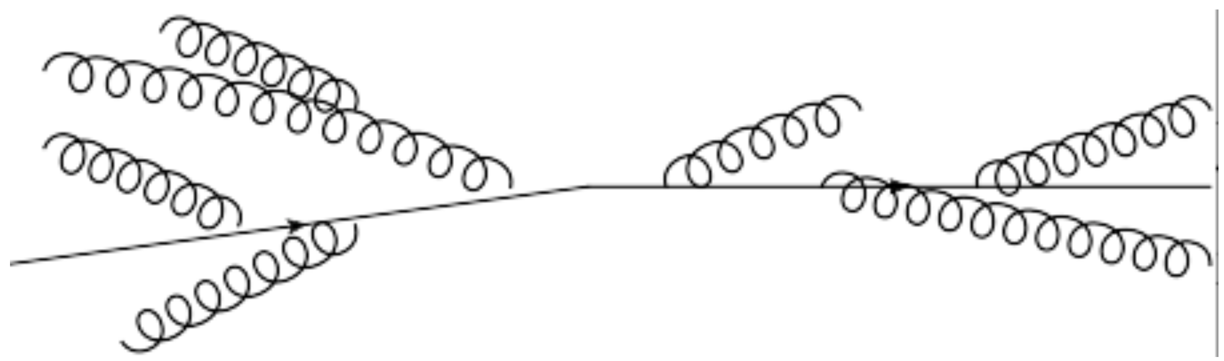
Monte Carlos enter any experimental study at current colliders

Parton shower & Monte Carlo methods

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



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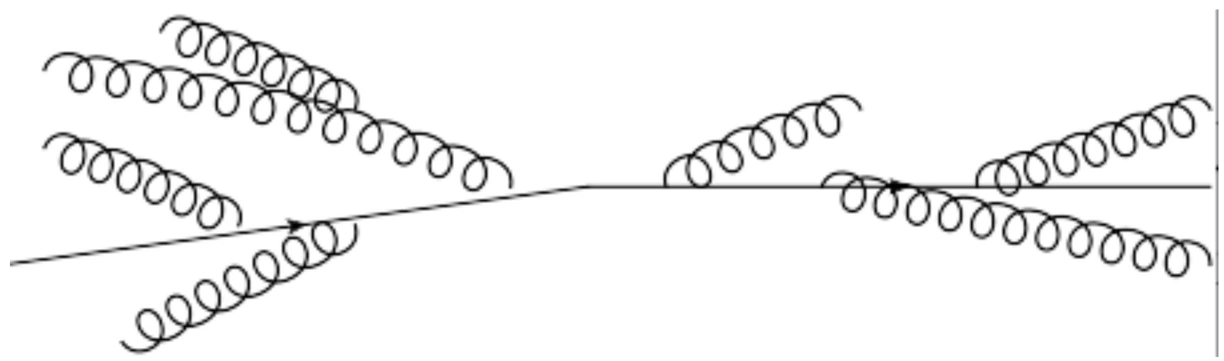

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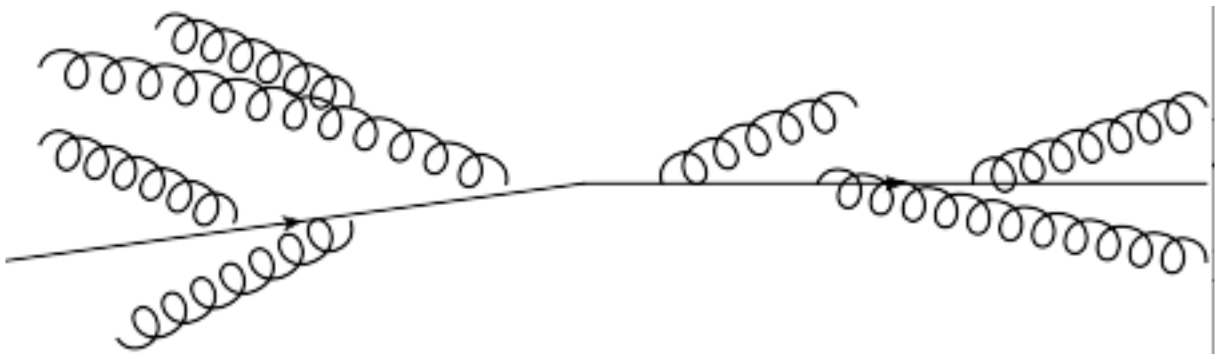

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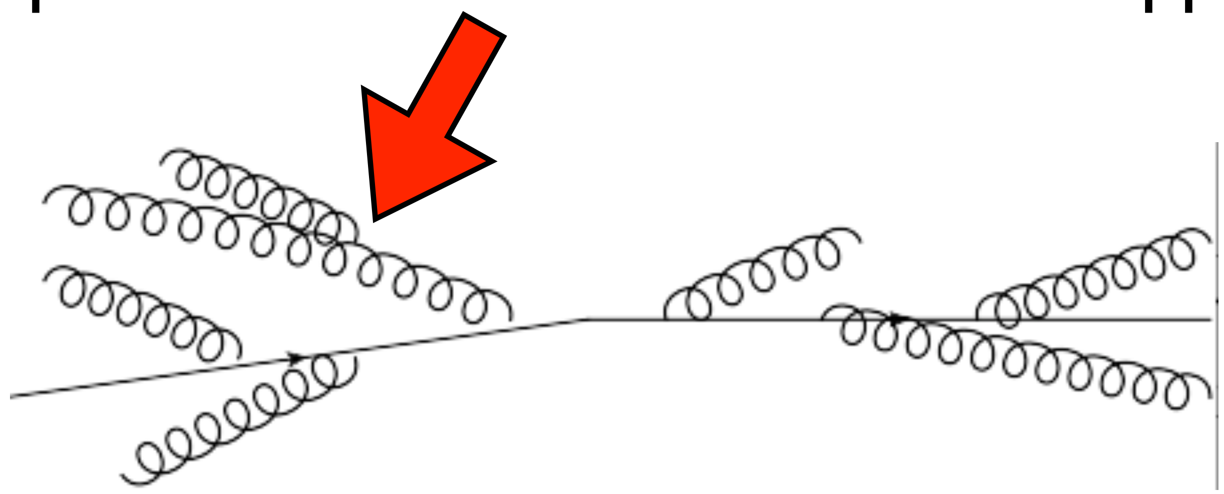

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- the probability for emitting a gluon above k_t can be computed in perturbation theory

- 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

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- 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 $\frac{dP}{dk_{t1}} = \frac{d\Delta(k_{t1}, Q)}{dk_{t1}}$

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

ε: IR cut-off for resolvable branching

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

Multiple branchings

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- 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

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

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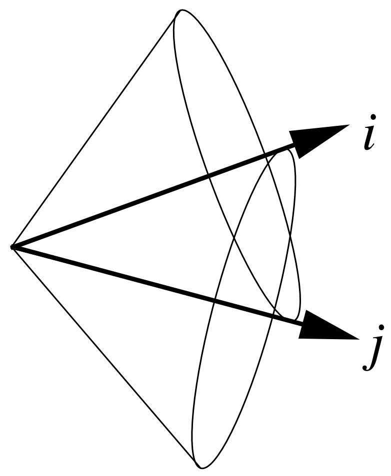
Angular ordering

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



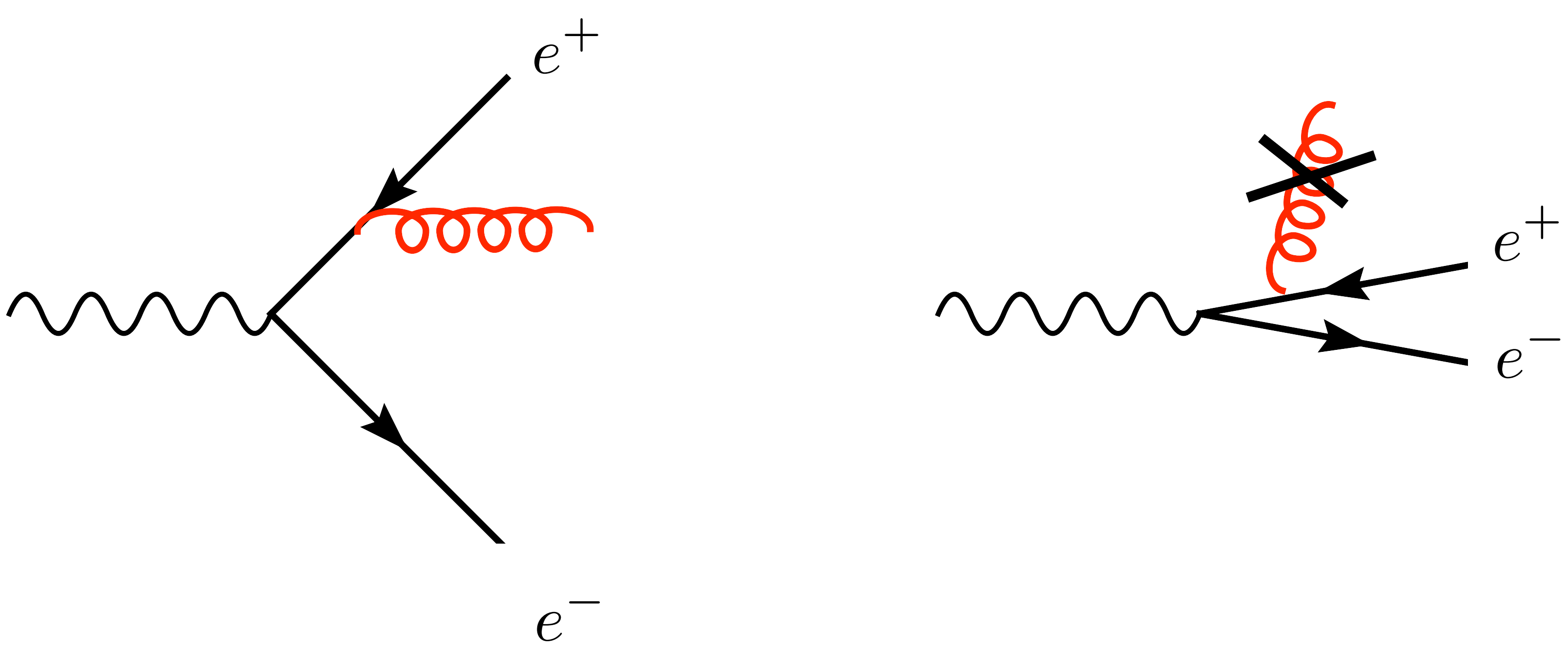
Proof: see e.g. QCD and collider physics, Ellis, Stirling, Webber

Angular ordering & coherence

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

In QED

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

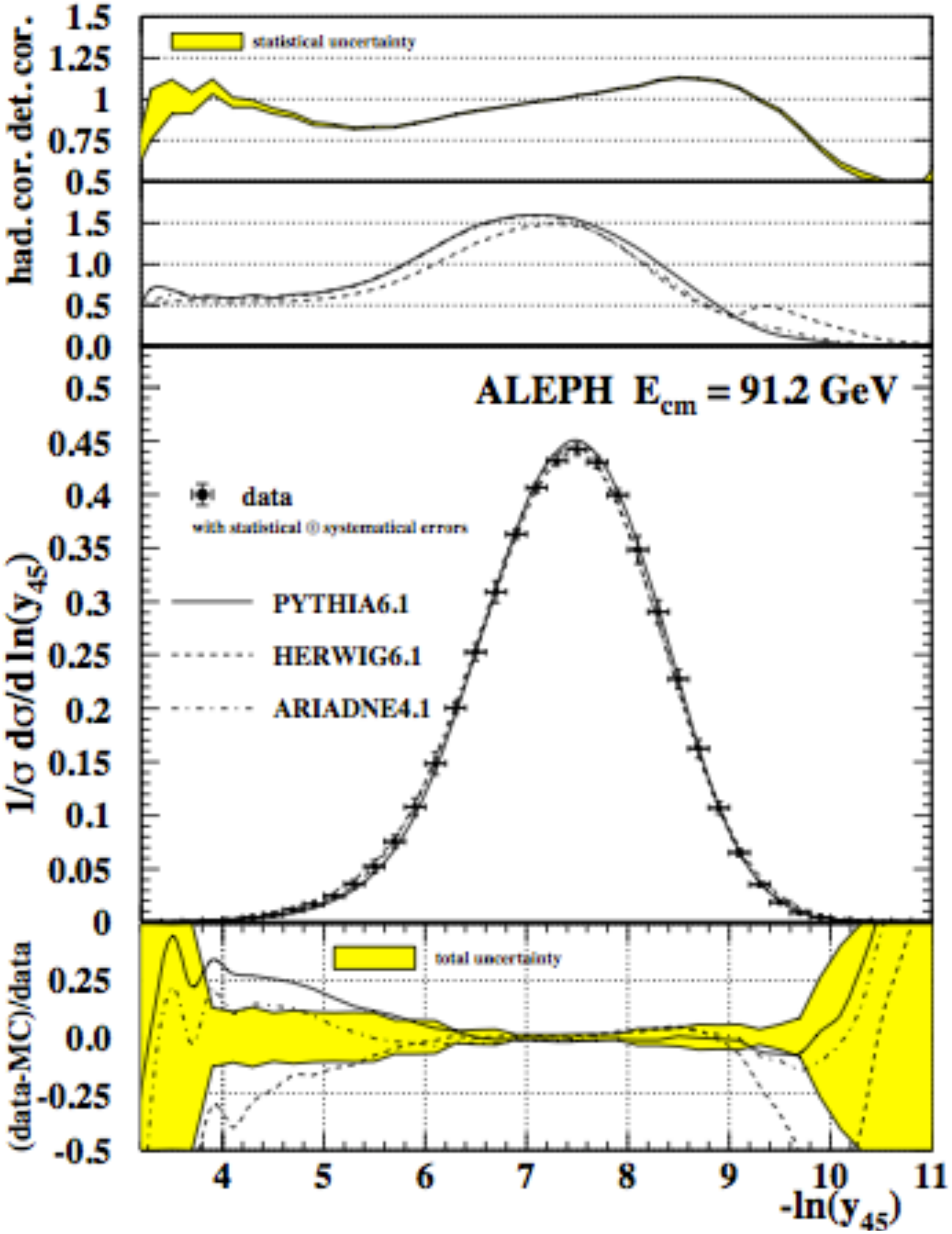


Herwig use the angle as an evolution variable, therefore has coherence built in. Other PS force angular ordering in the evolution.

Monte Carlos vs data

<u>Example</u>:
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



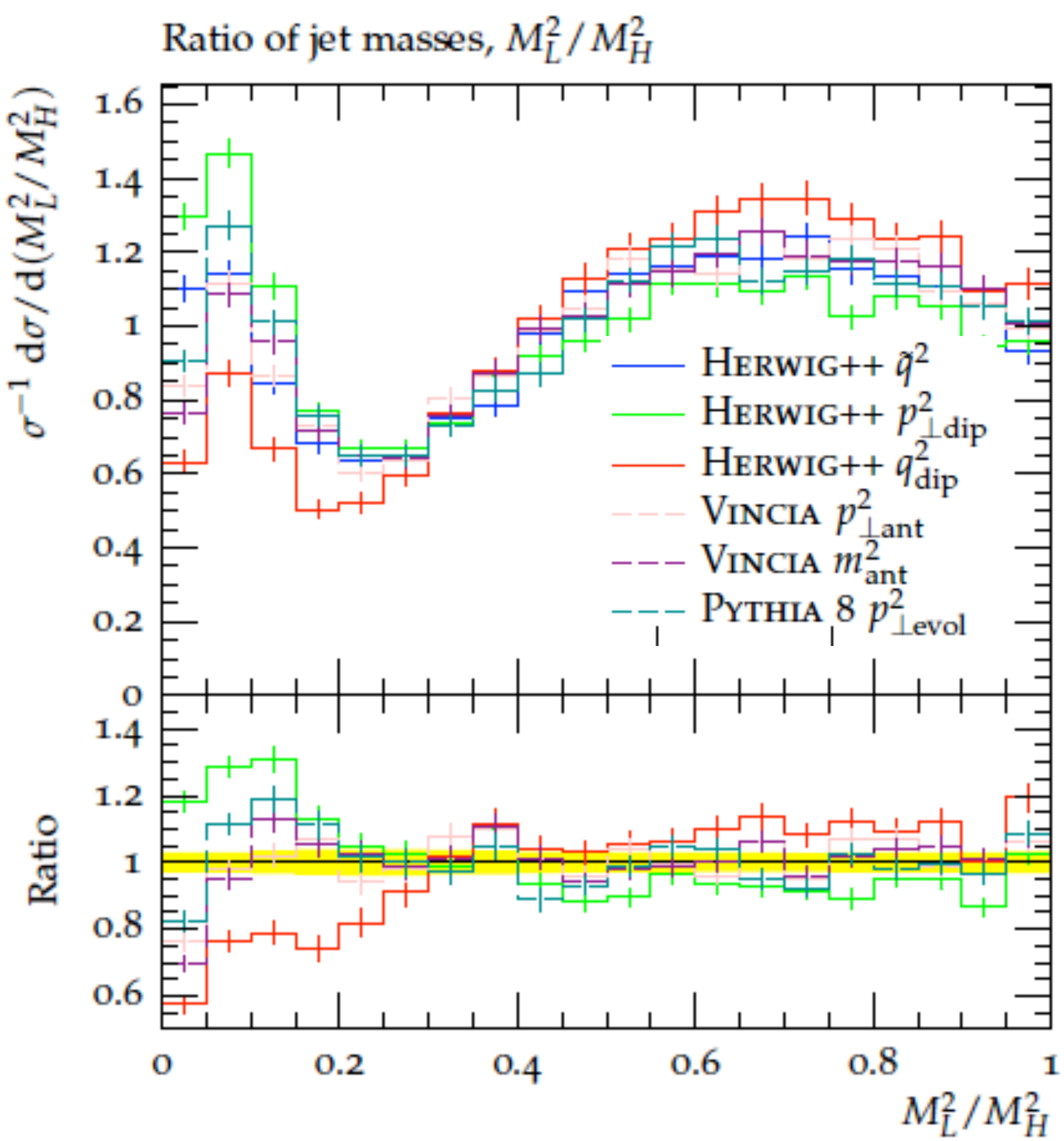
Choices in Monte Carlos

Some of the most relevant choices

- evolution variable (constraint in the collinear limit only). [Possibilities: k_t, mass, angle + many more ...]
- recoil scheme (can be global or local + different choices)
- finite terms in splitting kernels
- choices of coupling beyond one-loop
- internal cut-offs
- ....

