QCD resummation in the precision era

P. F. Monni
Rudolf Peierls Centre for Theoretical Physics
University of Oxford

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QCD in the IRC limit

- Gauge theories' perturbative predictions feature a logarithmic sensitivity to the Infrared and Collinear (IRC) dynamics

- Logarithms can appear both in amplitudes (e.g. large scale gaps) and at the cross section level whenever the measured observable probes kinematic regimes where the imbalance between real and virtual corrections affects the cancellation of IRC divergences (i.e. in the singular limit the cancellation only occurs when all perturbative orders are considered)

- e.g.
  - production of heavy systems near threshold in hadronic collisions
    -> Talks by M. Bonvini, C. Wever
  - high-energy scattering
    -> Talk by J. Smillie
  - limits of IRC-safe observables that constrain real radiation to soft and collinear configurations (e.g. exclusive regimes, shoulders,…)

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Resummation: LEP vs LHC

- The two topics would require, in principle, different talks given the different nature of the two experiments
- LEP was a precision machine, largely used to test QCD and its properties (radiation coherence, non-abelian structure, strong coupling, non-perturbative (NP) corrections,…)
  - this often required probing regimes in which all-order effects are important. Resummation is of primary relevance for these studies
- LHC so far has been, primarily, a discovery machine. Collisions are QCD driven and sensitivity to long-distance physics comes together with contamination from background, pile-up (PU) and underlying events (UE). Observables computable precisely for a single collision are smeared, sometimes completely changed, by the huge amount of uncontrolled (theoretically) radiation
- Very often is necessary to cut out radiation effects without depleting too much the underlying signal. Resummation effects often small

Precision at the LHC

- The increase in luminosity improves discovery reach and precision
- Several measurements are being (or will be) performed with few-% accuracy - theory precision can become the limiting factor
- So far theory progress met this challenge (fixed-order, generators, EW,…)

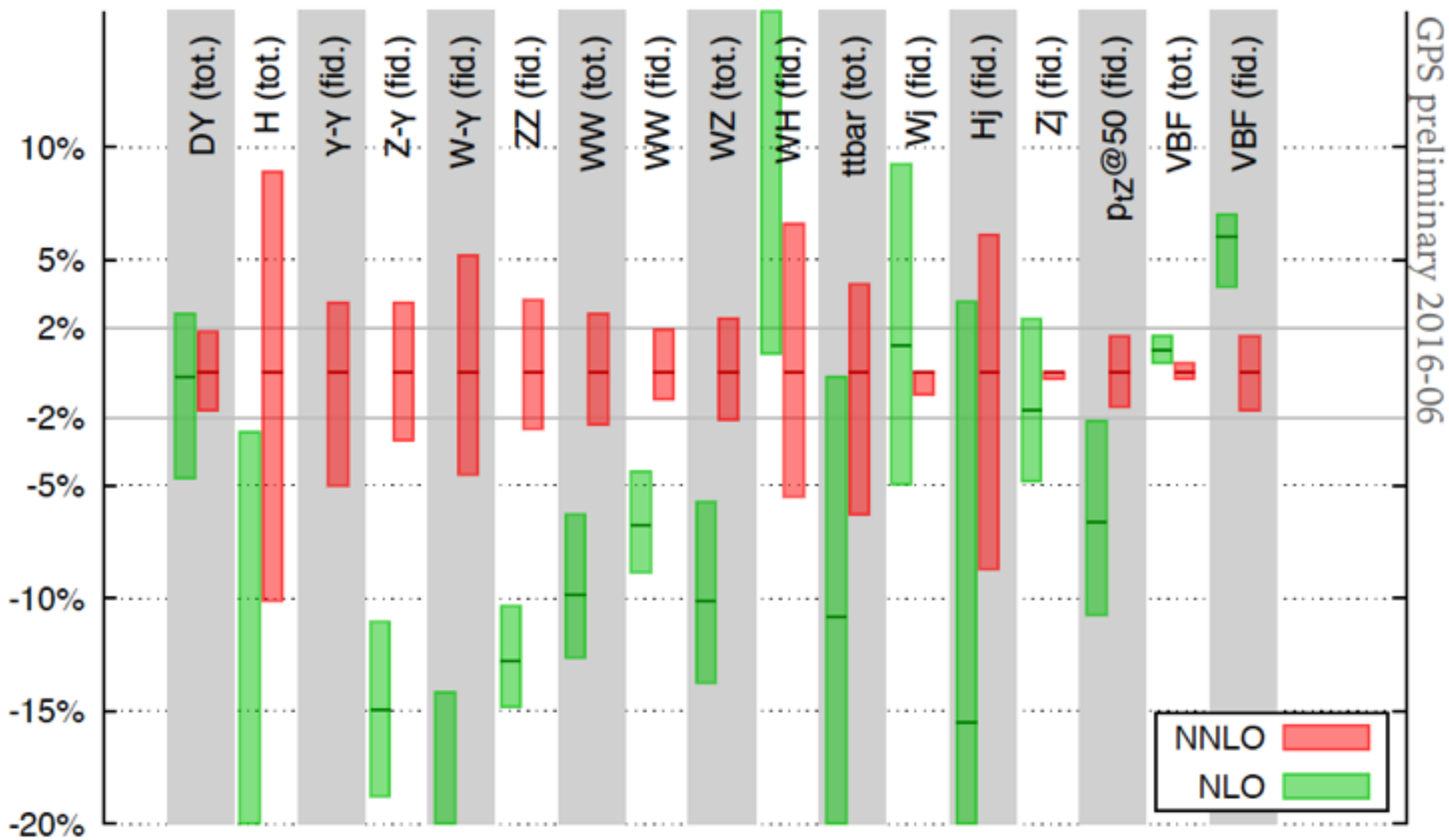


Image credit: G. Salam

Precision at the LHC

- At this level of accuracy many effects compete (higher-order/all-order QCD corrections, EW effects, hadronisation+NP corrections, PDFs + parameters), it's challenging to improve further.

- As far as resummation is concerned, a few questions come up:

    - Are all sources of all-order corrections under control (multiscale problems) ?

    - How's the contamination from radiation excluded/subtracted (e.g. what cuts) ? Is the resulting observable predictable (resummable) at all orders ?

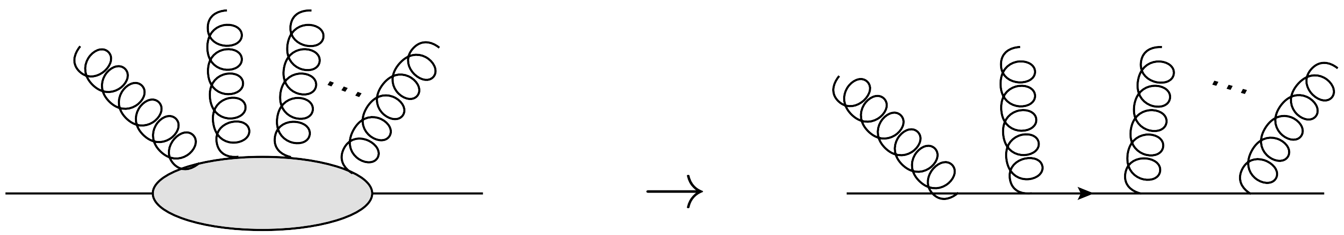
    - Can we start from our knowledge of the radiation dynamics to devise new observables which are predictable at all orders and free of PU+UE contamination ? i.e. can we exploit more data ?

What does "resummable" even mean ?

- The all-order treatment for an observable $V(\{\tilde{p}\}, k_1, \ldots, k_n)$ that satisfies the Sterman-Weinberg's criteria relies on the concept of factorisation …
  - … of the QCD amplitudes in the IRC limits
  - … of the observable. This implies that hard and singular IRC modes are not mixed when radiative corrections are considered
- The latter is often interpreted as the existence of factorised formula for the cross section in some conjugate space   Talks by T. Becher, L. Rothen
  - powerful tool: systematic, observable dependent
- Ultimately we want to use what we learn from the theory to design precise generators that accurately predict many observables for a given process
- We need to understand what hides behind factorisation to see if we can formulate an approach to resummation that applies to several observables

What does "resummable" even mean ?

- Consider e.g. n soft & collinear independent emissions off a quark line



- Consider limit (most singular) of gluons strongly ordered in energy + angle

$$\sigma = \sum_n \int \frac{1}{n!} \prod_{i=1}^{n} [dk_i] |M(k_i)|^2 \left[\Theta(v - V(\{\tilde{p}\}, k_1, \ldots, k_n)) - 1\right]$$

Amplitudes exponentiate in this limit

What if it doesn't scale this way ?

Exponentiation of the XS is preserved only if (in the considered limit)

$V(\{\tilde{p}\}, k_1, \ldots, k_n) \sim \max\{V(\{\tilde{p}\}, k_i)\}$

- Restrictions become a little more subtle when the primary emissions branch

- Formulate conditions for an observable to be resumed -> recursively IRC safety

    - if V is rIRC safe it can be systematically (and automatically) resummed

[@ NLL Banfi, Salam, Zanderighi '01-'04] [@ NNLL Banfi, McAslan, PM, Zanderighi '14 - '16; PM, Re, Torrielli '16]

for now only for global obs. with 2 coloured legs at LO

    - one can formulate a recipe with the corrections to be computed (and how to compute them) at a given logarithmic order

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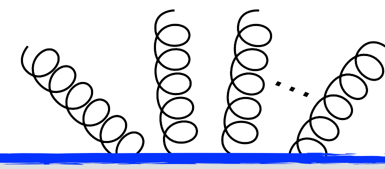

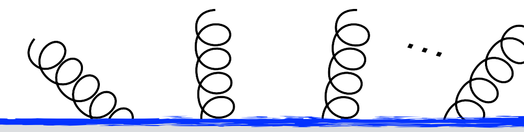

This is not a no-go theorem !

some non-rIRC safe observable could still be resummable,

although

no general structure emerges (yet)

No full resummations beyond LL exist today

in this limit

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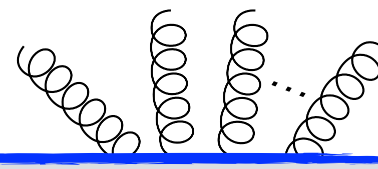

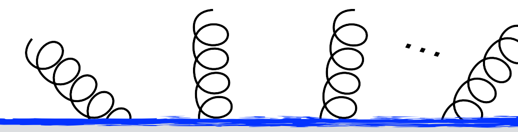

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(in the considered limit)

Keeping in mind this property when thinking of new observables might come in handy

- if V is rIRC safe it can be systematically (and automatically) resummed

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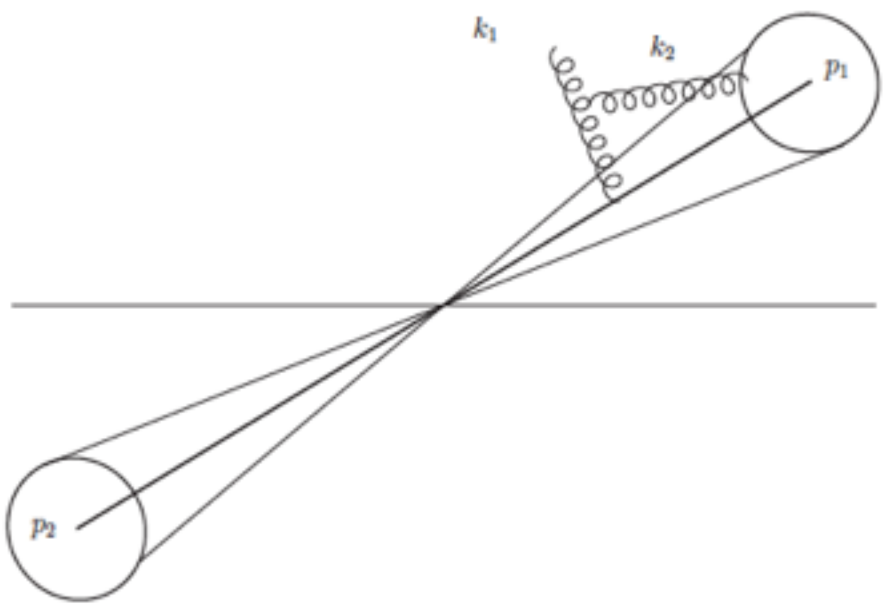
→ for now only for global obs. with 2 coloured legs at LO

- one can formulate a recipe with the corrections to be computed (and how to compute them) at a given logarithmic order

Globalness

- Often observables weigh differently the radiation in different regions of the detector (jets, angular cuts, …)

Additional logarithms appear due to the RV imbalance near the transition region
[Dasgupta, Salam '01]



- Two viable solutions:
  - non-global logarithms can be resummed at LL (general case in the planar limit) [Dasgupta, Salam '01; Banfi, Marchesini, Smye '02; Hatta, Ueda'14]
    - Recently fervent activity to understand NLL -> Talk by T. Becher
    [Caron-Huot '15; Larkoski, Moult, Neill '15; Becher, Neubert, Rothen, Shao '15-'16]
    - Possible to devise a general approach beyond LL ?
  - Define observables PU/UE-robust and *non-global free* -> substructure

Resummation in jet substructure

- Can these problems be modulated by grooming jets ?

