POWER CORRECTIONS FROM MILAN TO LHC

Gavin P. Salam, CERN

Giuseppe Marchesini Memorial Meeting

GGI, Florence, 19 May 2017

A PIVOTAL ARTICLE

set out systematics of power corrections for almost any QCD observable

"Wise Dispersive Method"

NUCLEAR PHYSICS B

Nuclear Physics B 469 (1996) 93–142

Dispersive approach to power-behaved contributions in QCD hard processes *

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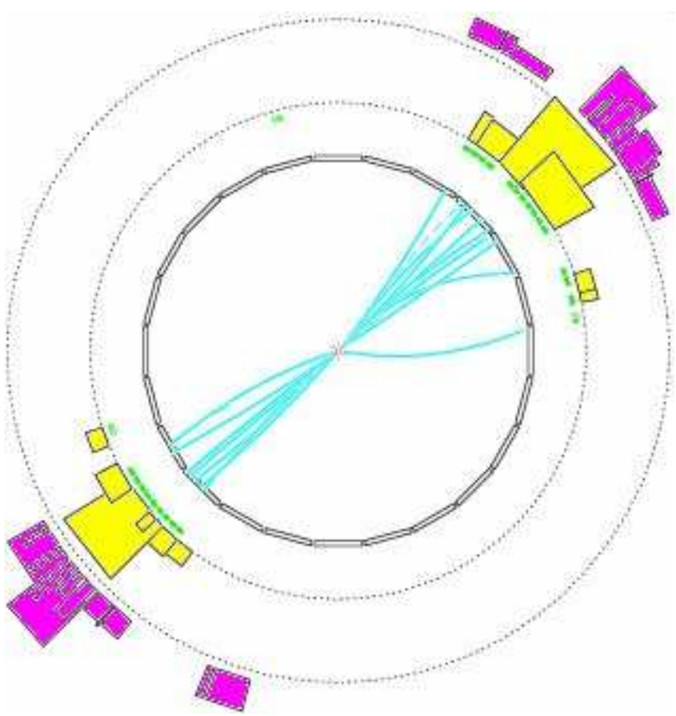
We analyse a wide variety of quark-dominated processes and observables, and show how the power contributions are specified in lowest order by the behaviour of one-loop Feynman diagrams containing a gluon of small virtual mass. We discuss both collinear safe observables (such as the e^+e^- total cross section and τ hadronic width, DIS sum rules, e^+e^- event shape variables and the Drell-Yan K-factor) and collinear divergent quantities (such as DIS structure functions, e^+e^- fragmentation functions and the Drell-Yan cross section).

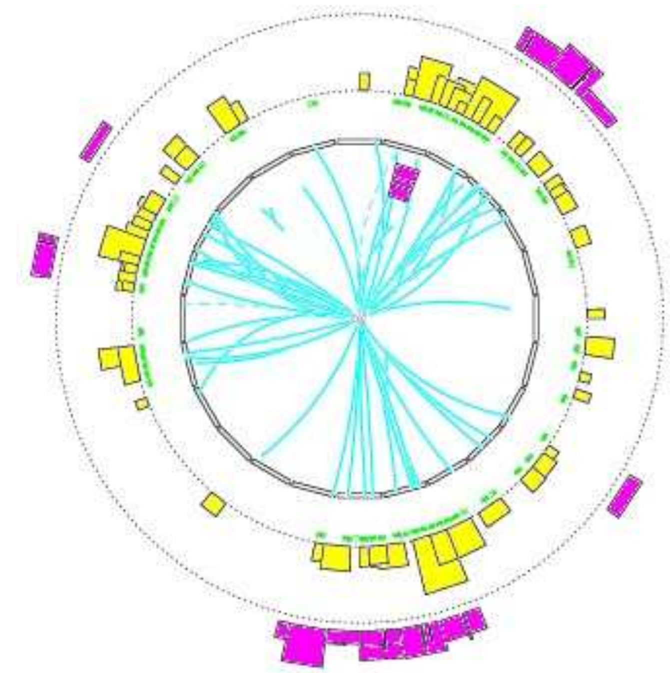
Testing place: event shapes

Thrust:

$$T = \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_i . \vec{n}_T|}{\sum_i |\vec{p}_i|} ,$$