Impact of choices

Fischer et al. 1402.3186



Today's focus on hadron-hadron collider, but e^+e^- clean laboratory

Four jet-observable:

- light-jet over heavy-jet mass ratio
- sensitive to sub-leading effects in MC

Comparing different MCs is used today to understand the assign theory error.

Future challenges:

- systematic improvement of logarithmic accuracy of MCs?
- solid procedure to assign errors?

NLO + parton shower

NLO + parton shower combines the best features of the two methods: correct rates (NLO) and hadron-level description of events (PS)

Difficult because need to avoid double counting

Two main working examples:

1. MC@NLO (aMC@NLO)

   Frixione&Webber '02 and later refs.

   - explicitly subtract double counting

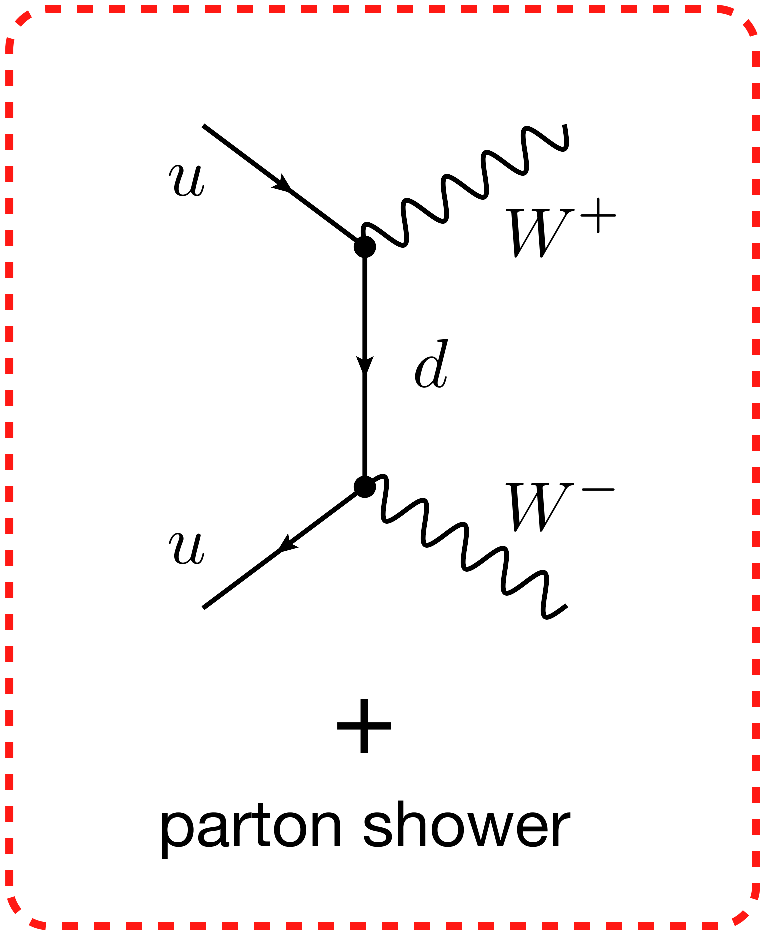
2. POWHEG (POWHEG-BOX)

   Nason '04 and later refs.

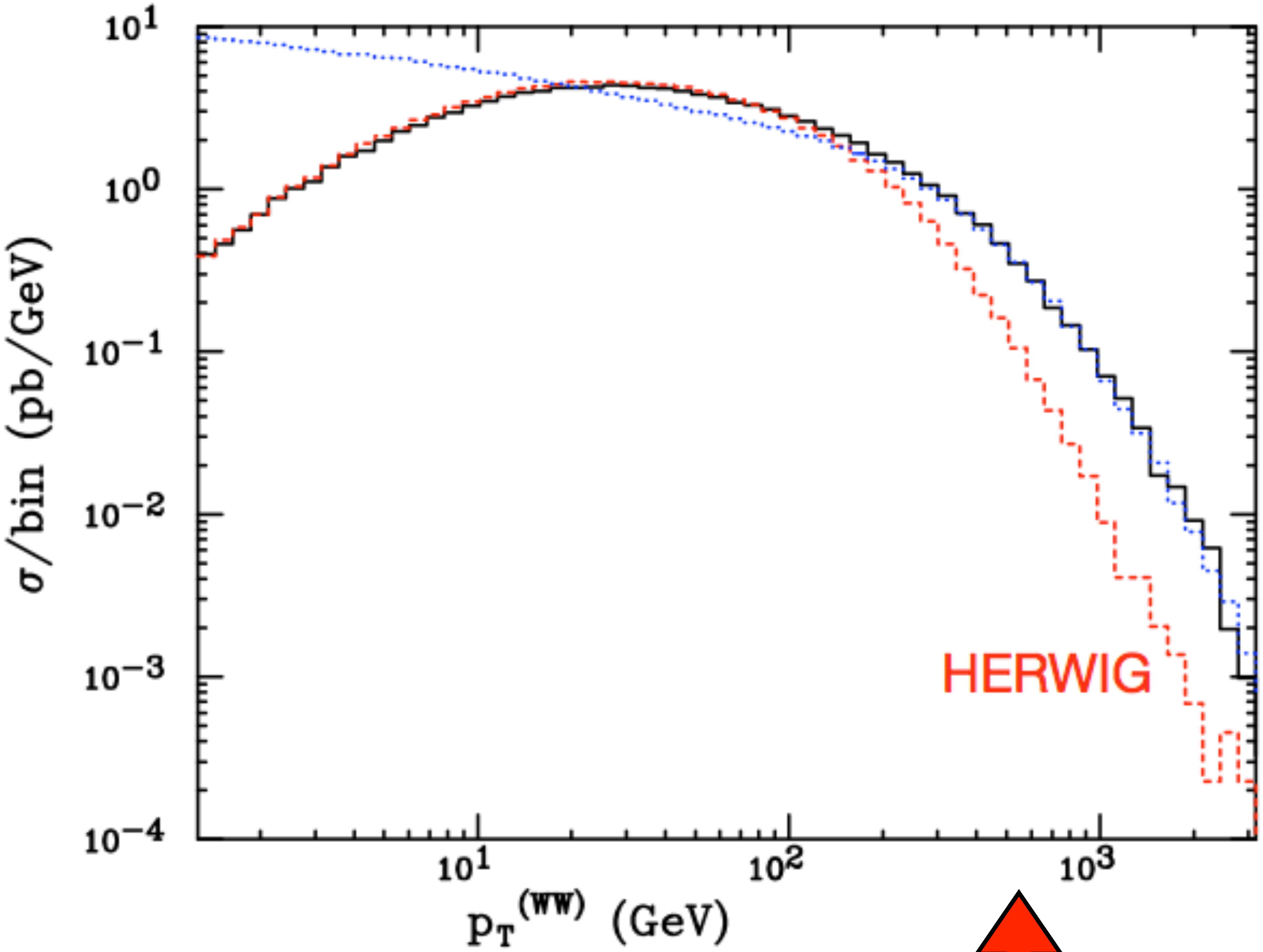
   - hardest emission from NLO (good for p_t ordered shower)

First only processes with no light jets in the final state, now large number of processes implemented. In fact, almost automated procedures reached in the POWHEG BOX and in aMC@NLO