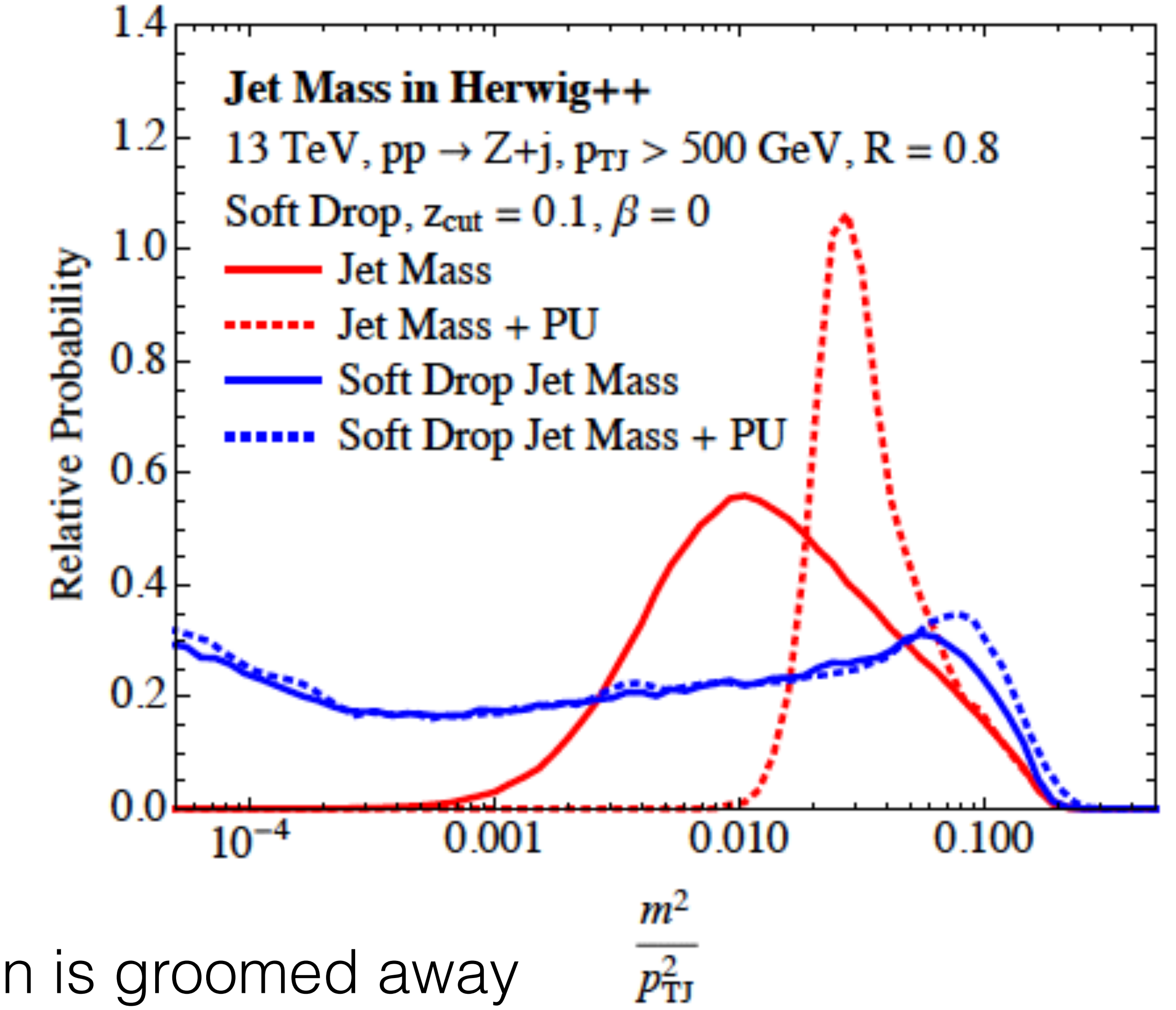
Proliferation of substructure technology in recent years

First analytic understanding at LL helped develop better-behaved observables

e.g. mMDT/Soft drop groomed jet mass:
[Dasgupta, Fregoso, Marzani, Salam '13]
[Larkoski, Marzani, Soyez, Thaler '14]

Recursive declustering of a C/A jet until

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$



In the regime $m_J^2/p_{t,J}^2 \ll z_{\rm cut}$ the soft radiation is groomed away in a rIRC-safe way:

→ $\beta = 0$: soft logarithms (wide-angle NG, interference effects) become $\ln(z_{\rm cut})$
jet mass logarithms $\ln(m_J^2/p_{t,J}^2)$ are exclusively of collinear origin

→ $\beta \neq 0$: additional NG logs of the jet mass are power suppressed

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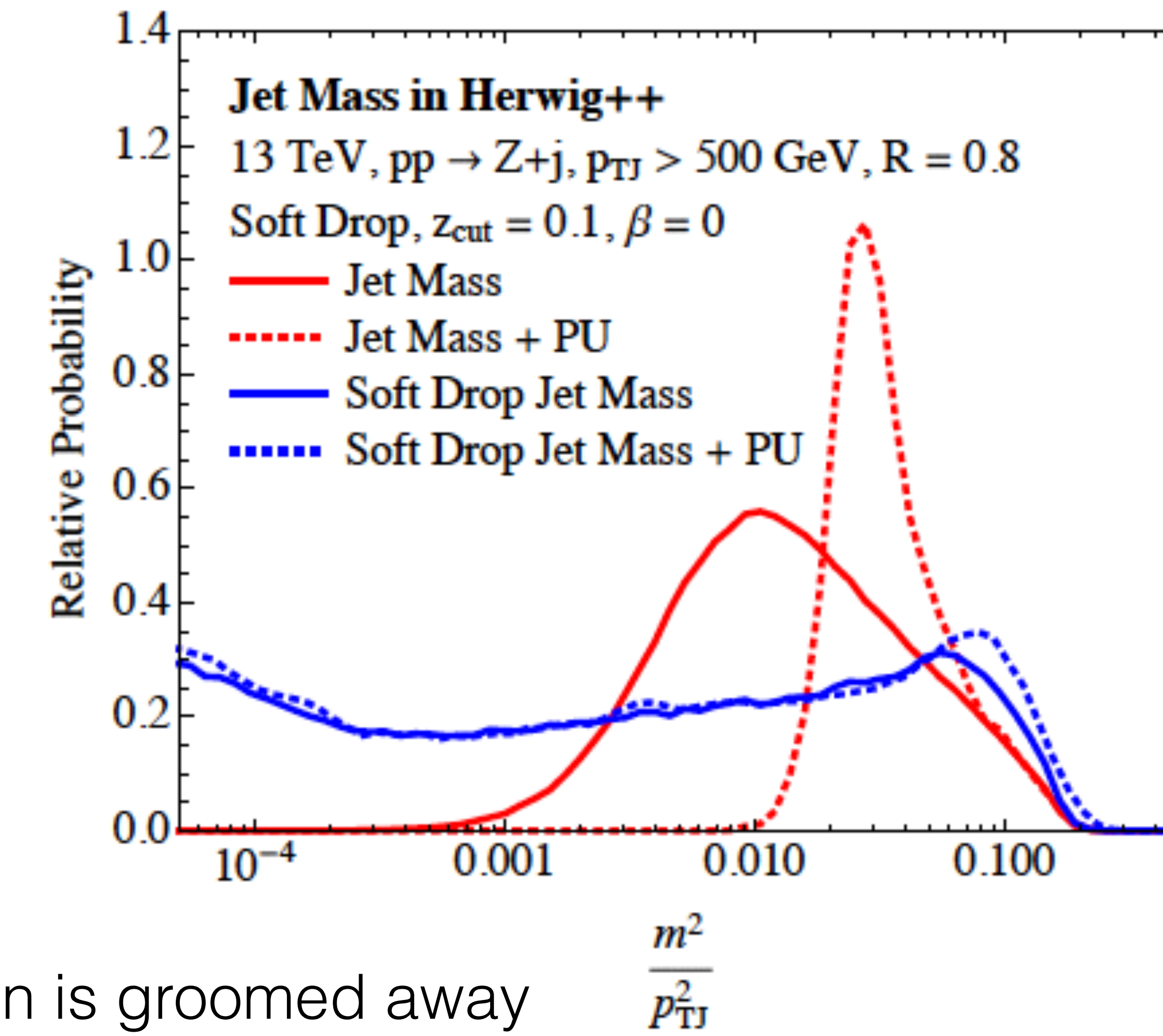

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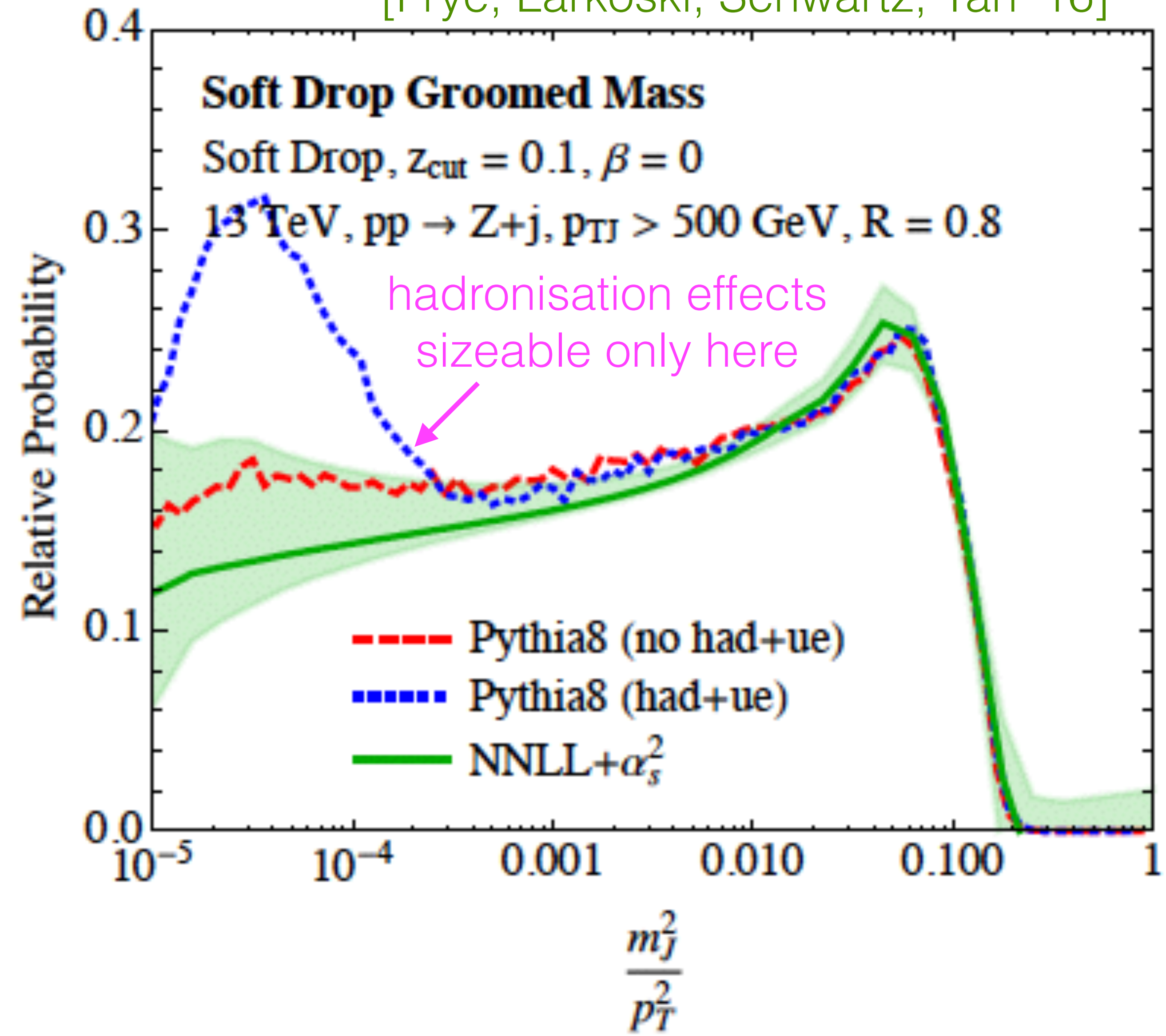
Resummation in jet substructure

- All order treatment of the jet-mass logarithms reduces to a process-independent collinear jet function

[Frye, Larkoski, Schwartz, Yan ‘16]

Computed at N(N)LL in the regime

$$m_J^2/p_{t,J}^2 \ll z_{\rm cut} \ll 1$$



Nice example of how an observable can undergo surgery to improve its PT behaviour

→ • This can be used to resurrect some observables overwhelmed by PU/UE effects. Useful for extractions of the strong coupling ?

