The QCD challenge for precision at colliders

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CERN

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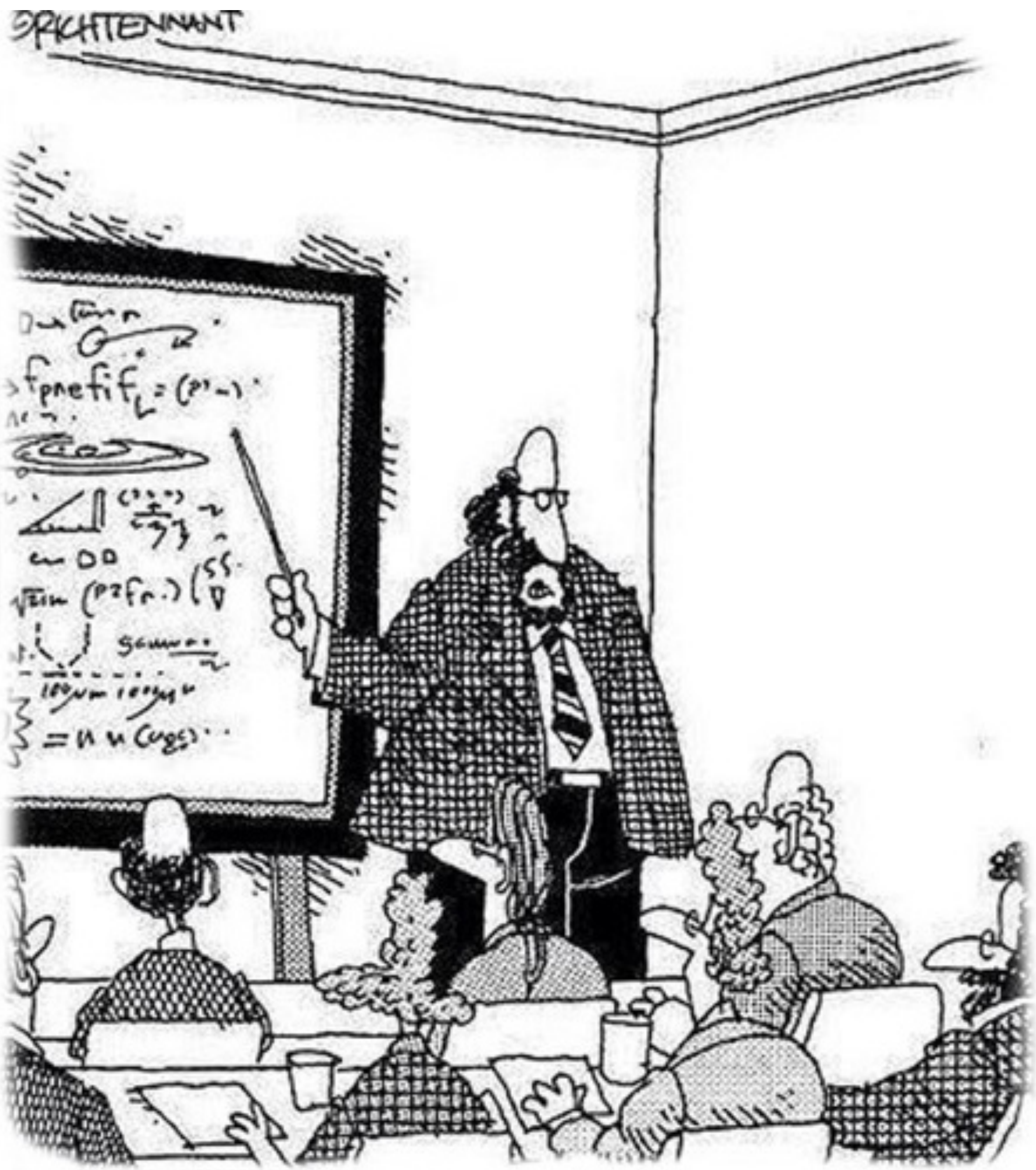
New Physics at the LHC (so far)



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New physics constrained to ~TeV scales at colliders, may leave elusive small signatures at currently probed energies

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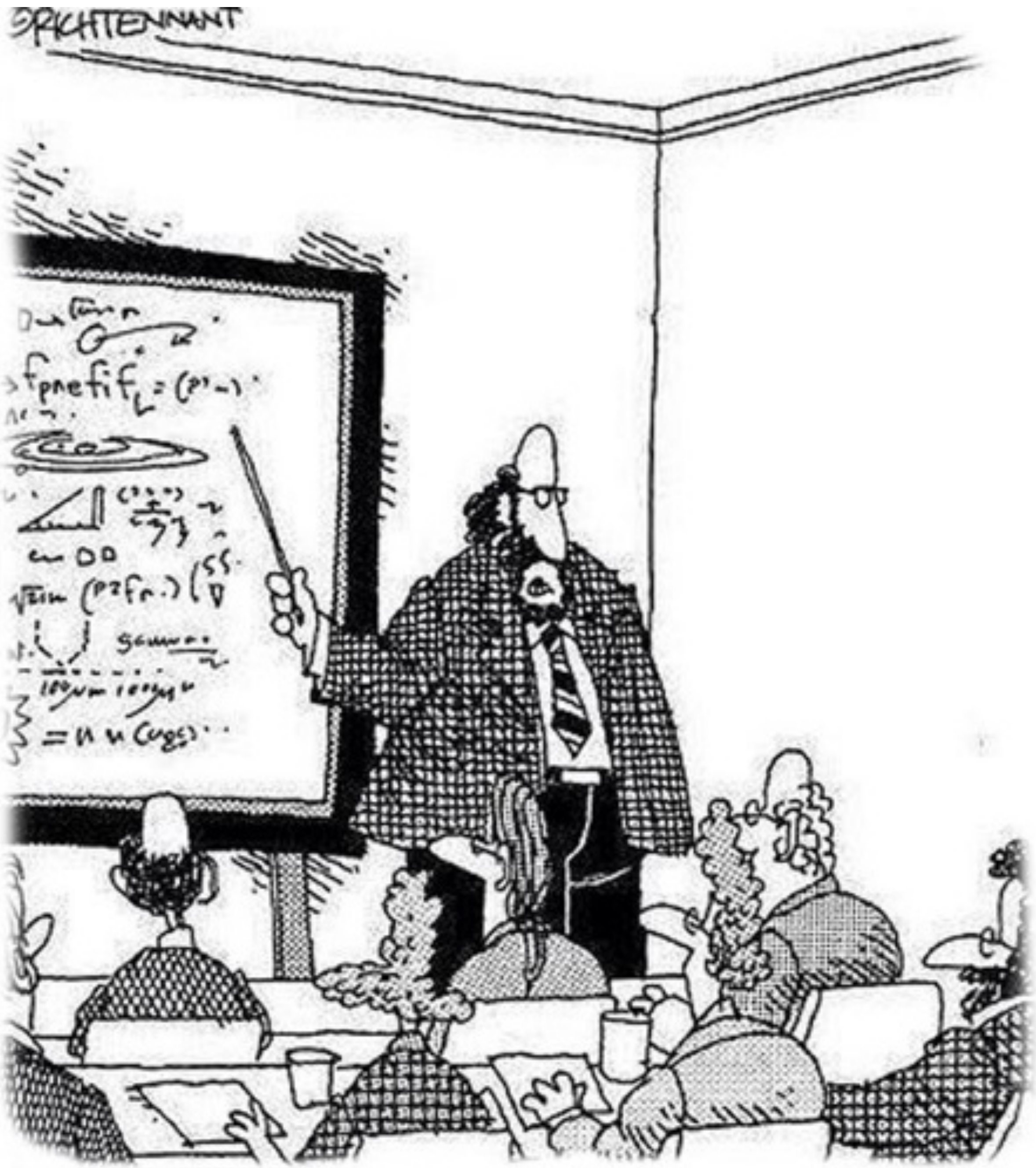

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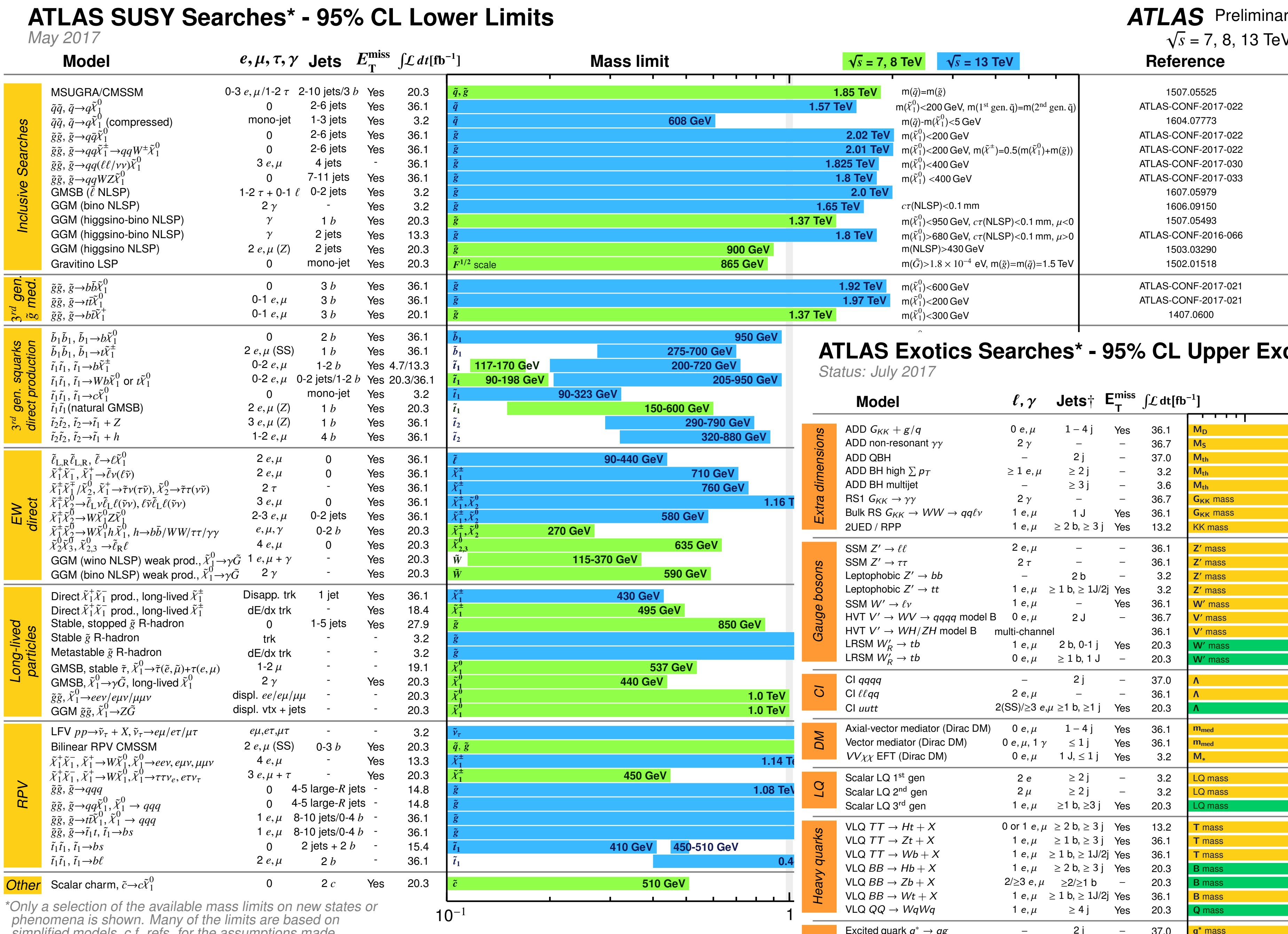

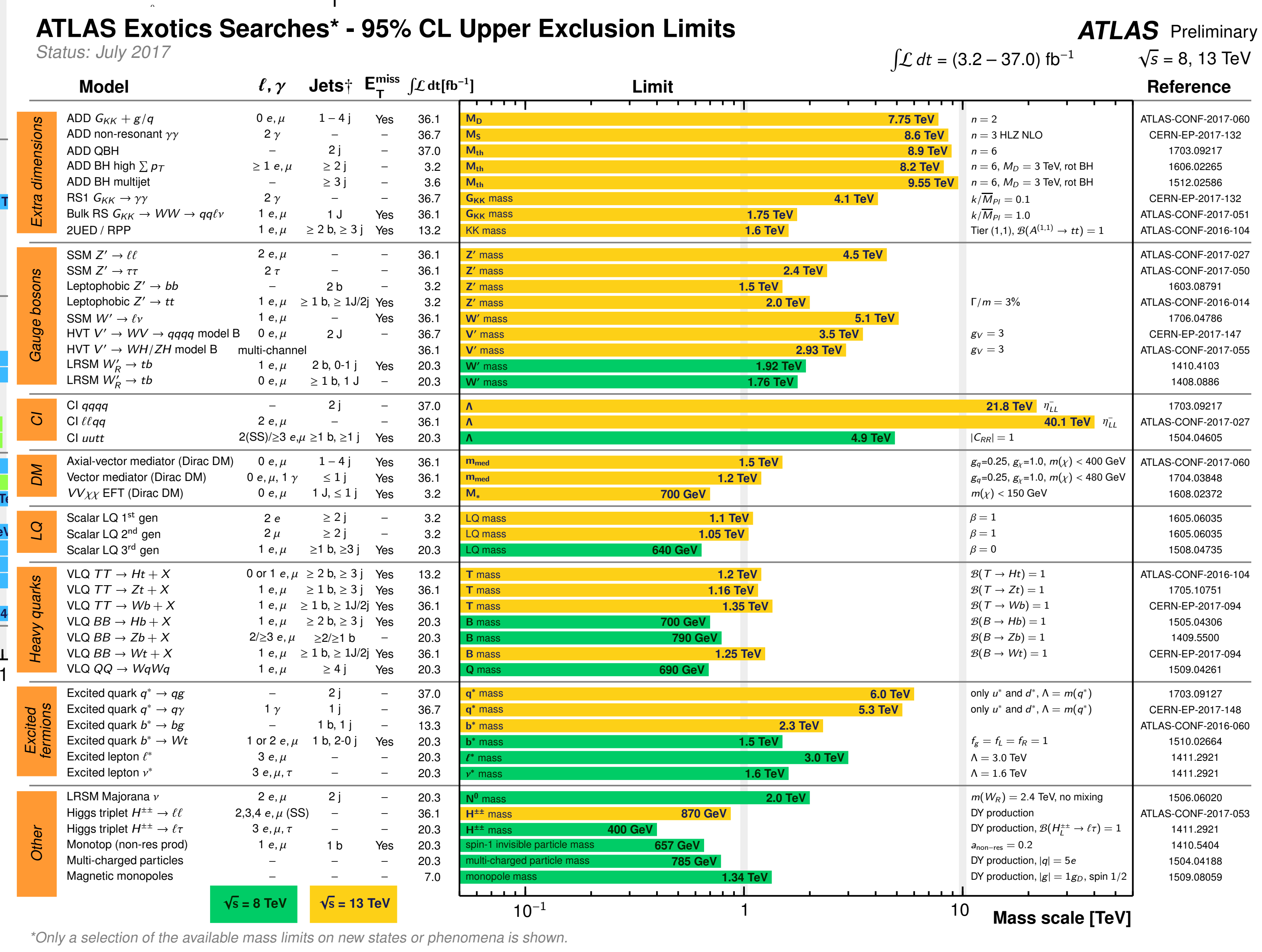

The quest for precision at the LHC

- The need for theory precision is twofold
  - As a precision machine, the LHC is providing us with %-accurate measurements SM parameters/dynamics (couplings, PDFs, masses,…). A full exploitation of these resources requires a deeper understanding of the theory than what we previously had. Also, precision often allows for indirect constraints on NP
  - In order to maximise its discovery reach, sensitive observables have to be conceived. This often requires measurements in extreme regions of phase space where large momentum transfer enhances the effects of new physics (e.g. boosted kinematics)
    - effects of NP could hide behind mild distortions of the kinematics (e.g. differential shapes, broad resonances,…)
    - A careful assessment of the SM background is essential in most cases. This reaches the few-percent level in some scenarios
  - Can we get to this level of precision ? What are the limitations of our current understanding ?

Theoretical framework: collinear factorisation

$$d\sigma_{pp\to X} = \sum_{i,j=q,g} \int dx_1 dx_2 f_i(x_1) f_j(x_2) d\hat{\sigma}_{ij\to X}(x_1, x_2) O(X) + \mathcal{O}\left(\frac{\Lambda^n_{\mathrm{QCD}}}{Q^n}\right)$$

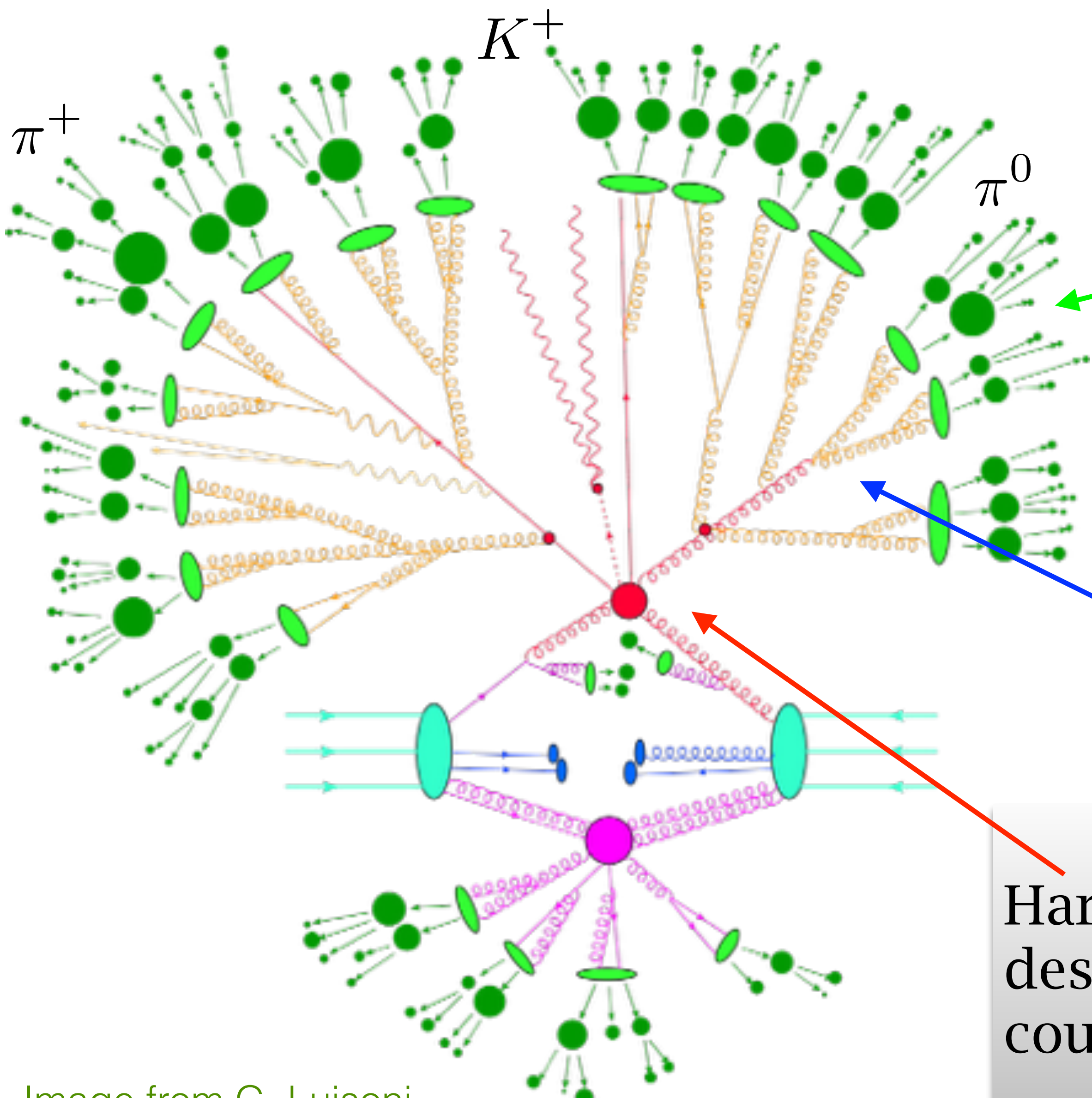

Image from G. Luisoni

At scales of the order of Λ_{QCD} hadronisation occurs, causing further (soft) kinematics reshuffling/recombinations

$\alpha_s(k_t) \sim 1$

As the coupling grows large, coloured particles are very likely to emit soft and/or collinear radiation (i.e. small kt) all the way down to hadronisation scales.