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

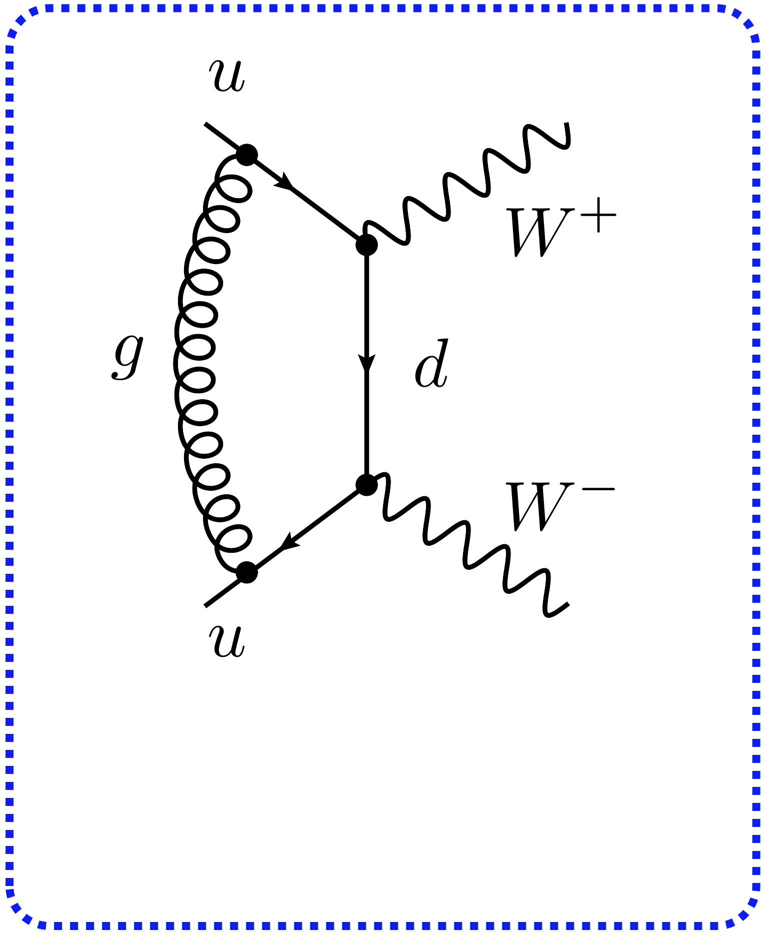


HERWIG

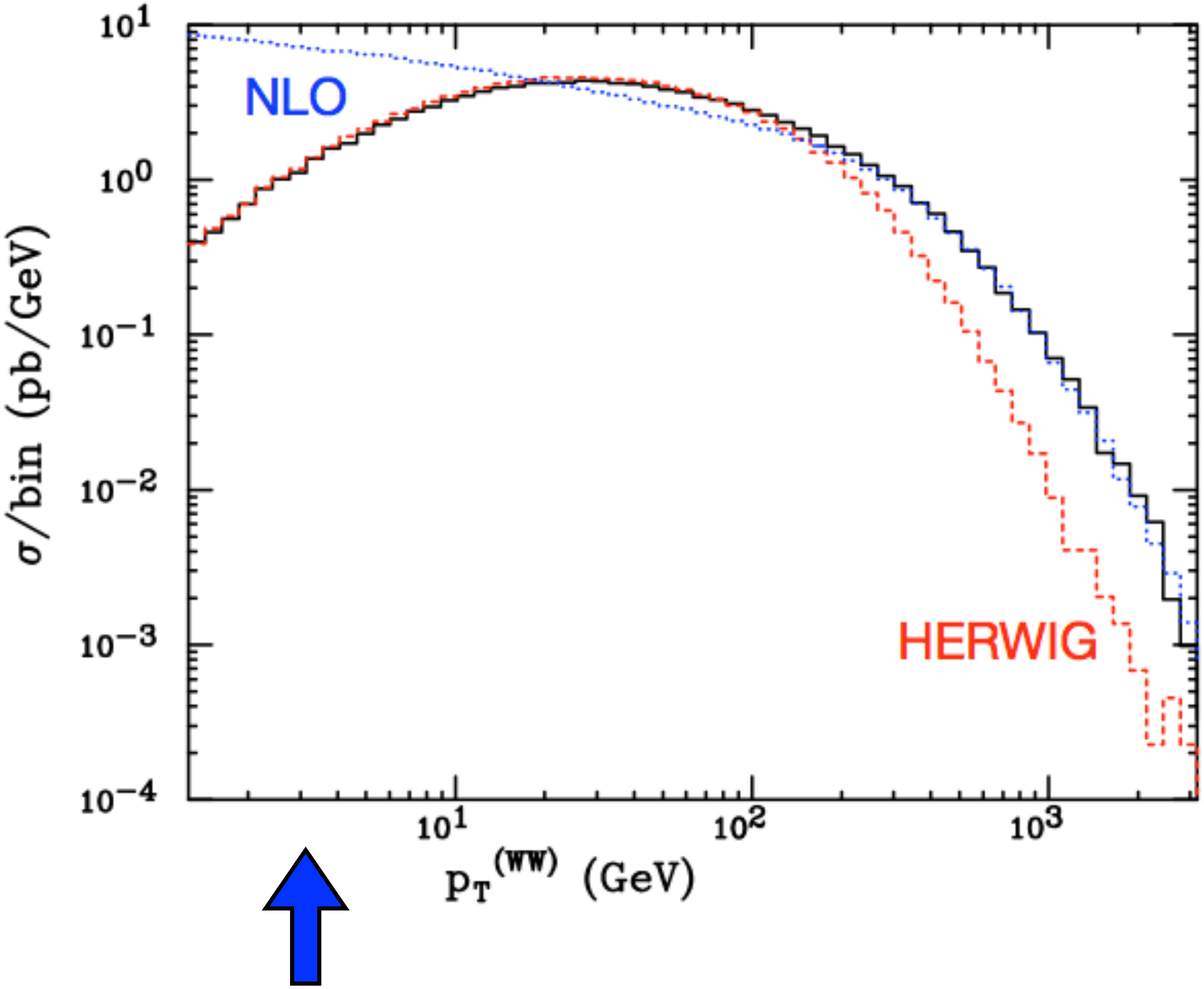


Herwig too soft in the high-p_t region

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

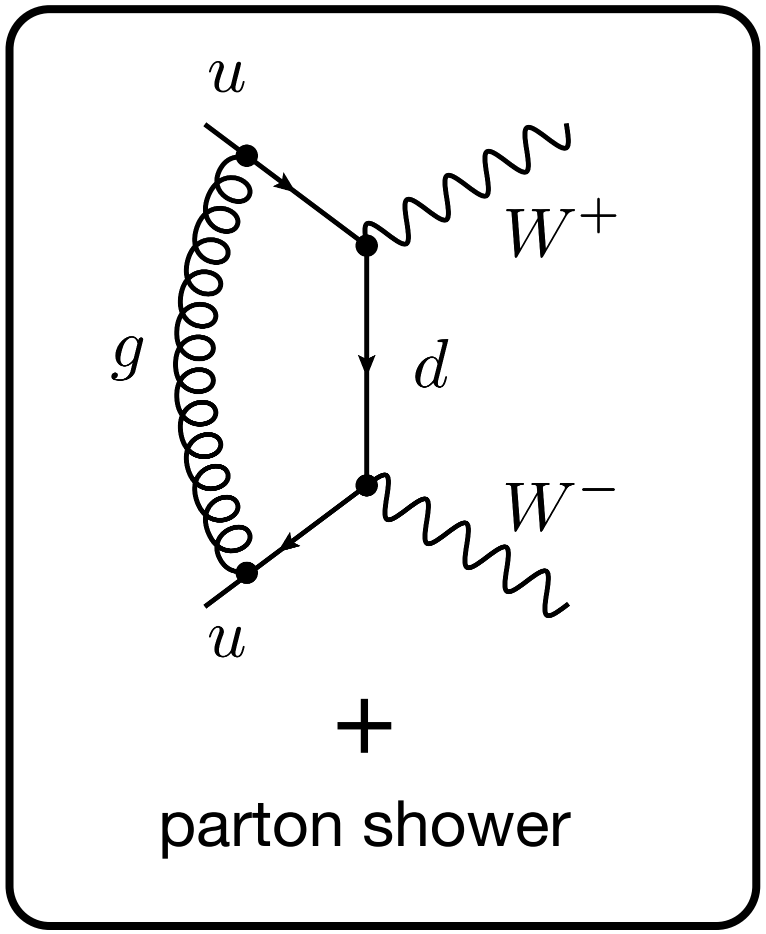


NLO

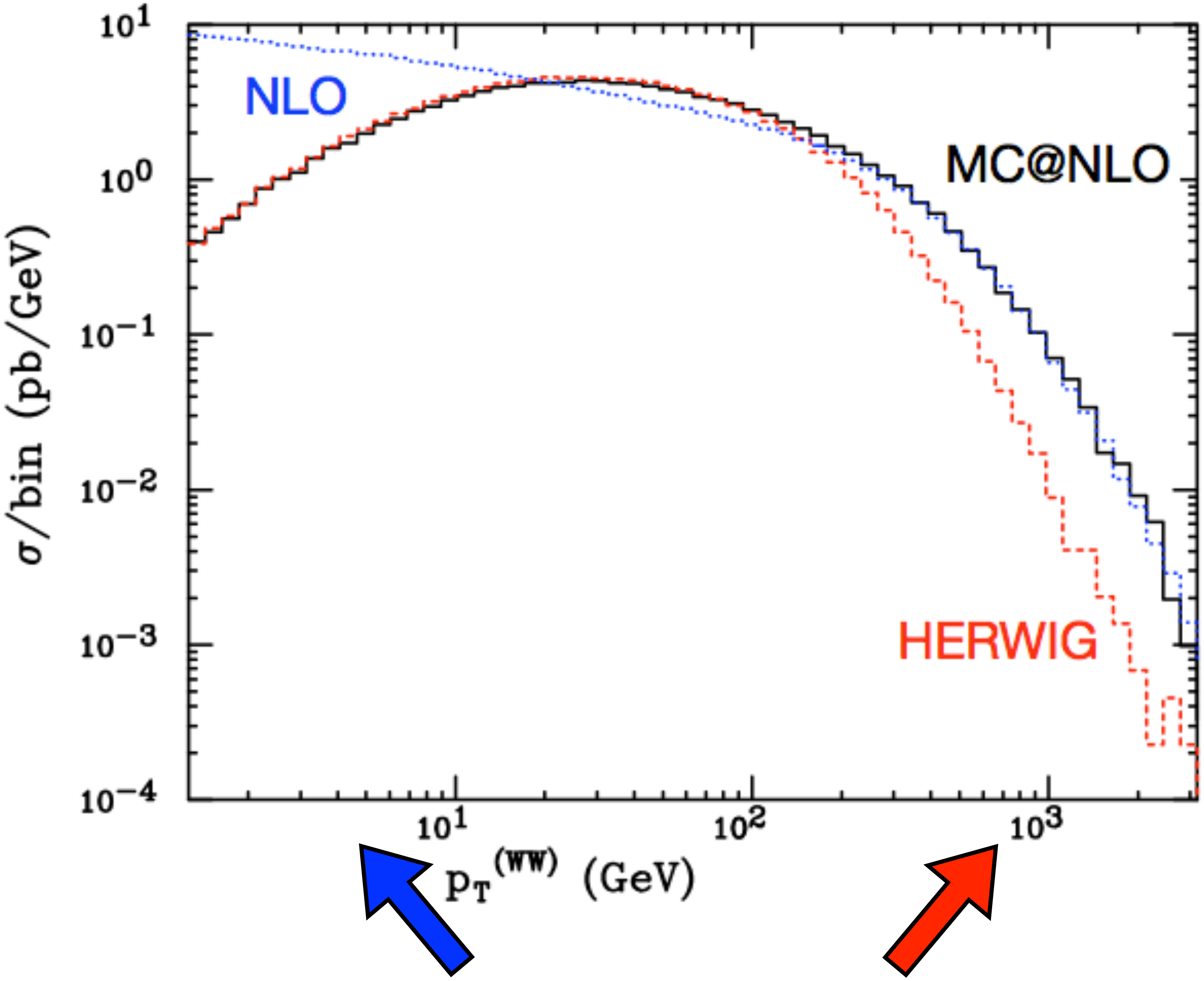


NLO divergent
in the soft region

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



MC@NLO



MC@NLO correctly interpolates between the two regimes

NNLO+PS

New challenge given the many recent NNLO results, natural to look for matching NNLO and parton shower

It turns out that this problem is intimately related to merging of NLO+PS for different jet multiplicities. Let me explain why.

NNLO+PS

Example: let's take

- Higgs at NLO+PS [H-NLOPS]
- Higgs + one jet at NLO+PS [HJ-NLOPS]
- a merged generator that is NLO+PS for H and HJ [H+HJ-NLOPS]
- Higgs at NNLO+PS [H-NNLOPS]

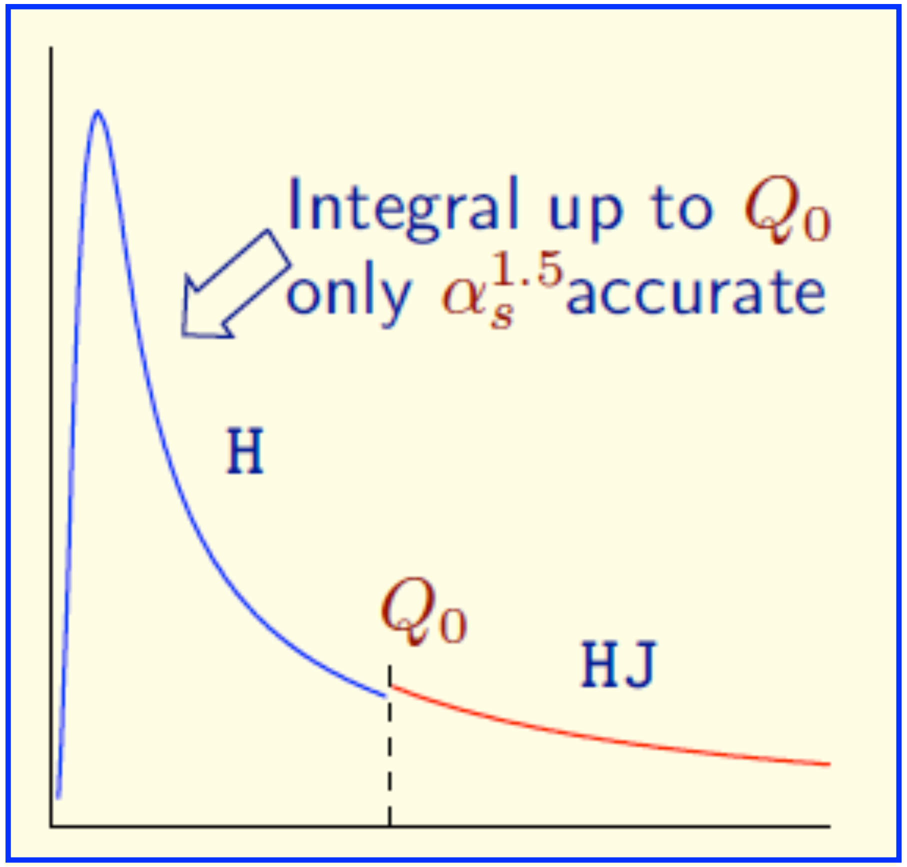
and compare the accuracies of these generators

	inclusive H	H+1jet (inclusive)	H+2jets (inclusive)
H-NLOPS	NLO	LO	soft-col. approx
HJ-NLOPS	divergent	NLO	LO
H+HJ-NLOPS	NLO	NLO	LO
H-NNLOPS	NNLO	NLO	LO

Conclusion: the merged H+HJ-NLOPS generator almost does the right job.

But setting up this is the real challenge.

Merging of H and HJ NLO generators



Typical approach

- introduce separation scale Q_0 (merging scale)
- use H-NLOPS for $p_{t,H} < Q_0$
- use HJ-NLOPS for $p_{t,H} > Q_0$

Problem

- Higgs pt distribution has a Sudakov peak at $\alpha_s \log^2\left(\frac{p_{t,H}}{M_H}\right) \sim 1$
- missing NNLL terms spoil the accuracy of the NLO, since neglected terms should be $O(\alpha_s^2)$, instead $\alpha_s^2 \log\left(\frac{p_{t,H}}{M_H}\right) \sim \alpha_s^{3/2}$

Solution?

set $Q_0 \approx M_H$, but this means loosing benefits of HJ calculation, e.g. jets of 100 GeV are described at LO only by H-NLOPS

Ways of (not) addressing the problem

- SHERPA traditional method with merging scales

  [Hoeche et al '12]

- aMC@NLO use merging scales, but keep them high to avoid problems

  [Frederix and Frixione '12]

- UNLOPS force unitarity by subtracting appropriate terms

  [Plaetzer '12; Lonnblad and Prestel '12]

- GENEVA improve accuracy of resummation (add NNLL terms)

  [Alioli et al '12]

- MiNLO no merging scale. Improve HJ so that it is NLO accurate for inclusive Higgs

  [Hamilton et al '12]

- VINCIA NLO+PS method with antenna subtraction

  [Hartgring et al '13]

Very active field. Optimal approach maybe not be found yet.

Getting to NNLO+PS

Suppose you have a merged H-NLOPS and HJ-NLOPS generator. How to get to H-NNLOPS?

1. just generate events with the H+HJ-NLOPS generator
2. re-weight the cross-section by the ratio of (where y_H is the Higgs rapidity)

$$\frac{\frac{d\sigma^{\mathrm{NNLO}}}{dy_H}}{\frac{d\sigma^{\mathrm{NLOPS}}}{dy_H}}$$

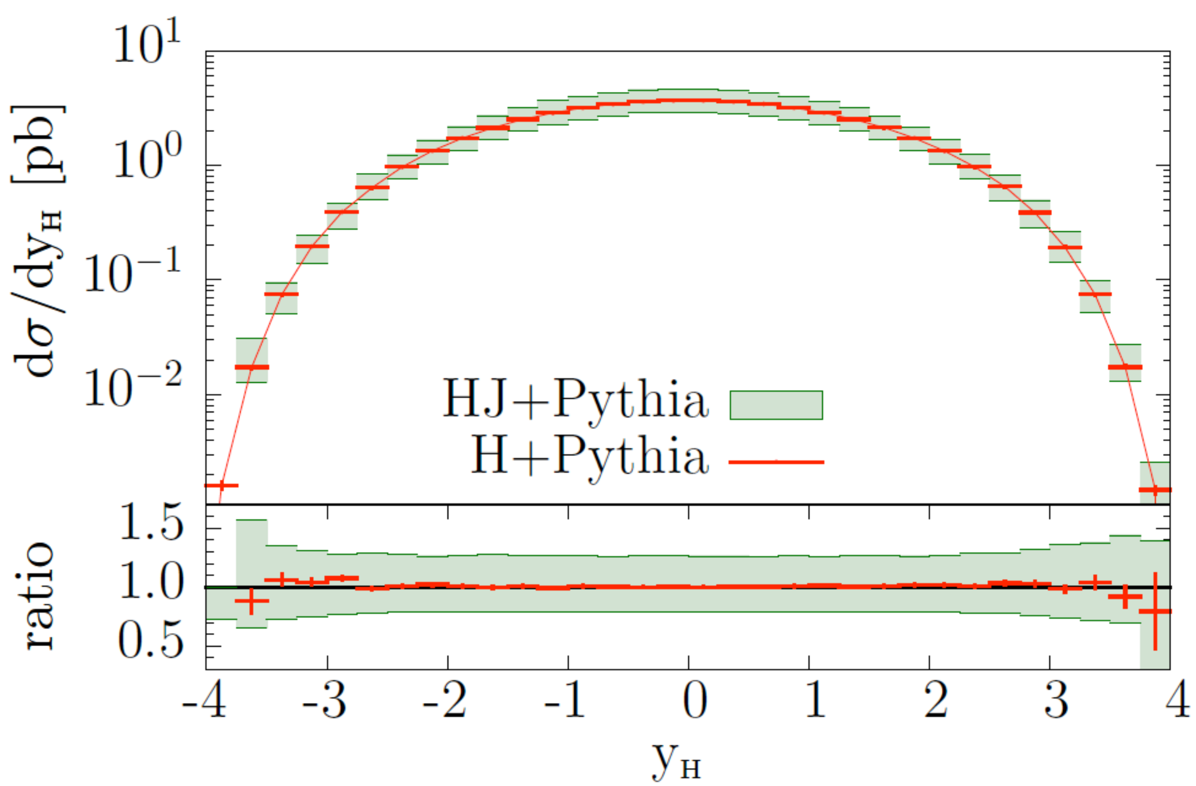
Critical property

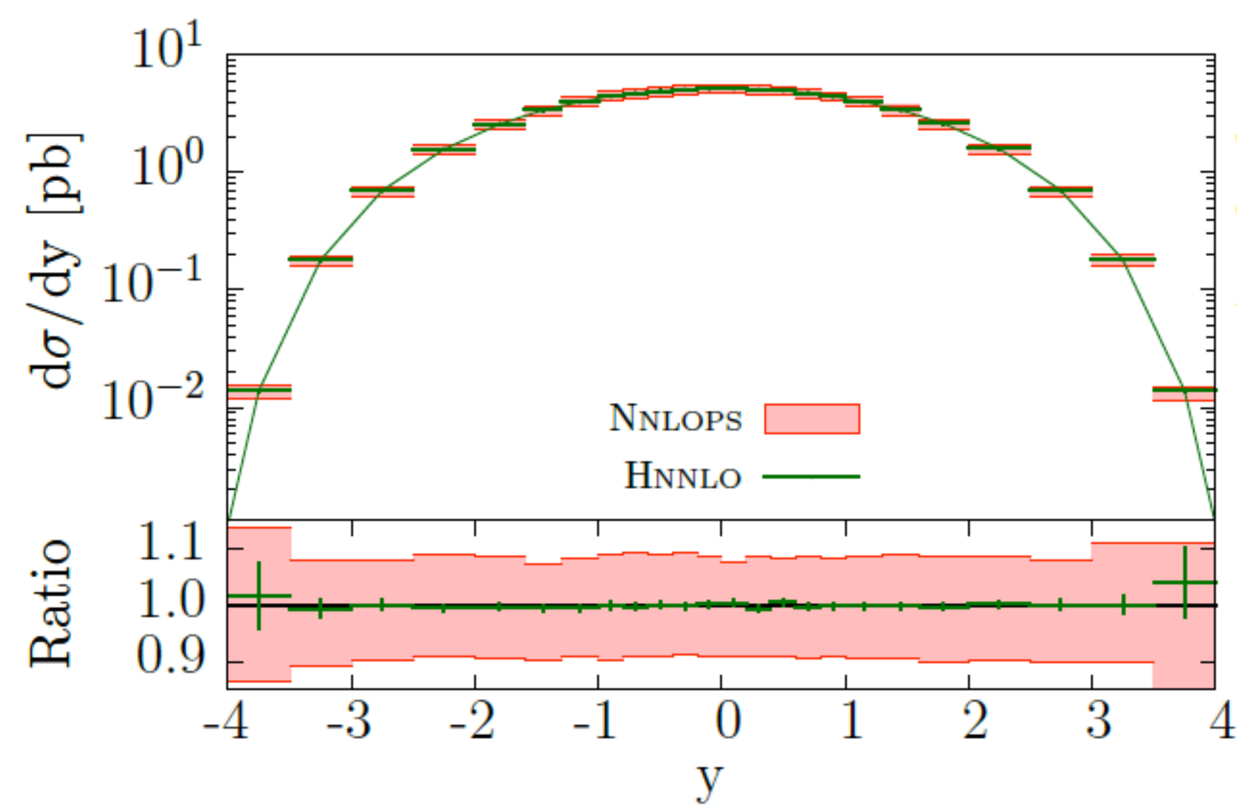
$$\frac{\frac{d\sigma^{\mathrm{NNLO}}}{dy_H}}{\frac{d\sigma^{\mathrm{NLOPS}}}{dy_H}} = \frac{c_0\alpha_s^2 + c_1\alpha_s^3 + c_2\alpha_s^4}{c_0\alpha_s^2 + c_1\alpha_s^3 + c_2'\alpha_s^4} = 1 + \mathcal{O}(\alpha_s^2)$$

This implies that this re-weighting does not spoil the NLO accuracy of the HJ-NLOPS generator

Example NNLO+PS for Higgs production

Higgs rapidity: comparison to HNNLO [Catani, Grazzini]