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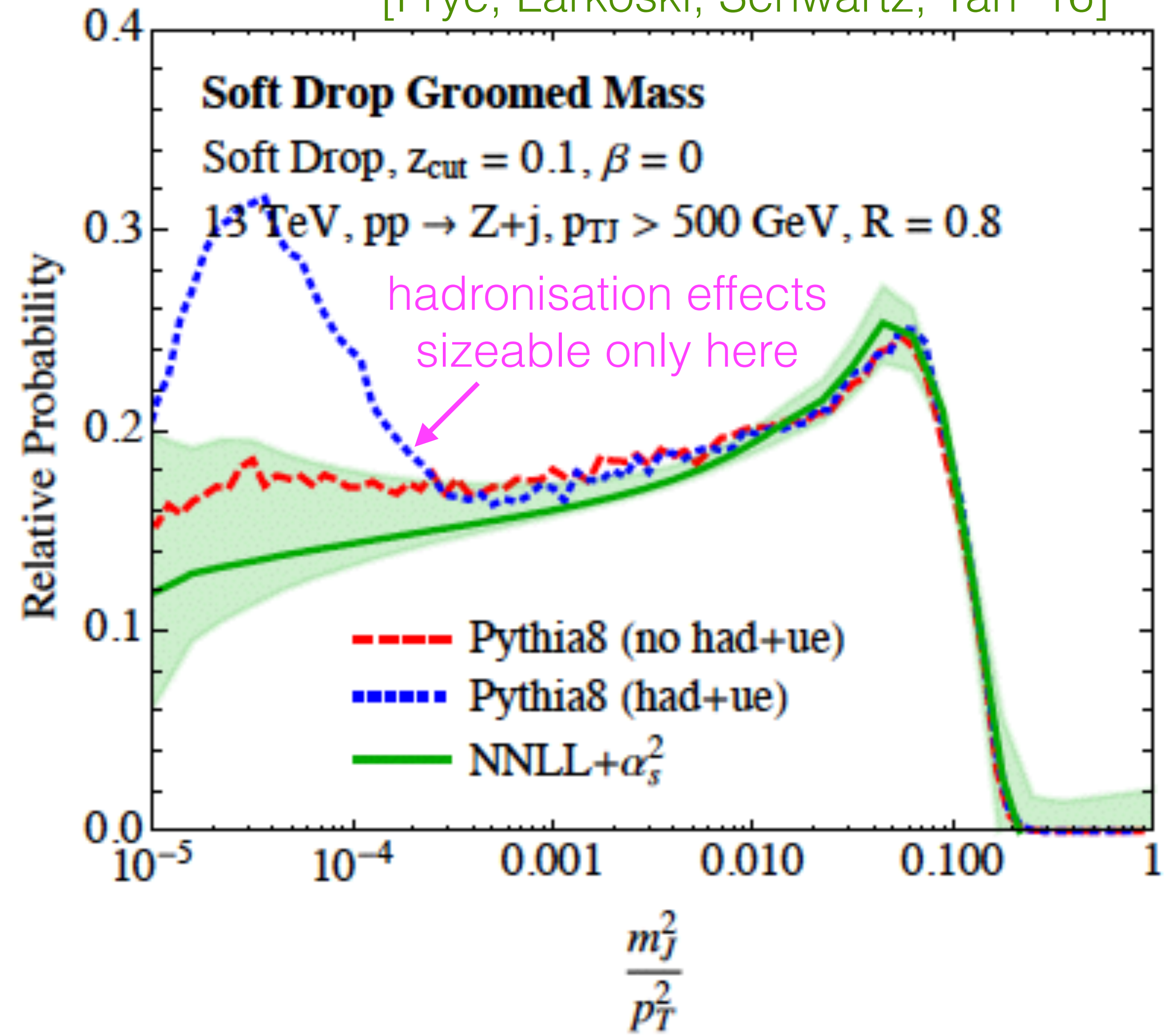

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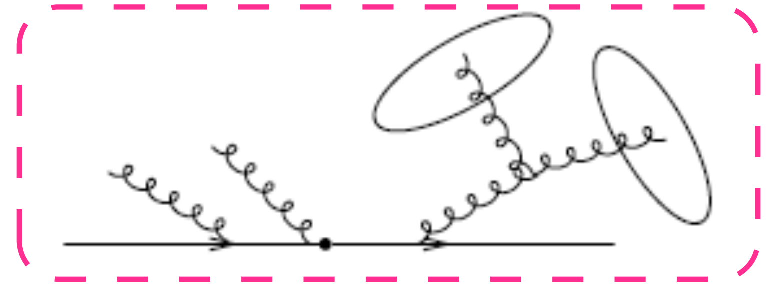
Jet-radius logarithms



- small-R jets have received some attention lately

LL resummation with generating functionals
[Dasgupta, Dreyer, Salam, Soyez '14 - '16]
Formulation in SCET: [Chien, Hornig, Lee '15]
[Kolodrubetz, Pietrulewicz, Stewart, Tackmann, Waalewijn '16]
[Kang, Ringer, Vitev '16]

- All-order effects can become relevant when R ~ 0.2-0.3 or smaller are employed (heavy ions, substructure, jet-rates studies,…)

e.g. inclusive jet spectrum

[Dasgupta, Dreyer, Salam, Soyez '16]
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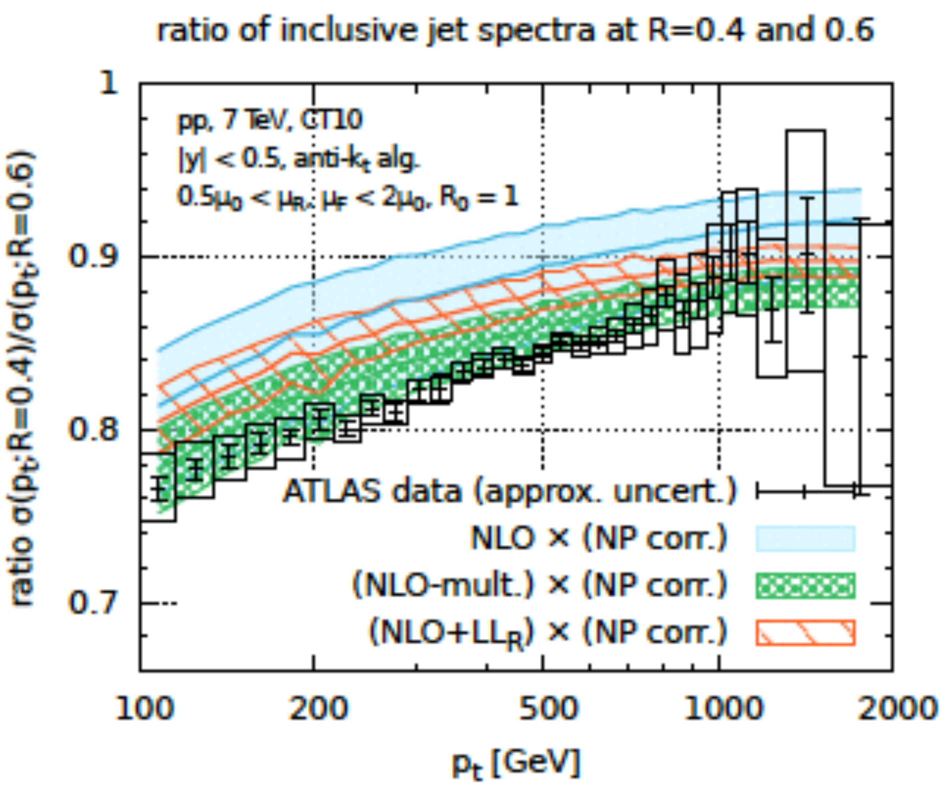
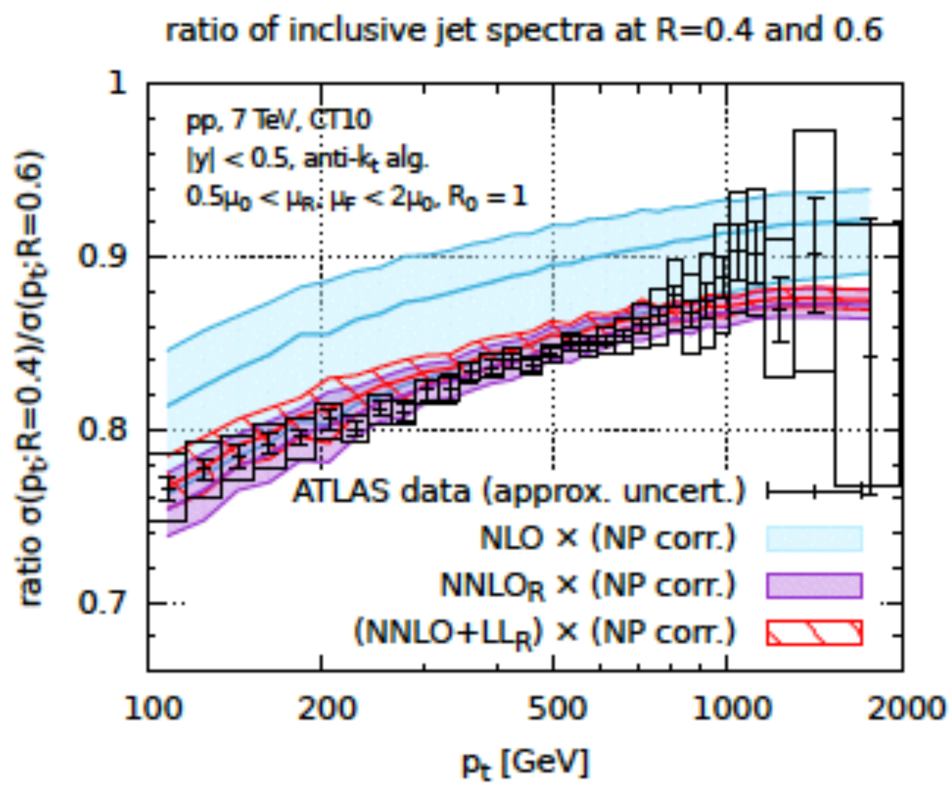
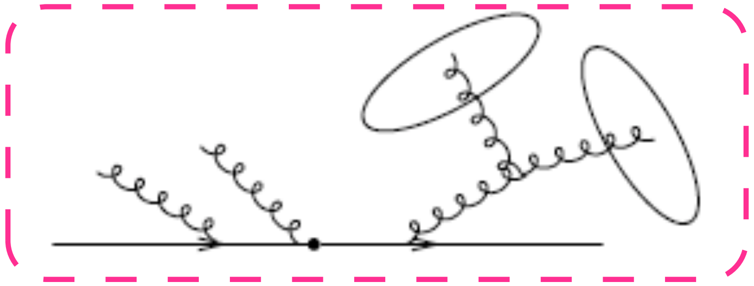




Full NNLO corrections necessary
[Currie, Gehrmann-De Ridder, Gehrmann, Glover, Pires '13]

-> Talk by J. Currie

Jet-radius logarithms



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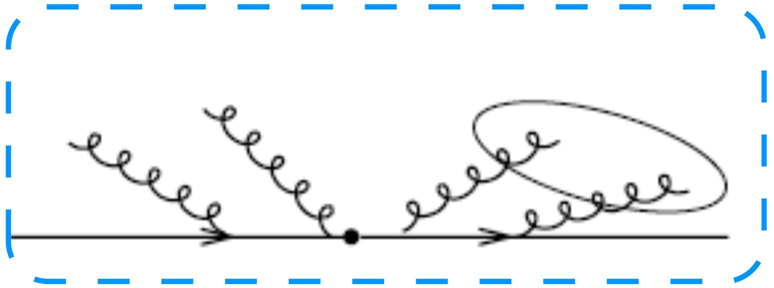
→ • Measurements at multiple R values powerful handle to modulate hadronisation/PT effects

[Dasgupta, Magnea, Salam ’08]

$$\text{had} \sim -\frac{1}{R}\,,\ \text{UE} \sim R^2\,,\ \text{PT} \sim \ln\frac{1}{R}$$

PT also has a R^2 contribution



Higgs physics - 0 jet cross section

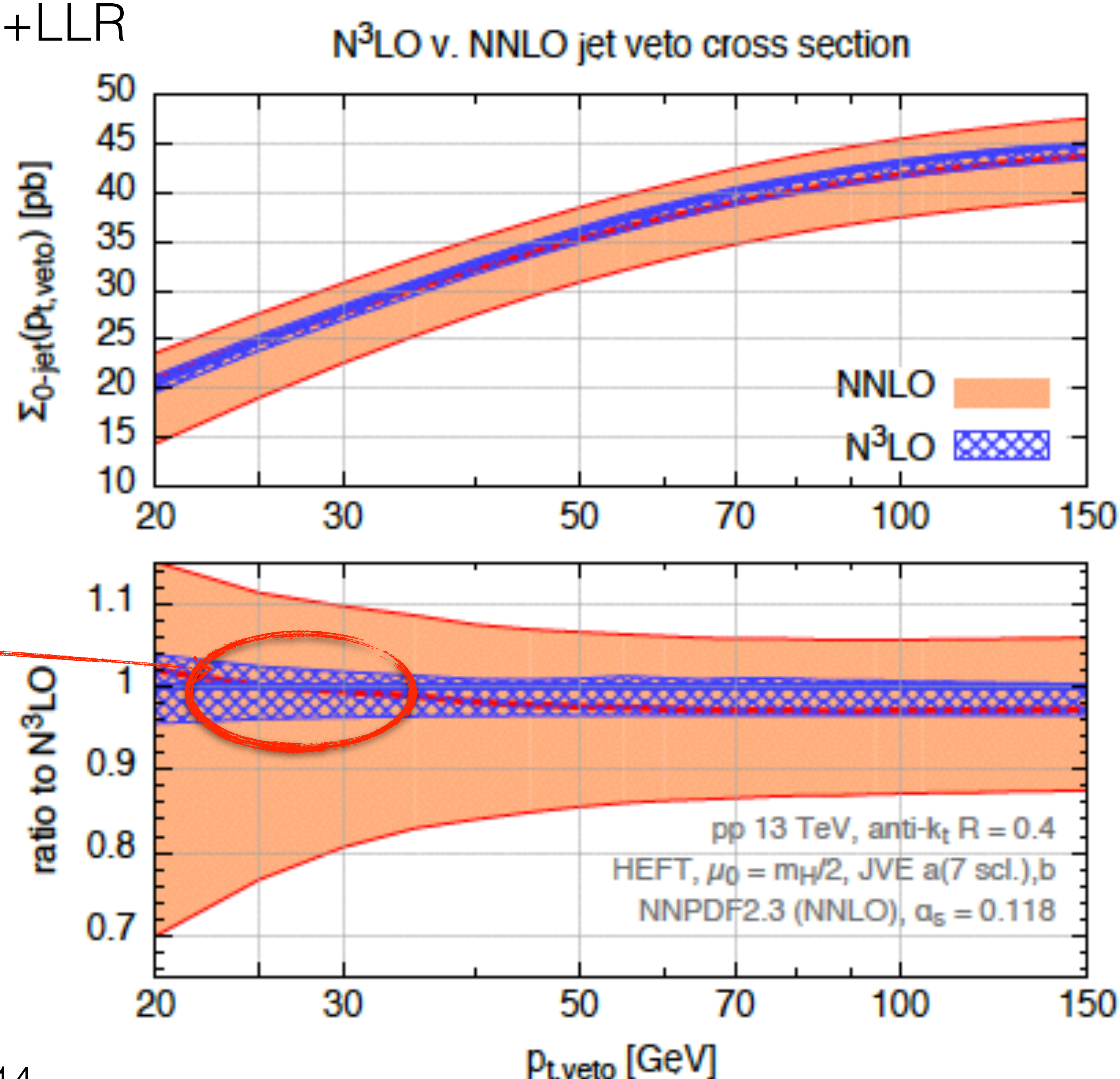
-> Talk by L. Rothen

- Important to understand (a priori) where exactly resummation and fixed-order are reliable (and estimate the matching uncertainty)

e.g. 0-jet cross section at N3LO+NNLL+LLR

[Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger '16]
[Boughezal, Caola, Melnikov, Petriello, Schulze '15]
[Banfi, Caola, Dreyer, PM, Salam, Zanderighi, Dulat '15]

at pt ~25-30 GeV
N3LO (pure fixed order) corrections
have a 1-2% impact
(this varies with central scales)