$\alpha_s(Q) \ll \alpha_s(k_t) < 1 \qquad \int \frac{dE}{E}\frac{d\theta}{\theta}\alpha_s(k_t) \gg 1$

Hard scattering between most energetic partons - description relies on perturbation theory as a small-coupling expansion (fixed-order) $\alpha_s(k_t) \sim \alpha_s(Q) \ll 1$

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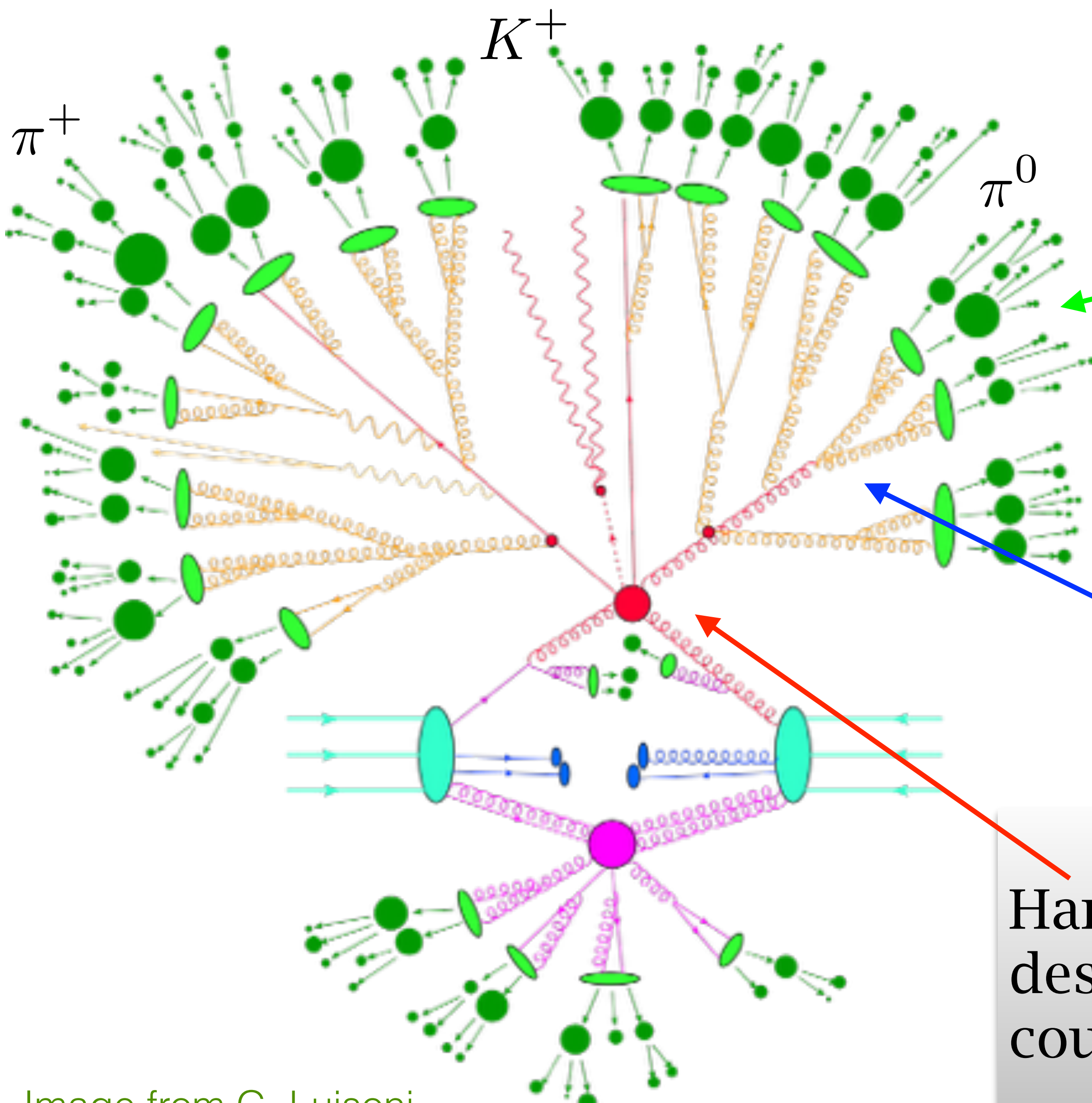

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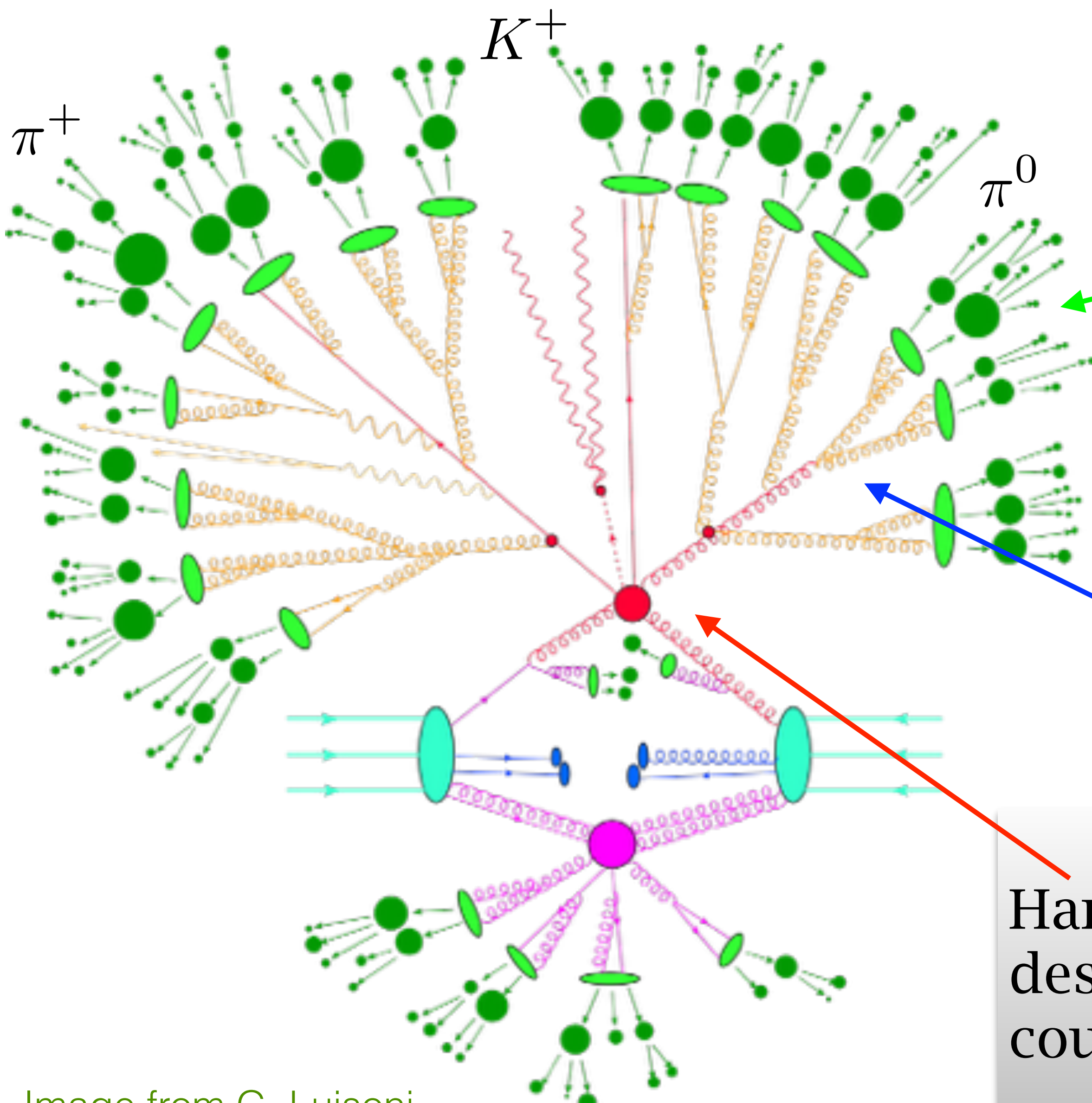

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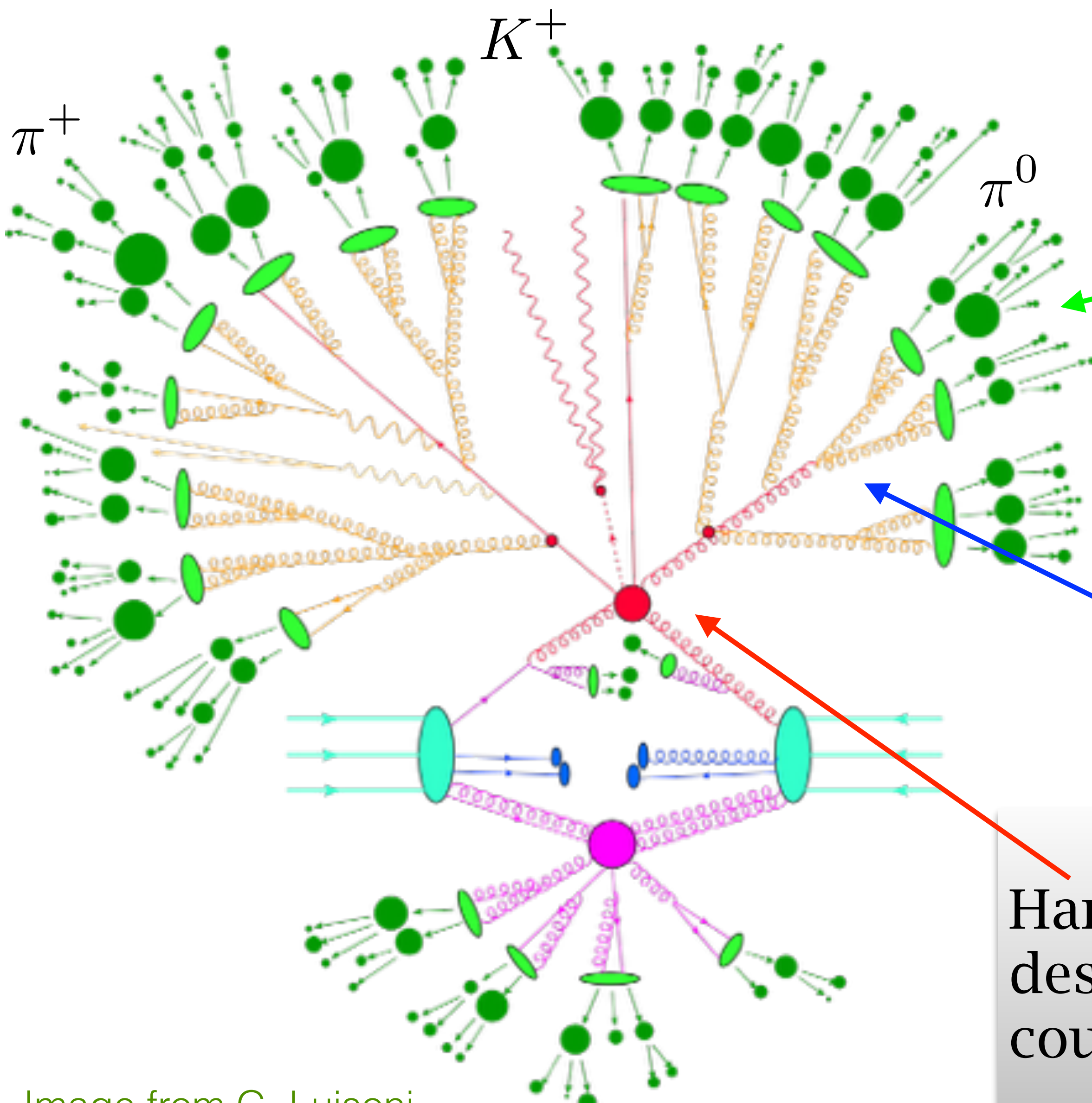

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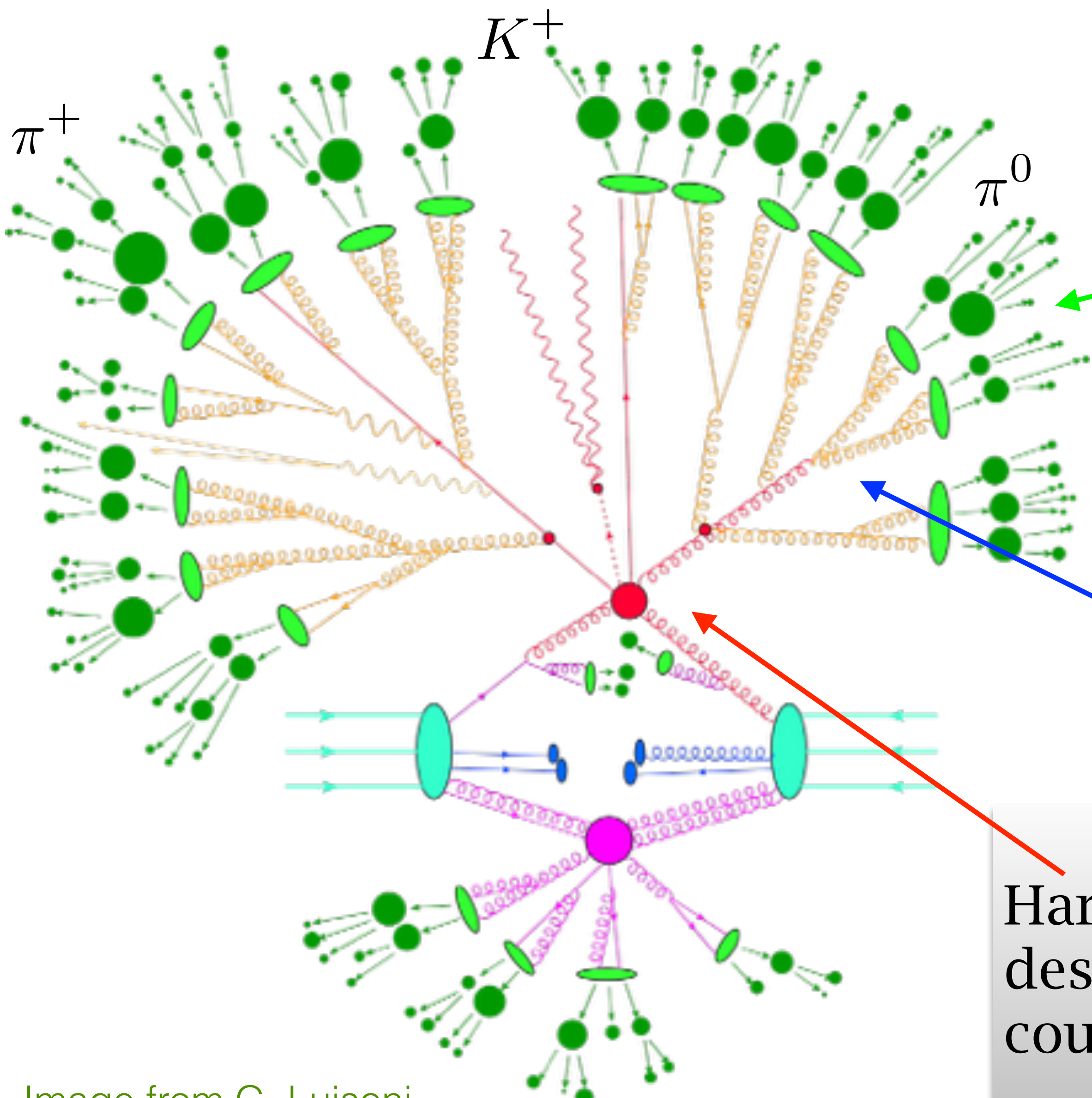
* factorisation violations at high orders in multi-jet reactions. Few-percent effect expected



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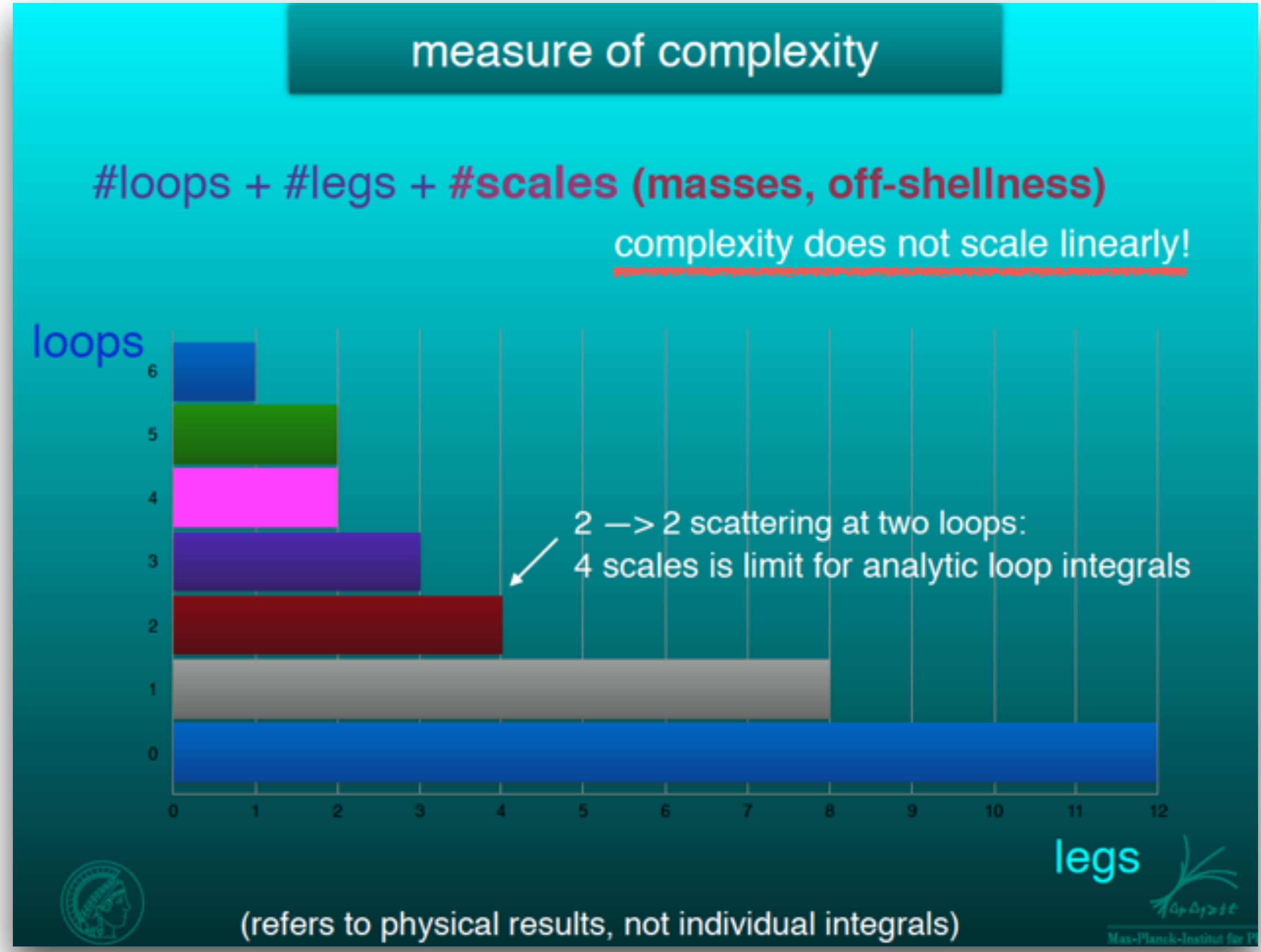
The hard scattering

- Asymptotic freedom: systematic expansion in powers of small couplings (LO, NLO, NNLO,…)
- Allows for a fully exclusive description of hard partonic final states at a fixed order in the perturbative expansion

G. Heinrich at CERN colloquium 2017



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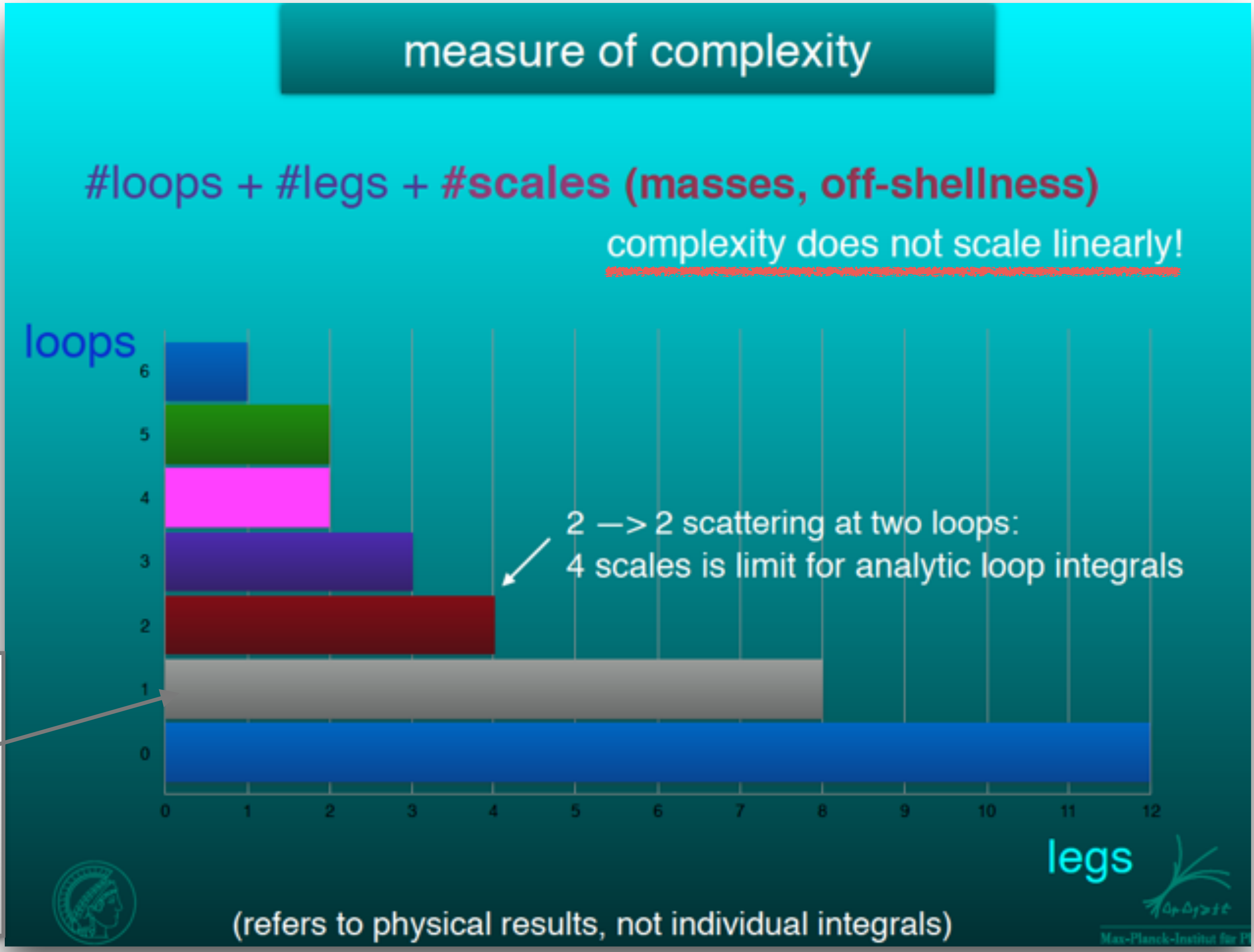

NLO QCD automated to a good extent with up to 5-6 FS particles (proc. dep.). Recent progress on multi-jet processes, off-shell effects, loop induced, EW corrections and how to combine them with QCD

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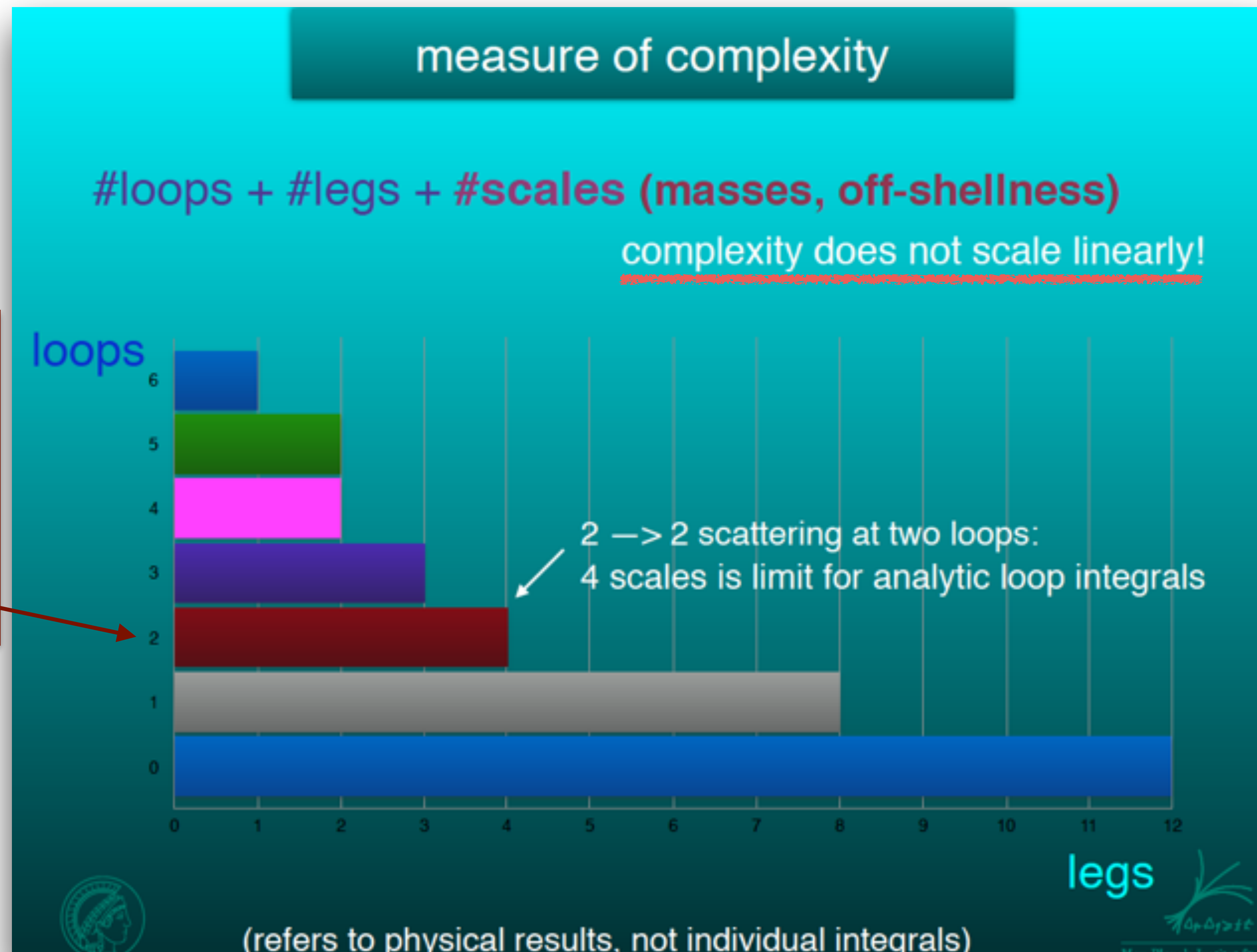