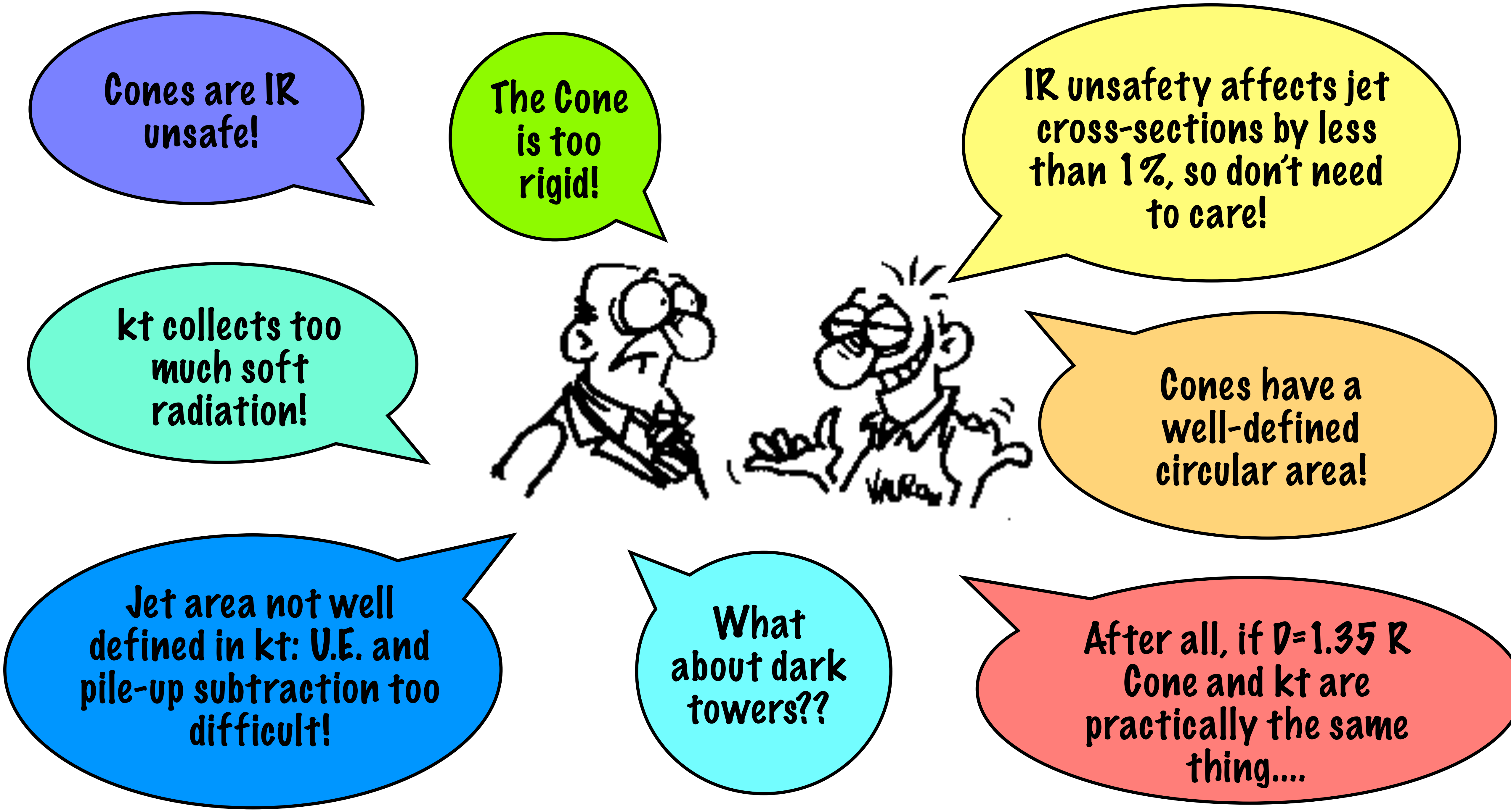


Accuracy:

(left) NLO+PS: ~ 30%

(right) NNLO+PS: ~ 10%

Jets: about 10 years ago...



Where do jets enter ?

Essentially everywhere at colliders!

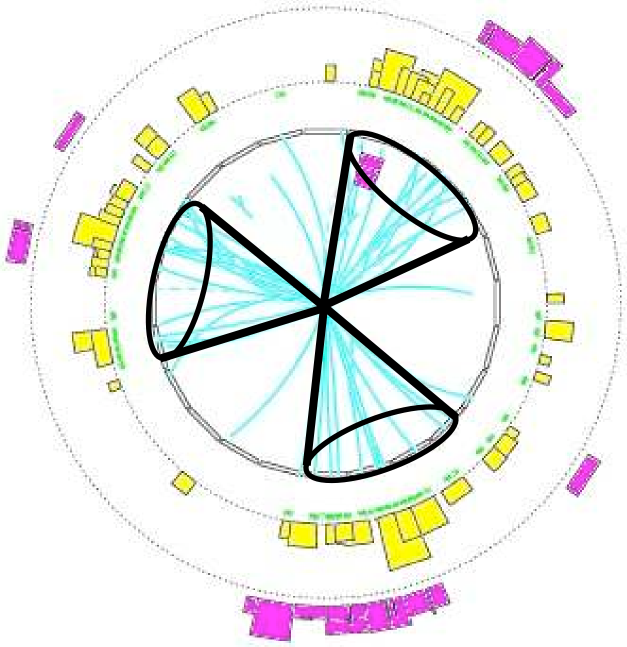
Jets are an essential tool for a variety of studies:

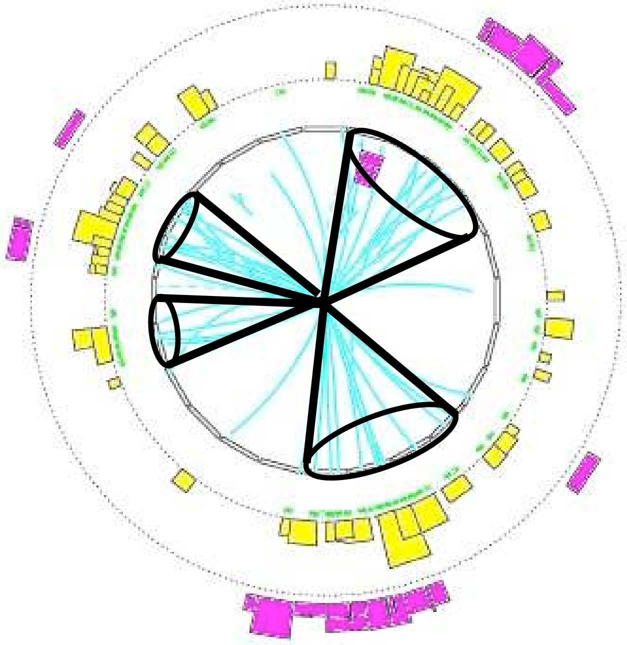
- top reconstruction
- mass measurements
- most Higgs and New Physics searches
- general tool to attribute structure to an event
- instrumental for QCD studies, e.g. inclusive-jet measurements
  $\Rightarrow$ important input for PDF determinations

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





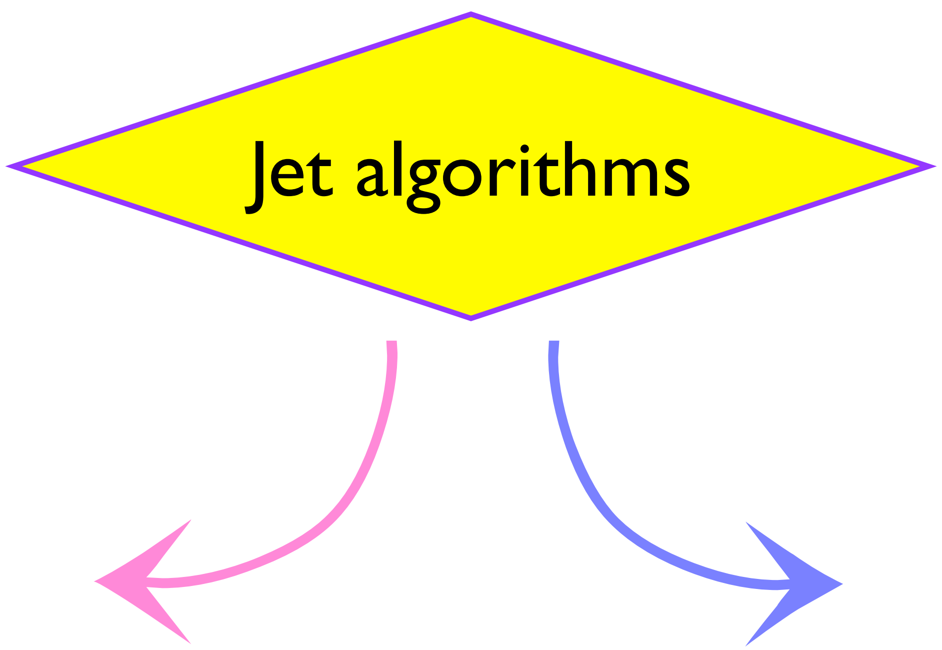
Ambiguities:

1) Which particles should belong to a same jet ?

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

Two broad classes of jet algorithms

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



Cone type
(UA1,JetCLU, Midpoint, SISCone..)

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

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

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

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

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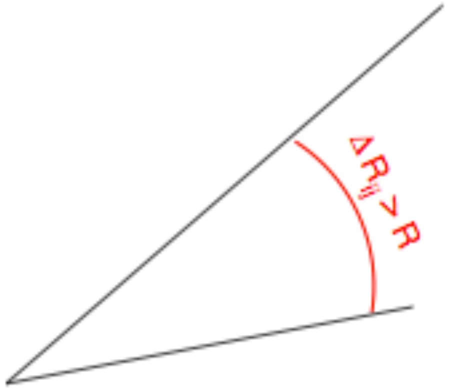
3. Find the smallest distance. If it is a d_{ij} recombine i and j into a new particle ($\Longrightarrow$ recombination scheme); if it is d_{iB} declare i to be a jet and remove it from the list of particles

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



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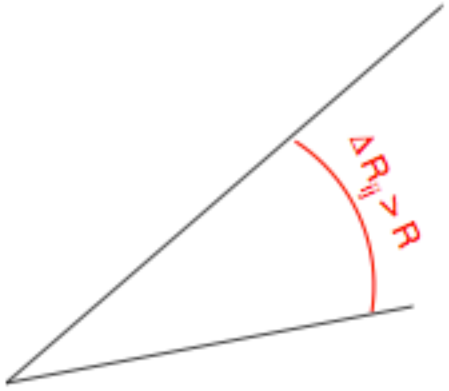

4. repeat the procedure until no particles are left

Exclusive k_t/Durham-algorithm

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

Exclusive 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

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 and Wengler '99

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Dotshitzer et. al '97;Wobisch and 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

The CA and the anti-k_t algorithm

<u>The Cambridge/Aachen</u>: 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 and Wengler '99

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Cacciari, Salam, Soyez '08

anti-kt is the default algorithm for ATLAS and CMS

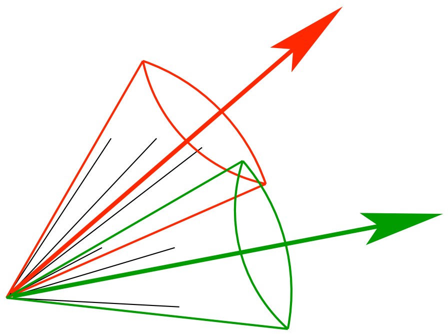
unfortunately with different default R 0.4 & 0.6 [ATLAS] 0.5 & 0.7 [CMS]

First time only IR-safe algorithms are used systematically at a collider

Cone algorithms

1. A particle i at rapidity and azimuthal angle $(y_i, \Phi_i) \subset$ cone C iff

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



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2. Define

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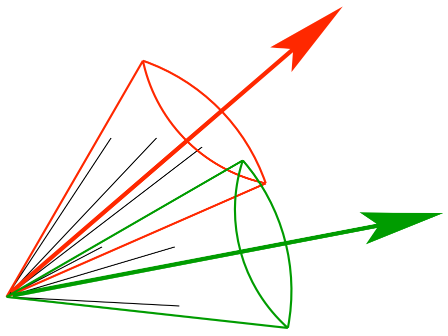

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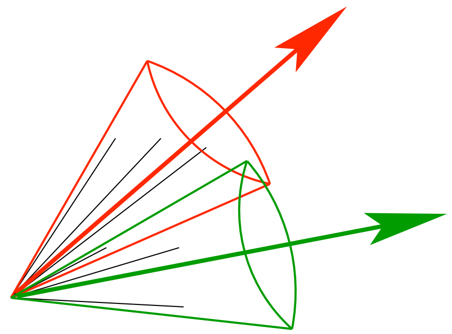

3. If weighted and geometrical averages coincide $(y_C, \phi_C) = (\bar{y}_C, \bar{\phi}_C)$ a stable cone (⇒ jet) is found, otherwise set $(y_C, \phi_C) = (\bar{y}_C, \bar{\phi}_C)$ & iterate

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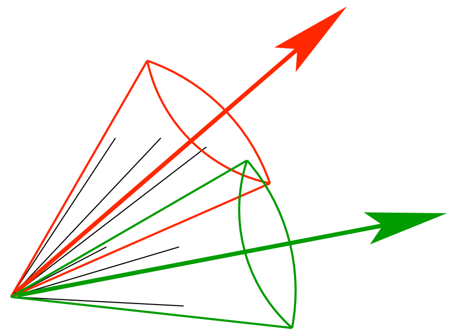

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   a stable cone (⇒ jet) is found, otherwise set $(y_C, \phi_C) = (\bar{y}_C, \bar{\phi}_C)$ & iterate

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 large 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.

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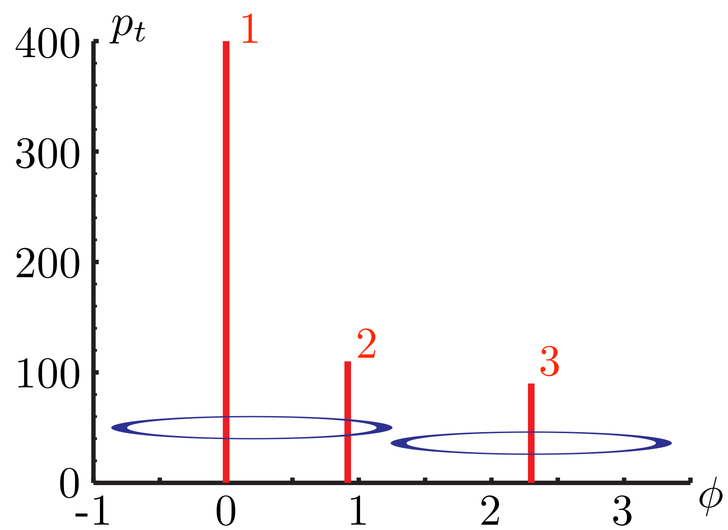
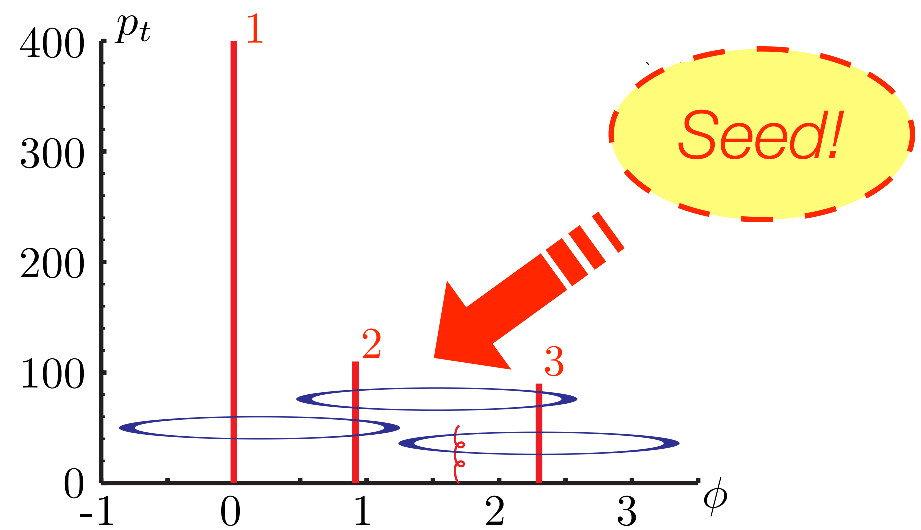
Seeds make cone algorithms infrared unsafe

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

<u>Midpoint algorithm:</u> take as seed position of emissions and midpoint between two emissions (postpones the infrared safety problem)

Seedless cones

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

Blazey '00

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)

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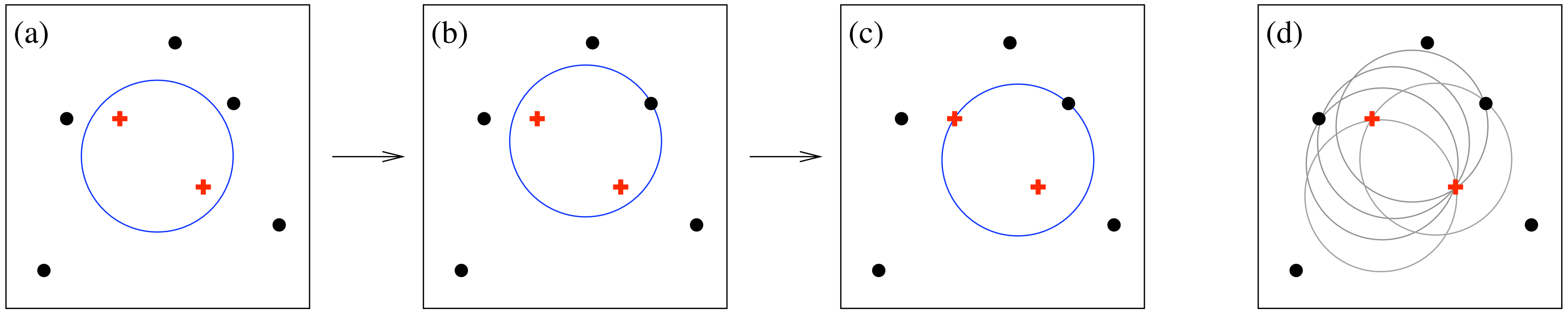
Blazey '00

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:

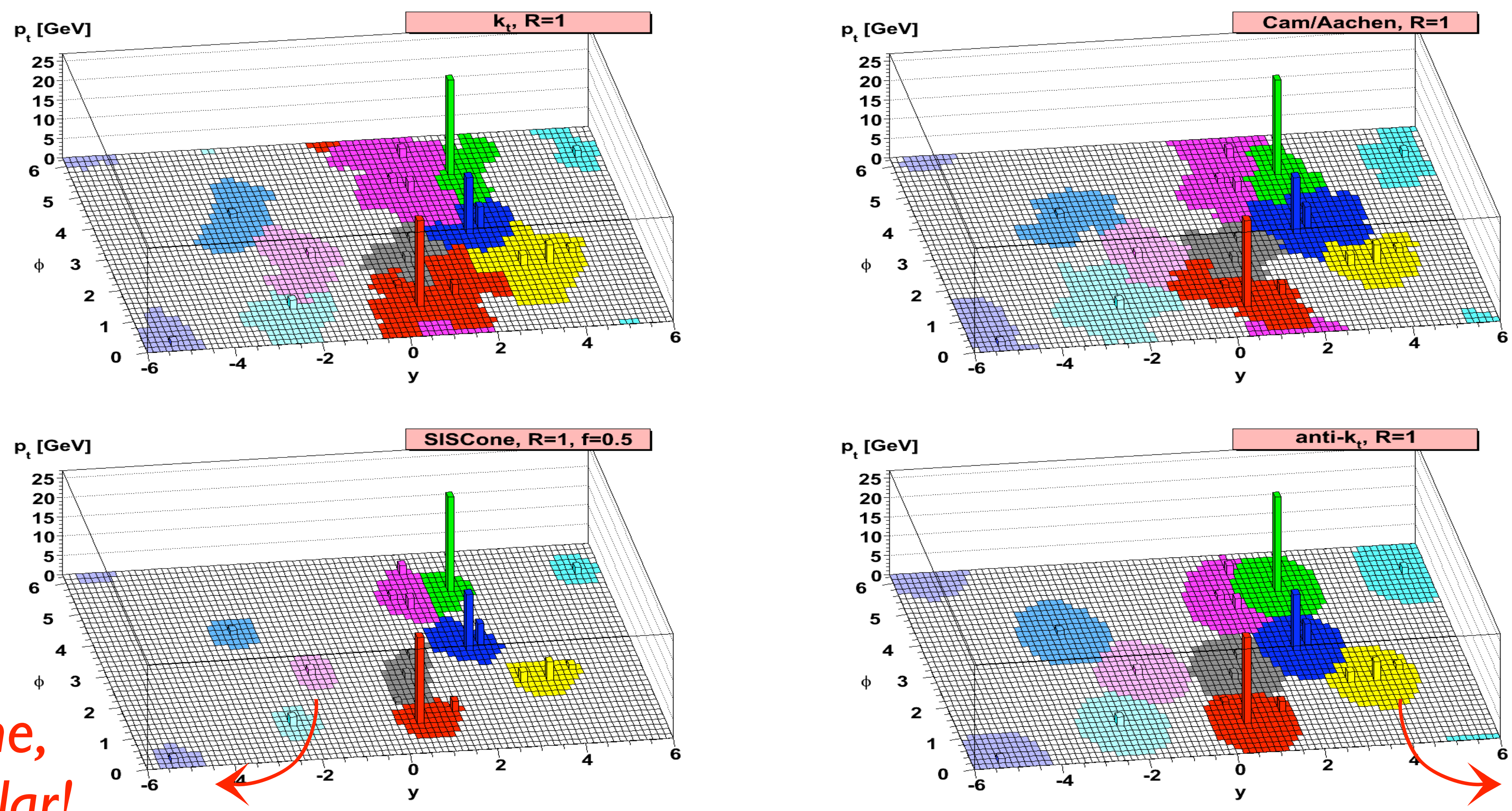
SISCone recasts the problem as a computational geometry problem, the identification of all distinct circular enclosures for points in 2D and finds a solution to that ⇒ $N^2 \ln N$ time IR safe algorithm



Salam, Soyez '07

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

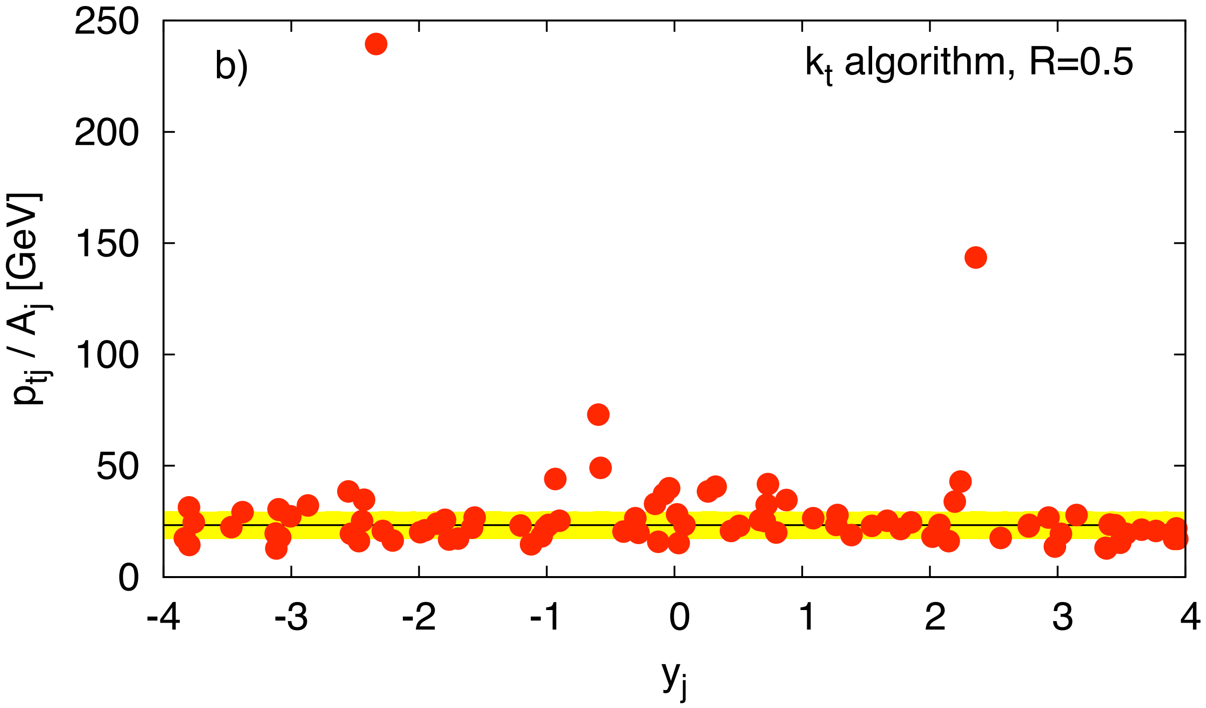
$$\rho = \frac{p_{t,j}}{A_j}$$

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

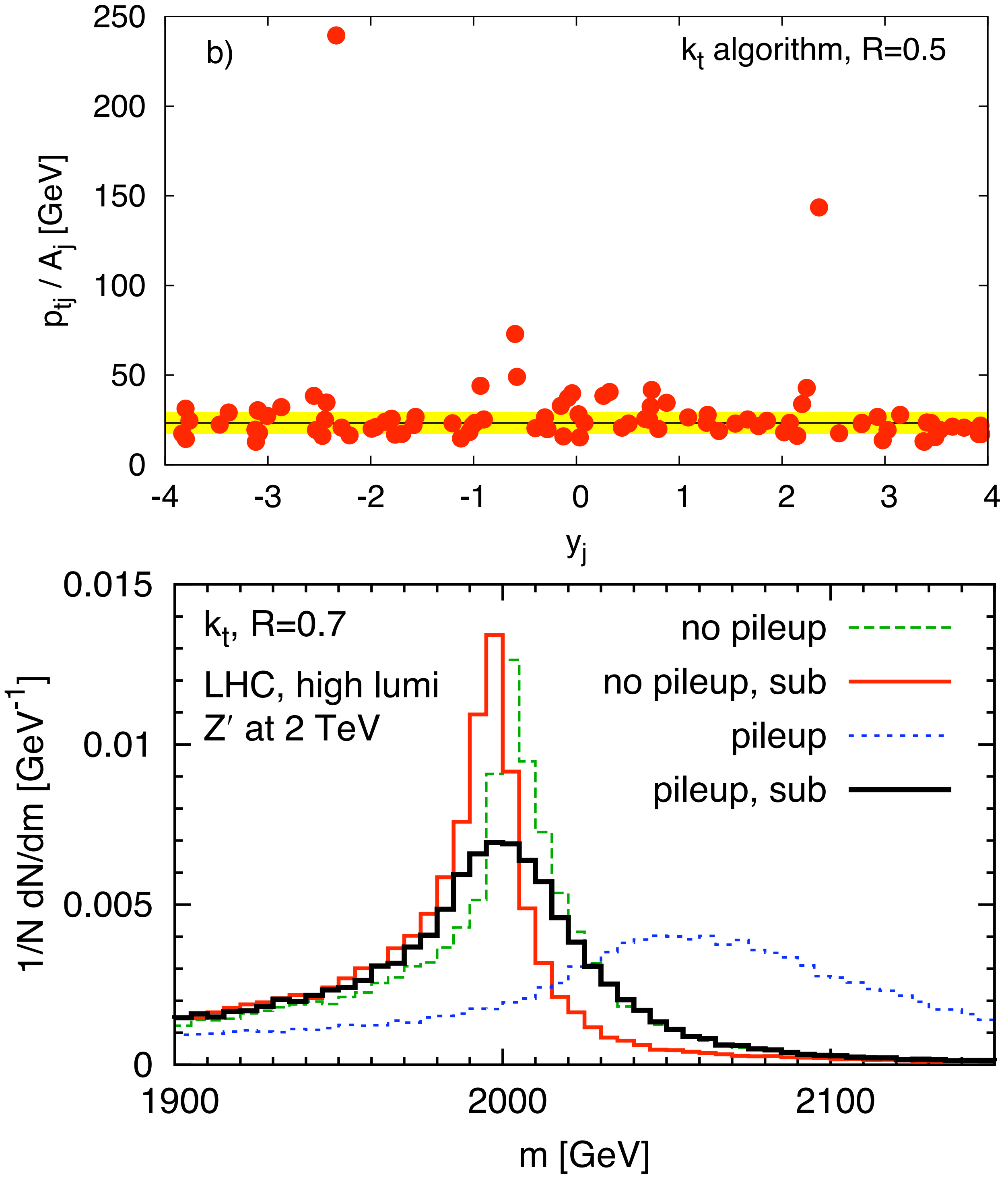
$$p_j^{\mathrm{sub}} = p_j - A_j \rho$$

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

Sample 2 TeV mass reconstruction



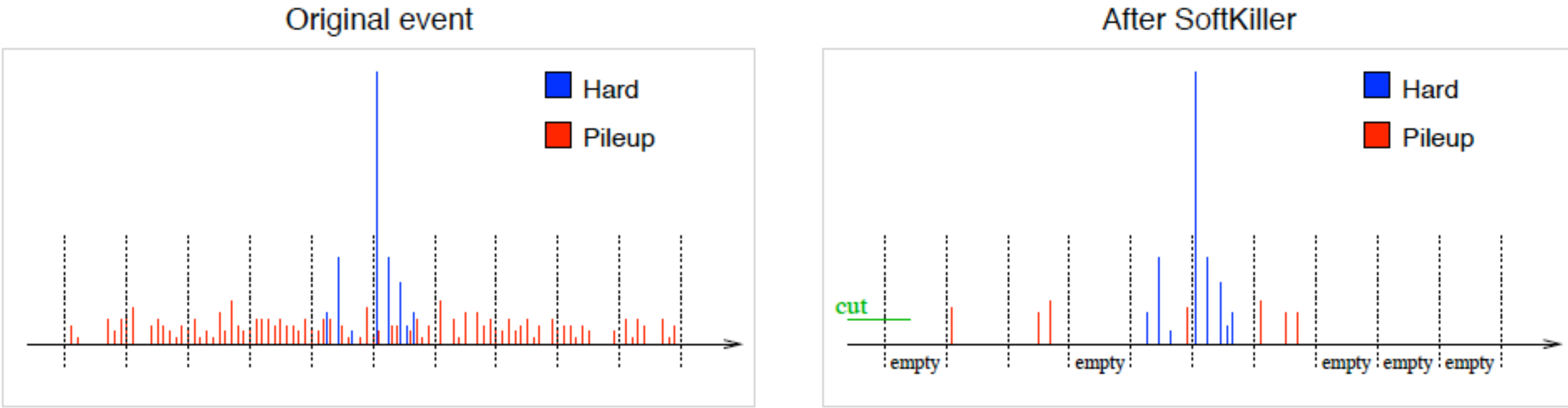
Sample 2 TeV mass reconstruction



Cacciari et al. '07

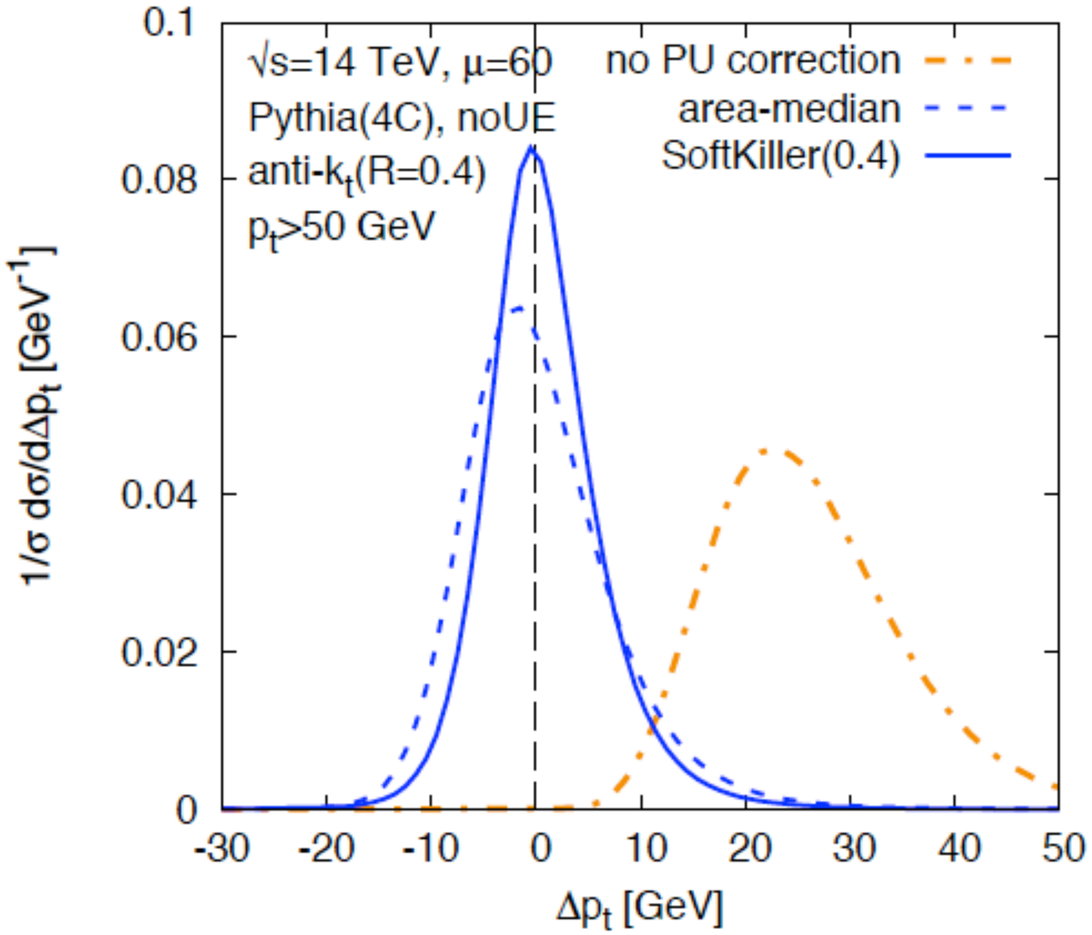
SoftKiller

Cacciari et al. 1407.0408



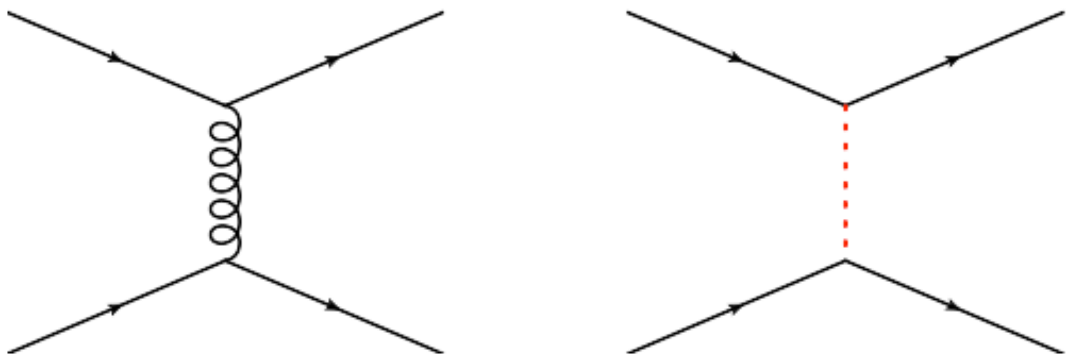
SoftKiller ≡ a particle based pile-up subtraction that removes softest particles in an event up to a dynamical transverse momentum threshold