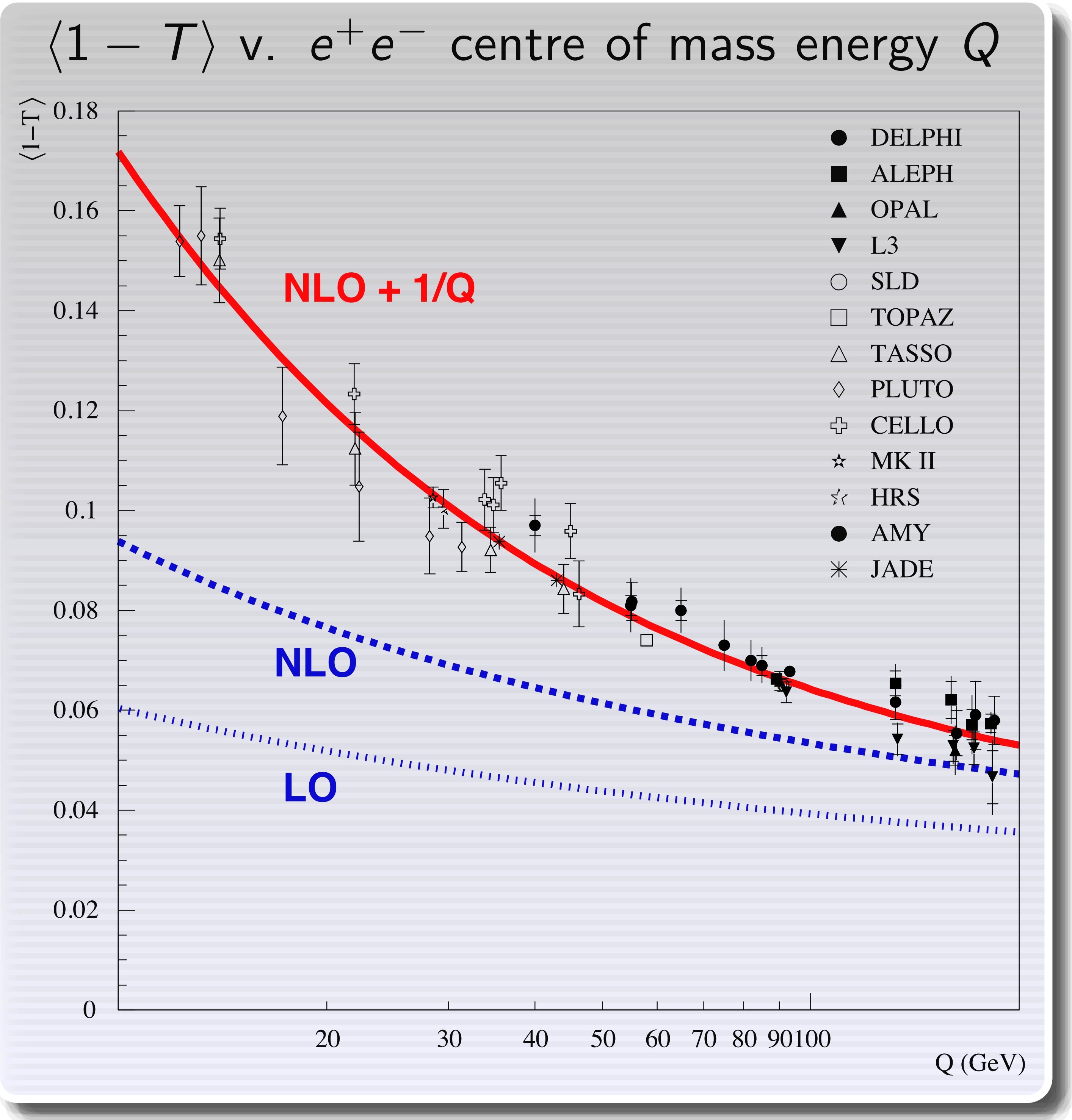
2-jet event: $T \simeq 1$



3-jet event: $T \simeq 2/3$

There exist many other measures of aspects of the shape: Thrust-Major, C-parameter, broadening, heavy-jet mass, jet-resolution parameters,. . .