NNLO corrections available for 2 -> 2 processes. Typically reach 2-7% accuracy for inclusive XS and 5-10% in kinematic distributions

The hard scattering

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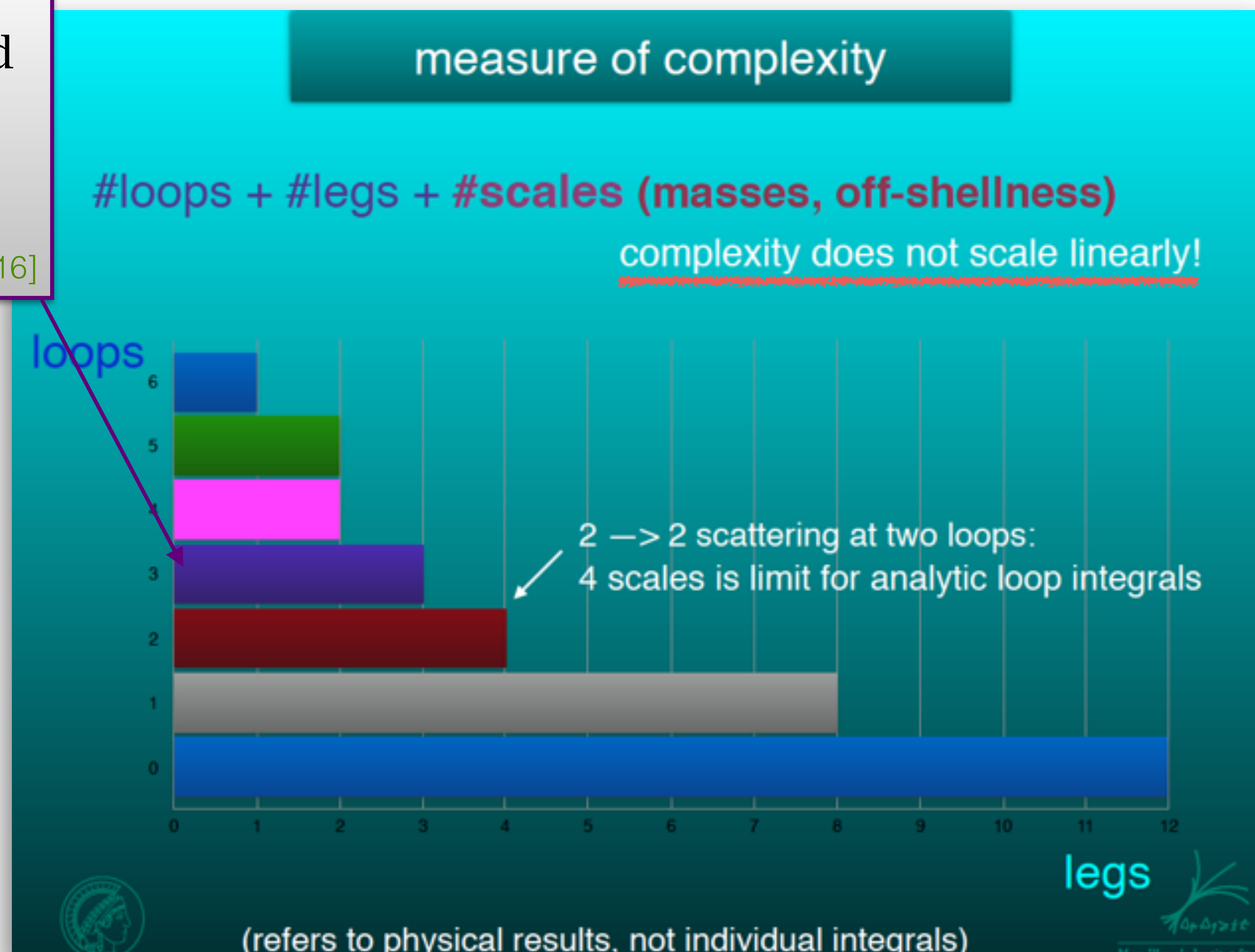
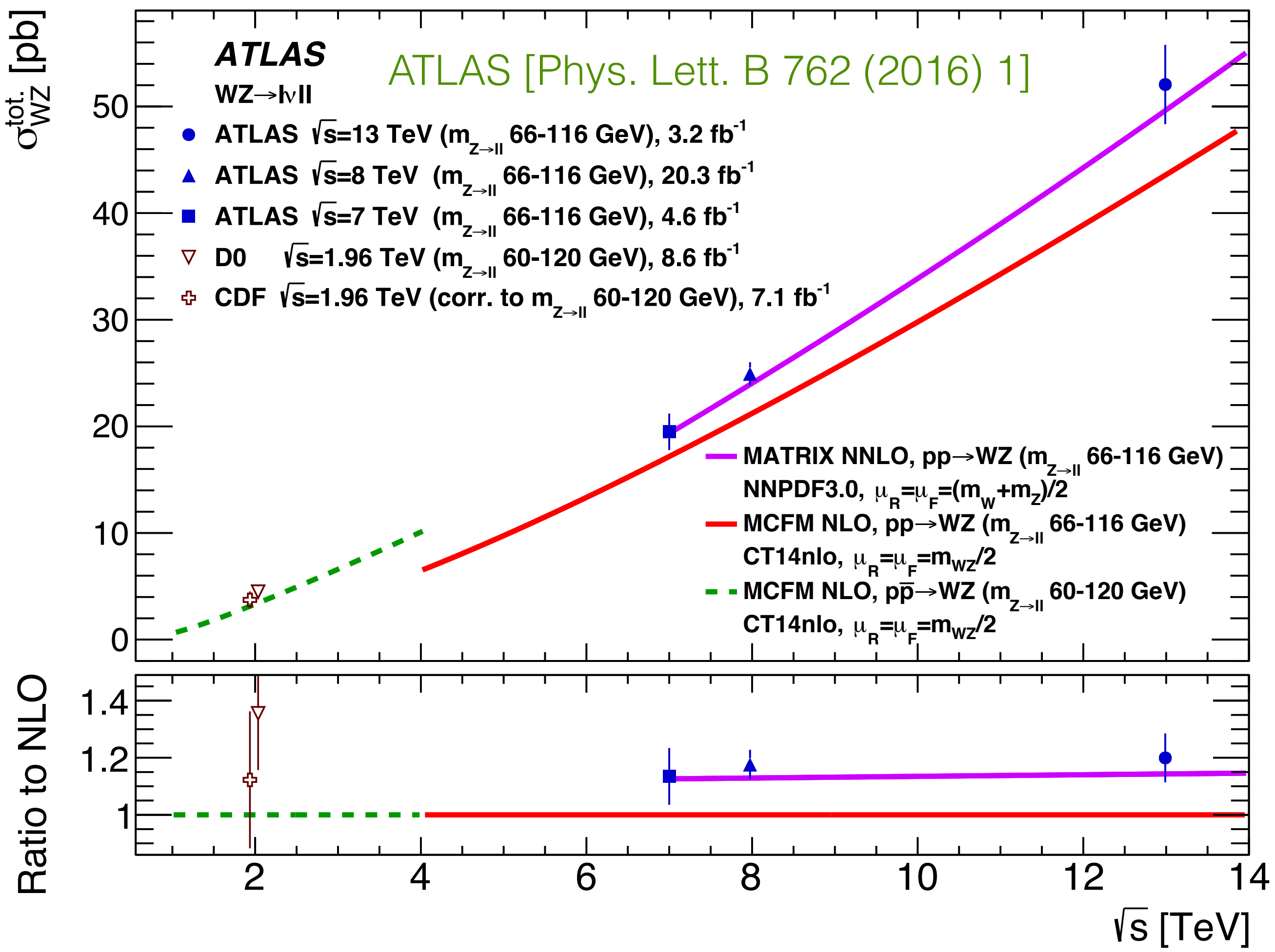
N3LO corrections may be required for gluonic processes with poor convergence of the series
e.g. Higgs —> 3-4% error

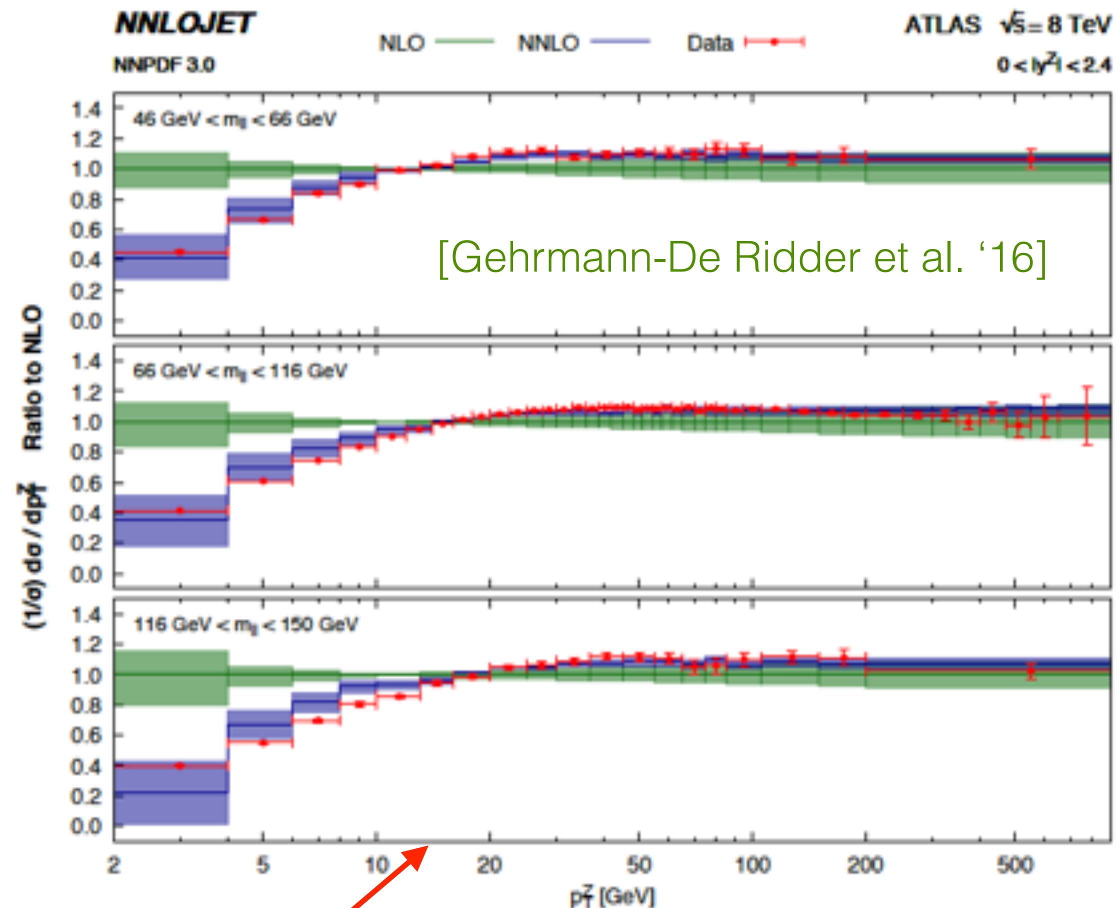
[Anastasiou et al. '16]

G. Heinrich at CERN colloquium 2017

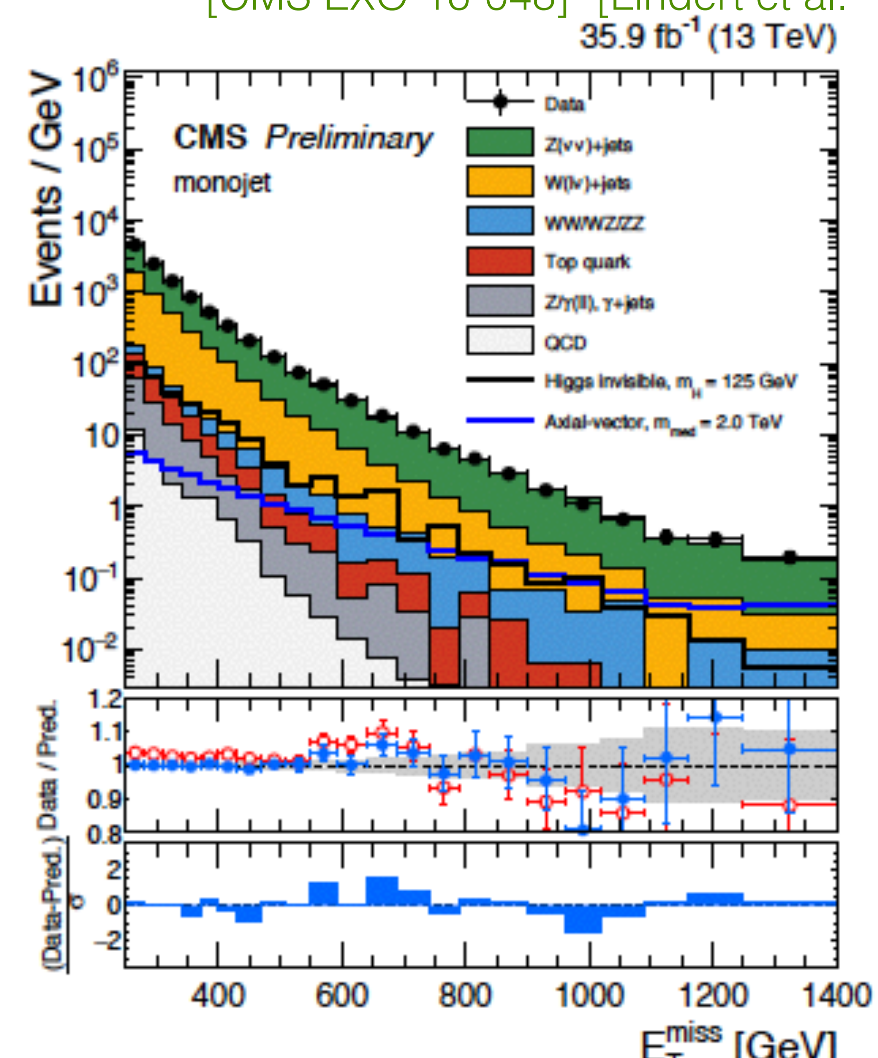


NNLO vs. Data





[CMS EXO-16-048] [Lindert et al. '17]



- Data favours NNLO in inclusive XS and differential SM distributions

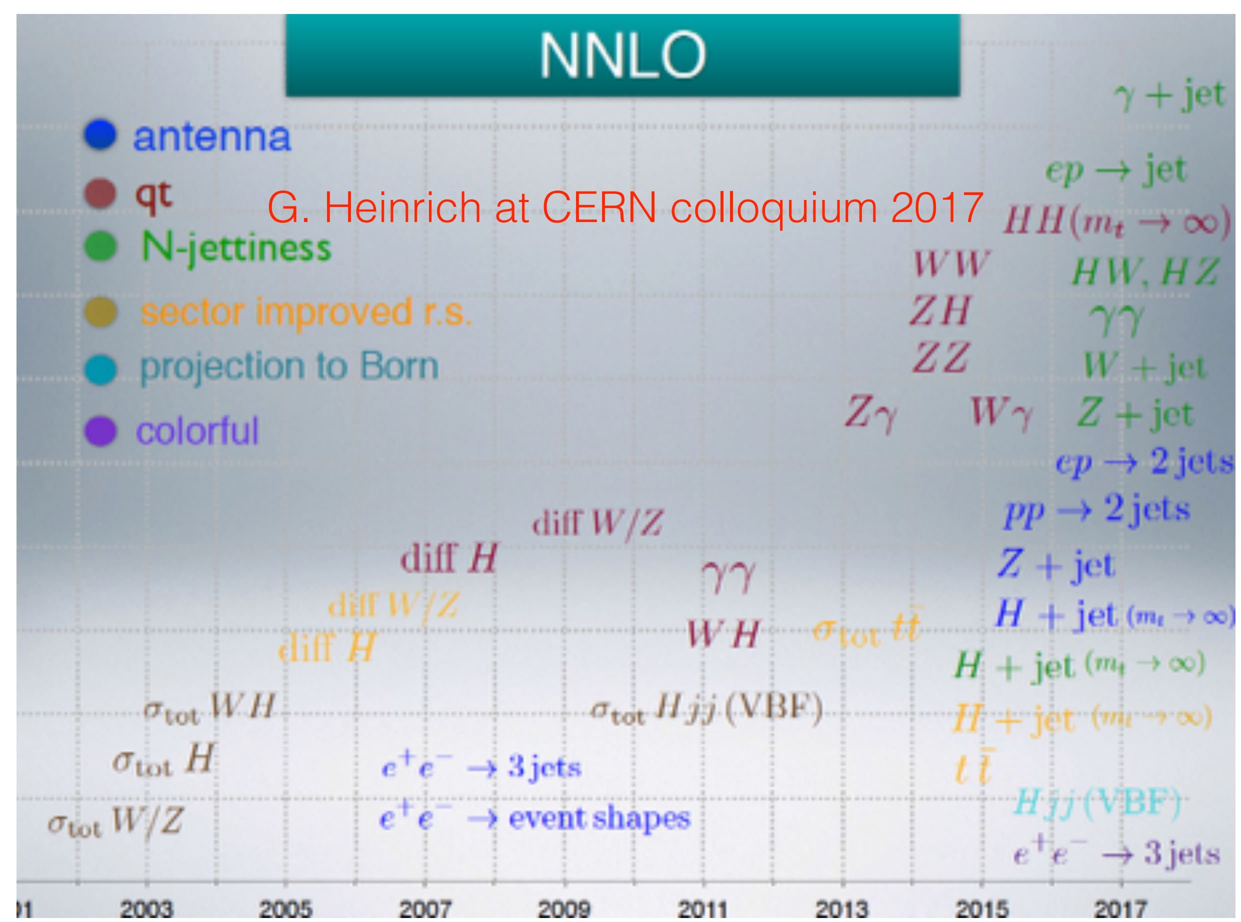
- Applications in BSM searches
  - background uncertainties for DM in MET+jets at the ~4-10% level in tails (estimate of EW effects crucial)

Amplitudes and subtraction at NNLO

- Amplitudes complexity grows rapidly with the number of scales (legs, masses). Recently progress in two-loop amplitudes for 2->2 processes with new techniques (analytically or numerically). e.g.
    - p p -> V V (‘,*) [Gehrmann et al.; Caola et al.]
    - p p -> t t~ , p p -> HH [Baernreuther et al.; Bonciani et al.; Borowka et al.]
  - Current focus on 2->3 processes and massive amplitudes [Badger et al., Dunbar et al., Gehrmann et al. Papadopoulos et al.; Bonciani et al., Melnikov et al.]
- Cancellation of IRC divergences:
- (local) subtraction

$$\int (|M_R|^2 - \mathcal{S})[d\mathrm{PS_R}] + \int \mathcal{S}[d\mathrm{PS_R}] + \int |M_V|^2[d\mathrm{PS_V}]$$

  - Sector decomposition [Anastasiou et al., Binoth et al.]
  - Antennae subtraction [Gehrmann et al.]
  - Sector-improved residual subtr. [Czakon et al.]
  - ColorFul subtraction [Del Duca et al.]
  - Projection to Born [Cacciari et al.]
  - Nested soft-collinear subtraction [Caola et al.]



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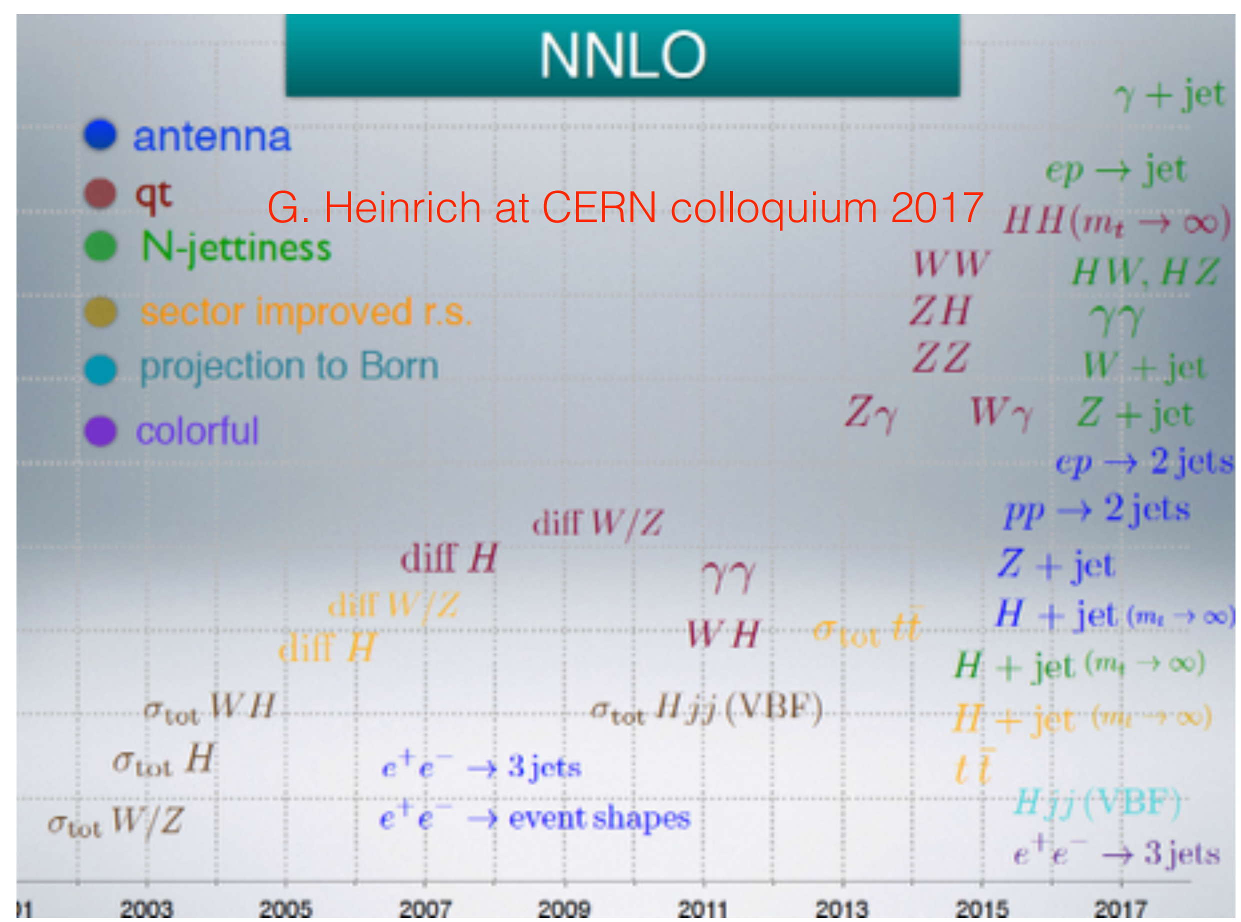
  - Current focus on 2->3 processes and massive amplitudes [Badger et al., Dunbar et al., Gehrmann et al. Papadopoulos et al.; Bonciani et al., Melnikov et al.]
- Cancellation of IRC divergences:
- slicing

$$\int_{\text{cutoff}} |M_R|^2[d\mathrm{PS_R}] + \int^{\text{cutoff}} |M_R|^2[d\mathrm{PS_R}] + \int |M_V|^2[d\mathrm{PS_V}]$$

  - qT subtraction [Catani et al.]
  - N-jettiness subtraction [Boughezal et al., Gaunt et al.]
    - power corrections [Boughezal et al., Moult et al.]