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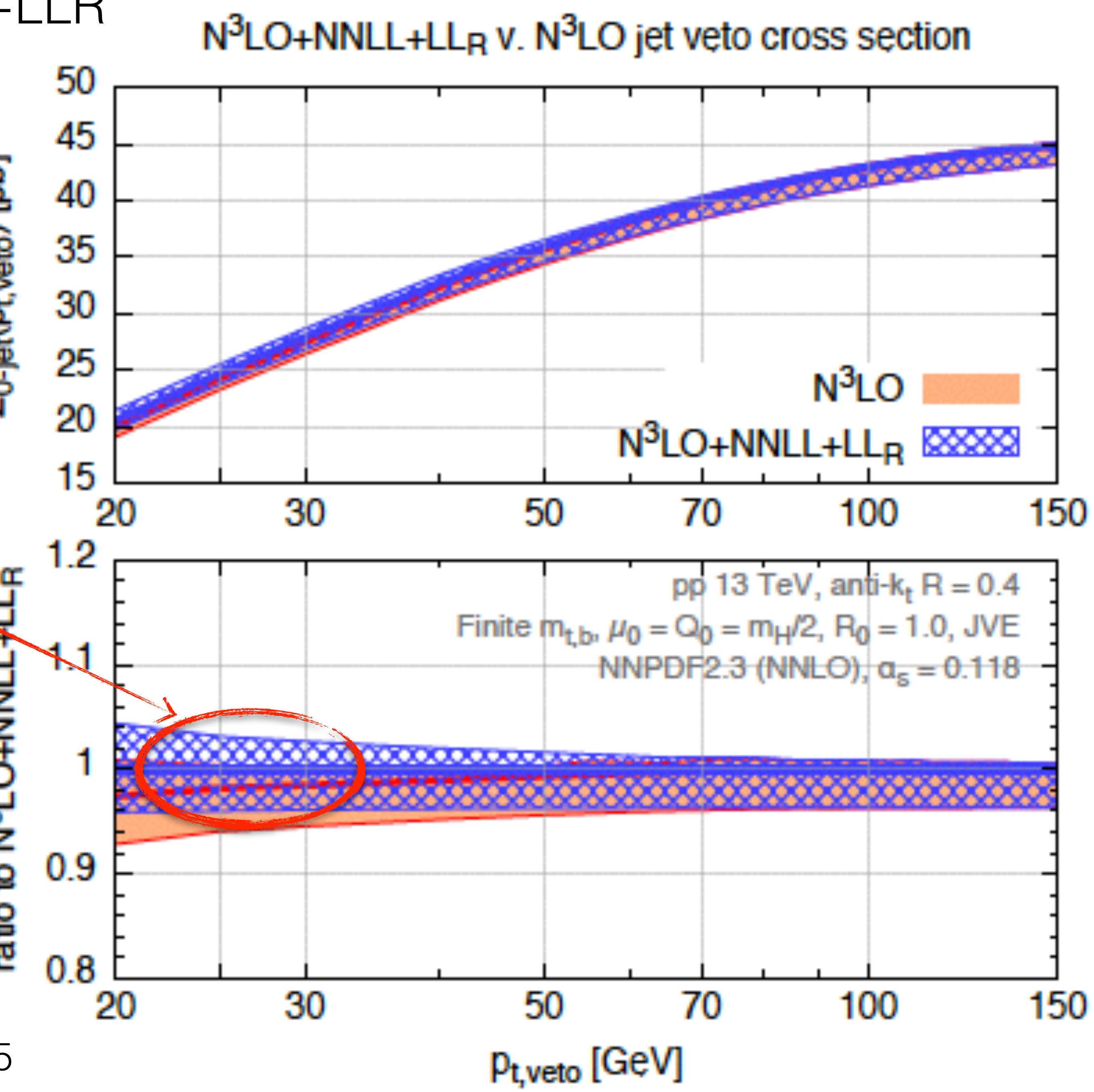


Impact of the resummation
is of the same order (~2%).
How accurate is this statement ?

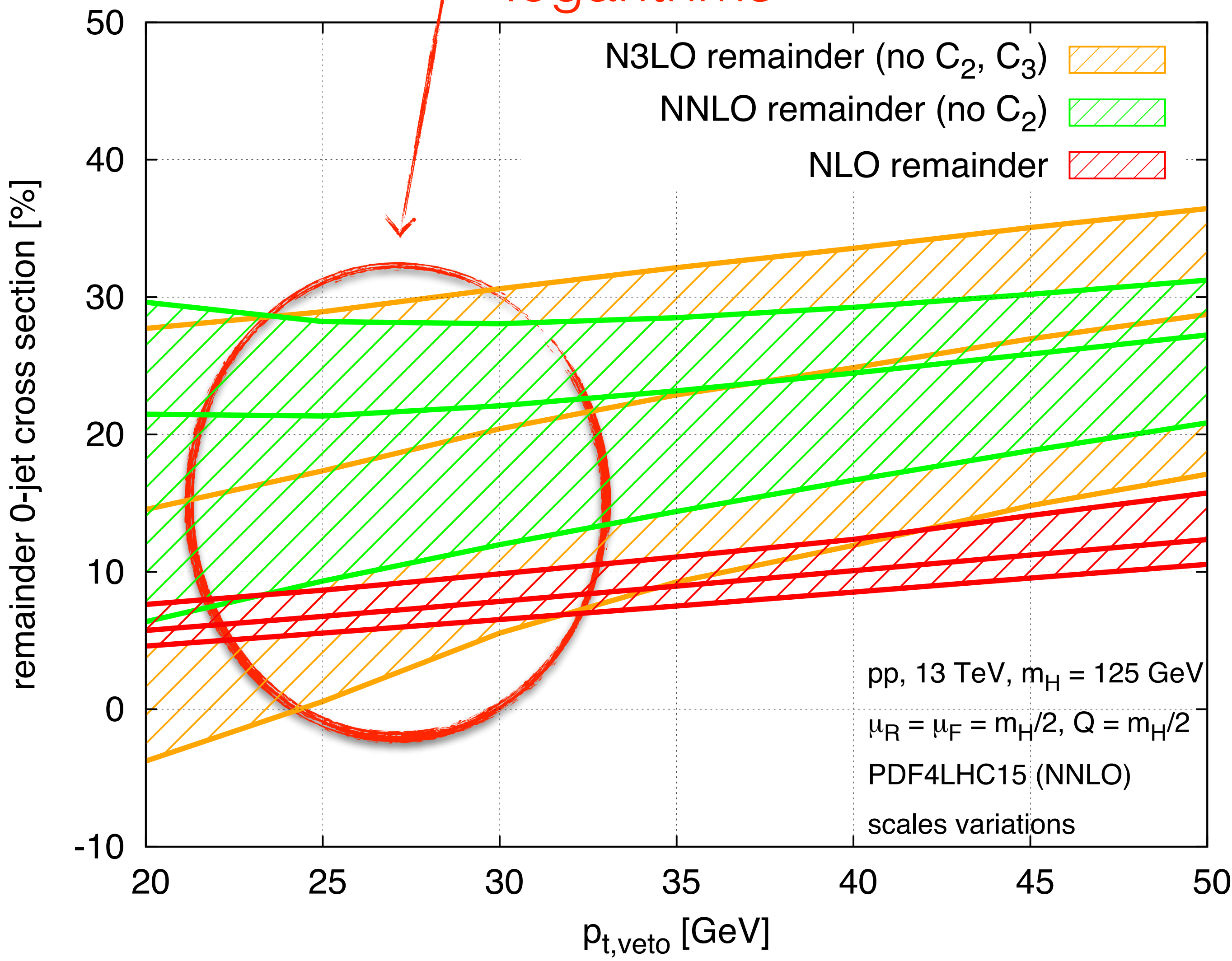
Higgs physics - 0 jet cross section

- Important to understand (a priori) where exactly resummation and fixed-order are reliable (and estimate the matching uncertainty)

e.g. 0-jet cross section at N3LO+NNLL+LLR

~ 70-80% of the perturbative expansion is made of logarithms

pt ~ 25-30 GeV is a transition region where logarithms are the dominant part of the perturbative expansion, although fixed-order still works fine (i.e. the coupling suppression is still effective) Resummation effects seem physical.



Higgs physics - pT distribution

-> see also talks by H. Sargsyan and M. Wiesemann

Currently known at NNLL+NNLO in HEFT:

N3LO tot: [Anastasiou, Duhr, Dulat, Herzog, Mistlberger '15 + Furlan, Gehrmann, Lazopoulos '16]

NNLO: [Boughezal, Caola, Melnikov, Petriello, Schulze '15; Caola, Melnikov, Schulze '15
Boughezal, Focke, Giele, Liu, Petriello '15; Chen, Cruz-Martinez, Gehrmann, Glover, Jaquier '16]

NNLL: [Grazzini, de Florian '01; Bozzi, Catani, de Florian, Grazzini '03; Becher, Neubert '10;
Neill, Rothstein, Vaidya '15; PM, Re, Torrielli '16]

Higgs physics - pT distribution

Currently known at NNLL+NNLO in HEFT:

- Interesting example (one of many) of observable with zeros away from the Sudakov limit (two kinematic mechanisms competing in the limit pt -> 0)
  - resummation if rIRC safe [PM, Re, Torrielli '16]
  - new handle on joint resummations and Sudakov shoulders

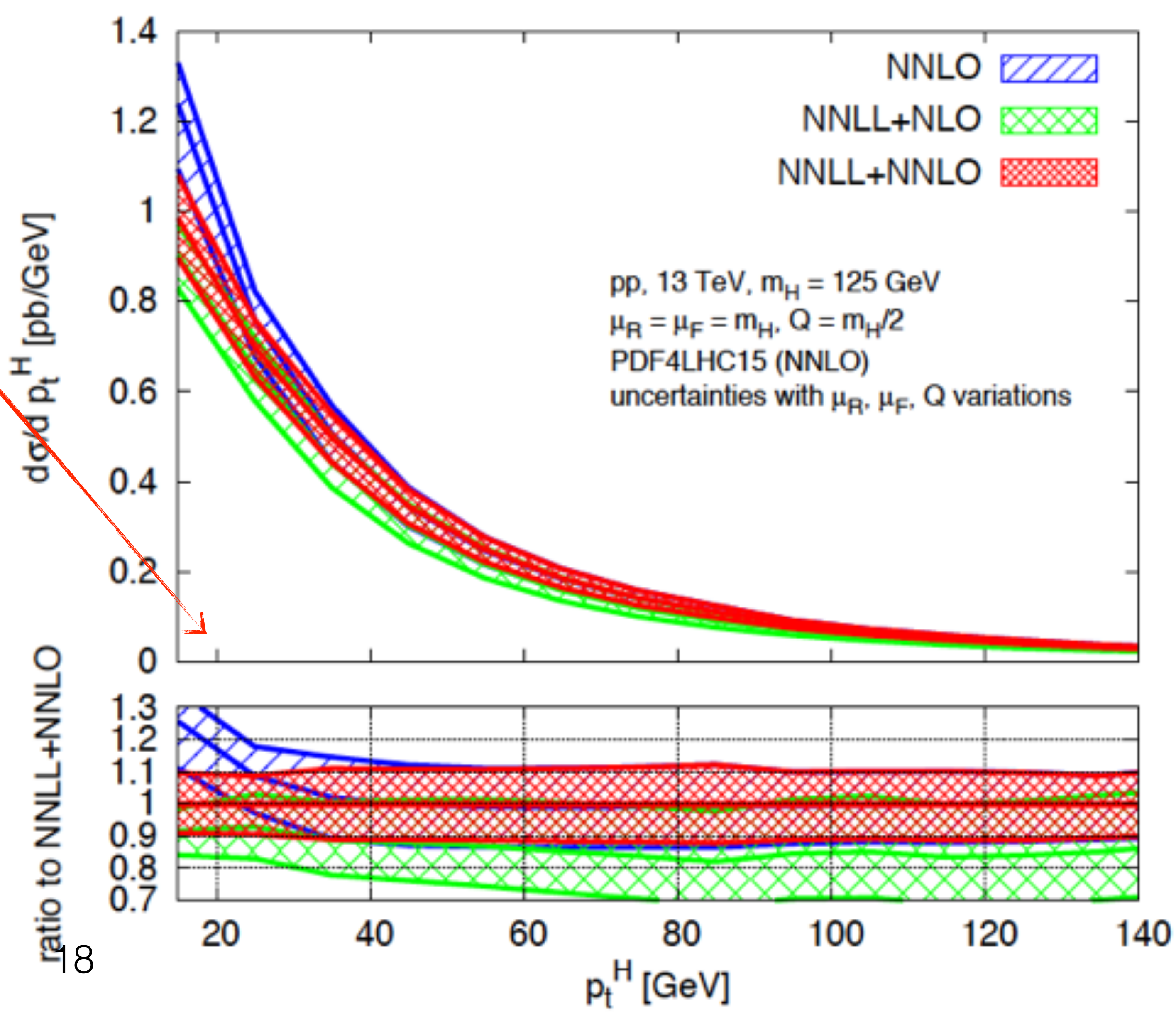
Resummation relevant below pt ~ 40 GeV - th. uncertainties ~ 10%

Many effects beyond this point:

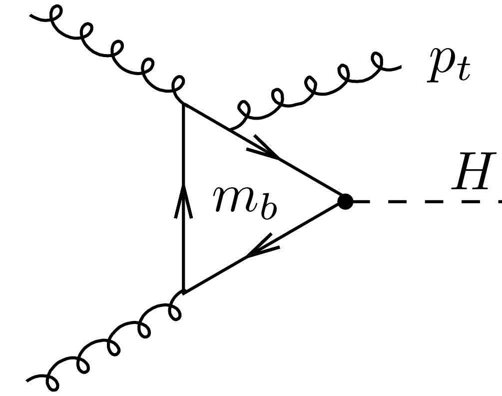
- Luminosity uncertainties estimated to be ~ 3%
- strong coupling unc. ~ 2%
- quark masses (known at LO) ~ 5-6% in this region
- hadronisation ~ 2-4%

- N3LL+NNLO on its way : little effect on central values, but theory uncertainties halved (~5%). We should start worrying about other effects

[Li, Zhu '16]



Quark masses

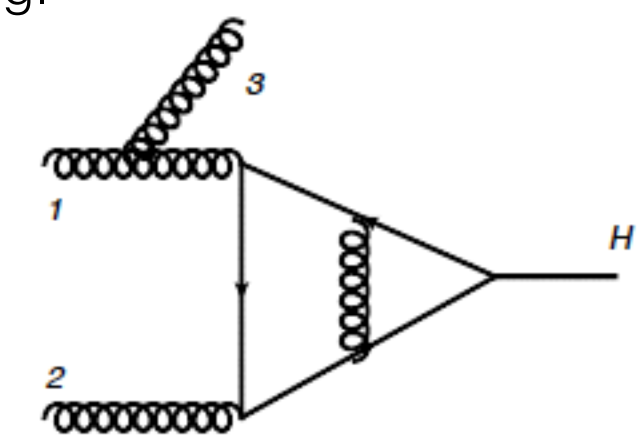


When the full theory is considered the bottom-quark amplitudes are enhanced by (regular) logarithms of the ratio p_t/m_b in the region $m_b^2 << p_t^2 << m_H^2$

- Subject of discussion in the past years: what's their impact at HO ? Should they be resummed ?