Almost 2 order of magnitude faster than area-based pile-up subtraction



Jets and New Physics searches

New Physics can modify the scattering of quarks and gluons, e.g. through the exchange of a heavy object



At energies much smaller than M, the details of the new particles exchanged can not be resolved. The effect can be simulated by adding new terms to the QCD Lagrangian, typically dimension 6 operators

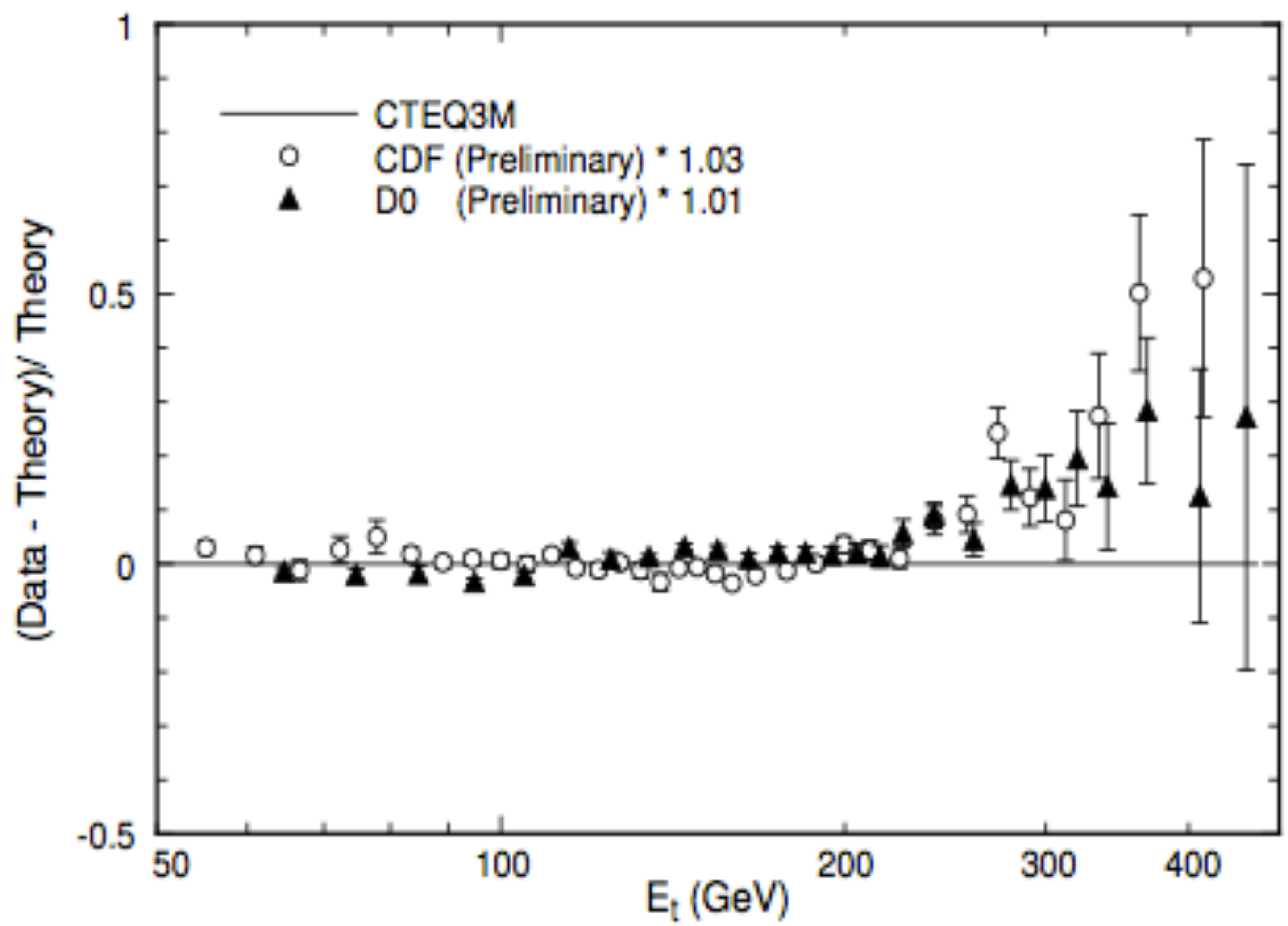
$$\Delta\mathcal{L} = \frac{\tilde{g}^2}{M^2}\bar{\psi}\gamma^\mu\psi\bar{\psi}\gamma_\mu\psi$$

Then one expects a correction to the transverse energy cross-section of the form

$$\sim \tilde{g}^2 {E_T}^2/M^2$$

Jets and New Physics searches

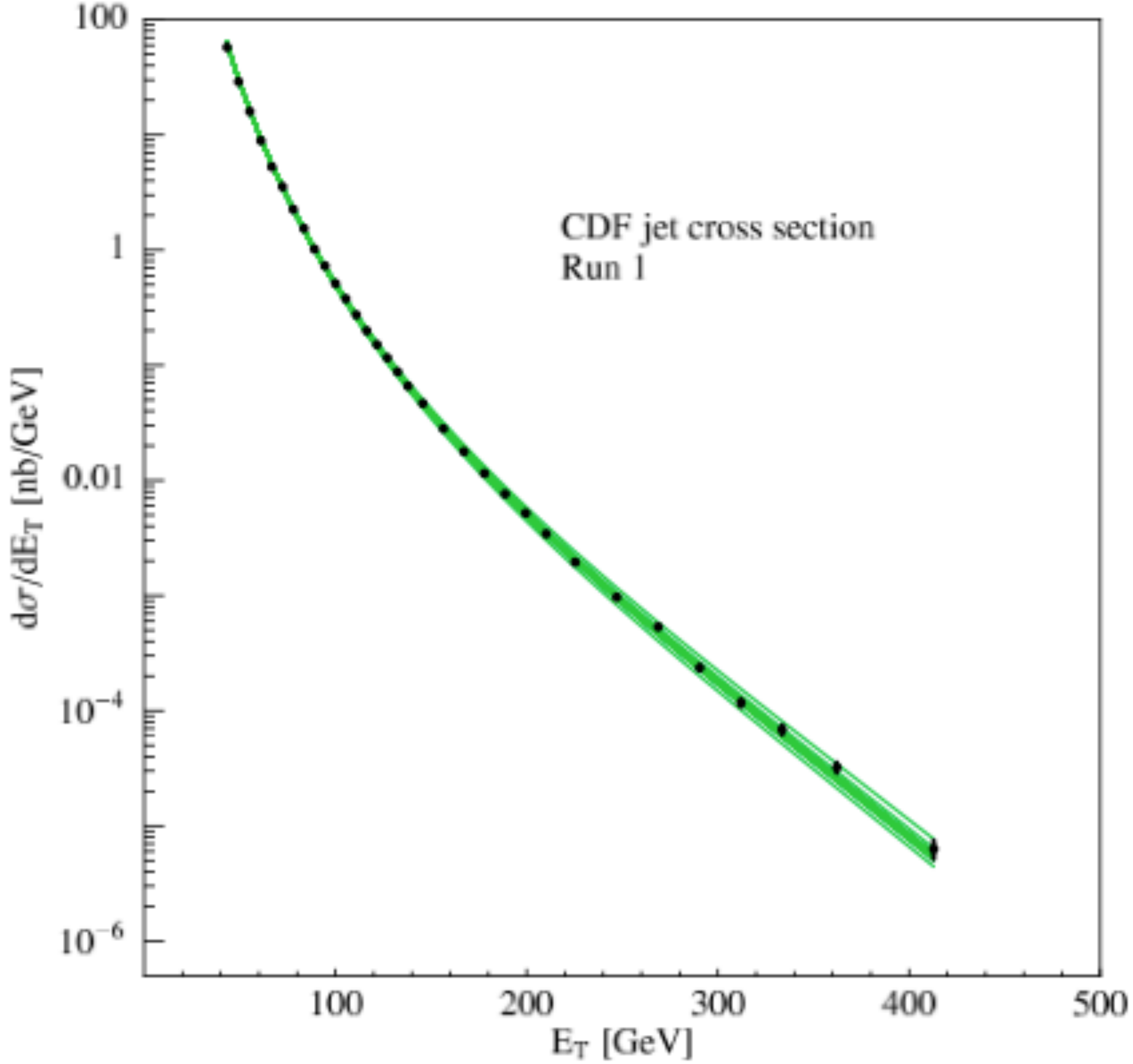
An example: NLO QCD vs Tevatron data (1996)

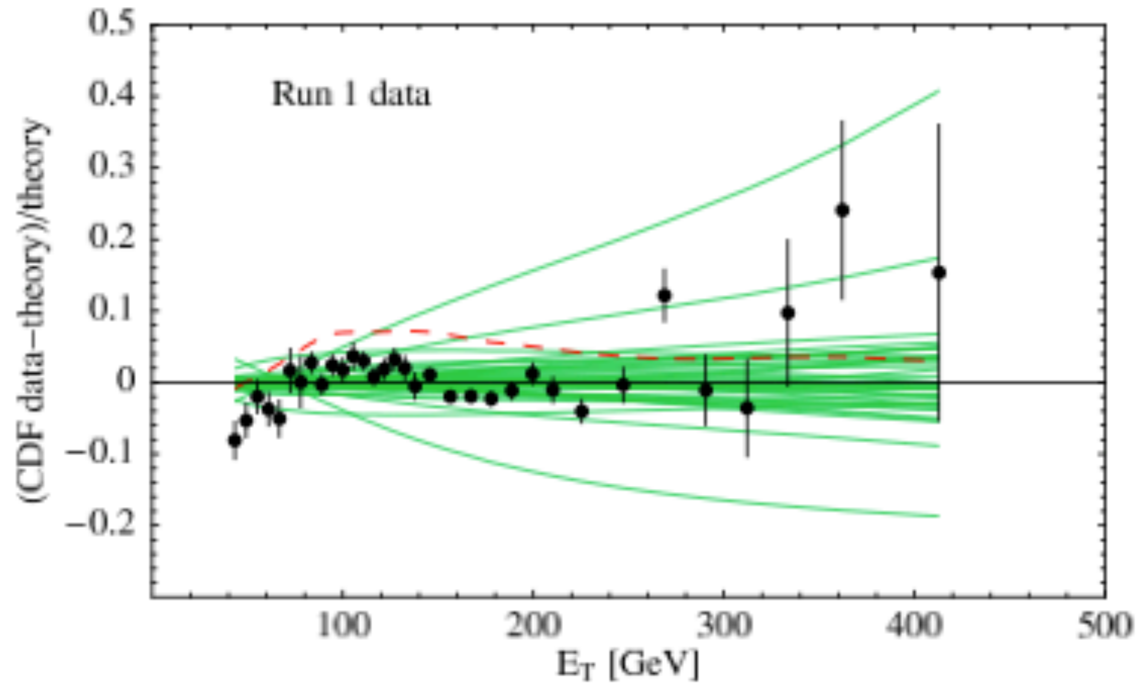


New Physics ? No! Poor modeling of gluon PDF at large x.

Jets and New Physics searches

With better treatment and inclusion of uncertainties on gluon PDFs

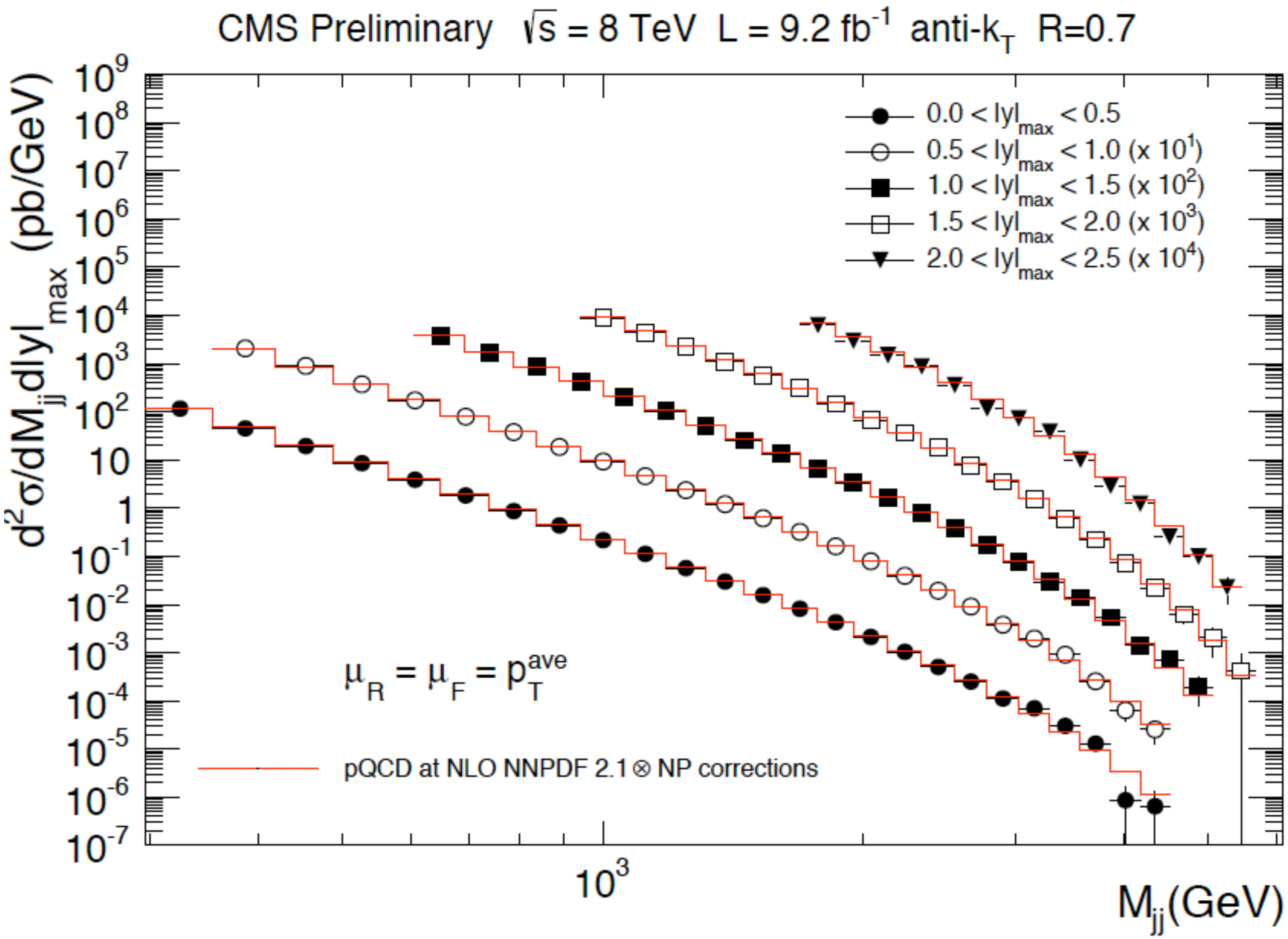




Lots of care is needed in data interpretation, especially when PDF are probed in regions with none or little data

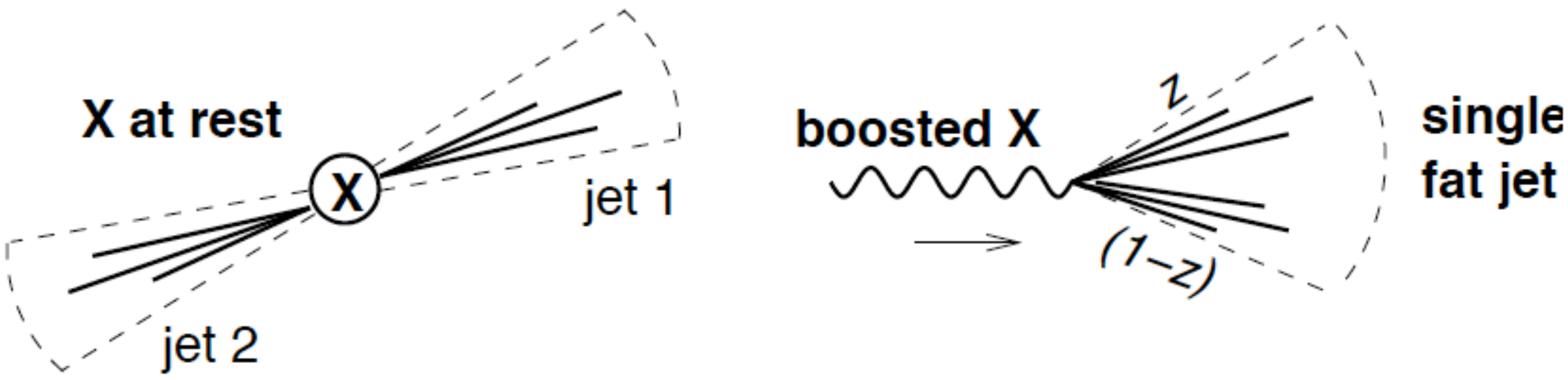
Jets today at the LHC

At the LHC jets could probe the highest (TeV) energy scales: remarkable agreement with the SM