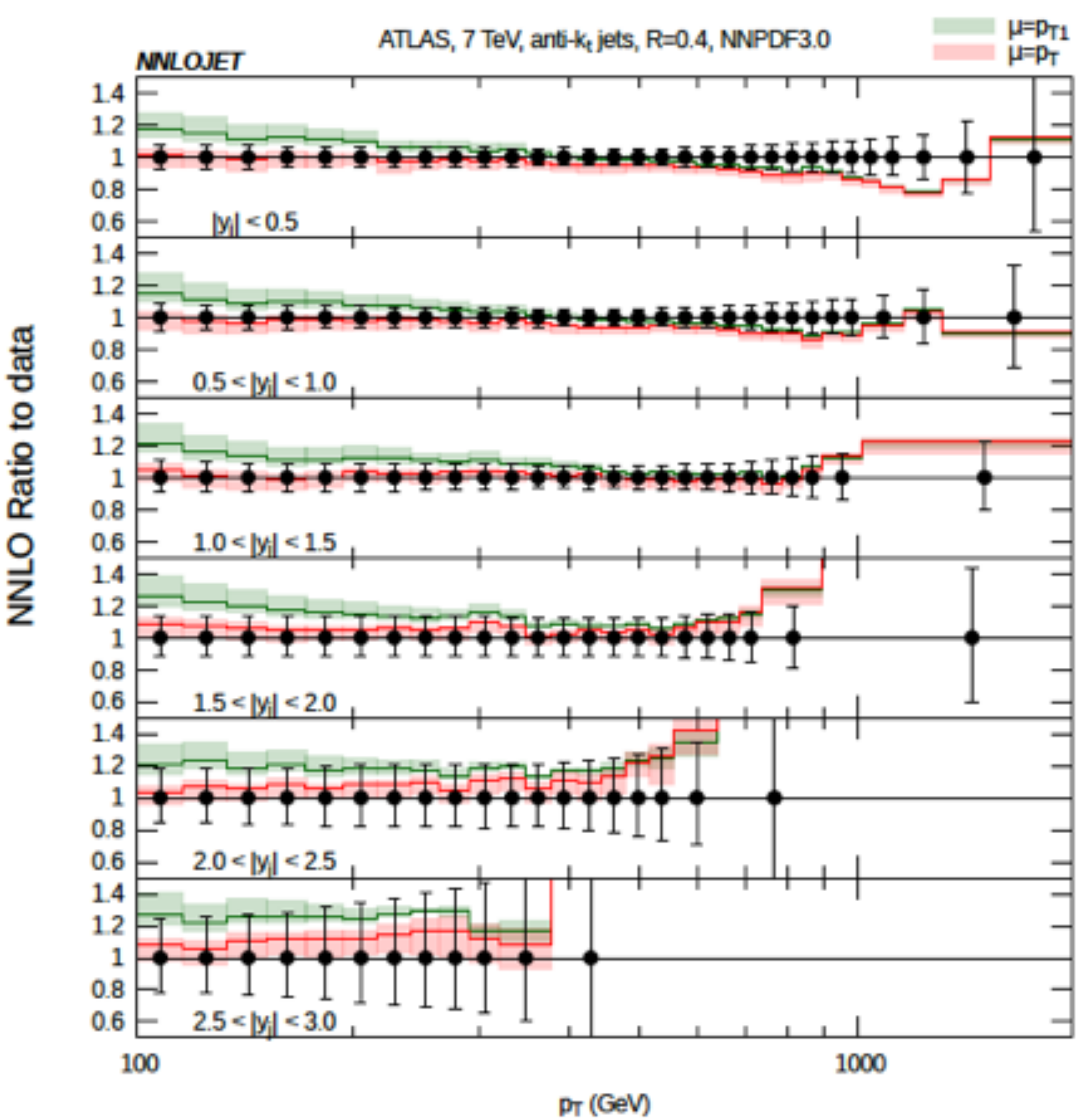
Scale choices

Differential distributions in tt~ production [Czakon et al. '16]

$$\mu_0 = \begin{cases} \frac{m_T}{2} & \text{for :} \quad p_{T,t},\ p_{T,\bar{t}} \text{ and } p_{T,t/\bar{t}}\,, \\ \frac{H_T}{4} & \text{for :} \quad \text{all other distributions}\,. \end{cases}$$

- Scale dependence much reduced at (N)NNLO
- Multijet (i.e. multi-scale) processes make choice of central scale cumbersome (obs. dependent)
  - difference between scales can be large (several criteria-unclear which is best)

Inclusive jet spectrum at NNLO [Currie et al. '17]



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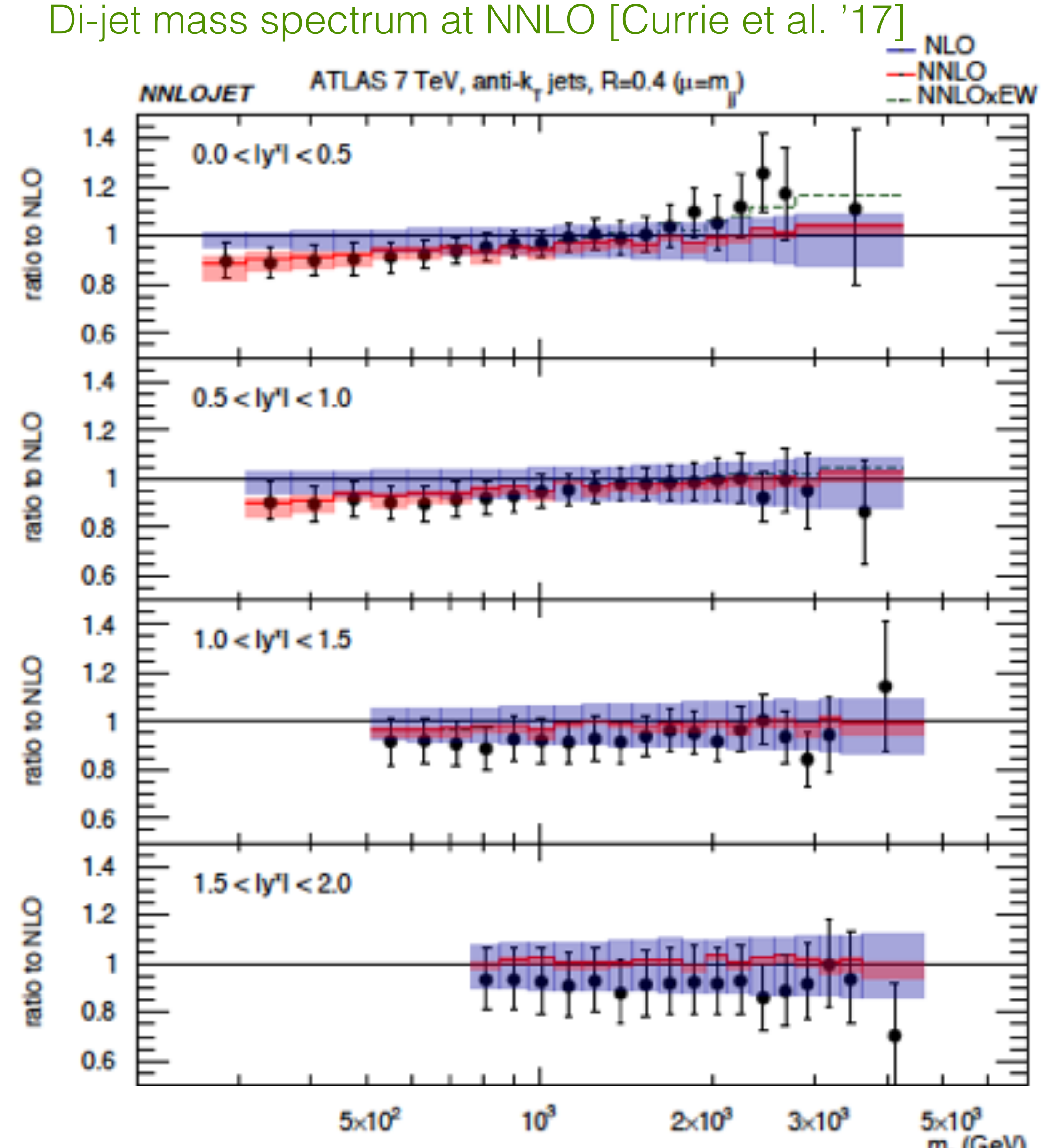

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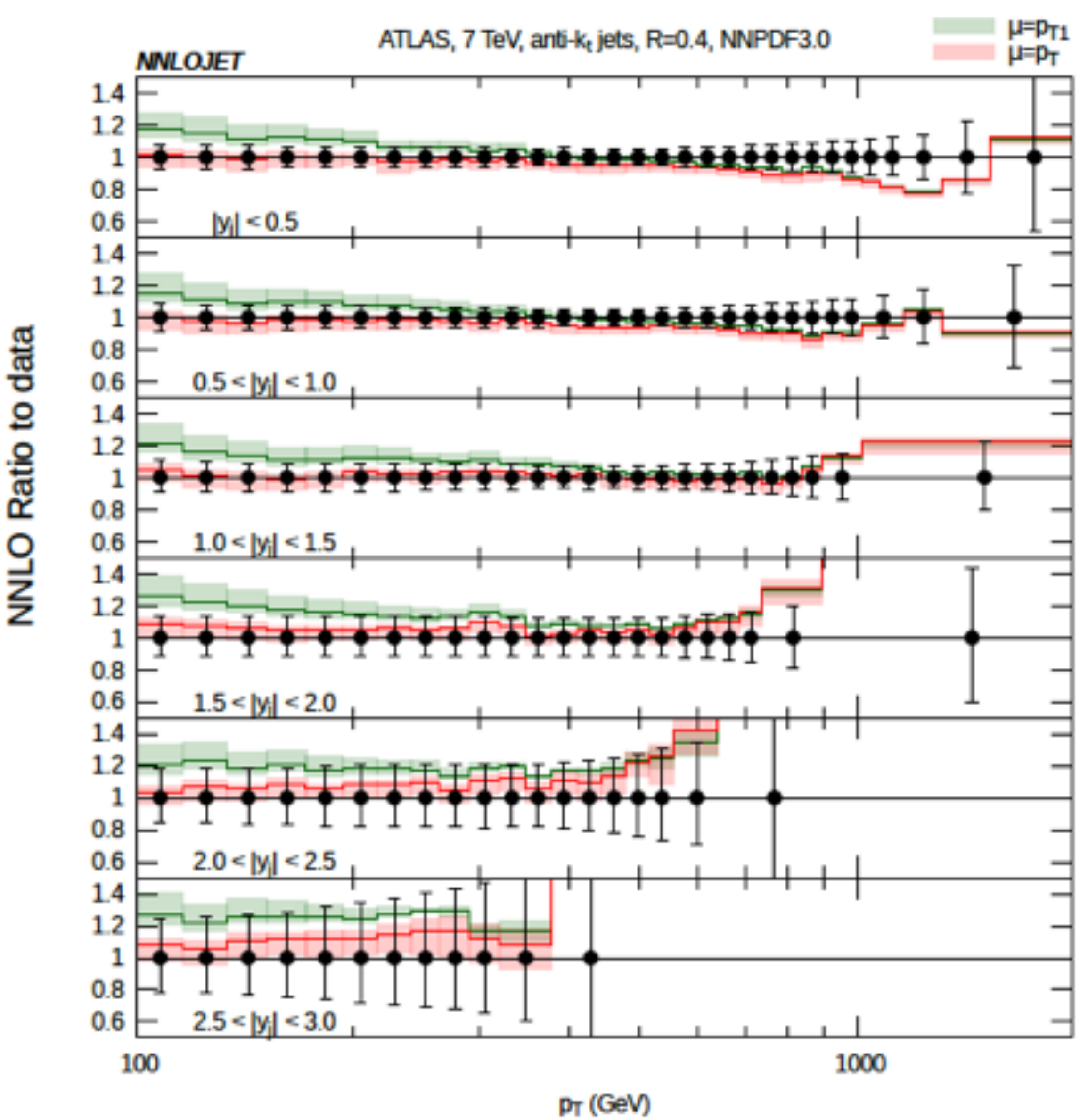

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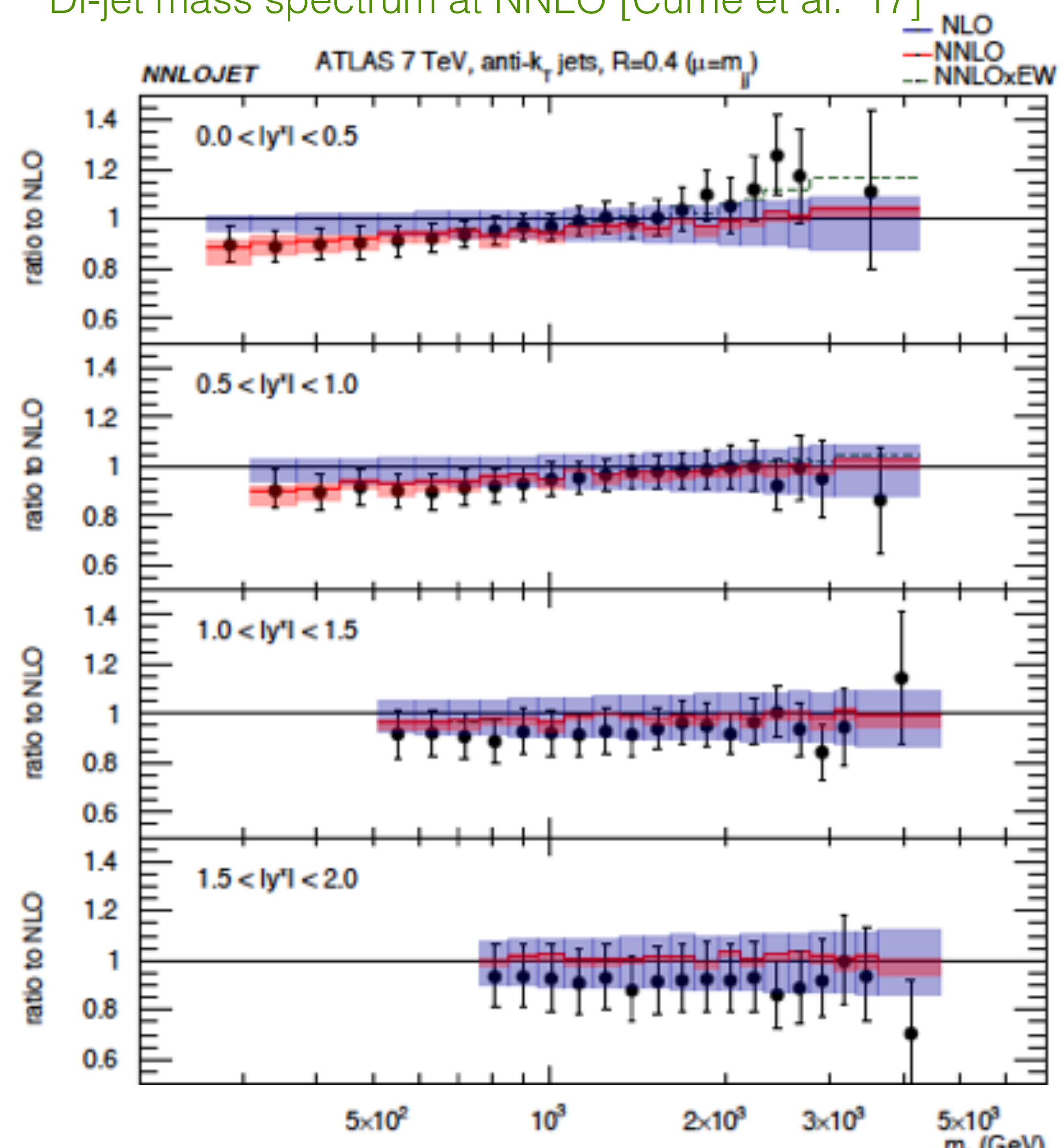
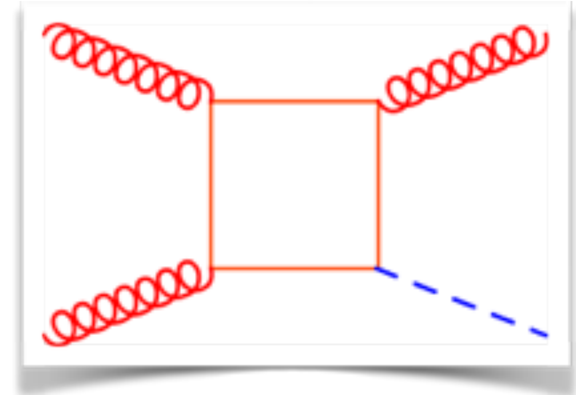
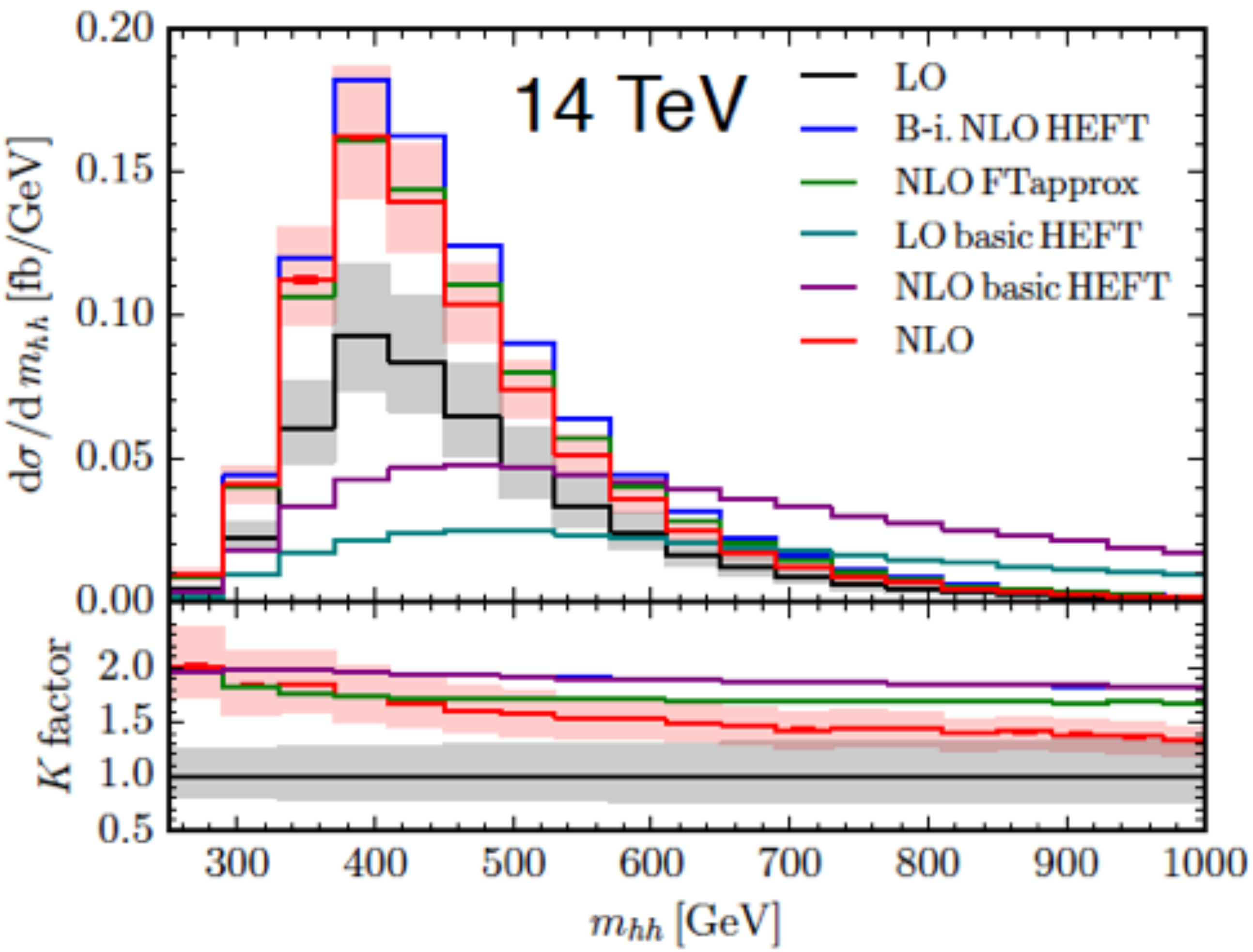


Loop-induced processes at NLO



- Formally start at O(as^2), but enhanced by gluon densities
  - Recent progresses with light quarks gg -> VV [Caola, Melnikov, Roentsch, Tancredi '15]
  - top-quark corrections are substantial in the tails (boosted regime very sensitive to NP). Normally described in a EFT where the top is infinitely heavy. Full analytic calculation of two-loop amplitudes highly involved
- Numerical solution for HH production

[Borowka, N. Greiner, Heinrich, Jones, Kerner, Schlenk, Zirke '16]
[Heinrich, Jones, Kerner, Luisoni, Vryonidou '17]