- Amplitude DL resummed in the abelian limit ~Cf^n as^n L^2n [Melnikov, Penin '16]

e.g.



$$\to A_{++\pm} = \pm 2 \ln \frac{m_b^2}{m_H^2} \int_0^{1-\tau_t} \frac{1 - e^{-x\eta(1-\eta)}}{x\eta} d\eta \ , \tau_t \sim \ln \frac{m_b^2}{p_t^2} / \ln \frac{m_b^2}{m_H^2}$$

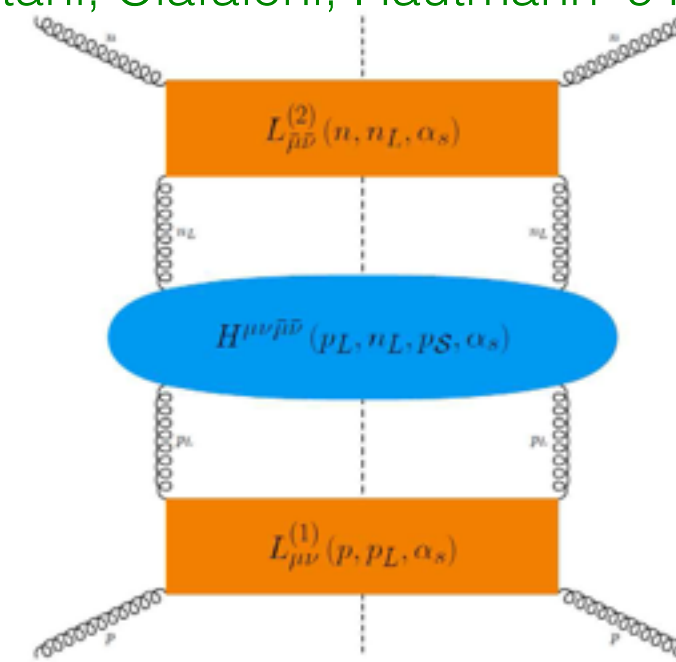
Corrections in the abelian limit beyond LO are moderate: at two loops ~ 2% of which only 0.2% is pt dependent (strong cancellations) - an order of magnitude smaller at 3 loops…

→ Full NLO result important for %-level theory, all-order corrections expected to remain moderate

Quark masses

The problem can be approached also from the high-energy limit (small-x)

[Catani, Ciafaloni, Hautmann '91]



- LLx -> ladder of gluons strongly ordered in kt ~ Ca^n

$$z \ll 1\,,\; k_t^2 \ll s$$

- One can be differential in the higgs rap. and pt

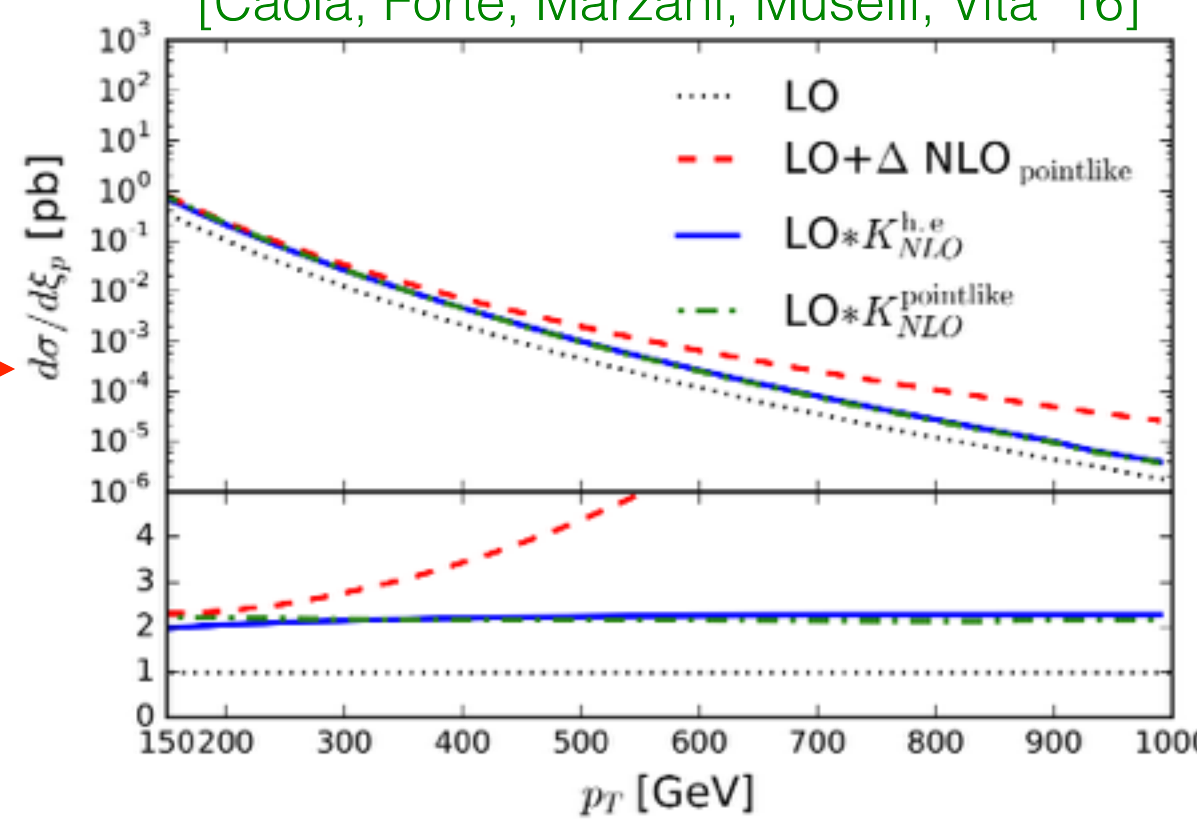
[Caola, Forte, Marzani '11] [Forte, Muselli '15]

Due to strong kt ordering only one gluon at a time probes the bottom loop, so it's only sensitive to ln^2(pt/mb) (amplitude level) at all orders. Plausible that subleading small-x terms carry more information

→ impact small within this approximation

[Caola, Forte, Marzani, Muselli, Vita '16]

HE approx works well for x < 0.5 - 0.6
This allows one to derive an estimate for the NLO corrections in the high-pt tail (top loop) →



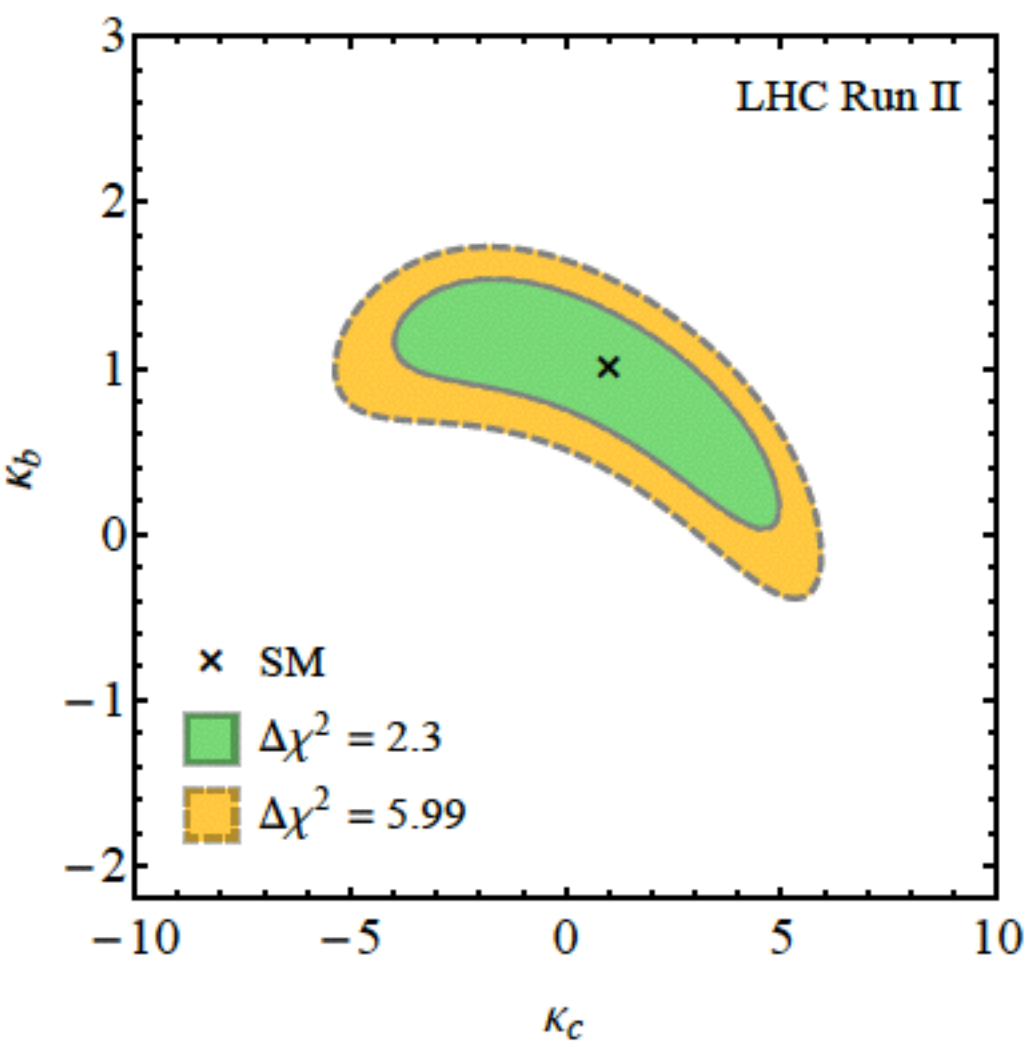
Formulation for joint small-x/pt resummation also obtained recently [Marzani '16]

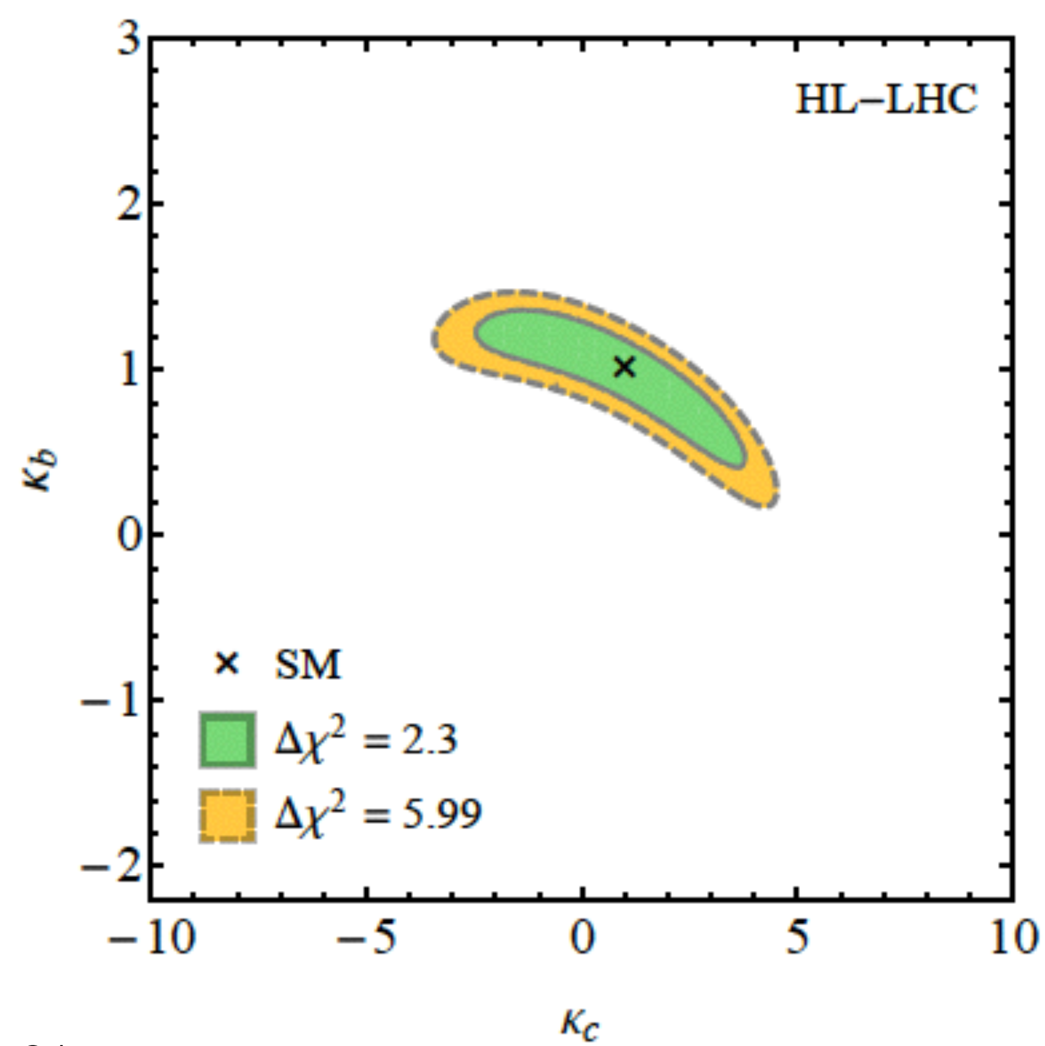
Quark masses - Yukawa couplings

Although moderate in the SM, all-order effects can be useful when studying constraints on the light-quark Yukawa couplings using transverse momentum distributions of the Higgs and recoiling jets —> few % precision required