Power corrections matter for event shapes

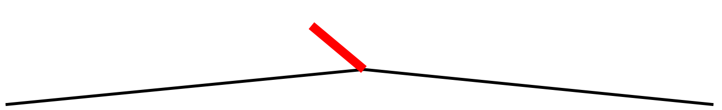


Schematic picture:

$$\langle 1-T\rangle \simeq \underbrace{A\alpha_s}_{LO} + \underbrace{B\alpha_s^2}_{NLO} + c_T\frac{\alpha_0}{Q}$$

several papers, notably Dokshitzer, Marchesini & Webber '95

- α_0 is non-perturbative but should be **universal**
- c_T can be **predicted** through a calculation using a single massive-gluon emission



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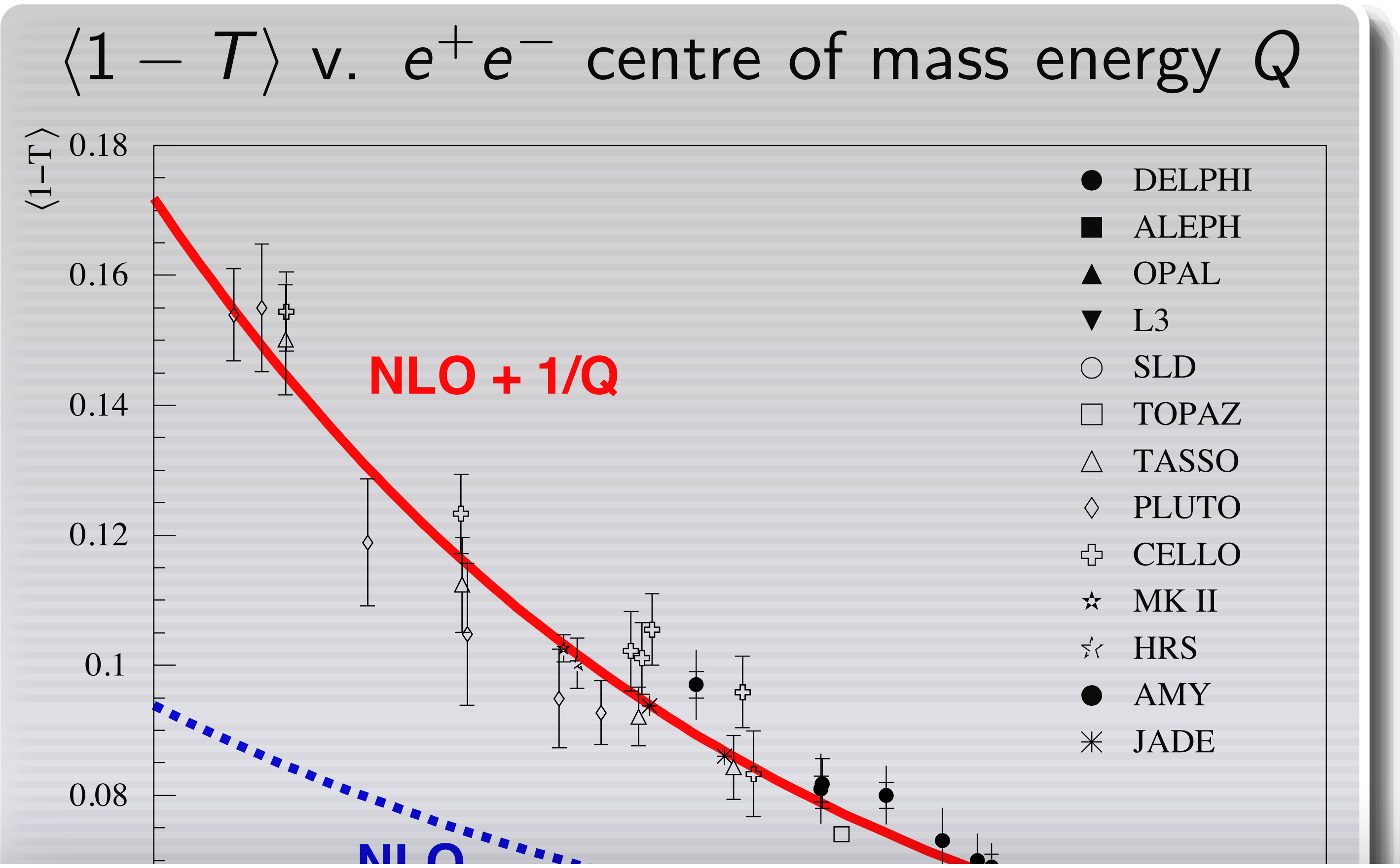