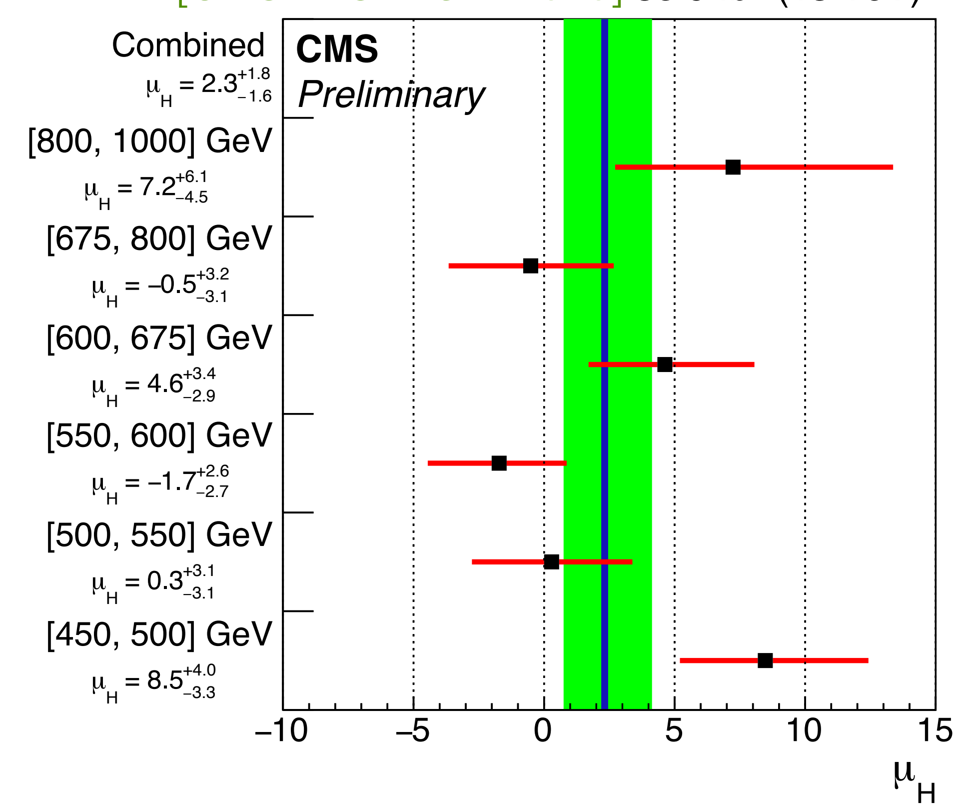


- Desirable for H+jet

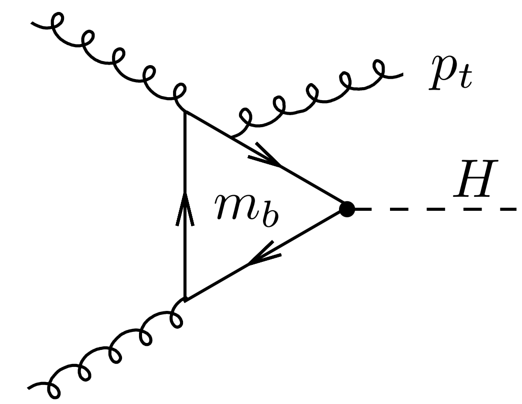
Progress in [Bonciani et al. '17]

  - first measurements of tail for H->bb~ with substructure

[CMS-PAS-HIG-17-010] 35.9 fb^{-1} (13 TeV)



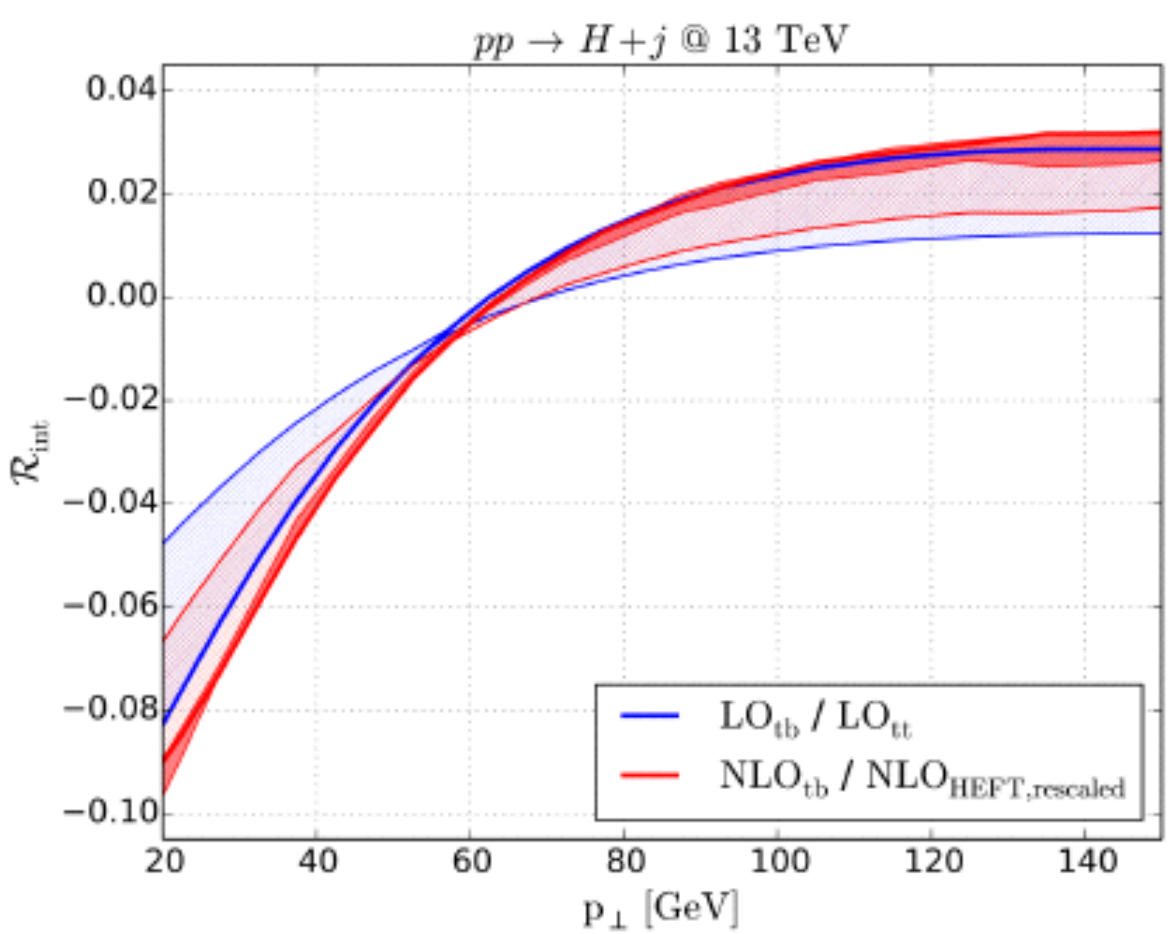
An example: bottom quark in H+jet



- Analogous problem for bottom loop in H+jet at pT <~ mH
  - NNLO EFT description accurate at ~10% in this region. Heavy-quark (not top) corrections ~5-6% —> suppressed by small coupling, but log-enhanced (jet probes the loop structure)

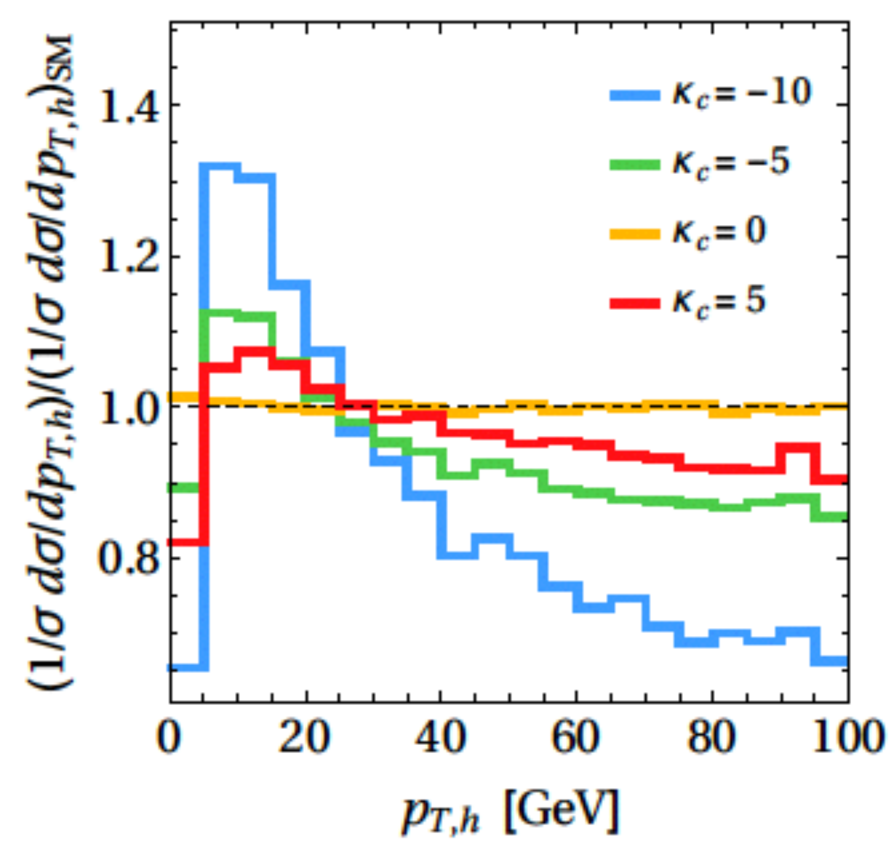
$$A_t A_b^* \sim y_t m_b^2 / m_H^2 \ln^2(p_\perp^2/m_b^2) \sim 10^{-2}$$

- Recent NLO computation of two-loop virtual amplitudes via small-mass expansion [Lindert, Melnikov, Wever, Tancredi '16-'17]



- Important to match the exp. systematics in future measurements at the LHC.
- Sensitivity to charm and bottom couplings

[Bishara et al. '16; Soreq et al. '16]



Summing logarithms (in a nutshell)

- Logarithms can appear both in amplitudes (e.g. large scale gaps) and cross sections whenever the radiation is constrained to be soft and/or collinear

  e.g.
  - production of heavy systems near threshold in hadronic collisions, high-energy scattering, edges of phase space of of IRC-safe observables (e.g. exclusive regimes, vetoes, small pT, …)

- At the LHC, often is necessary to cut out radiation effects without depleting too much the underlying signal. This operation may develop logarithms that require an all-order treatment

- Resummation aims at answering questions like:

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

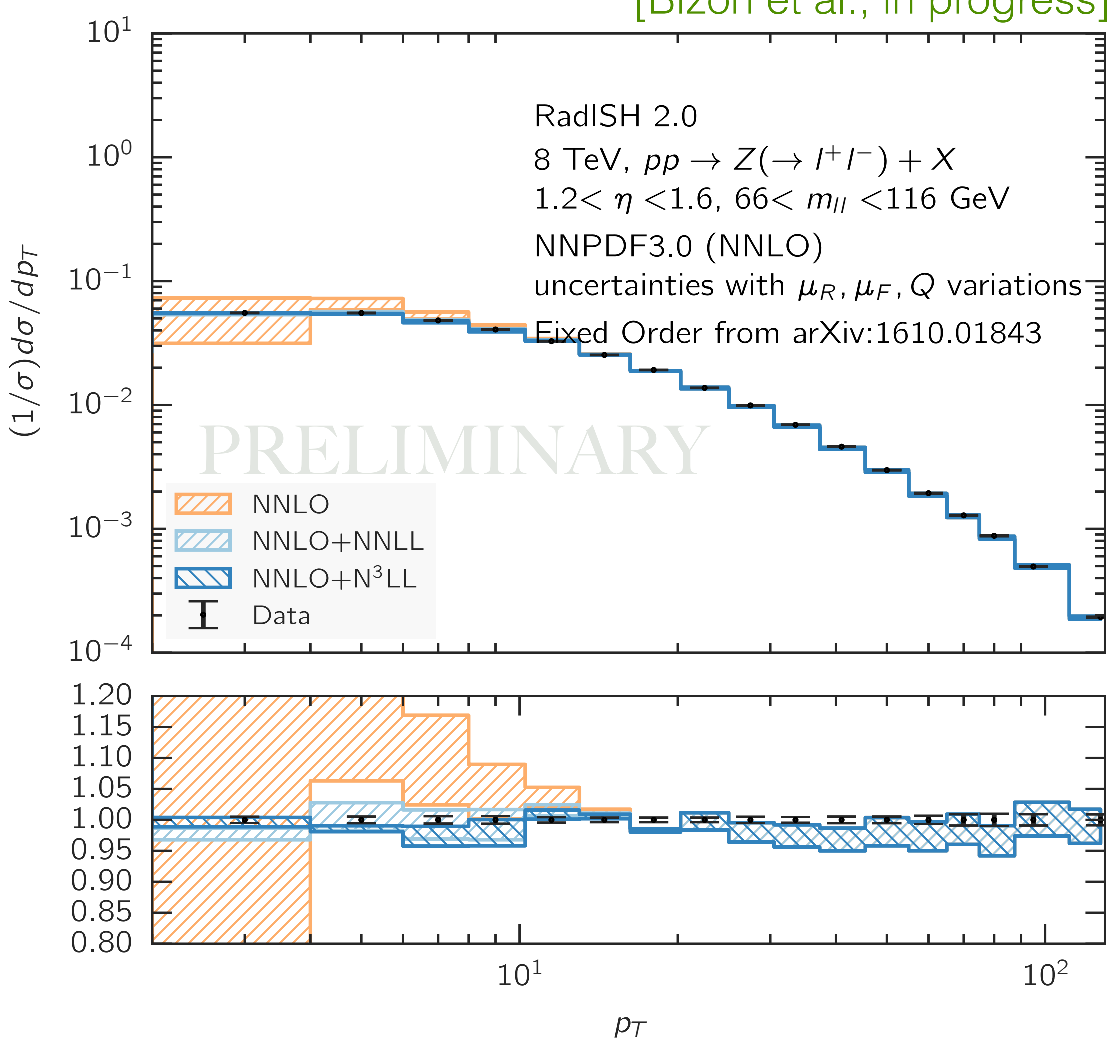
  - Can we start from our knowledge of the radiation dynamics to devise new observables which are predictable at all orders and free of pile-up contamination ? i.e. can we exploit more data ?
  - …

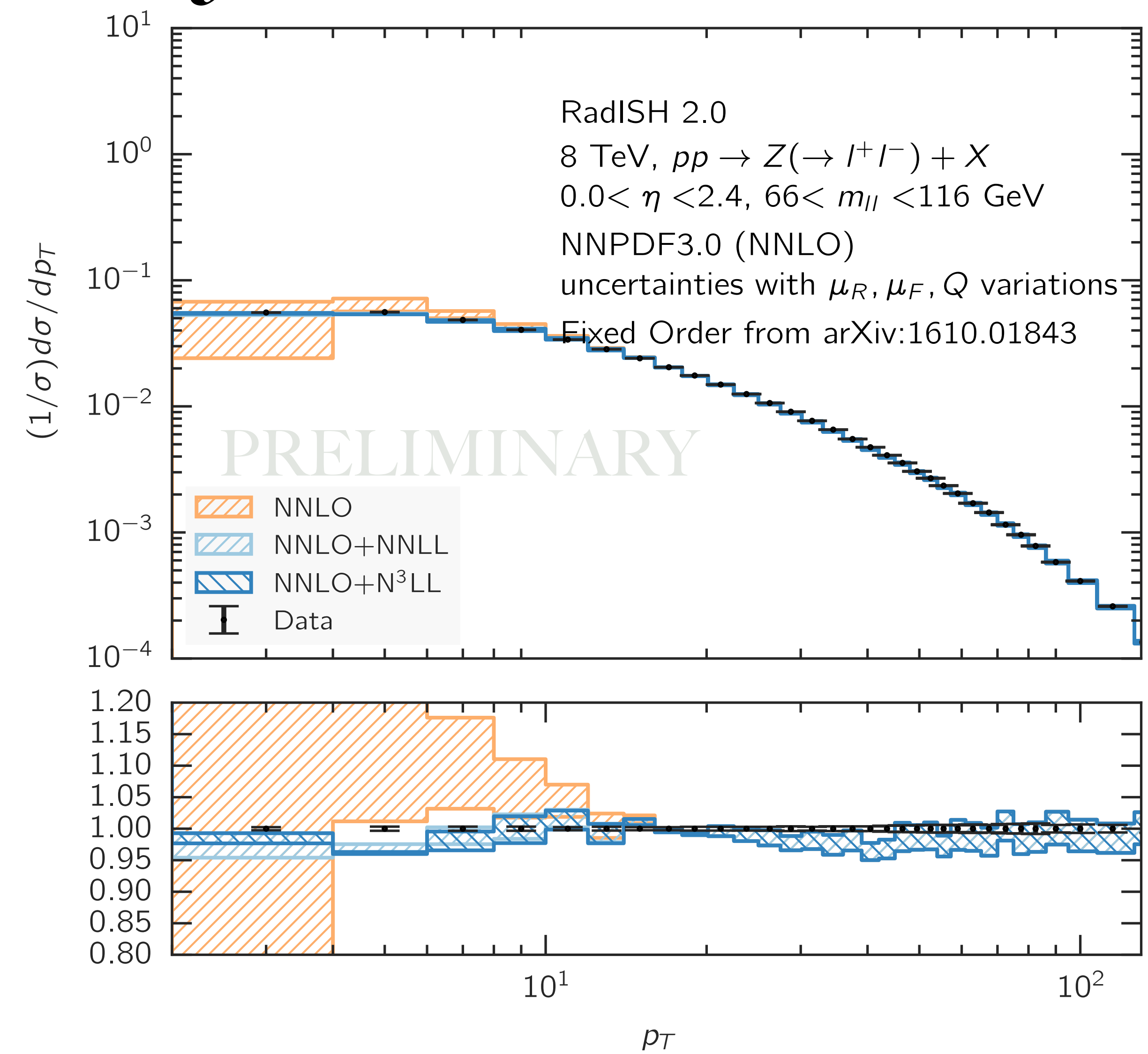
An example: Z+jets

Astonishing precision in the Z kinematic distributions (~1% or less)

- distributions relevant for PDFs, Mw,…
- NNLO+N3LL needed to match exp. precision (not even sufficient at central rapidities)

[Bizon et al., in progress]





Fixed-order obtained with NNLOJET, computationally demanding

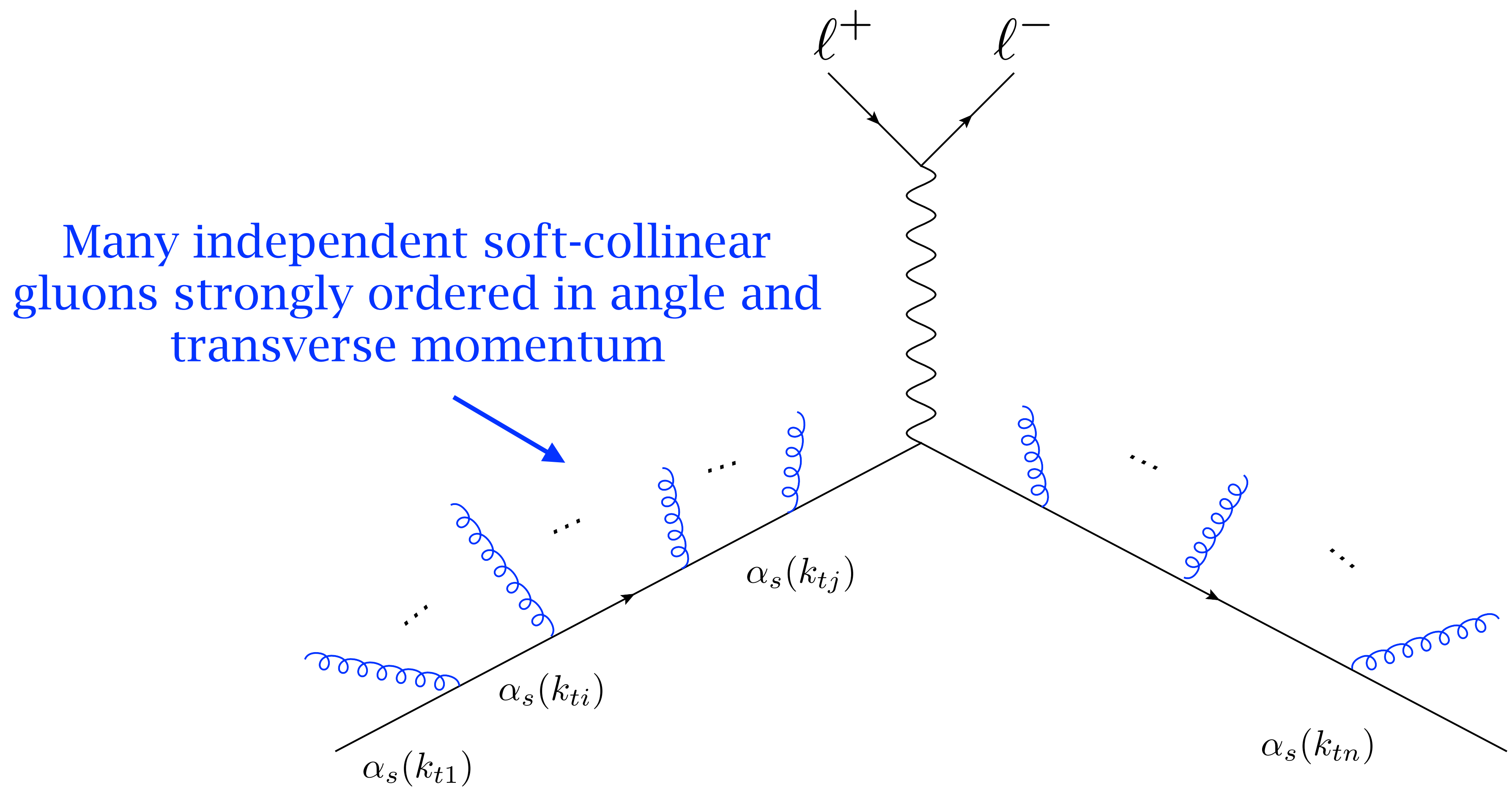
[Gehrmann-De Ridder et al. '16]

Hit the limits of PT, non-perturbative corrections have comparable size…start worrying about hadronisation. Heavy-quark effects also relevant at this stage

Logarithmic counting: a schematic example

- e.g. measure transverse energy of partonic radiation in colour-singlet production

$$\Sigma(E_\perp) \sim e^{\mathcal{O}(\alpha_s^n \ln^{n+1}(M_{\ell\ell}/E_\perp))}$$