[Bishara, Haisch, PM, Re '16]
[Soreq, Zhu, Zupan '16]
[Bonner, Logan '16]

e.g. bottom and charm Yukawas





Z+jet

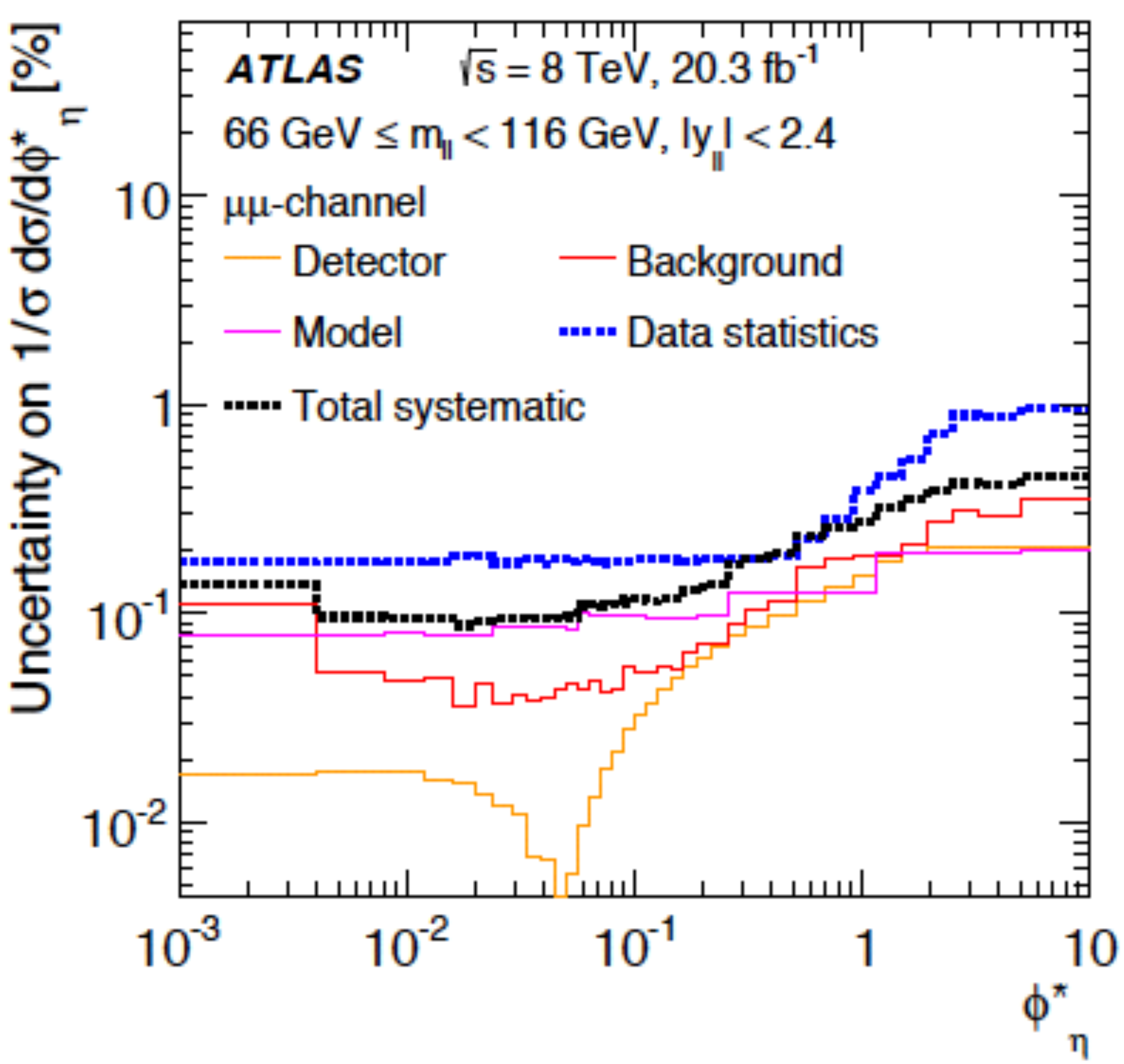
Astonishing precision in the Z pt spectrum (and related observables)

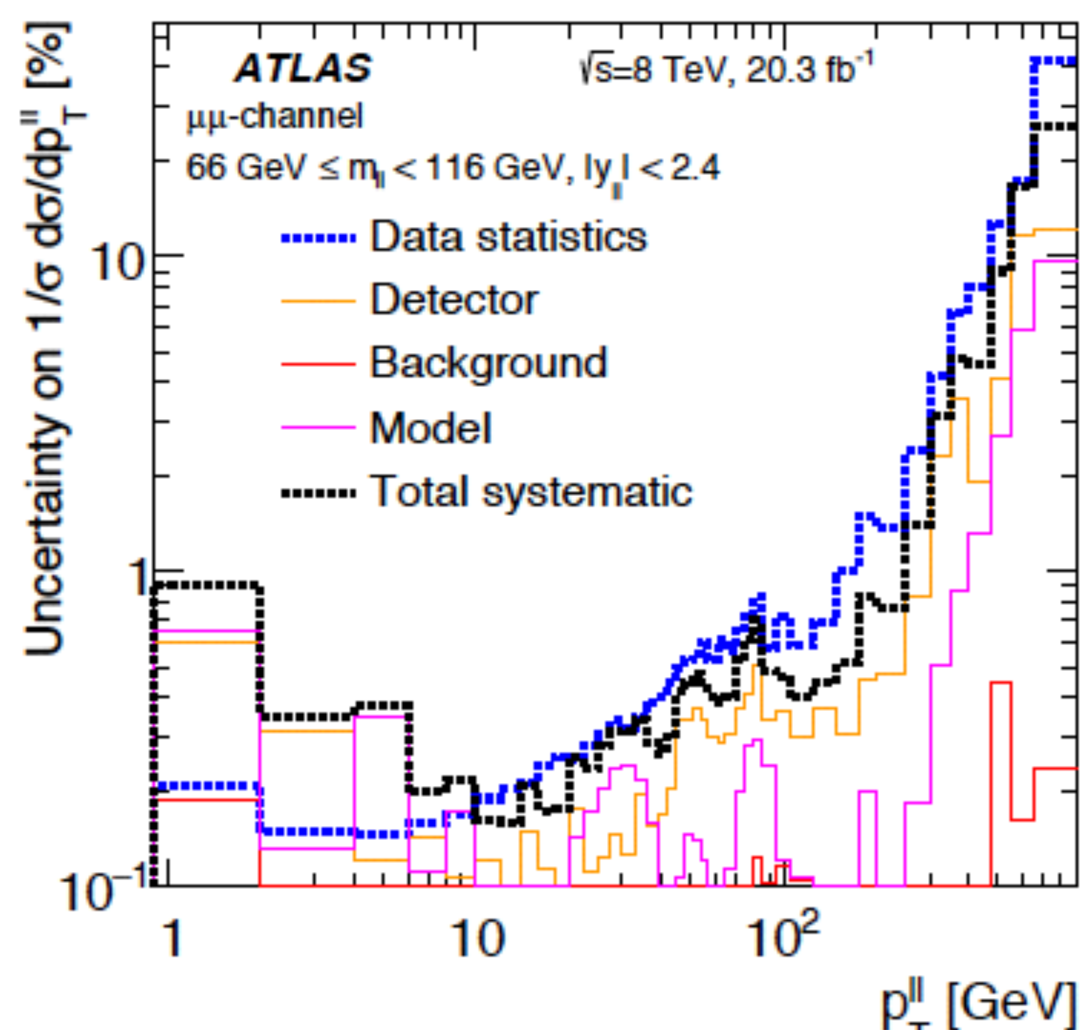
- ~1% uncertainty down to pt ~ 1 GeV - an order of magnitude smaller for phi* !
- modest discrepancy at pt > 30 GeV with NNLO
- consider normalised fiducial distribution

-> Talk by A. Huss

[Gehrmann-De Ridder et al. '16]
[Boughezal et al. '16]

[ATLAS 1512.02192]





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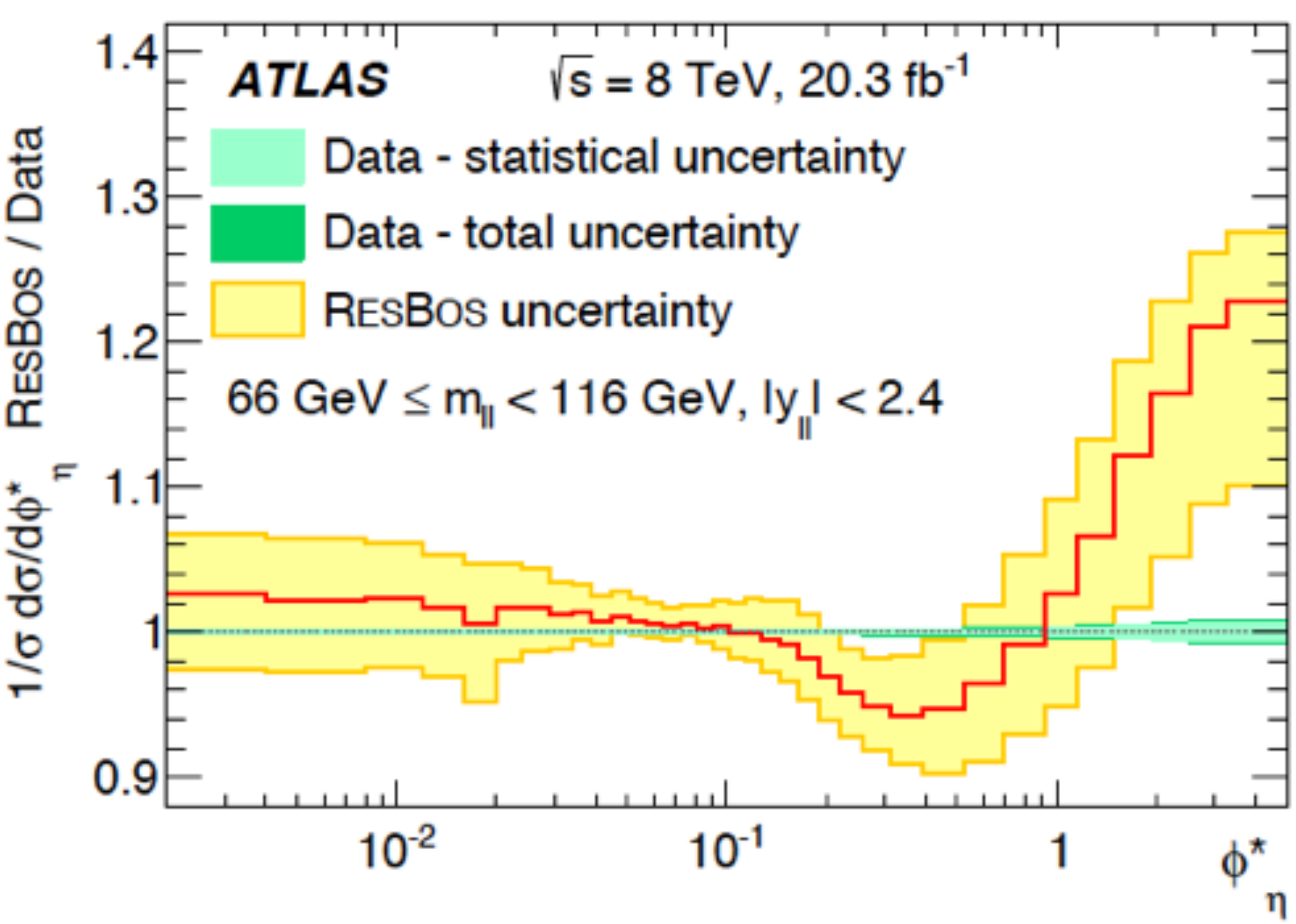
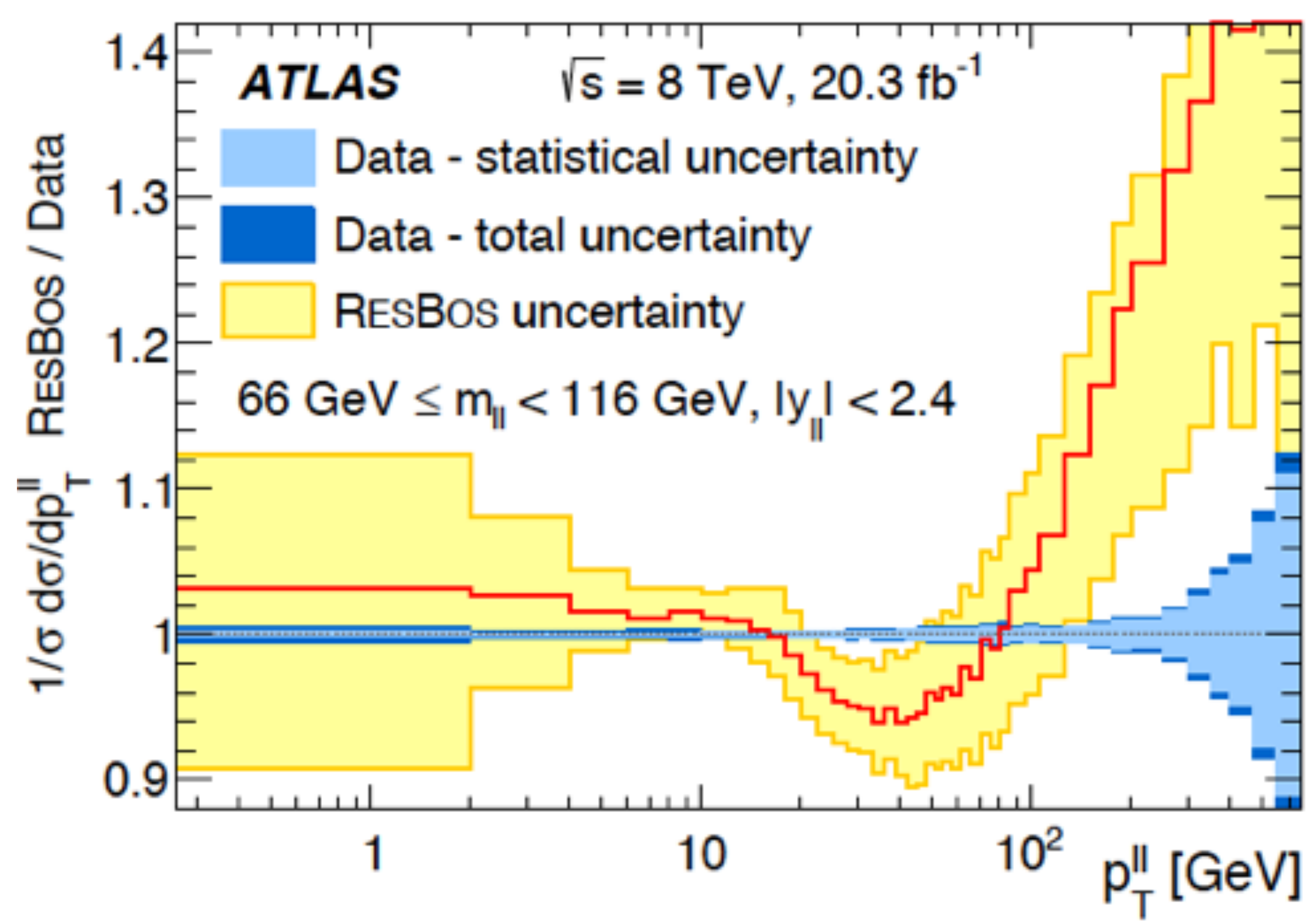
- consider normalised fiducial distribution
- lack of theory at small pt - N3LL already necessary below 10 GeV