CMS-PAS-SMP-14-002

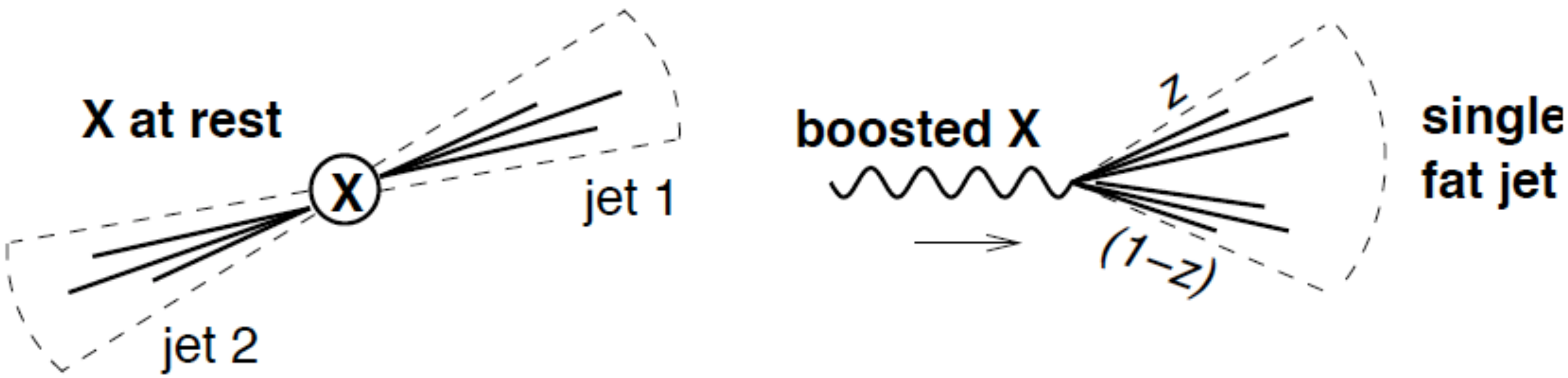
Jet-substructure at the LHC



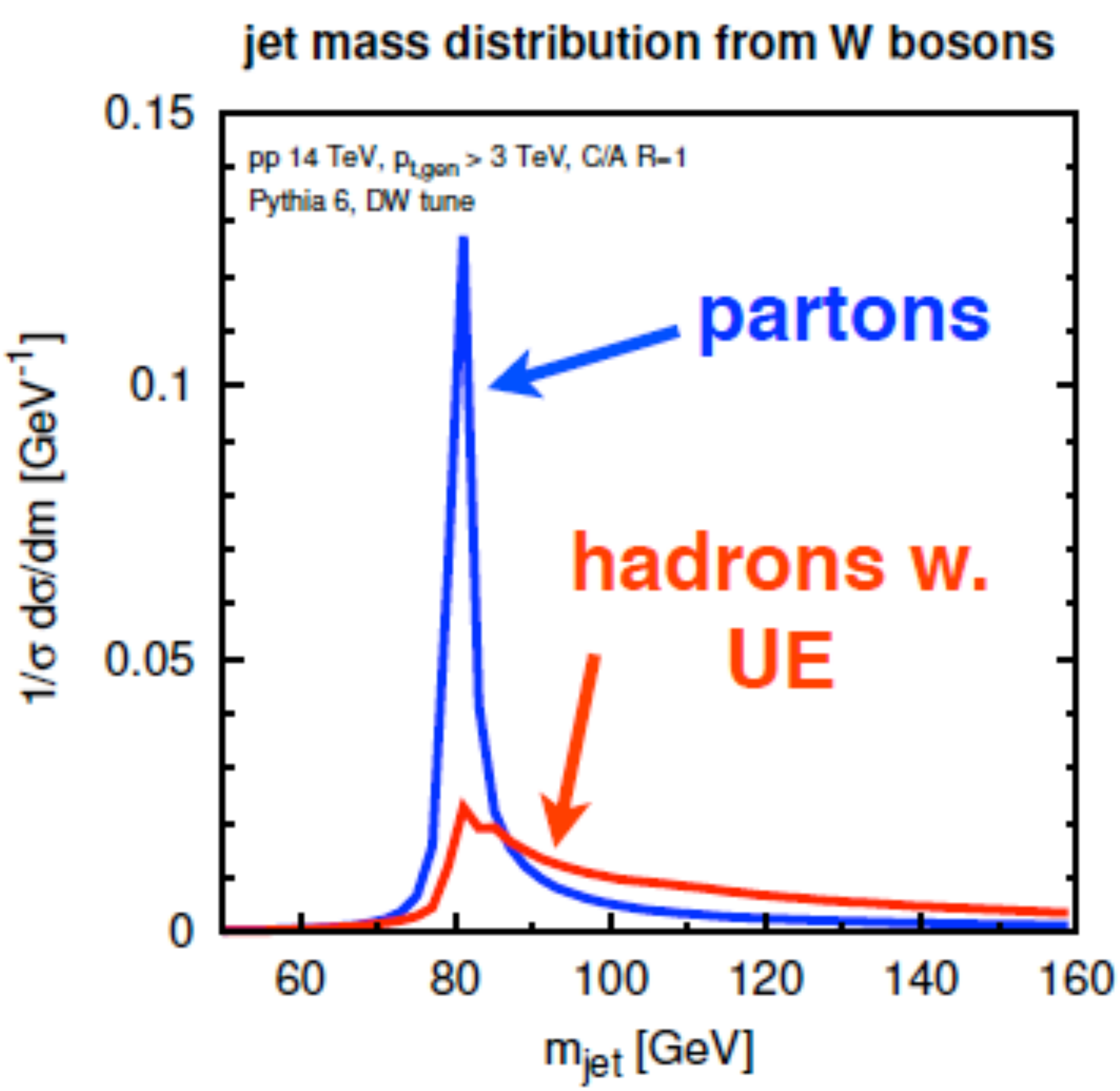
Triggered by a paper in 2008 by Butterworth, Davison Rubin, Salam ["Jet substructure as a new Higgs search channel at the LHC"] vibrant new sub-field emerged using jet-substructure to discover boosted heavy new particles

- well over 100 papers in the past 5 years
- dedicated conferences and write-ups (see e.g. 1012.5412, 1311.2708 or 1312.2708)
- upcoming BOOST2014 conference in August at UCL
- new nomenclature (trimming, pruning, filtering, mass-drop, N subjettiness, shower deconstruction ...)

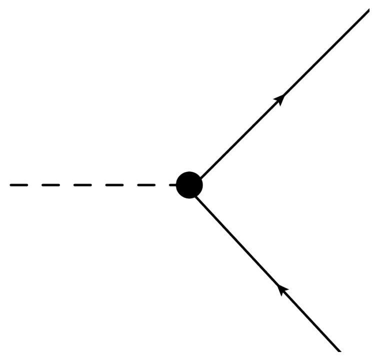
Jet-substructure at the LHC



Jet-mass is a natural variable to look for massive particles, but very large smearing from QCD radiation, hadronization, underlying event/pileup ...

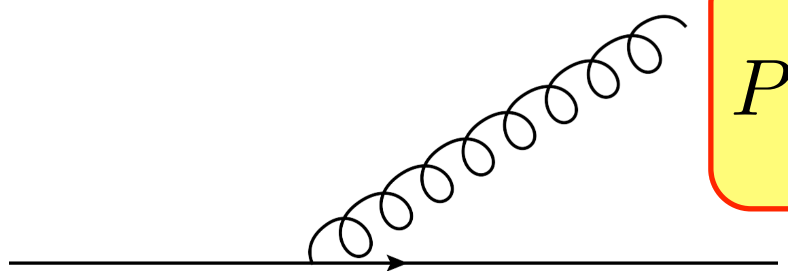


Jet-substructure at the LHC



$$P(z) \propto 1$$

BSM signal



$$P(z) \propto \frac{1+z^2}{1-z}$$

QCD background

Two main handles to

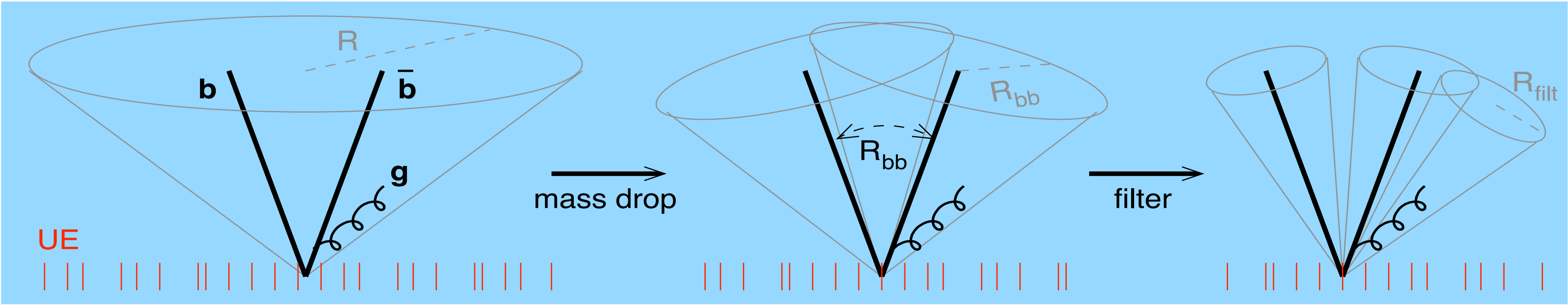
- signal prefer symmetric splittings, while background (QCD) prefers soft radiation, i.e. asymmetric splitting
- large angle radiation from color singlet is suppressed (angular ordering) $\rightarrow$ cutting wide angle radiation kills the background and does not affect much the signal

A large variety of methods (10-20?) to achieve these goals.

Typically: performance of new method tested with Monte Carlo

Mass-drop tagger for H → bb

Butterworth, Davison, Rubin, Salam '08



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

Exploit the specific pattern of H → bb vs g → gg, q → gg

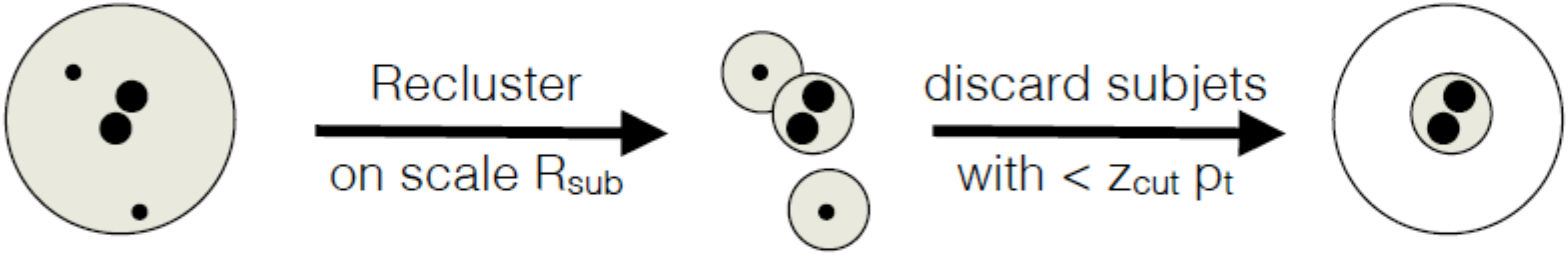
- QCD partons prefer soft emissions (hard → hard + soft)
- Higgs decay prefers symmetric splitting
- try to beat down contamination from underlying event
- try to capture most of the perturbative QCD radiation

Subsequently changed (modified mass-drop tagger) to follow the higher p_t branch

Dasgupta, Marzani, Fergoso, Salam '13

Pruning and trimming

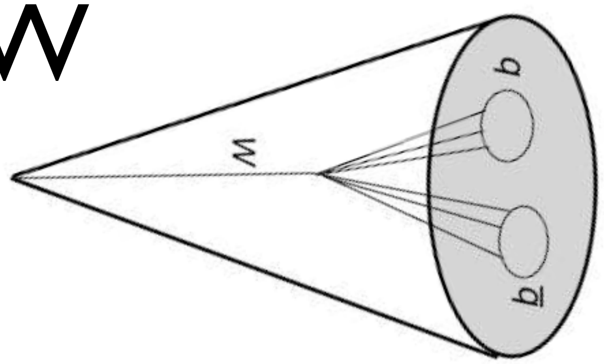
Pruning fixes a radius $R=m/p_t$ and reclusters the jet such that if two object are separated by angles larger then this and the branching is asymmetric, i.e. $\min(p_{t,a}, p_{t,b}) < z_{cut}\, p_{t,a+b}$, then the softer object is discarded.