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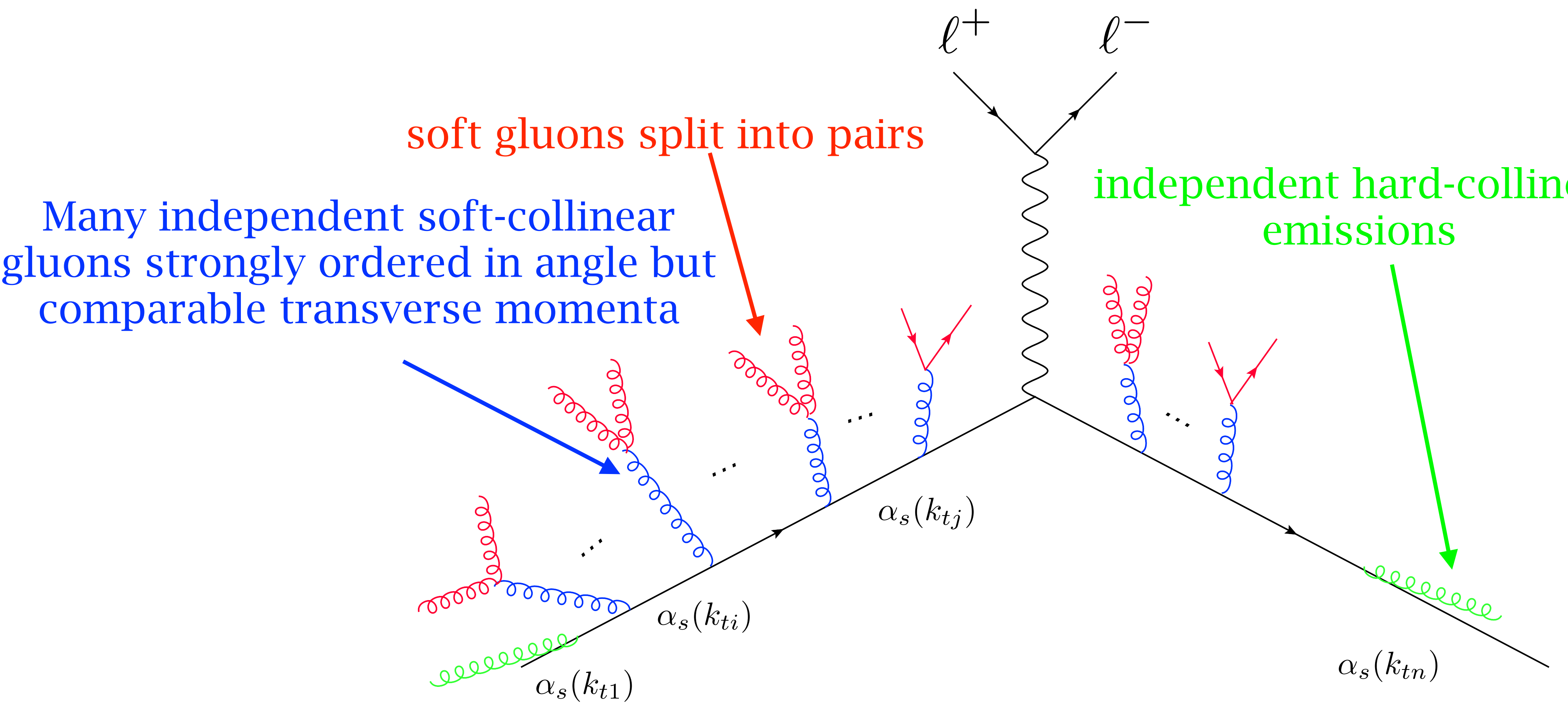
$$\Sigma(E_\perp) \sim e^{\mathcal{O}(\alpha_s^n \ln^{n+1}(M_{\ell\ell}/E_\perp)) + \mathcal{O}(\alpha_s^n \ln^n(M_{\ell\ell}/E_\perp))}$$



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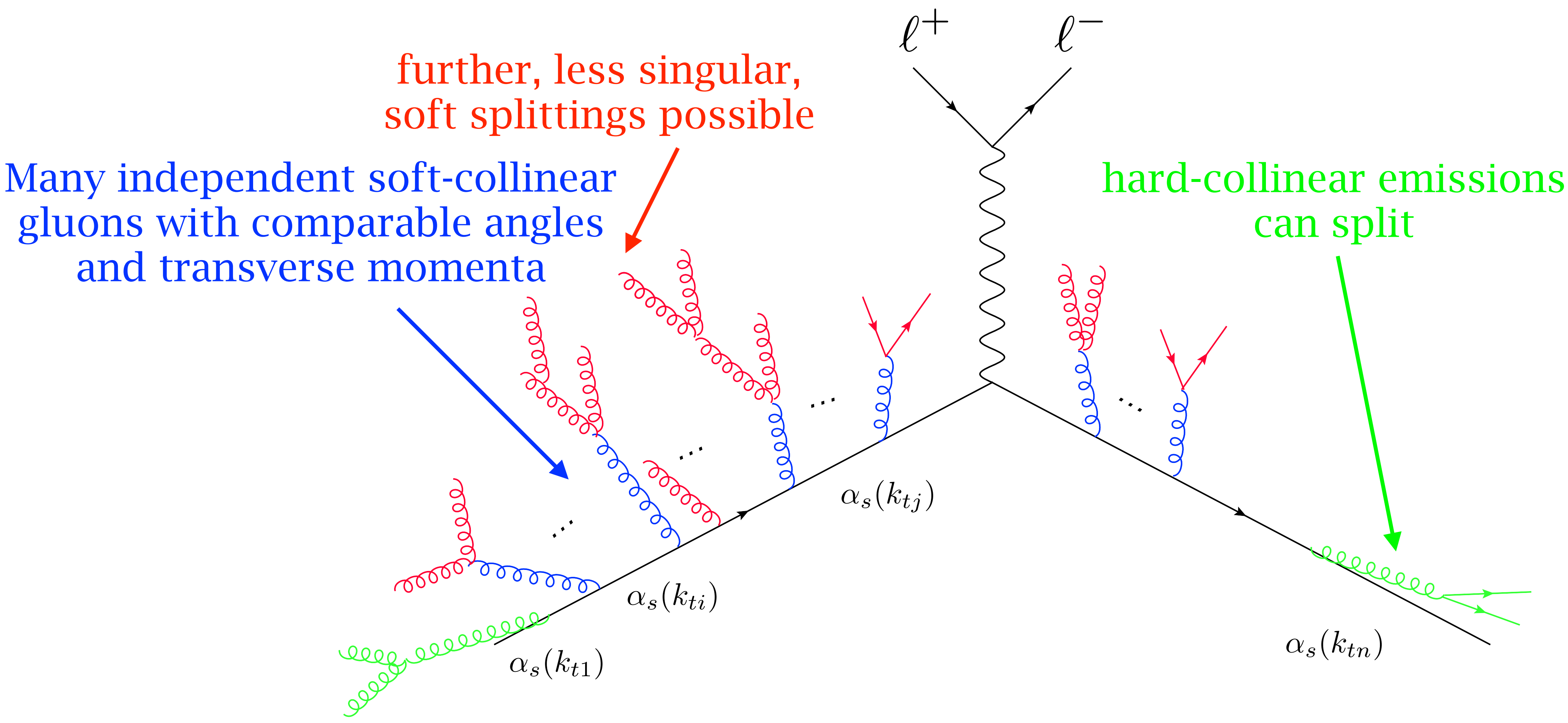

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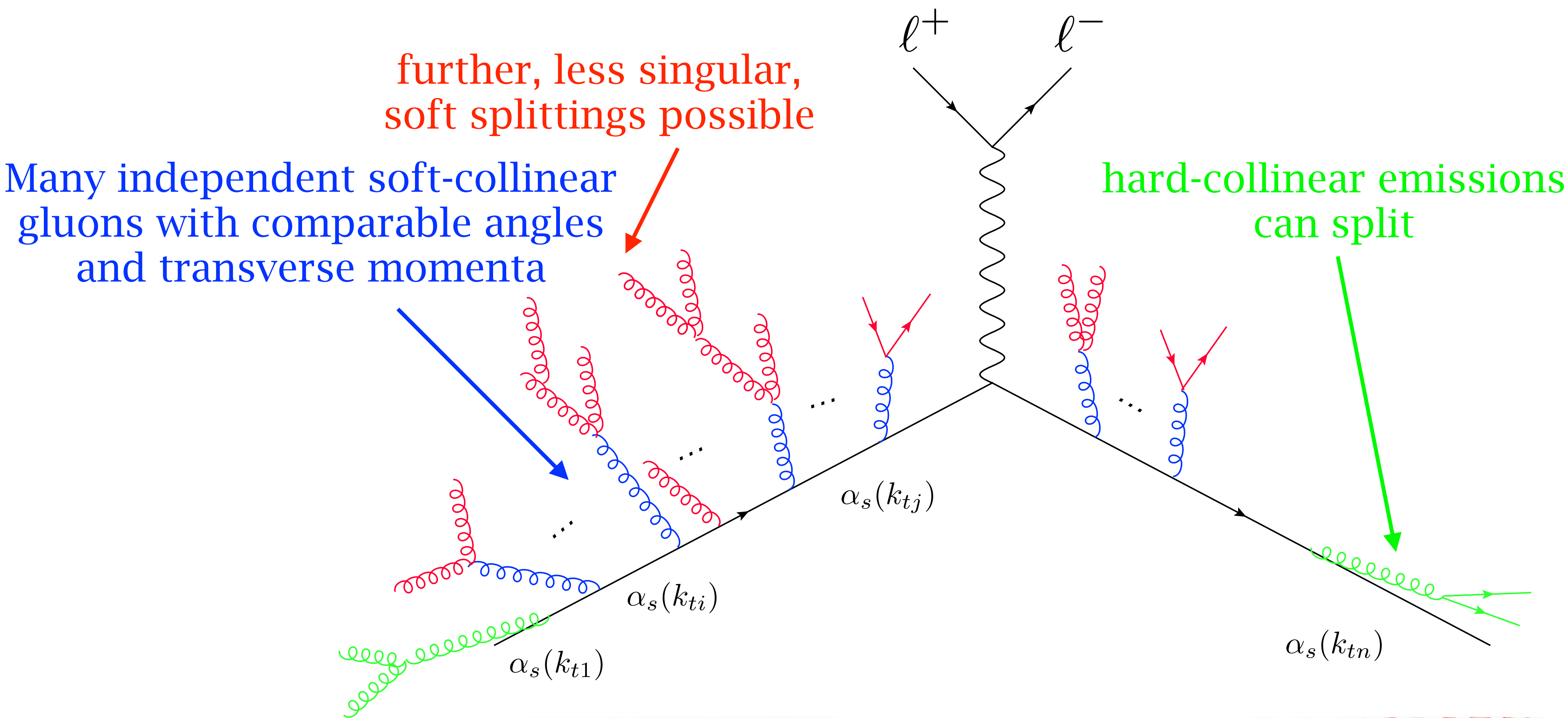
$$\Sigma(E_\perp) \sim e^{\mathcal{O}(\alpha_s^n \ln^{n+1}(M_{\ell\ell}/E_\perp)) + \mathcal{O}(\alpha_s^n \ln^n(M_{\ell\ell}/E_\perp)) + \mathcal{O}(\alpha_s^n \ln^{n-1}(M_{\ell\ell}/E_\perp))}$$



Higher logarithmic order implies a more accurate description of the radiation dynamics and its kinematics in less singular limits

- Hard to summarize state of the art in a single slide: unlike fixed order (one process, all IRC safe observables), in resummations each observable requires, to some extent, dedicated ingredients (lately progress towards reducing the gap)
- Goal: computation in soft and/or collinear limits at all orders in the coupling. Cancellation of IRC divergences requires computation to be done in D=4-2*ep dims.

Large progress in the past decade

Two main concepts:

- Devise a factorisation theorem for a specific observable.
- Factorise singular structure in a conjugate space where the IRC singularities are multiplicatively renormalizable.
- Renormalization -> anomalous dimensions -> resummation

e.g. Soft Collinear Effective Theory, Collins Soper Sterman, Sterman et al.

- Introduce a resolution scale for the real radiation.
- Compute reals below the resolution scale (unresolved) in D dimensions, and cancel virtual singularities (Sudakov FF).
- Compute remaining resolved real radiation in 4 dimensions

—> resummation with MC/analytically

e.g. branching algorithm, CAESAR/ARES, generating functionals

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e.g. branching algorithm, CAESAR/ARES, generating functionals

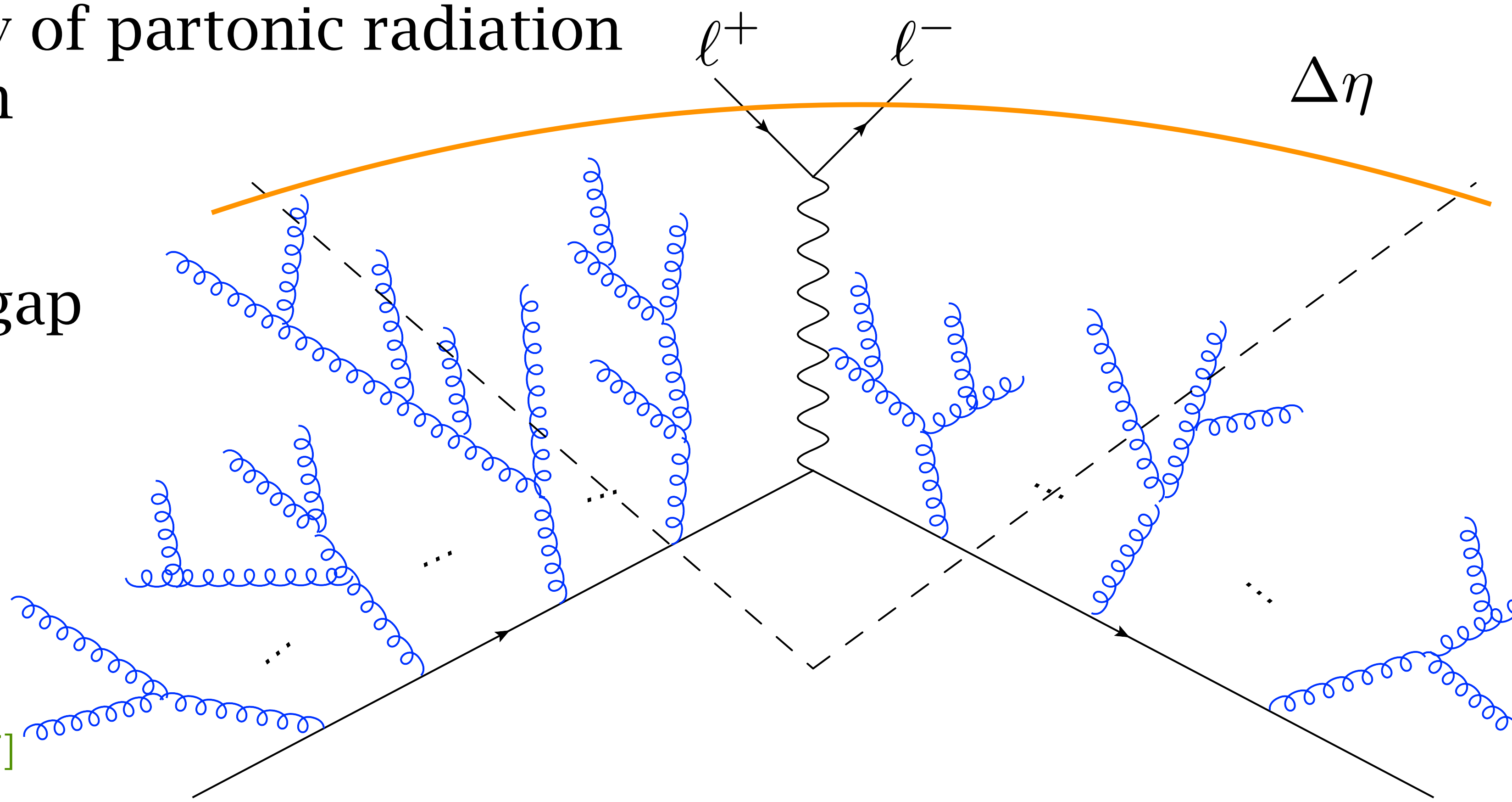
formal bridge between the two formulations still missing, important to exploit the synergy between them

Non-Global logarithms

$$\Sigma(E_\perp) \sim e^{\mathcal{O}(\alpha_s^n \ln^n (M_{\ell\ell}/E_\perp))+\ldots}$$

- e.g. measure transverse energy of partonic radiation in an angular phase space patch
- Need to simulate the whole coherent radiation outside the gap to control NGLs (challenging)
- Despite the lot of progress in recent years, no full result beyond LL exists

[Dasgupta, Salam '01; Banfi et al. '02]
[Caron-Huot '15; Larkoski et al. '15; Becher et al. '15-'17]



- Their understanding is necessary for precise control of very exclusive obs.
- Non-global logarithms arise from the observable's sensitivity to soft radiation with large angles. Large NGL at the LHC would also imply large PU contamination
  - Define PU-robust observables and reduce impact from NGL -> substructure

Inspecting jets: substructure

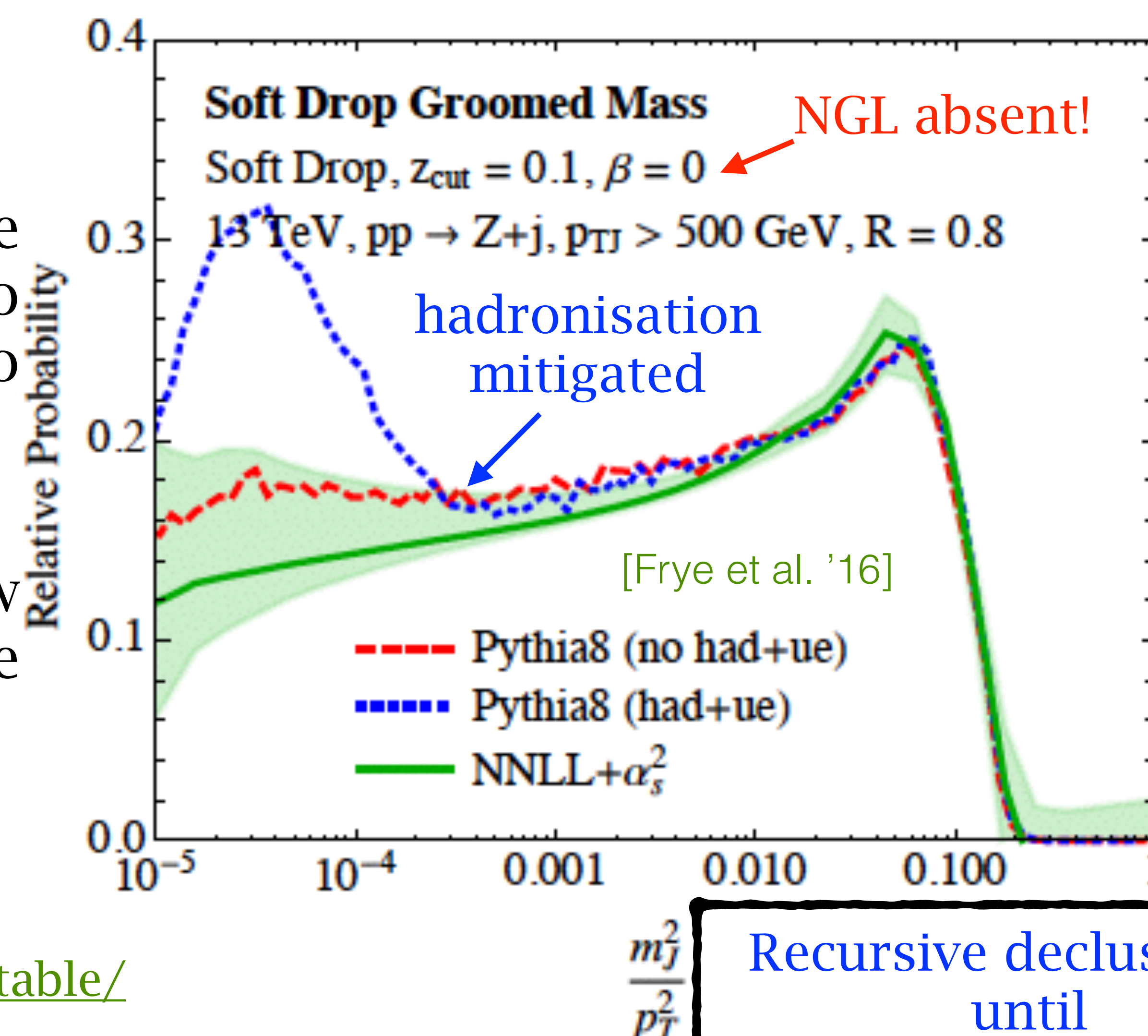
- Can these problems be mitigated by grooming jets ?

- An analytic understanding of substructure technology is essential to groom the effect of soft radiation without inducing large perturbative corrections. Moreover, better tools can be devised for which an all-order treatment is possible

e.g. mMDT/Soft drop groomed jet mass: [Dasgupta et al. '13; Larkoski et al. '14]

- This progress made it possible to evolve the substructure concept from a tool to tag boosted objects to a method to groom soft radiation in a controlled way

- Explosion of methods in the past few years with immediate applications at the LHC



e.g. Boost 2017:

https://indico.cern.ch/event/579660/timetable/

Recursive declustering until

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

An alternative approach: PS

angular ordering
kt ordering
virtuality ordering
antenna shower
global recoil
CS dipole shower
local recoil

- Parton Showers generate collinear radiation from the hard process scale Q down to hadronic scales, in a fully differential way
  - in spirit analogous to resummation, but several very deep conceptual differences in the design/formulation
  - set initial condition for hadronisation (better kinematics -> good tune)
  - matching/merging to the hard process at NLO possible, even NNLO matching for colour singlets. Need higher logarithmic accuracy to match the theory uncertainties in the hard scattering

- Perturbative accuracy of PS currently unknown!

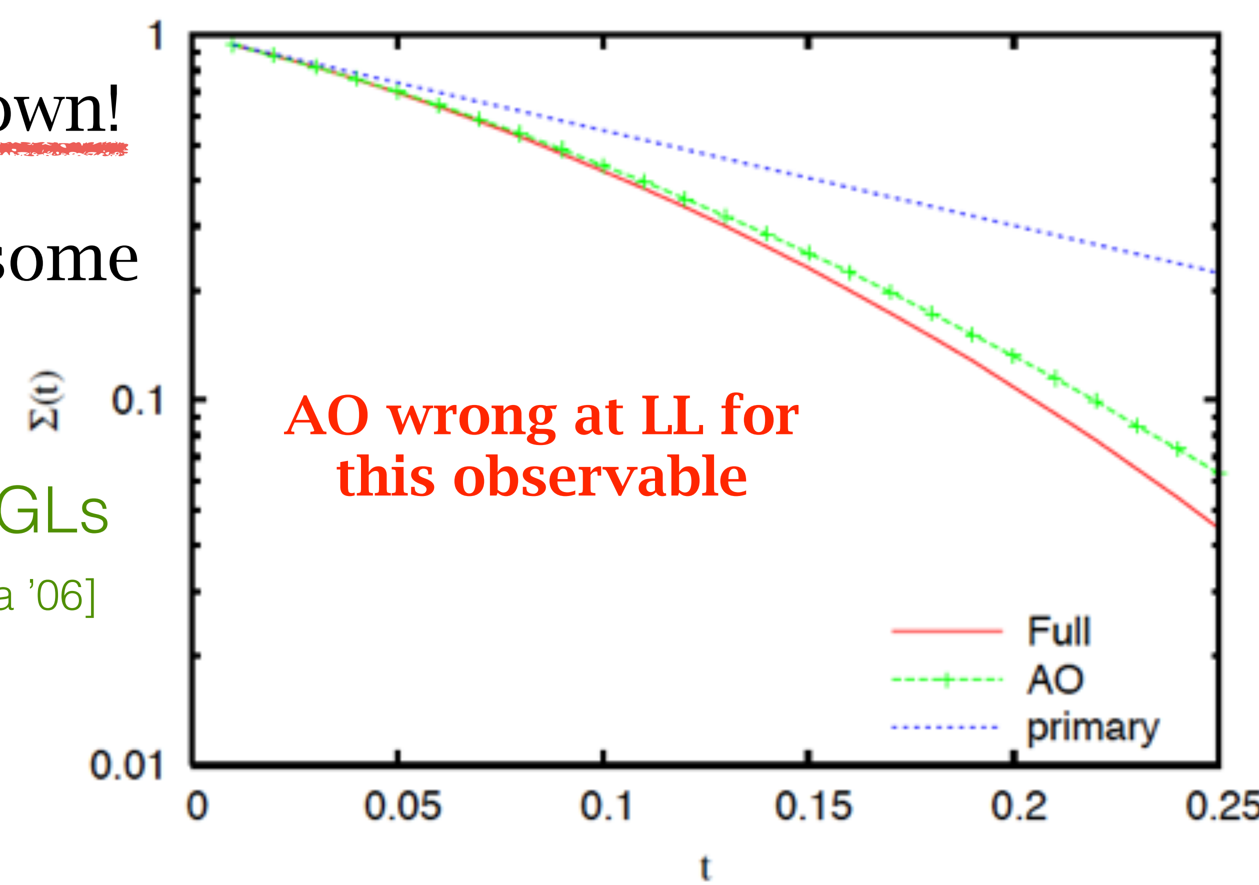
  Some designs known to be pathological in some configurations:

e.g.