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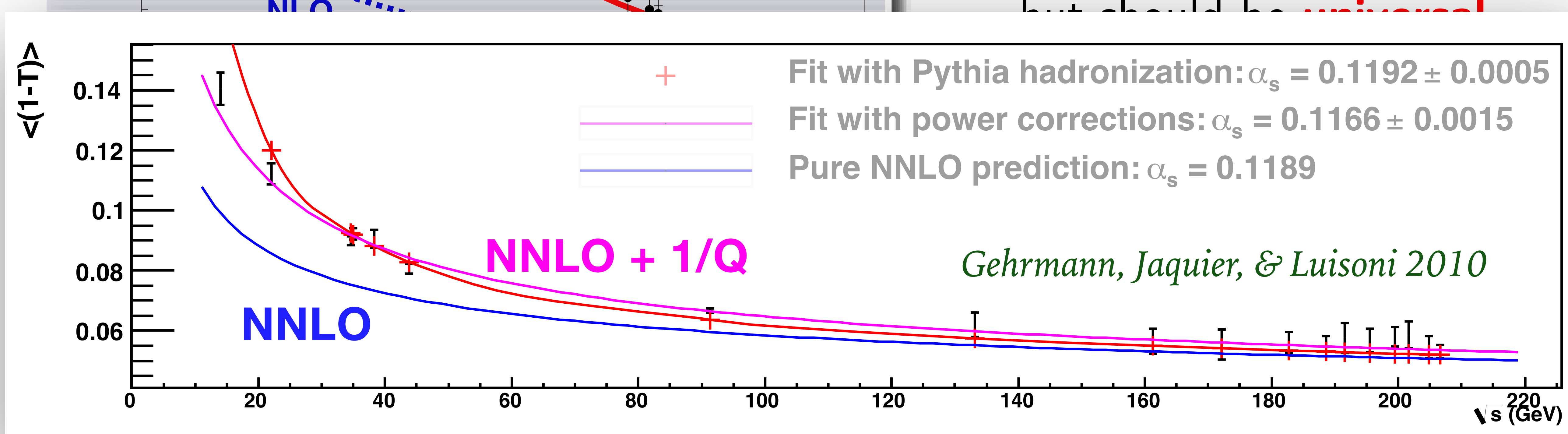
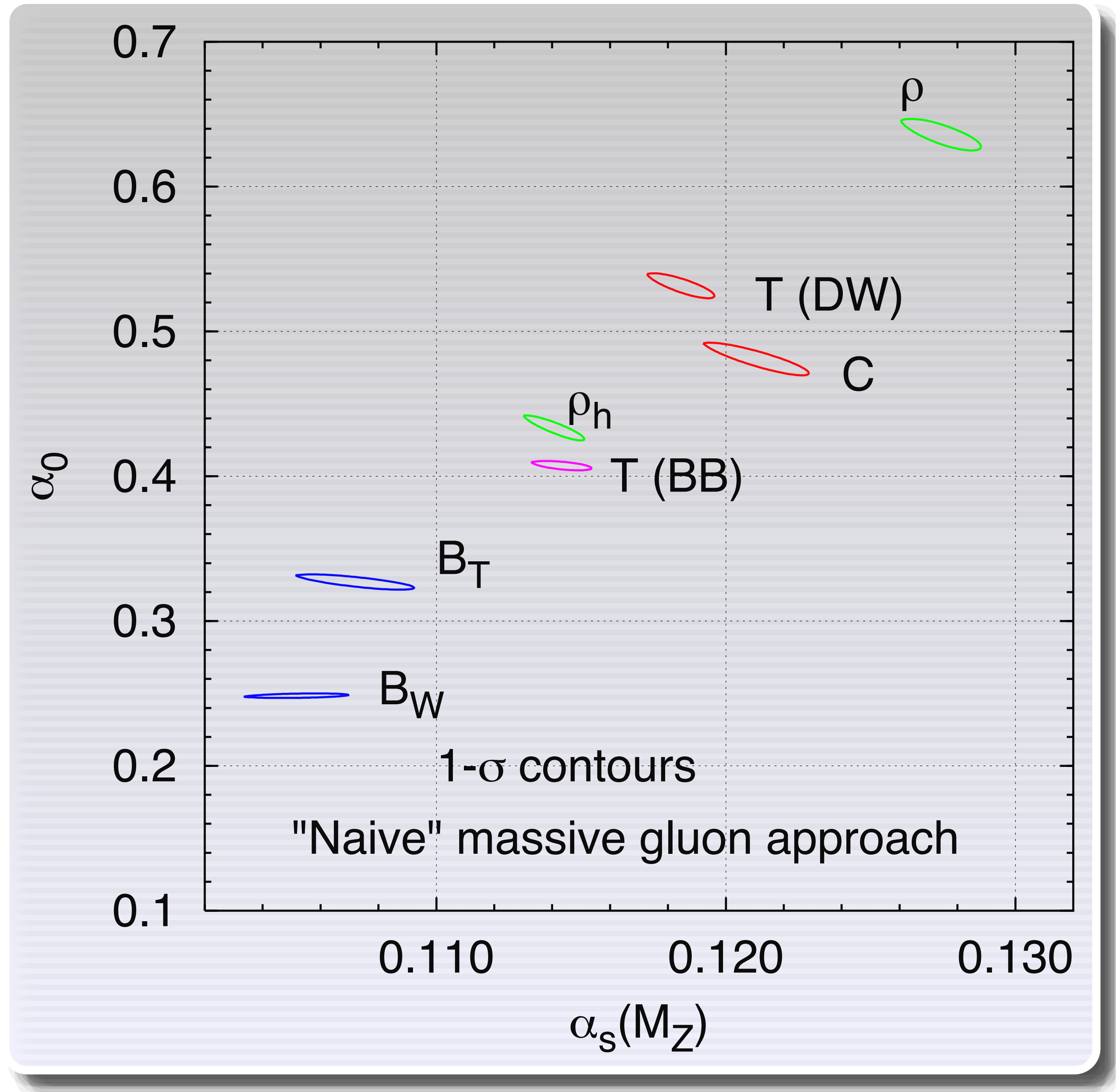
- α_0 is non-perturbative