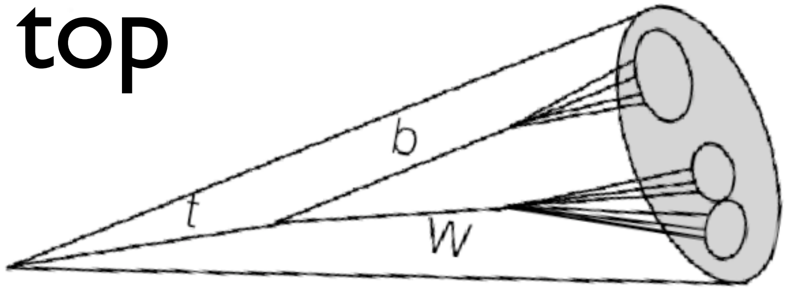
Trimming uses a fixed radius R_{trim}

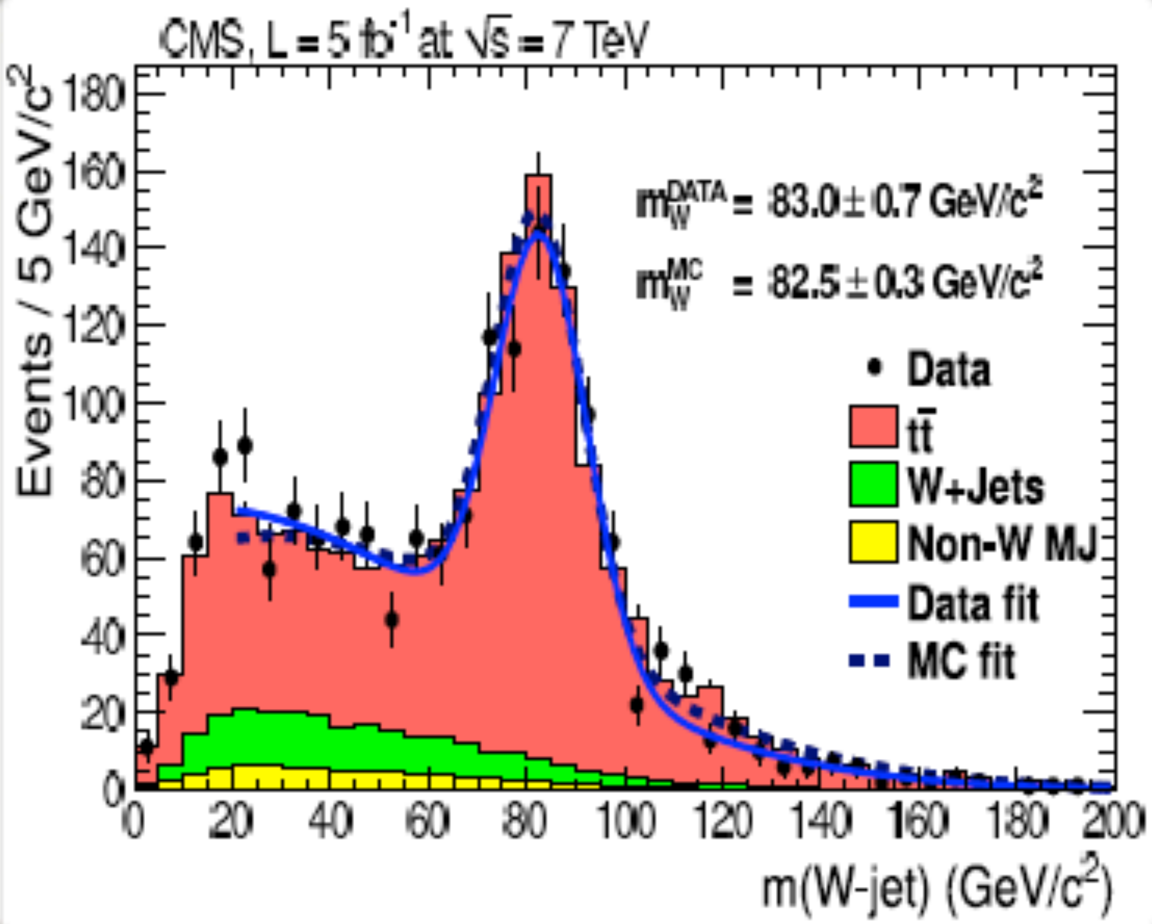
Seeing Ws and tops in a single jet

W

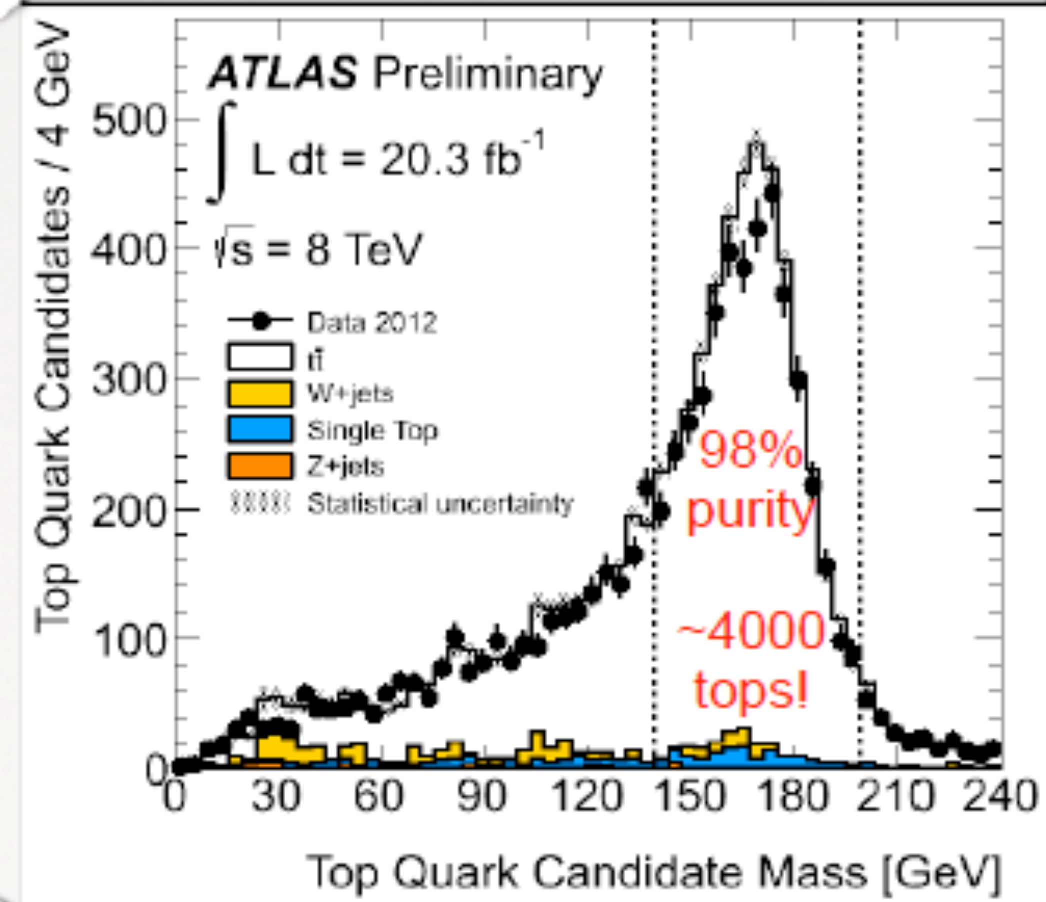


top





Pruning applied to C/A jets in events that have a $W \rightarrow l\,\nu$ and b tags



C/A R=1.5 jets with p_T > 200 GeV after $W \rightarrow \mu\nu$ preselection and default HEPTopTagger criteria

Jet-substructure at the LHC

Typical procedure:

introduce a way to analyze/deconstruct the event . Methods introduce energy/angular constraints, cuts (fixed or dynamical)

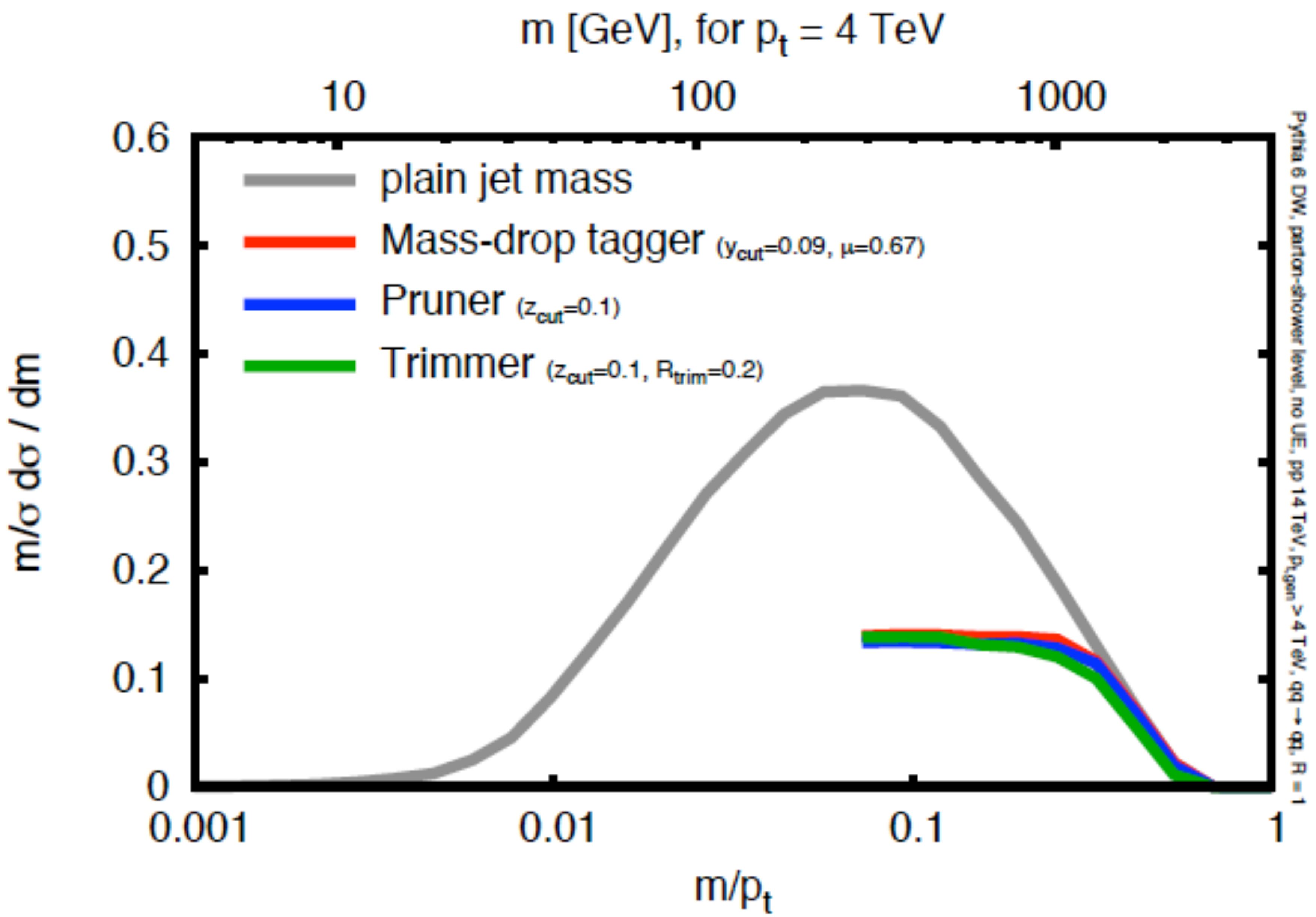
As a consequence:

- many parameters, complicated procedure, transparency lost
- potential of duplication/redundancy

Important questions

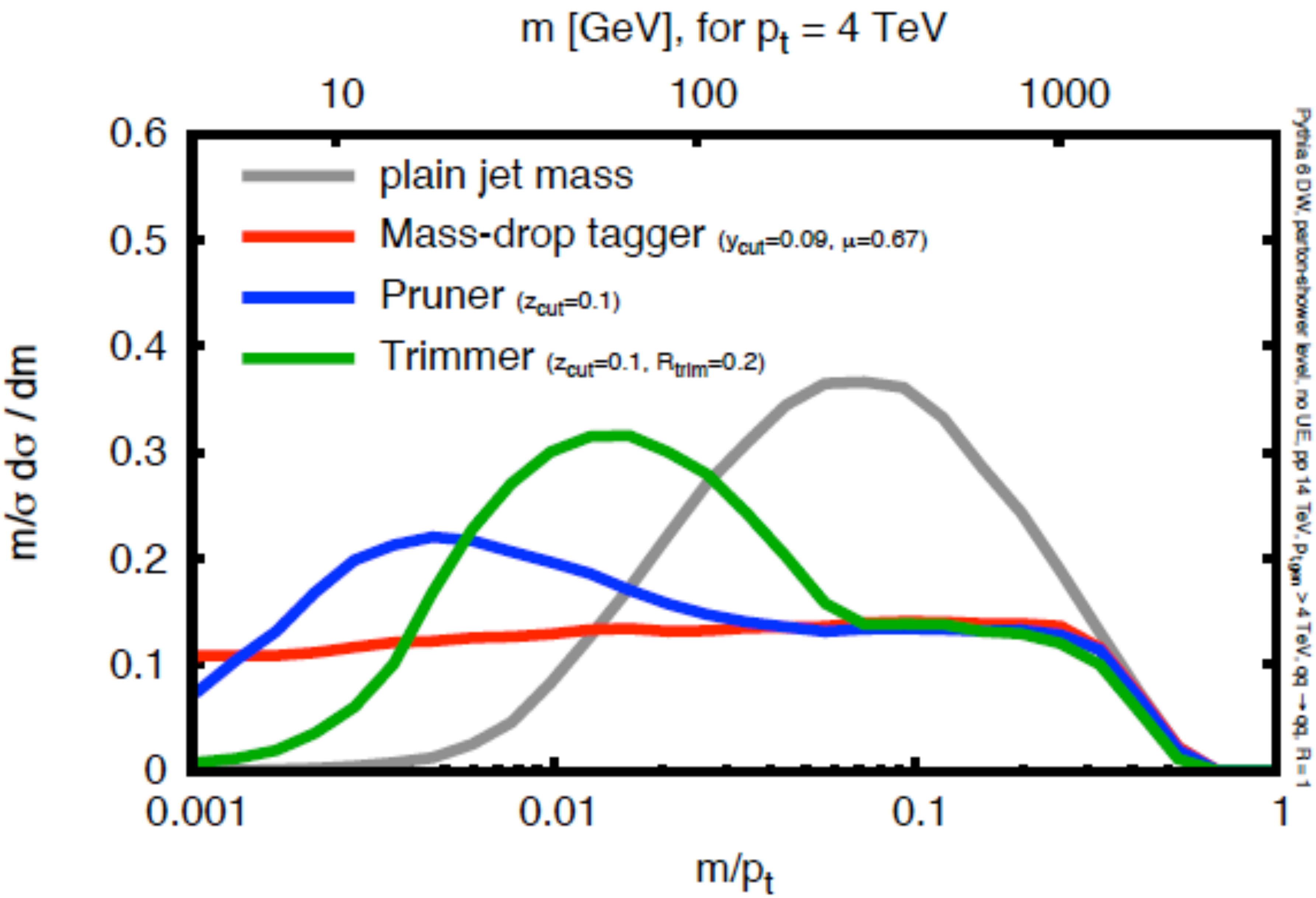
- how to judge/optimize performance? obvious answer: run Monte Carlo. But only a limited number of studies can be performed
- robustness: how much do results depend on parameters?
- how can one chose parameters a priori (without knowing where/what BSM physics might show up?)

Monte Carlo comparison of taggers



Taggers look quite similar ...

Monte Carlo comparison of taggers



Taggers look quite similar ... but only in a limited region

Can one understand the shapes, kinks, peaks analytically ?

NB: kinks particularly dangerous for data-driven background estimate

Analytic approaches to taggers

from M. Schwartz, Boost 2012

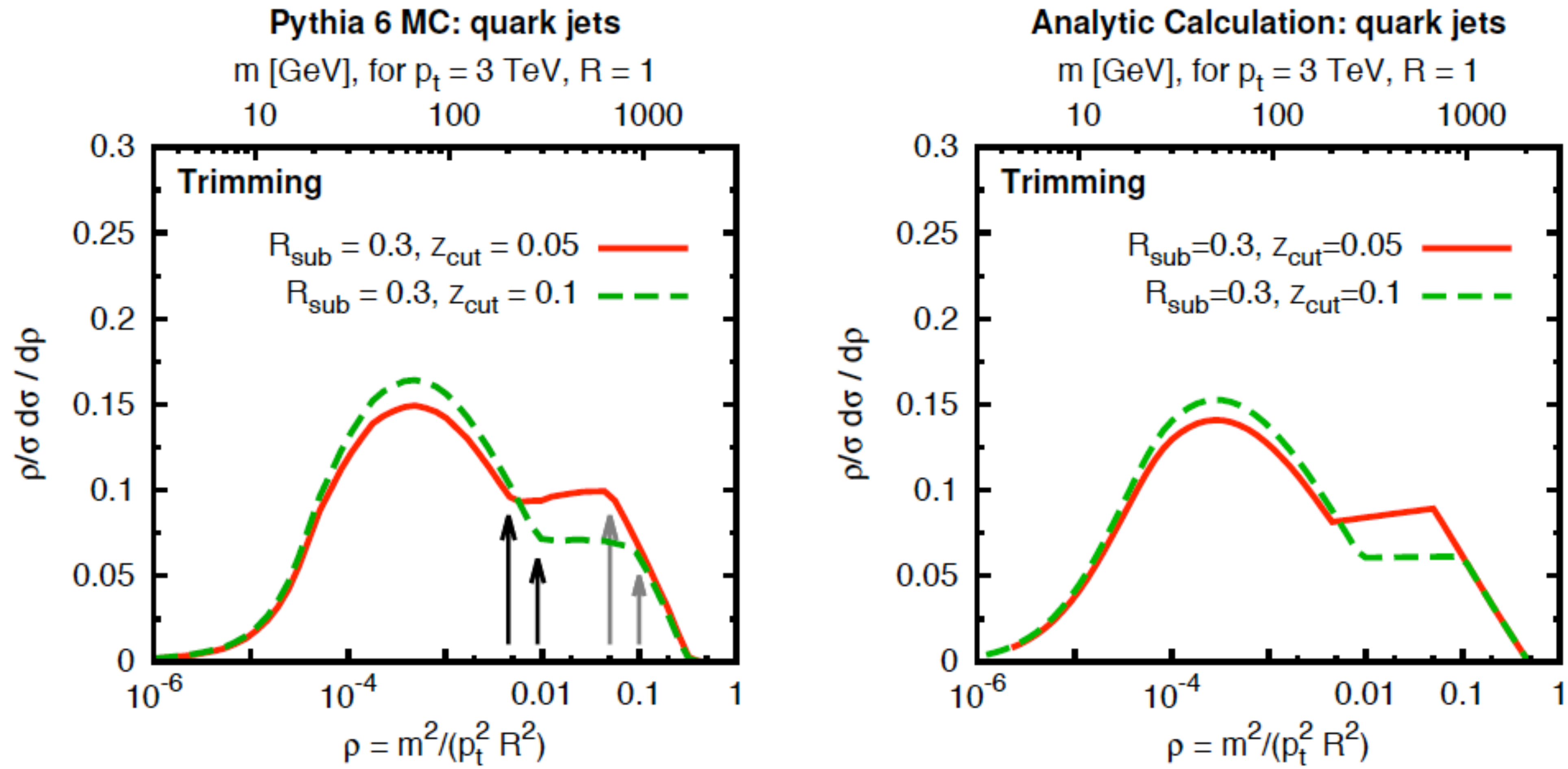
precision QCD

Can we describe taggers without having to give up precise pQCD calculations?

Don't want soft (few GeV) physics to affect BSM discoveries

First analytic approaches ...

Dasgupta, Fregoso, Marzani, Salam, Powling 1307.007



$$\rho \frac{\partial}{\partial \rho} \exp\left[-C_F \frac{\alpha_s}{2\pi}\left(-\frac{3}{2}\ln\frac{1}{\rho} + \Theta(\rho - z)\ln^2\frac{1}{\rho} + \Theta(z-\rho)\, 2\ln\frac{z}{\rho}\ln\frac{1}{z} + \Theta(zr^2-\rho)\ln^2\frac{zr^2}{\rho}\right)\right]$$

Simple analytic calculation allows to understand these features !

This means: have control and predict. Then use MC only to check/validate ...

Much more to come in the next years ...

Recap on jets

- The era of infrared unsafe algorithms (used at the Tevatron) is over
- Two major types of standard jet-types: sequential (k_t, CA, anti-k_t...) and cone-based (SISCone, ...)
- Jet-substructure: very power tool for BSM searches
- Studies done so far mostly based on
  - understanding pattern of radiation in QCD and BSM/Higgs
  - gearing jet-reconstruction to a specific search
  - validation/optimization with Monte Carlo
- Very recent developments:
  - first analytic understandings of taggers

My top ten high-precision theory challenges

Theory challenge	Status
1. automated NLO	(✓)
2. reliable PDF error	(✓)
3. PDF with EW effects	✗
4. NNLO for generic $2 \to 2$ processes	4-5 years?
5. analytic understanding of jet-substructure	first results
6. NNLO + parton shower	Higgs, Drell Yan
7. N^3LO for Higgs and Drell Yan (differential?)	partial results
8. multi-jet merging	2-3 years?
9. automated NNLL resummations	✓ at NLL
10. improve Monte Carlo (+reliable error estimate)	only some ideas