ET in a rapidity slice: Angular Ordering vs. NGLs

[Banfi, Corcella, Dasgupta '06]

$$E_\perp = \sum_{i\in\Omega} E_{ti} < Q_\Omega, \qquad t = \int_{Q_\Omega}^{Q} \frac{dk_t}{k_t}\frac{\alpha_s(k_t)}{2\pi}$$



MC and precision: m_t^{pole}

Tevatron comb.: 174.30 +- 0.65 GeV
ATLAS comb.: 172.84 +- 0.7 GeV
CMS comb.: 172.44 +- 0.48 GeV

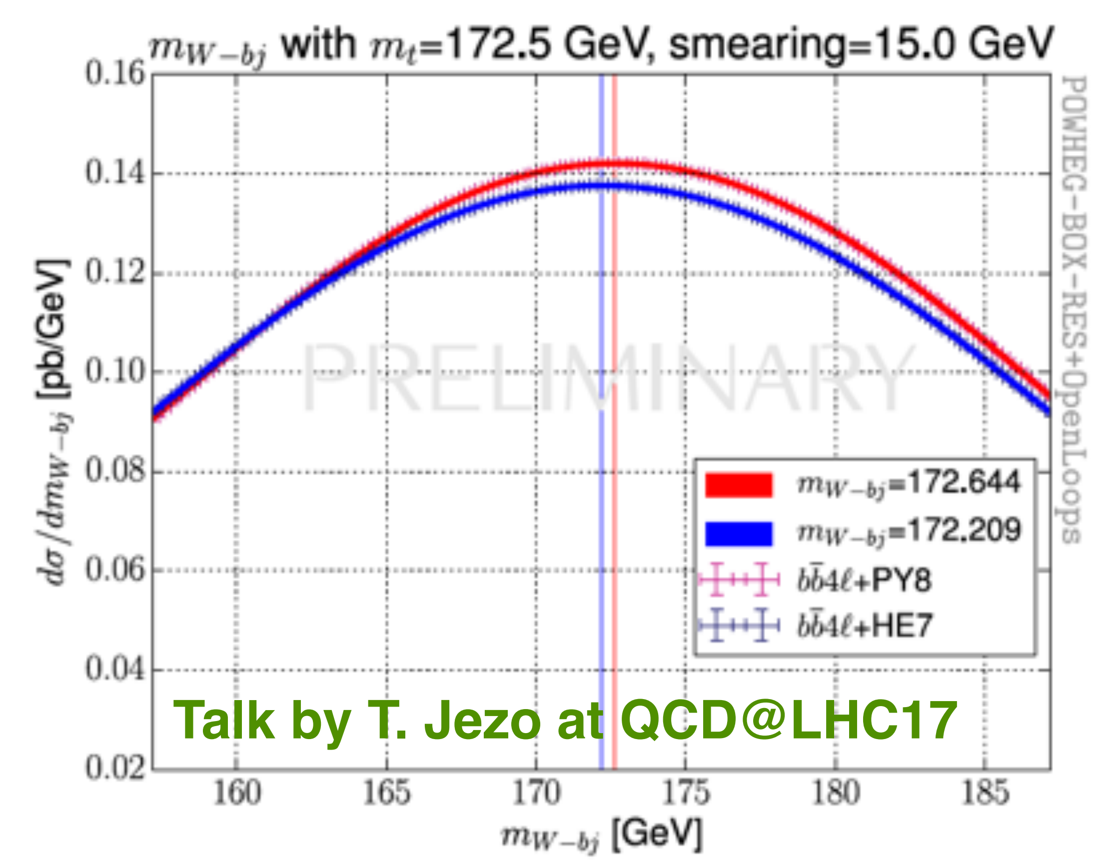
- Although the top pole mass suffers from an intrinsic theoretical ambiguity, this is estimated to be of the order of Λ_{QCD} (hadronisation, renormalon ~ 110 MeV) [Beneke et al. '16; Hoang et al. '17]
- Experimental sensitivity can reach ~ 500 MeV precision ($3^o/_{oo}$!)
- e.g. precise extraction from fits of reconstructed $m_{\ell b}^{\text{reco}}$ to MC (template method)

l+jets and dilepton channels in tt~

[ATLAS Phys. Lett. B761 (2016) 350]

	$\sqrt{s}=7$ TeV		$\sqrt{s}=8$ TeV
	$m_{\text{top}}^{\ell+\text{jets}}$ [GeV]	$m_{\text{top}}^{\text{dil}}$ [GeV]	$m_{\text{top}}^{\text{dil}}$ [GeV]
Results	172.33	173.79	172.99
Statistics	0.75	0.54	0.41
Method	0.11 ± 0.10	0.09 ± 0.07	0.05 ± 0.07
Signal Monte Carlo generator	0.22 ± 0.21	0.26 ± 0.16	0.09 ± 0.15
Hadronisation	0.18 ± 0.12	0.53 ± 0.09	0.22 ± 0.09
Initial- and final-state QCD radiation	0.32 ± 0.06	0.47 ± 0.05	0.23 ± 0.07
Underlying event	0.15 ± 0.07	0.05 ± 0.05	0.10 ± 0.14
Colour reconnection	0.11 ± 0.07	0.14 ± 0.05	0.03 ± 0.14
Parton distribution function	0.25 ± 0.00	0.11 ± 0.00	0.05 ± 0.00
Background normalisation	0.10 ± 0.00	0.04 ± 0.00	0.03 ± 0.00
W/Z + jets shape	0.29 ± 0.00	0.00 ± 0.00	0
Fake leptons shape	0.05 ± 0.00	0.01 ± 0.00	0.08 ± 0.00
Jet energy scale	0.58 ± 0.11	0.75 ± 0.08	0.54 ± 0.04
Relative b-to-light-jet energy scale	0.06 ± 0.03	0.68 ± 0.02	0.30 ± 0.01
Jet energy resolution	0.22 ± 0.11	0.19 ± 0.04	0.09 ± 0.05
Jet reconstruction efficiency	0.12 ± 0.00	0.07 ± 0.00	0.01 ± 0.00
Jet vertex fraction	0.01 ± 0.00	0.00 ± 0.00	0.02 ± 0.00
b-tagging	0.50 ± 0.00	0.07 ± 0.00	0.03 ± 0.02
Leptons	0.04 ± 0.00	0.13 ± 0.00	0.14 ± 0.01
E_T^{miss}	0.15 ± 0.04	0.04 ± 0.03	0.01 ± 0.01
Pile-up	0.02 ± 0.01	0.01 ± 0.00	0.05 ± 0.01
Total systematic uncertainty	1.03 ± 0.31	1.31 ± 0.23	0.74 ± 0.29
Total	1.27 ± 0.33	1.41 ± 0.24	0.84 ± 0.29

- TH uncertainty dominated by PS and hadronisation
- Is this a realistic estimate ? How well do we control MCs ?



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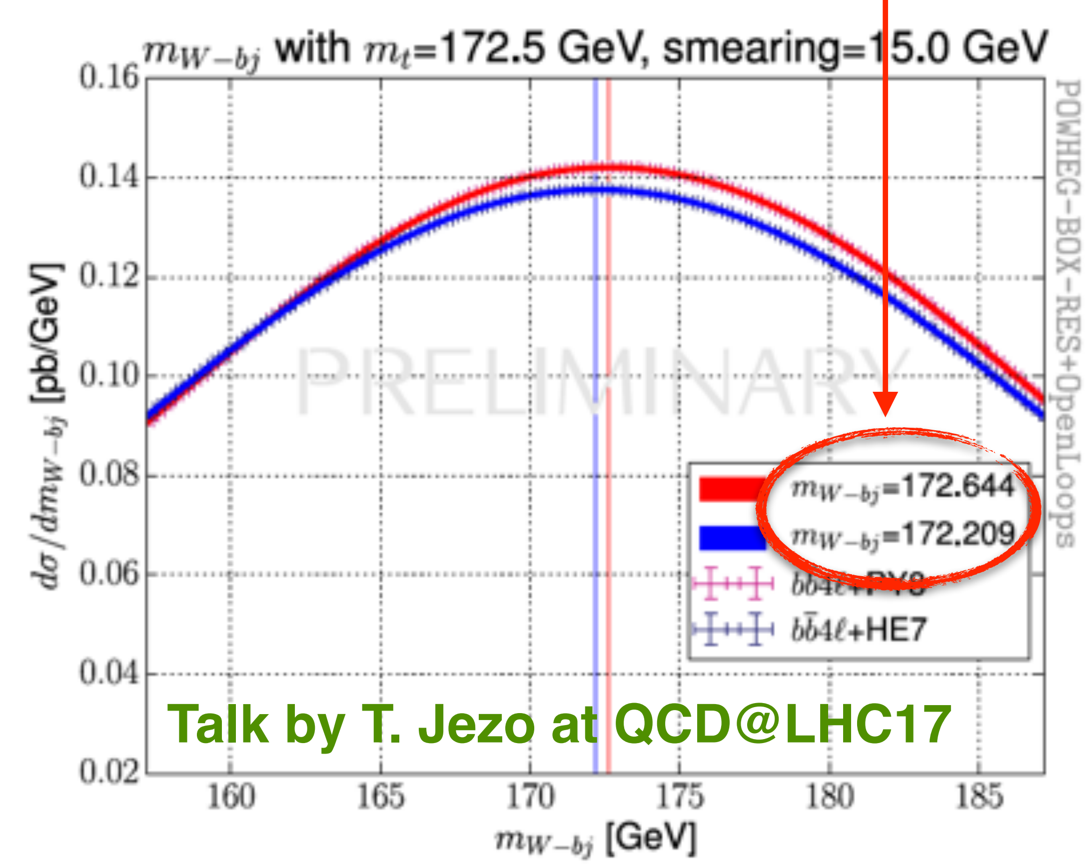
0.5 GeV shift plausible with current tools. Possible to do better ?



MC and precision: M_W

- Measured using template fits to lepton observ. (small W pT modelling critical)

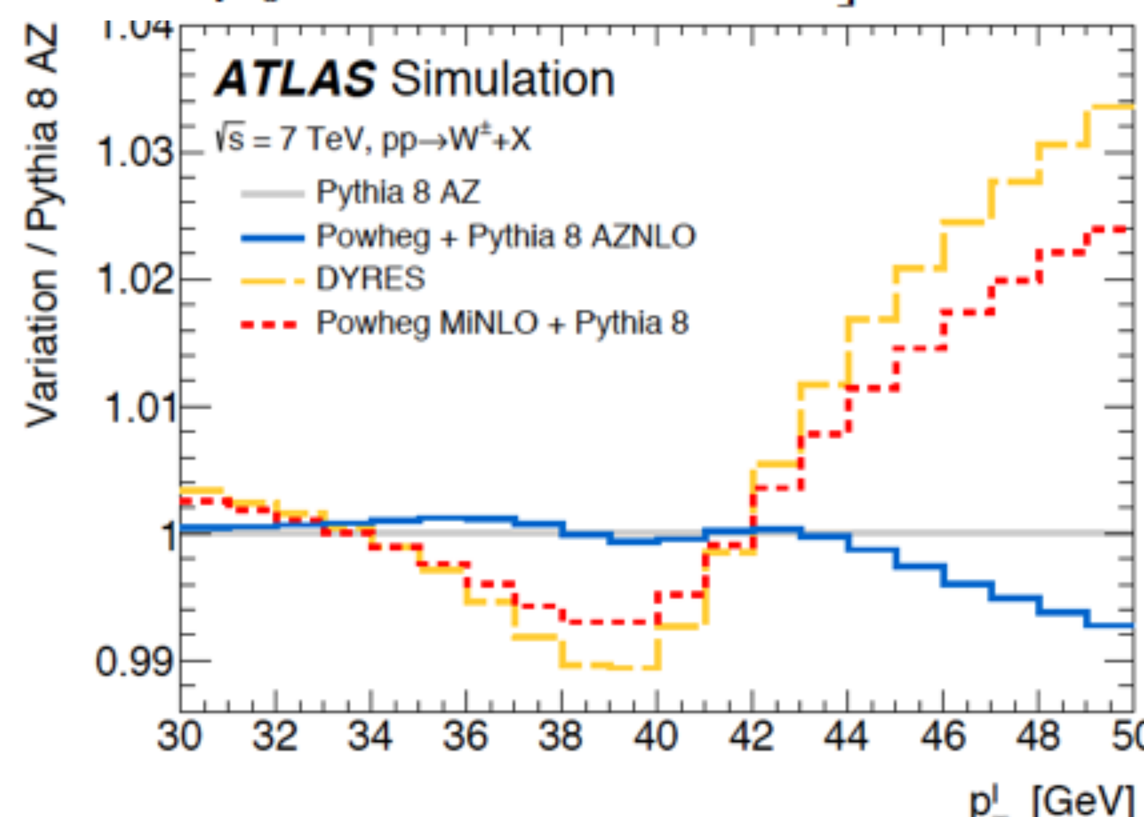
Breit-Wigner parametrisation

Fixed-order QCD (DYNNLO)

$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T,y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_T,y)P_i(\cos\theta,\phi)\right]$$

MC generator Pythia 8 (LO !)

- Hard for pQCD to achieve data precision. Use Z to calibrate MC (AZ tune) and then model the W template distributions



$M_W = 80370 \pm 19$ MeV [ATLAS 1701.07240]

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

Important to understand the uncorrelated sources of uncertainty.
New way to perform EW precision measurements

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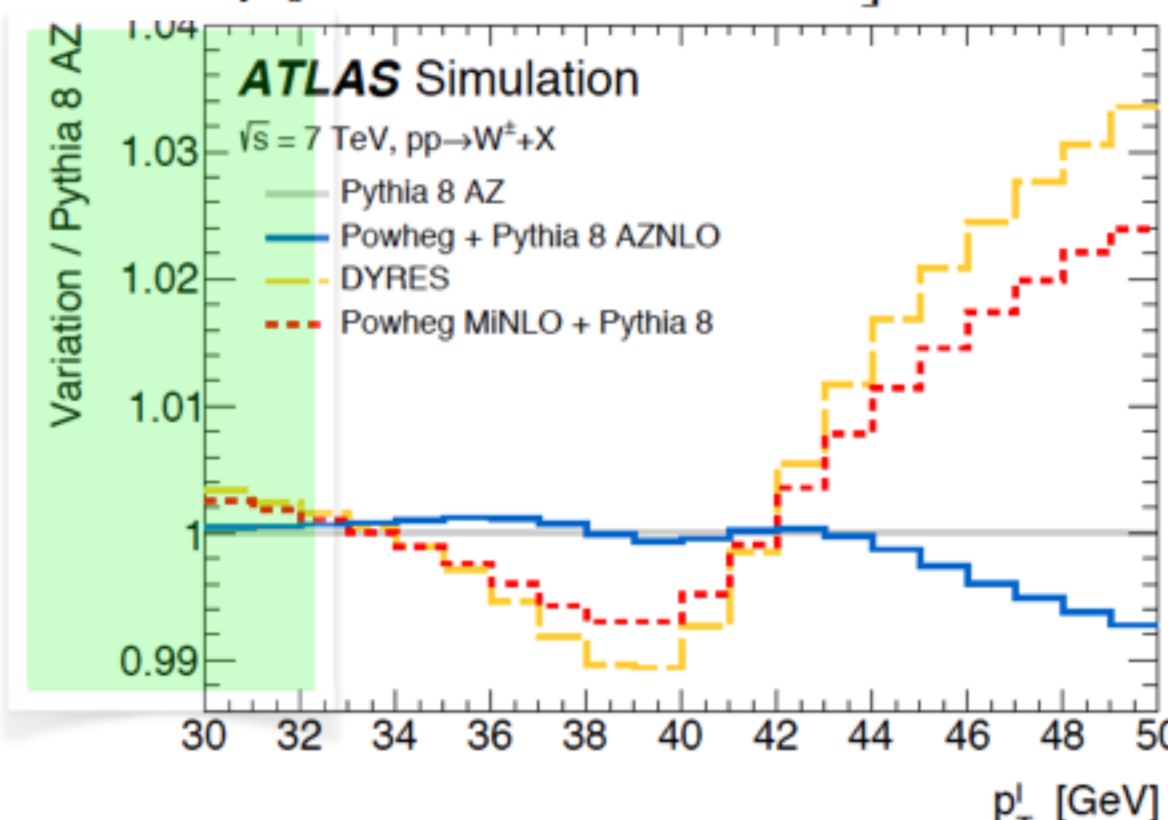

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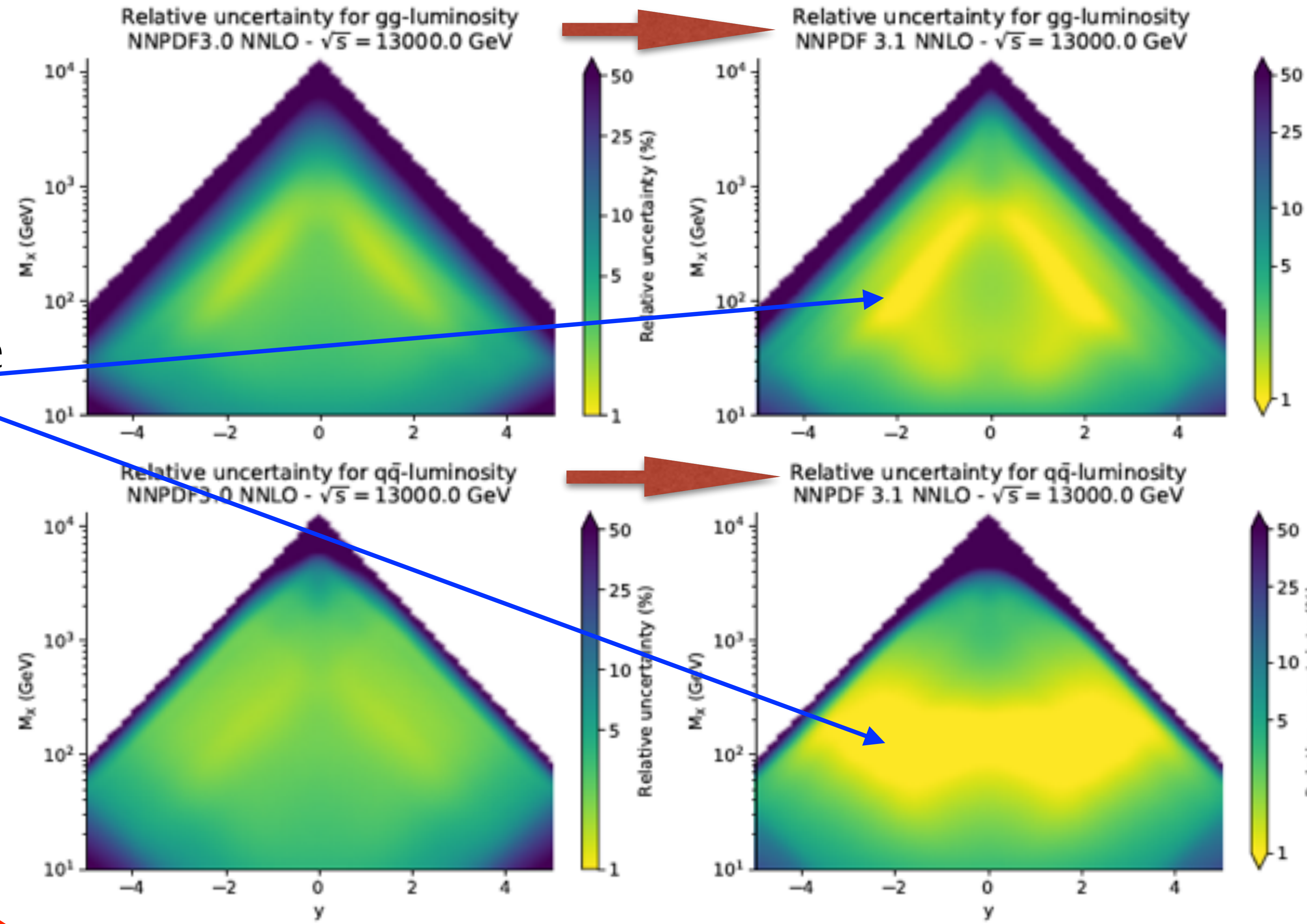
New way to perform EW precision measurements

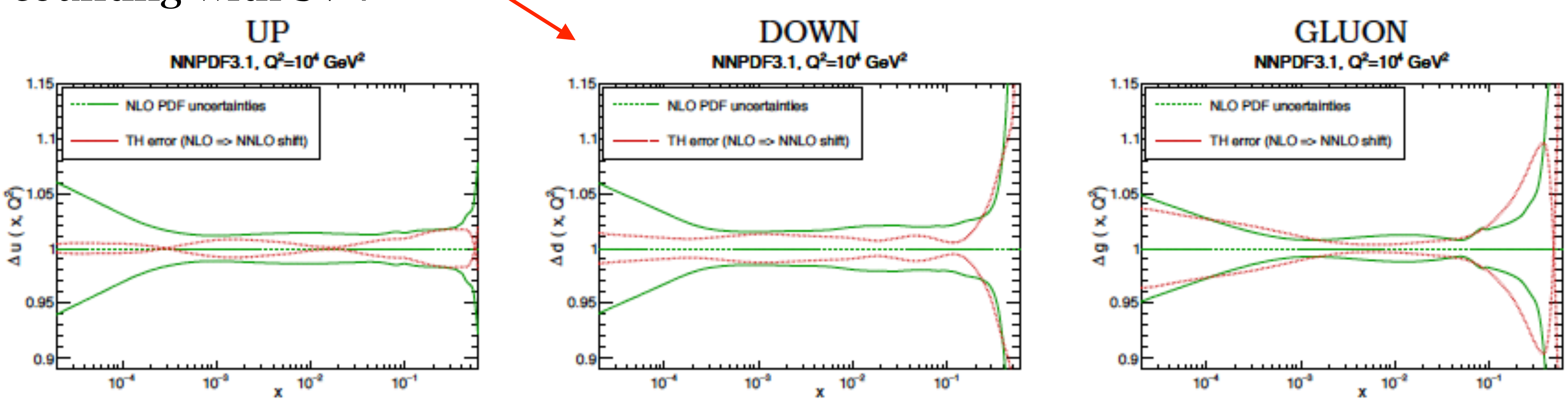
Parton densities and LHC data

e.g. [Ball et al. '17]