universality of α_0 v. data (ellipses should all coincide...)

You could legitimately ask the question:

Given the complexity of real hadronic events, could dominant non-perturbative physics truly be determined from just a single-gluon calculation?



The data clearly say something is wrong with this assumption

initially, most clearly pointed out by the JADE collaboration

A first key result with Pino (+Yuri & A. Lucenti)

Idea of "wise dispersive method": probe non-perturbative effects by integrating over virtuality of an infrared gluon.

But such a "massive" gluon will necessarily decay to two gluons or $q\bar{q}$ that go in different directions.

issue raised: Nason & Seymour '95

So: explicitly include the calculation of that splitting.
A very simple result: for thrust, non-perturbative correction simply gets rescaled by a numerical "Milan" factor

$$\mathcal{M} \simeq 1.49$$

Matrix elements from Berends and Giele '88 + Dokshitzer, Marchesini & Oriani '92

$\mathcal{M}$ first calculated for thrust: Dokshitzer, Lucenti, Marchesini & GPS '97

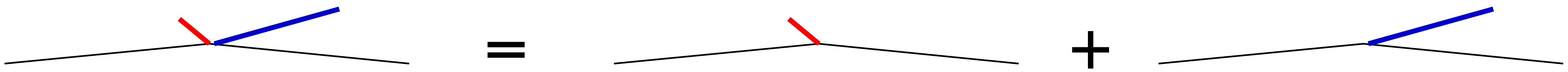
n_f piece for σ_L: Beneke, Braun & Magnea '97

calculation fixed: Dasgupta, Magnea & Smye '99

2nd key observation with Pino et al.

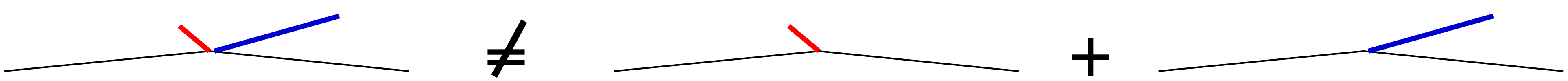
There are two classes of event shape

1) those that are a **linear** combination of contributions from individual emissions $i = 1 \ldots n$



$$\left(\text{e.g.} \quad 1 - T \simeq \sum_{i=1}^{n} p_{ti} e^{-|\eta_i|}\right)$$

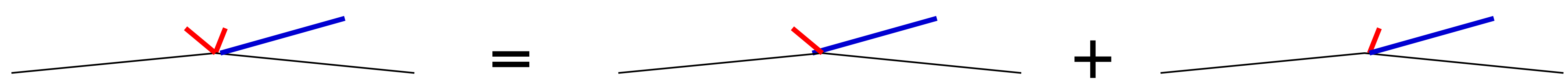
2) those that are **non-linear**, e.g. B_W, B_T, ρ_h



for the latter, the non-perturbative correction cannot possibly be deduced just from a one-gluon calculation (2-gluon $\mathcal{M}$ diverges)