[ATLAS 1512.02192]



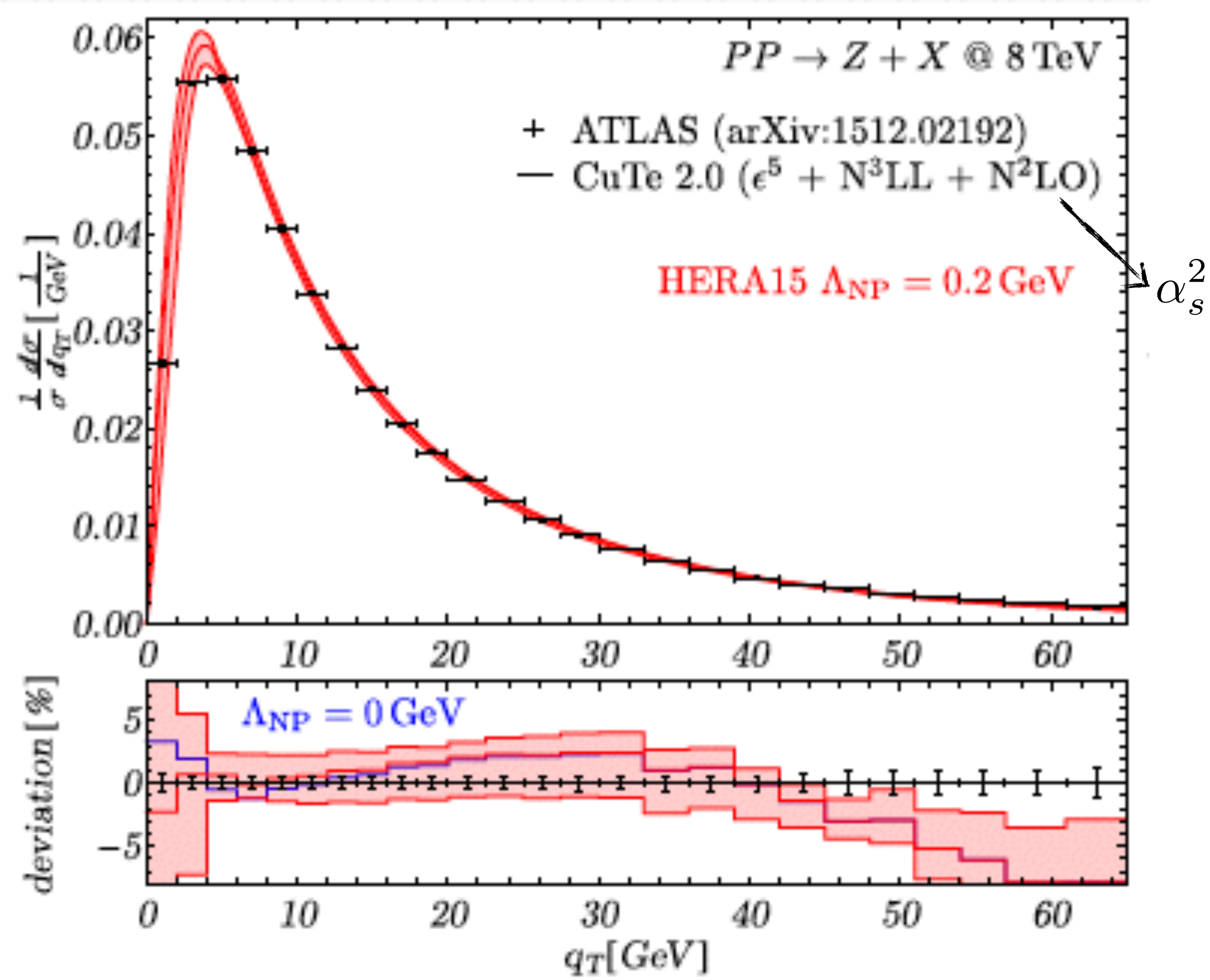


Z+jet

Astonishing precision in the Z pt spectrum (and related observables)

- ~1% uncertainty down to pt ~ 1 GeV - an order of magnitude smaller for phi* !
- modest discrepancy at pt > 30 GeV with NNLO -> Talk by A. Huss
- consider normalised fiducial distribution
- lack of theory at small pt - N3LL already necessary below 10 GeV

T. Luebbert's talk at SCET 2016



e.g. approx N3LL+NLO pT distribution give a residual 2-3% uncertainty down to ~4 GeV (potentially better for phi*)

Can we use this data to learn something on running coupling or NP effects (some discrepancies between MCs and analytic models) ?

$$F^{(3,0)} = f_F(4\pi)F^{(2,0)}$$

now computed exactly [Li, Zhu '16]

Strong coupling constant

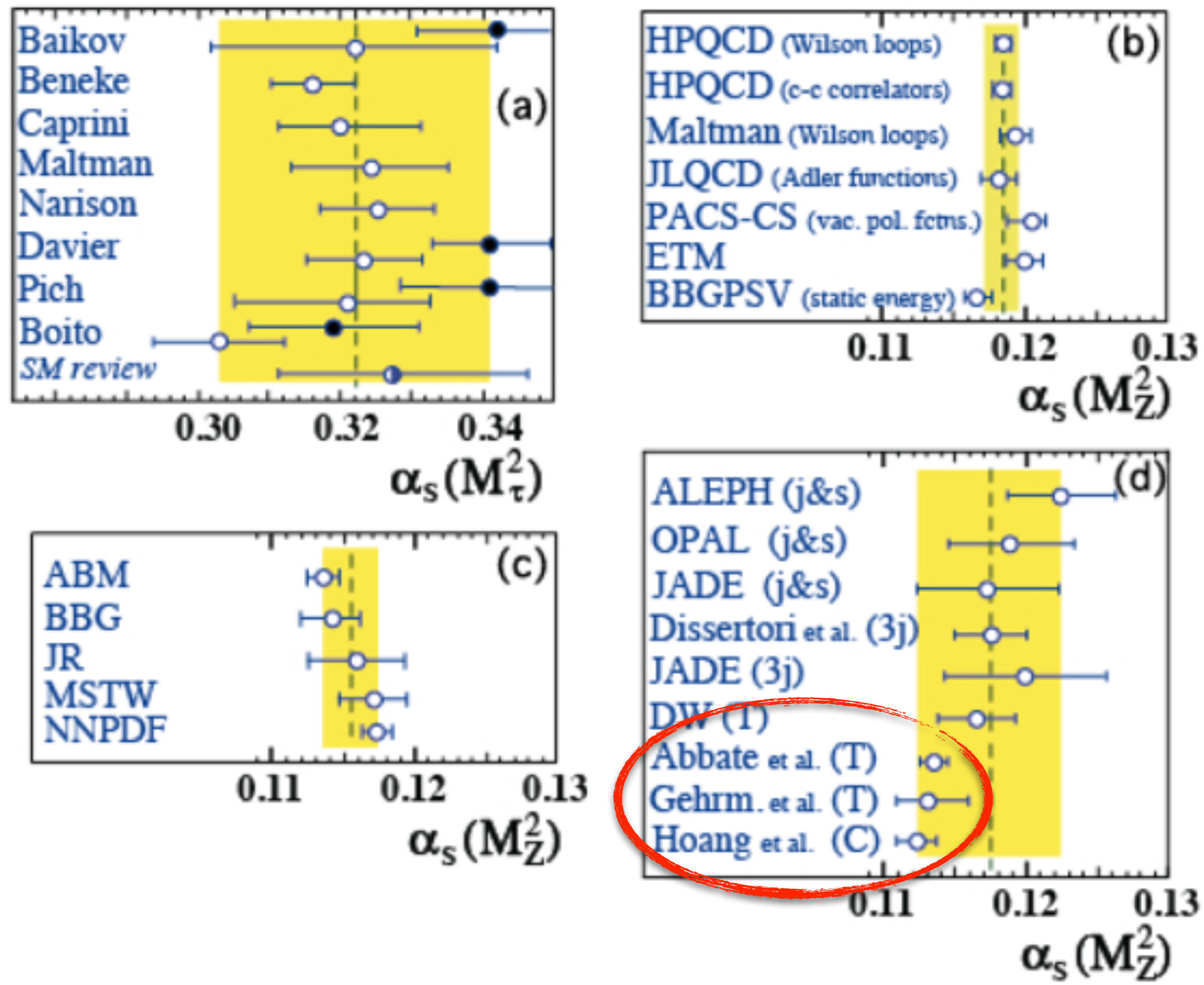
World average: [Bethke, Salam, Dissertori '15]

$\alpha_s(M_Z) = 0.1177 \pm 0.0013 (1.1\%)$ weighted

$\alpha_s(M_Z) = 0.1181 \pm 0.0013 (1.1\%)$ unweighted

Tension between NNLL (N3LL)+NNLO extractions event-shape

- Large tension between extractions from NNLL (N3LL)+NNLO event shapes and lattice calculations
- At LEP energies issues with high correlation between perturbative and hadronisation corrections from analytic models
- Thrust and C-parameter very similar (correlated) observables, with very same NP behaviour
- Low values of as are disfavoured by some LHC measurements