- Inclusion of LHC data (tt~, jets, EW production) leads to a better determination of PDFs
- %-level errors are achieved in some kinematic configurations
- With these uncertainties, it is important to assess the impact of the errors in the theory used to extract the PDFs
- TH uncertainties comparable to PDF uncertainties
  - how to include them ?
  - double counting with SV ?

e.g. NLO sets
S. Forte at
SCALES '17
(PRELIMINARY)

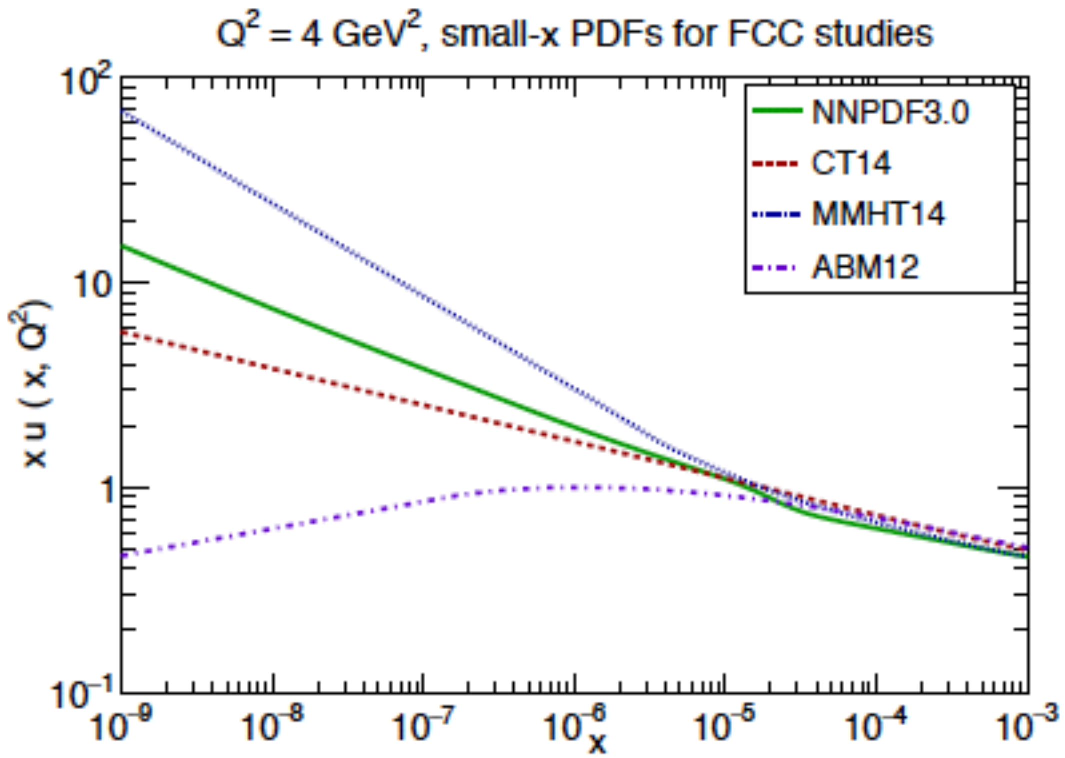


PDFs and future colliders

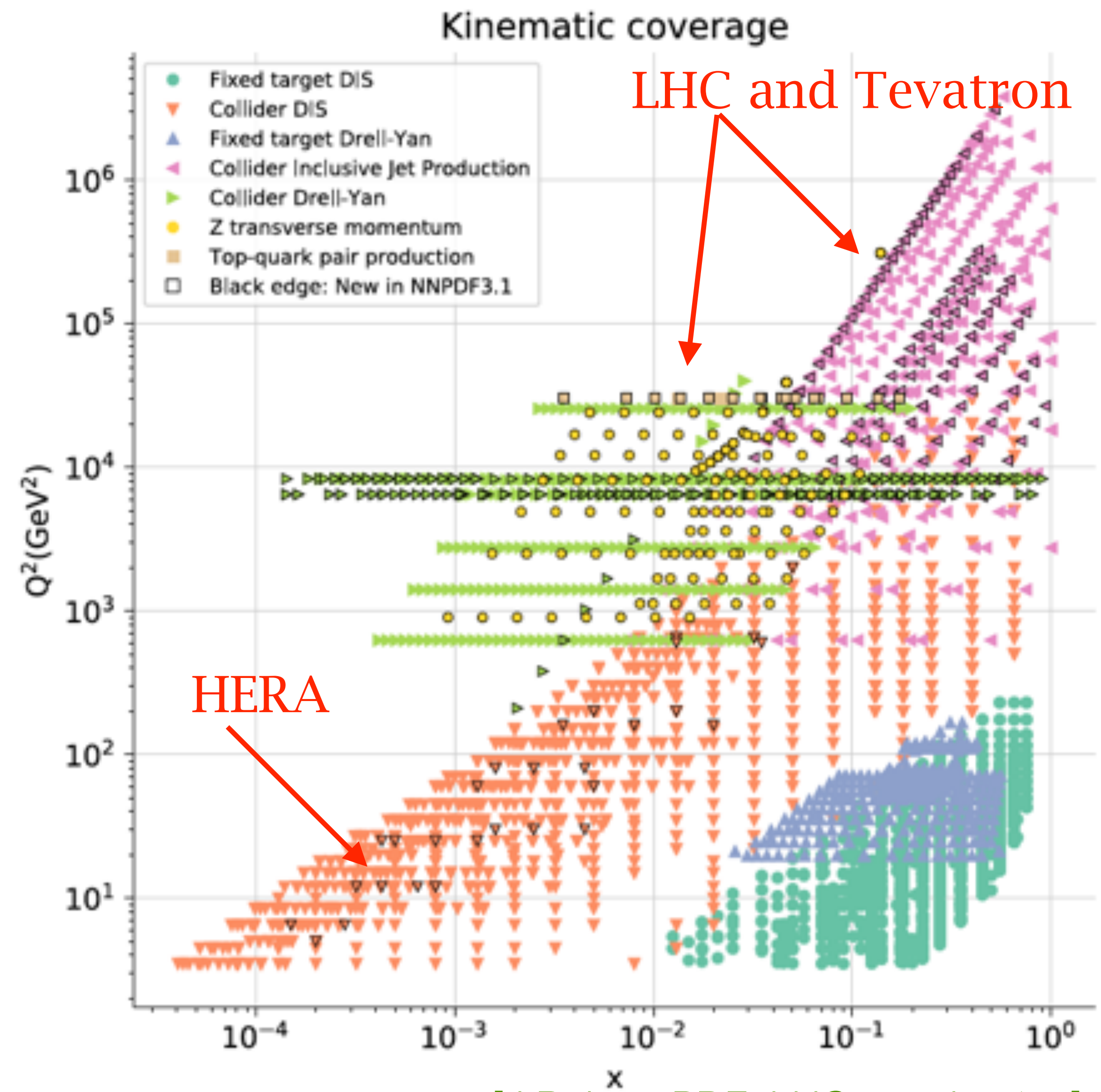
- The kinematic coverage of current (and past) experiments allows for a successful description of PDF evolution in terms of the DGLAP equation

- Higher energies probe smaller x regions, currently unconstrained/extrapolated

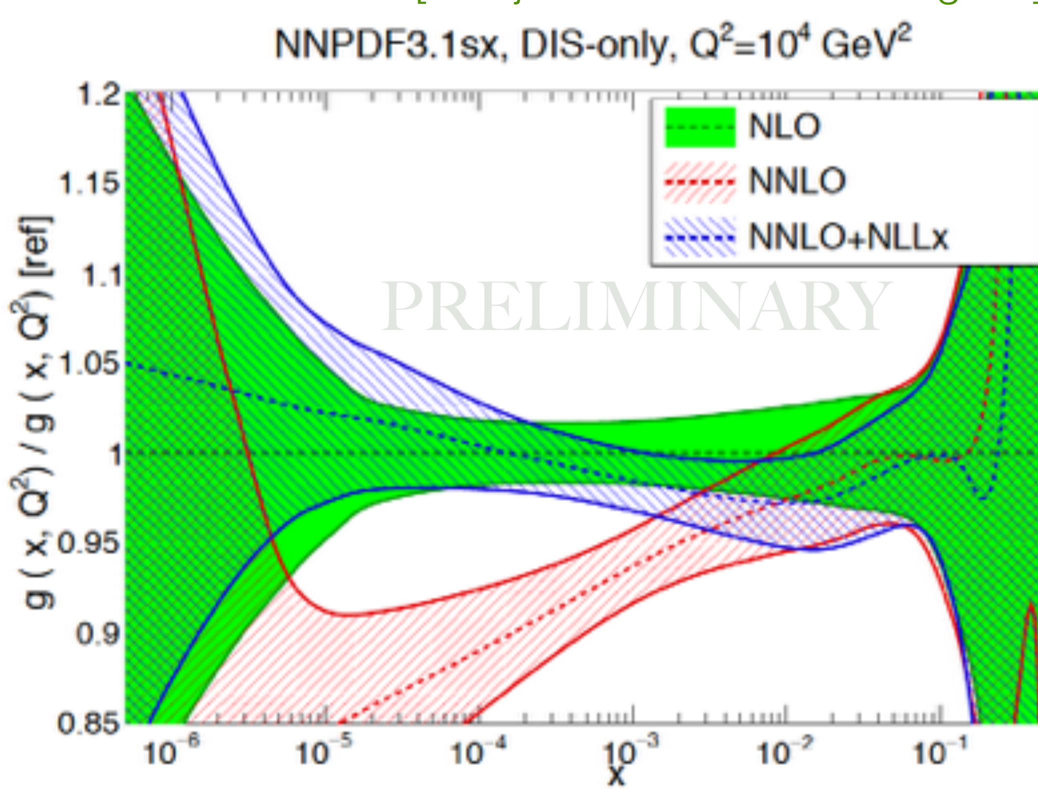
[Mangano et al '16: Physics at 100 TeV pp collider]



- Besides experimental constraints (e.g. forward production, LHCb,…), it is important to understand whether we have a robust theory understanding of these regions (BFKL effects ? Some effect already at small-x HERA ?)



[J.Rojo at PDF4LHC meeting '17]



What's the uncertainty in alpha_s ?

World average: [Bethke et al. '15]

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

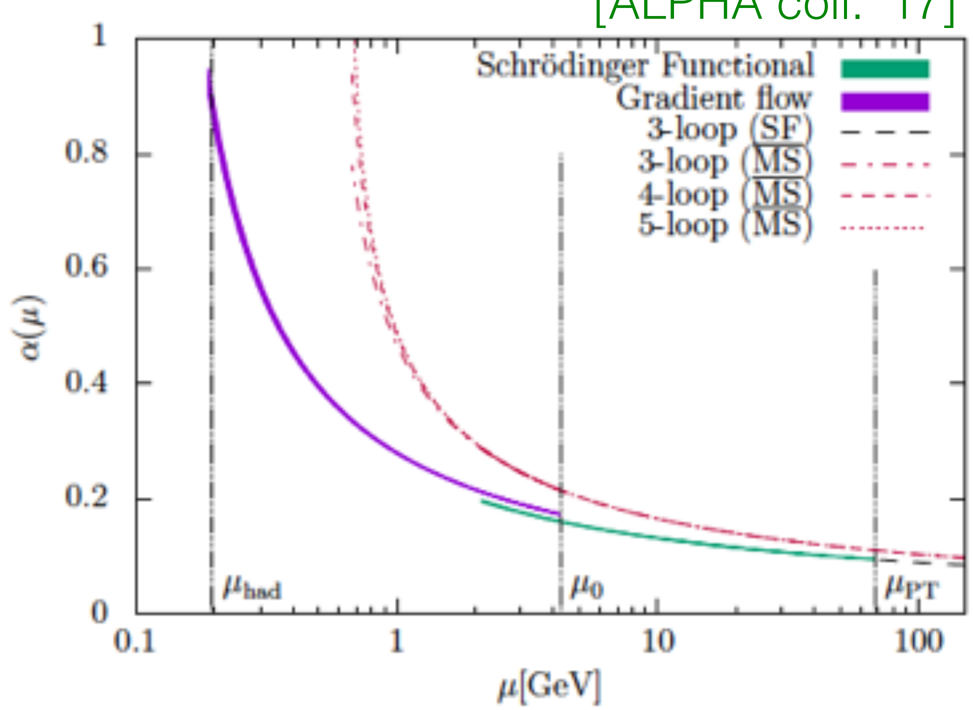
$$\alpha_s(M_Z) = 0.1181 \pm 0.0013(1.1\%) \text{ unweighted}$$

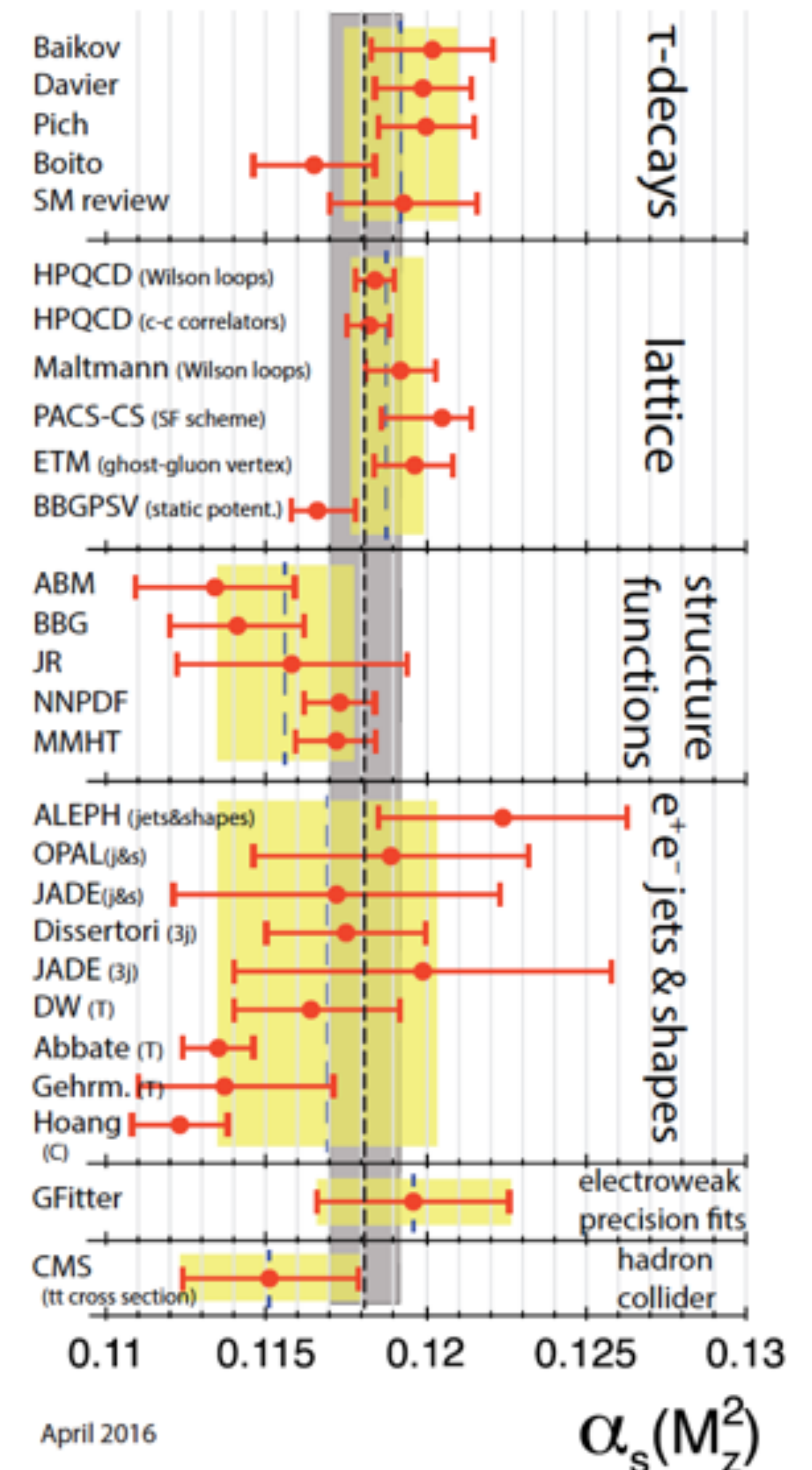
- World Average quotes a ~1% uncertainty
- Some tension with precision extractions from LEP data (event shapes), and some PDFs. Strong hints that these low values are disfavoured (LHC, lattice), but we need to understand what's going on
- Recent determinations agree with WA
  - tt~ cross section: $\alpha_s\,(m_Z) = 0.1177 \begin{array}{l} +0.0034 \\ -0.0036 \end{array}$ [Klijnsma et al. '17]
  - Lattice QCD

    finite-size scaling evolution to PT scales (dominant uncertainty)

    $\alpha^{(5)}_{\overline{\rm MS}}(m_Z) = 0.11852(84)$

[ALPHA coll. '17]





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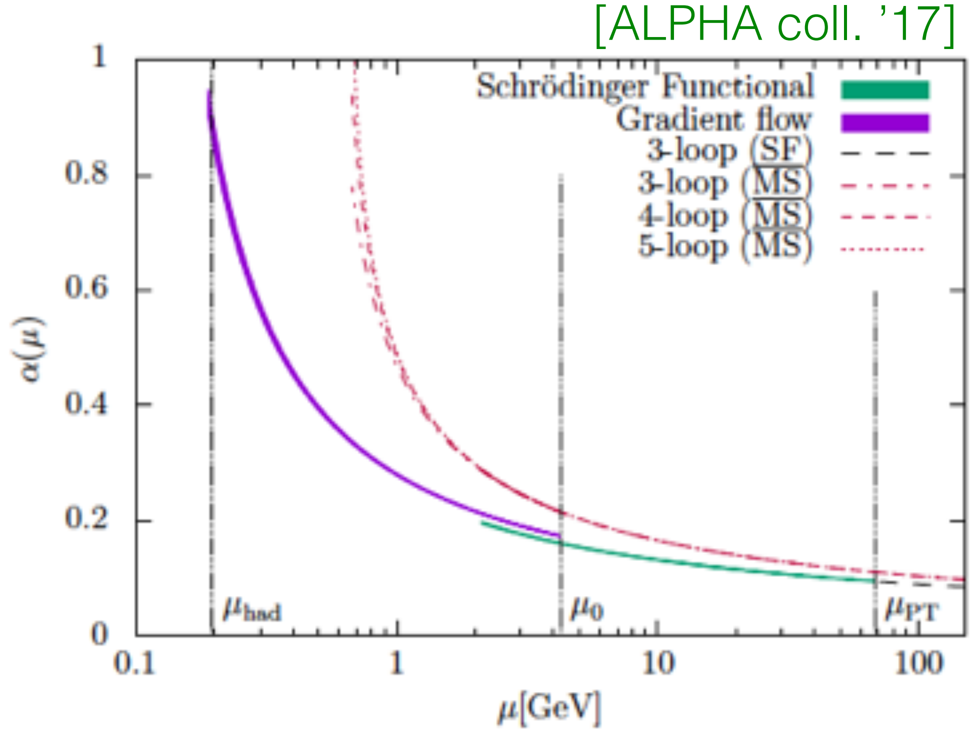

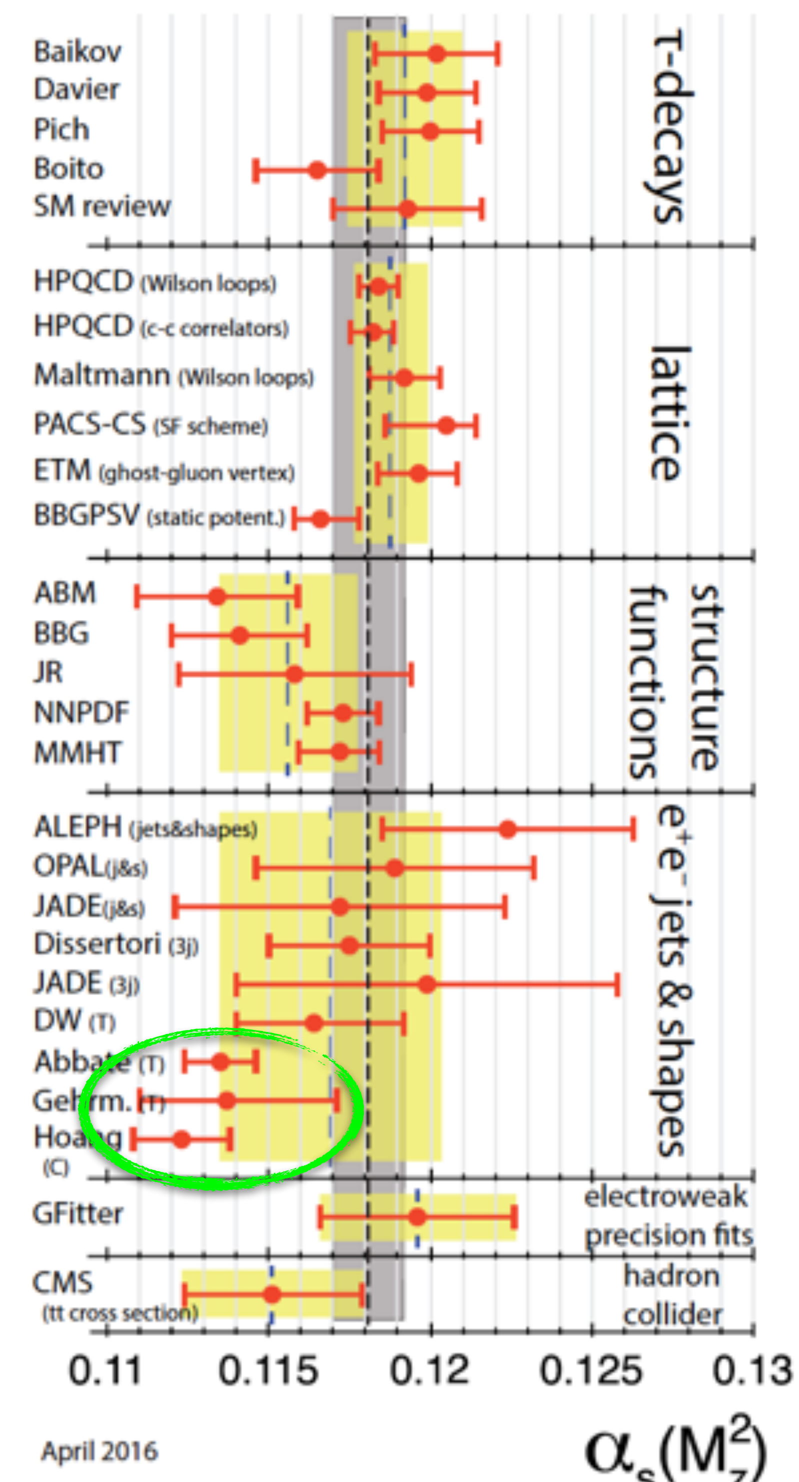

Conclusions

- Experimental precision + sensitivity is demanding a huge theoretical progress

- This, in turn, often leads to new ideas for more sensitive measurements and tools

- Recent progress in the understanding of QCD so far has kept up this incredible pace. Few-percent theoretical accuracy is now a reality for many observables, and already not enough for others

- The full exploitation of future data at the (HL-)LHC will require further advances in all directions, that may go beyond PT (better observables, amplitudes, subtraction, resummations, parton showers, parton densities, EW, non-perturbative modelling,…)

Thank you for your attention