3rd key observation with Pino et al

In the presence of **perturbative emissions** with $p_t \gg \Lambda_{QCD}$, then all the non-linear event shapes turn out to have an "emergent" linearity for **non-perturbative emissions** at scales $\sim \Lambda_{QCD}$



➥ non-perturbative (NP) effects can still be deduced from the effect of a single non-perturbative gluon, but its impact must be determined by averaging over perturbative configurations

$$\langle \mathrm{NP} \rangle \simeq \int [d\Phi_{pert.}] \, |M^2(pert.)| \times \mathrm{NP}(pert.)$$

first such observation, for ρ_h: Akhoury & Zakharov '95

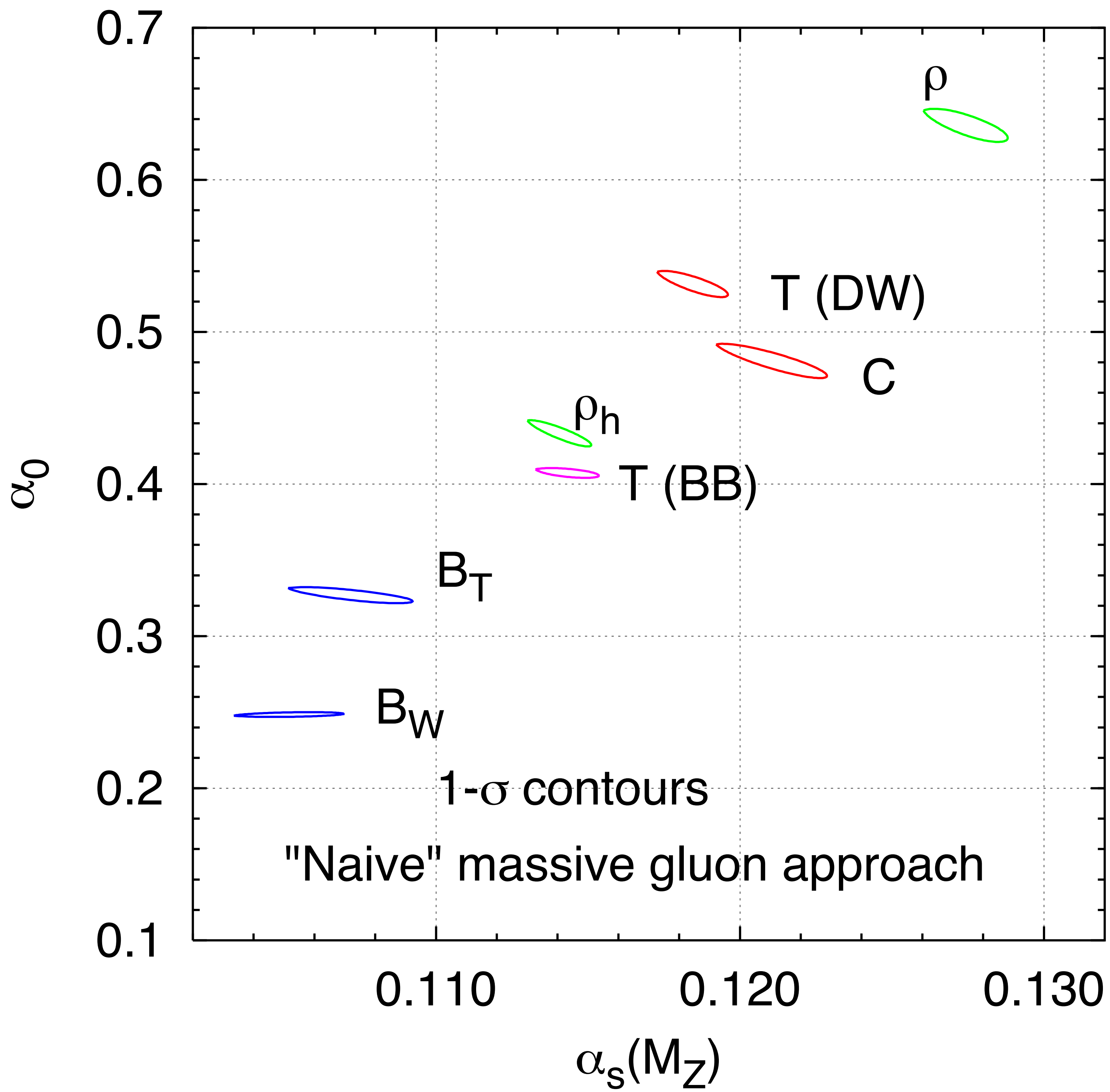
universality of "Milan" factor in e^+e^-: Dokshitzer, Marchesini, Lucenti & GPS '98