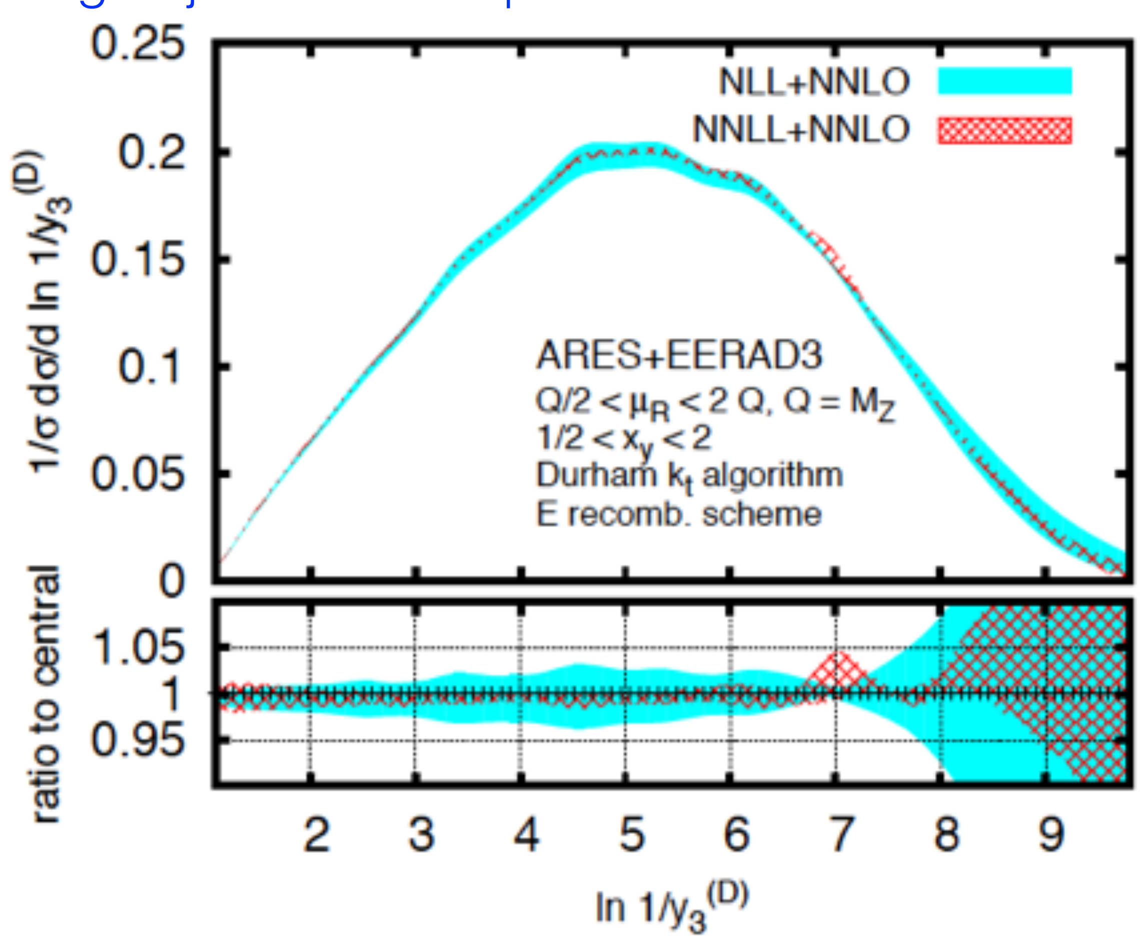
Strong coupling constant

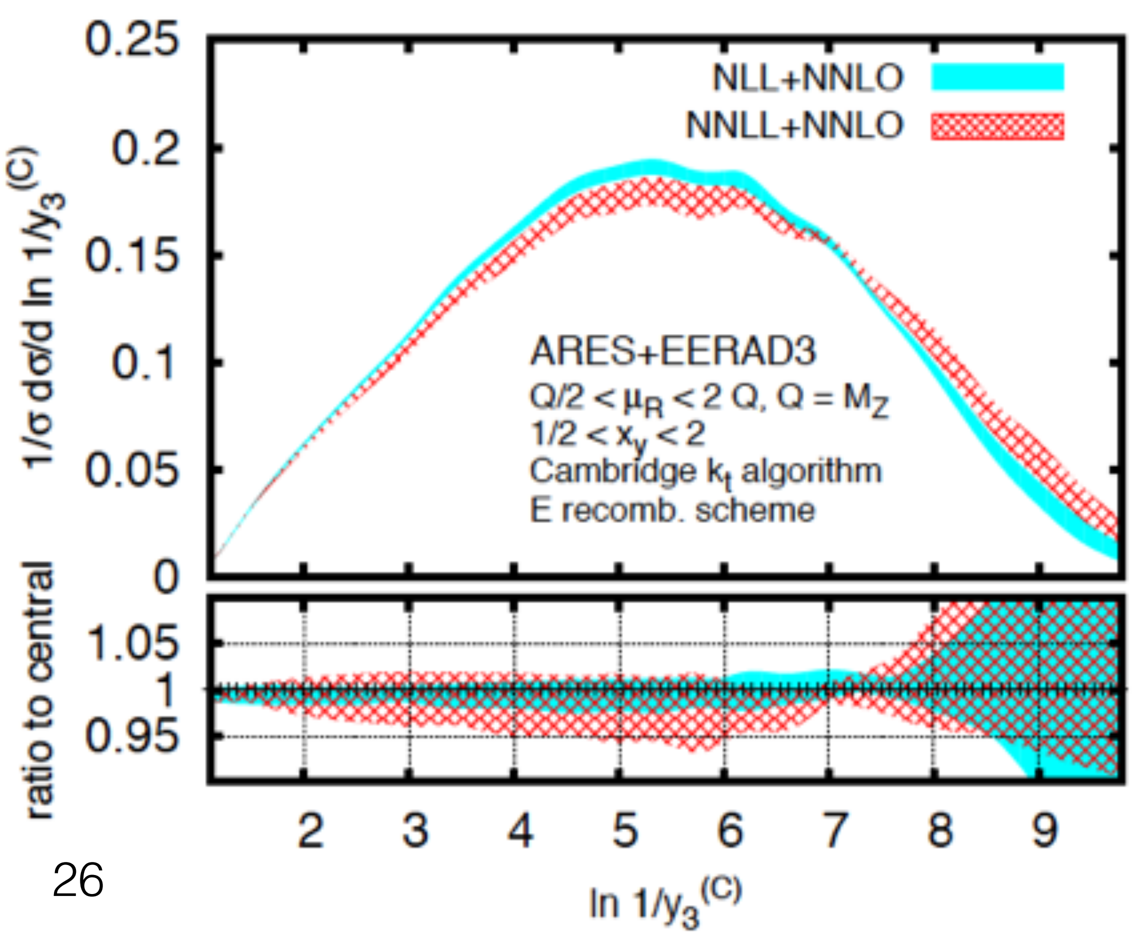
- Important to perform a fit (possibly global) using observables with different (lower if possible) sensitivity to hadronisation effects (e.g. jet broadening, 3-jet resolution) at NNLL+NNLO
- Now this is possible given the advances in the field of the past years - all LEP 2-jet-like observables are known to this accuracy

[Gehrmann-De Ridder, Gehrmann, Glover, Heinrich ’07] [Weinzierl ’09] [Del Duca, Duhr, Kardos, Somogyi, Szor, Trocsanyi, Tullipant ’16]

[Becher, Schwartz ’08] [Chien, Schwartz ’10] [Becher, Bell ’12] [Hoang et al. ’14] [Banfi, McAslan, PM, Zanderighi ’14-’16] [Bell, Hornig, Lee, Talbert ’16 (in progress)]

e.g. 3-jet resolution parameter





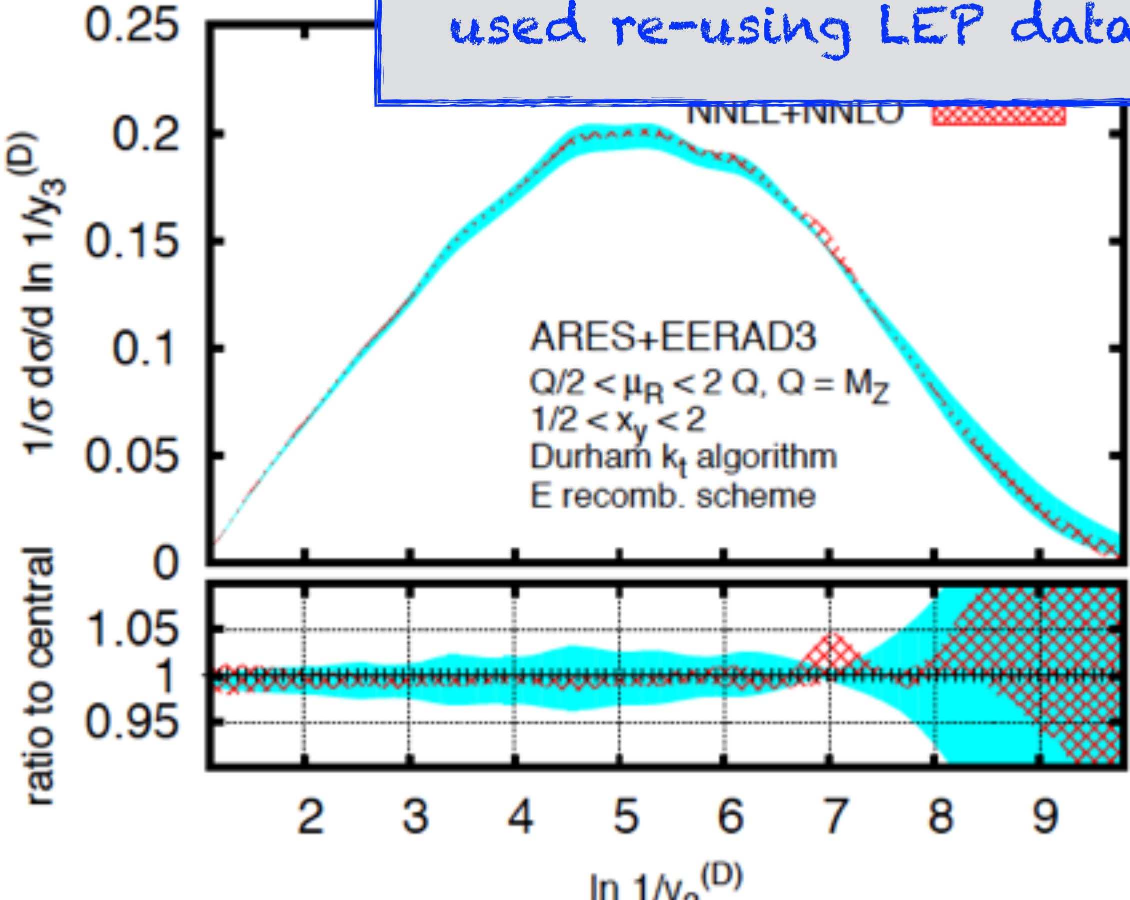
Strong coupling constant

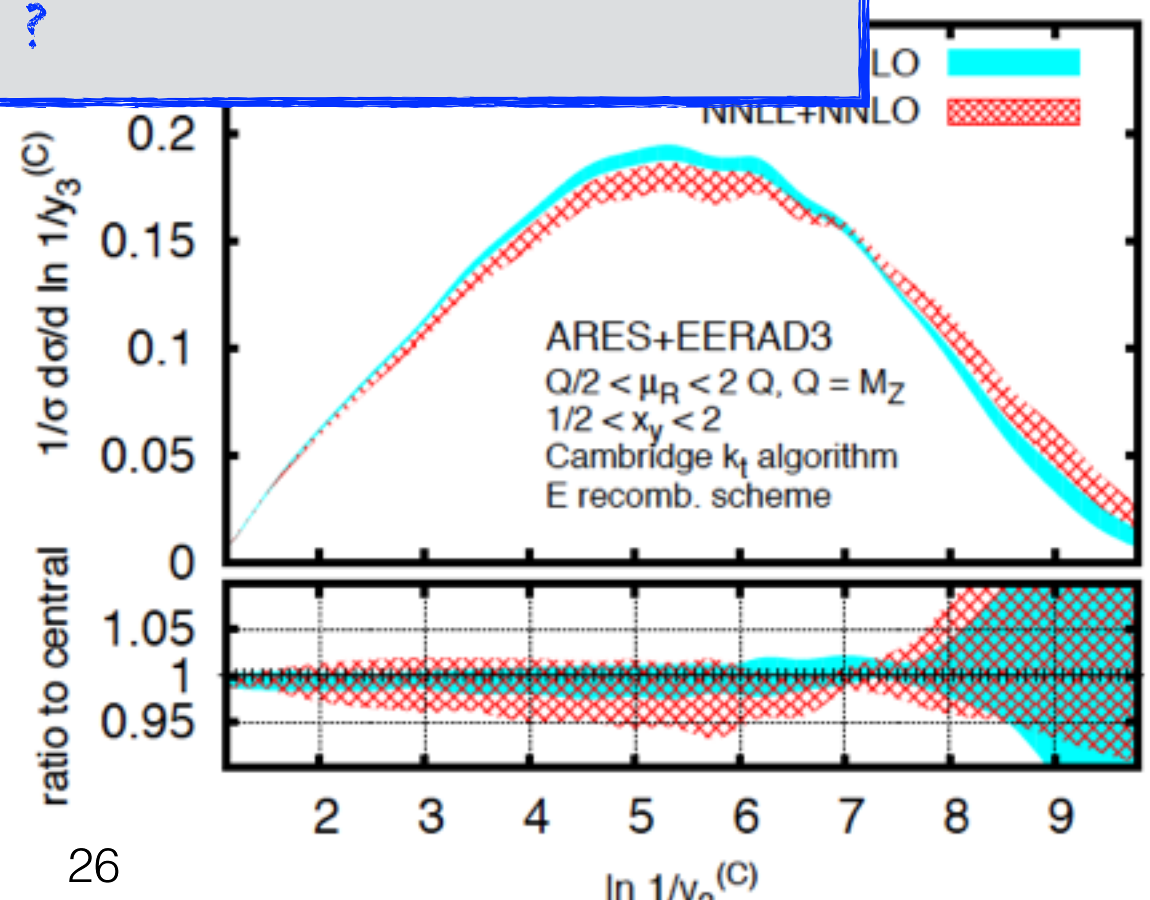
- Important to perform a fit (possibly global) using observables with different (lower if possible) sensitivity to hadronisation effects (e.g. jet broadening, 3-jet resolution) at NNLL+NNLO
- Now thi … years - all LEP 2-j …

[Gehrmann-De Ridde … Chien, Schwartz '10]
[Weinzierl '09] [Del D … et al. '14]
Trocsanyi, Tullipant '1 … nderighi '14-'16]
… t '16 (in progress)]

- Would a global fit with all observables lead to any improvement ? -> new modelling of hadronisation (new tunes ?)/limit ourselves to high-energy data ?
- New observables (jet algorithms, substructure) to be used re-using LEP data ?

e.g. 3-jet resol…





Conclusions

- With the precision foreseen at the LHC we often need control over few-% effects
  - With higher precision all-order effects can often be relevant even when cuts on radiation are applied to mitigate them
  - Understanding their dynamics would improve on PT control, and on future PS generators (PT and some NP effects)
  - In parallel with future (often motivated by theoretical interest) progress towards more complicated processes (multilegs, multiscale, non-global,…), it is important to figure out ways to exploit data using our knowledge of perturbative QCD beyond fixed order

Thank you for your attention