PT and NP effects together in jet broadenings: Dokshitzer, Marchesini & GPS '98

universality of "Milan" factor in DIS: Dasgupta & Webber '98

cross-talk between shape functions: Korchemsky & Tafat '00

comparing improvements to data



Original results for fits of α_s and the non-perturbative parameter α_s.

↓

Including all the "DLMS" improvements

Pino et al '97-98

↓

Taking care not just of gluon masses, but also hadron masses

GPS & Wicke '01

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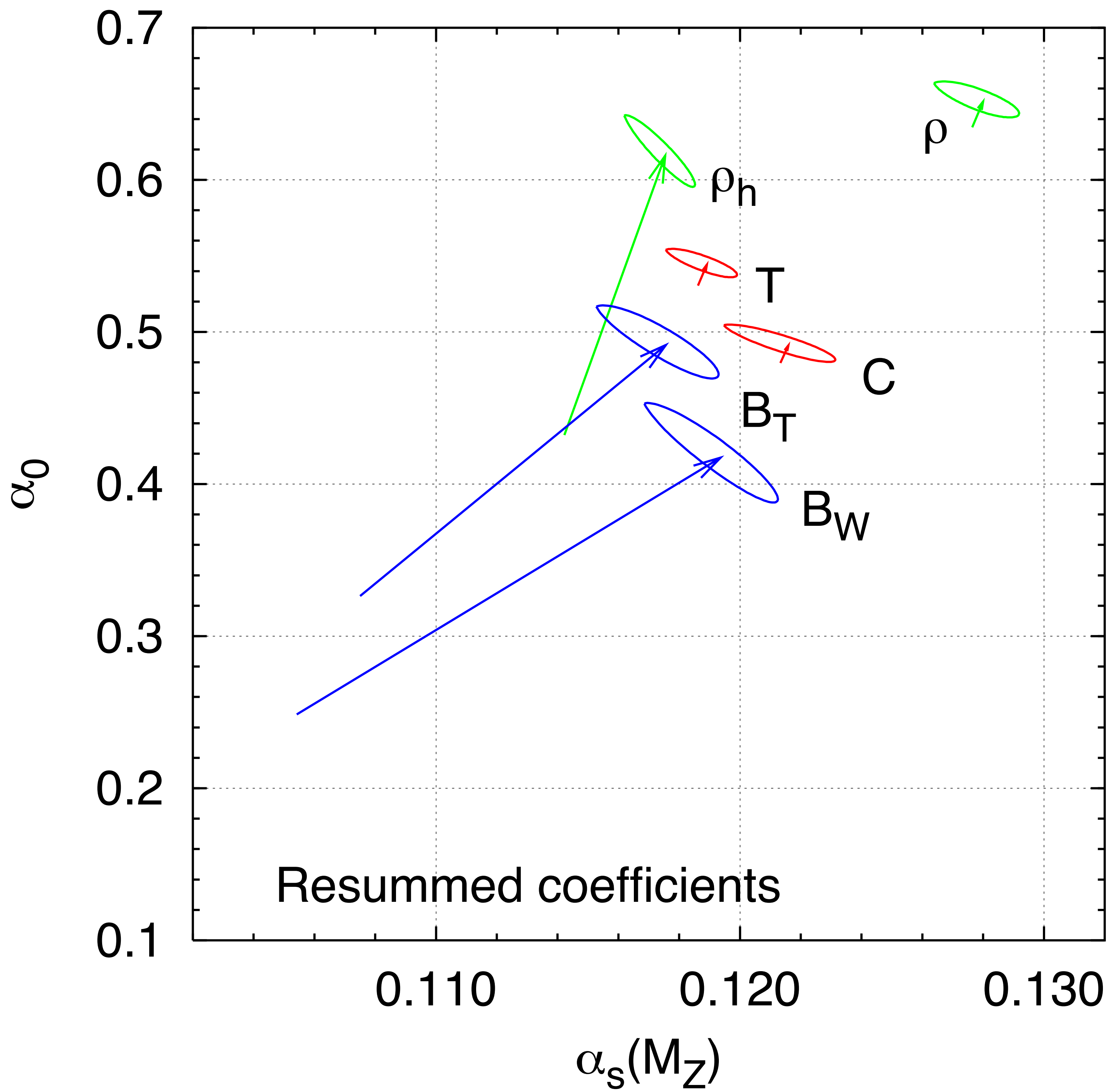

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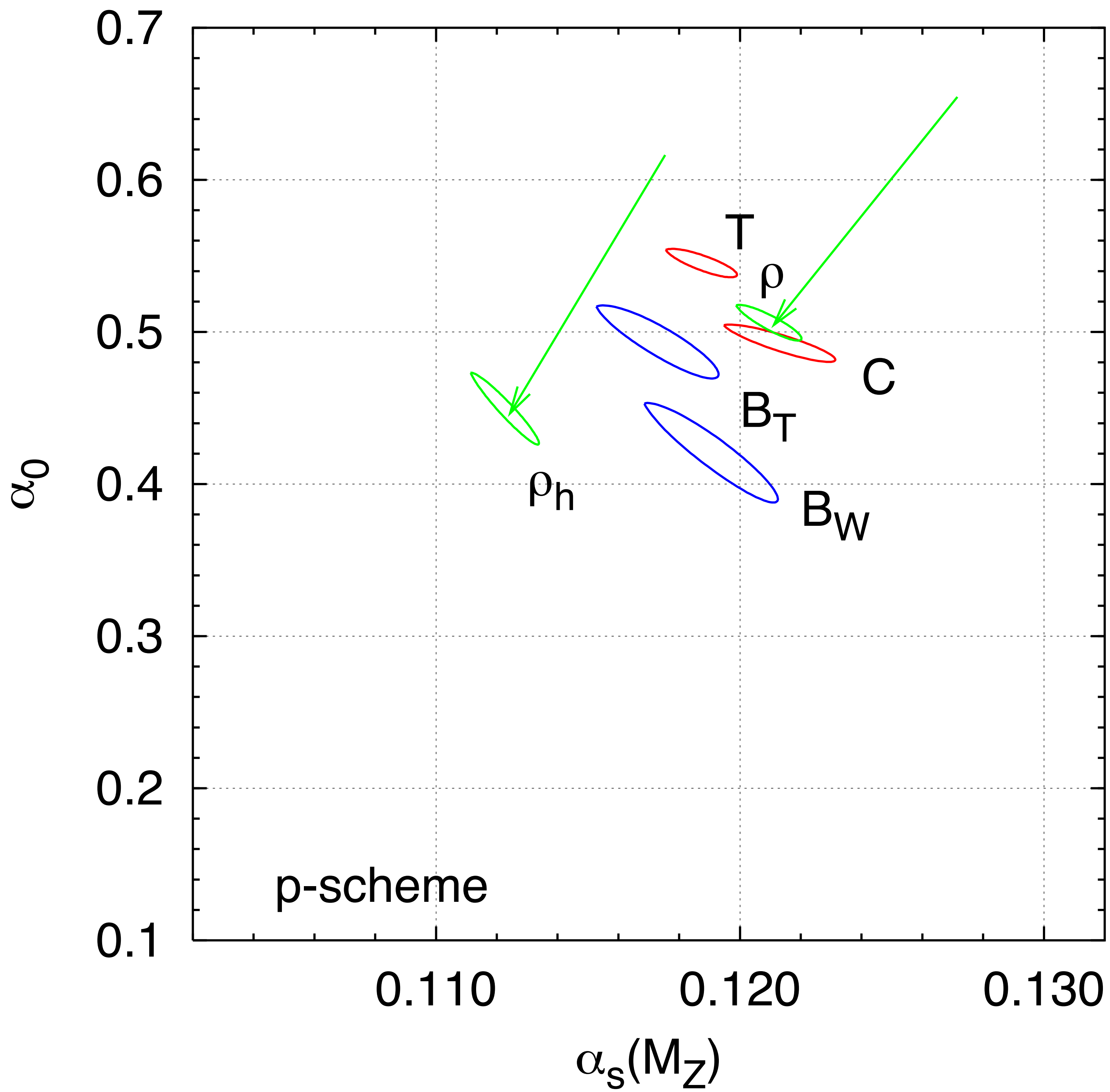

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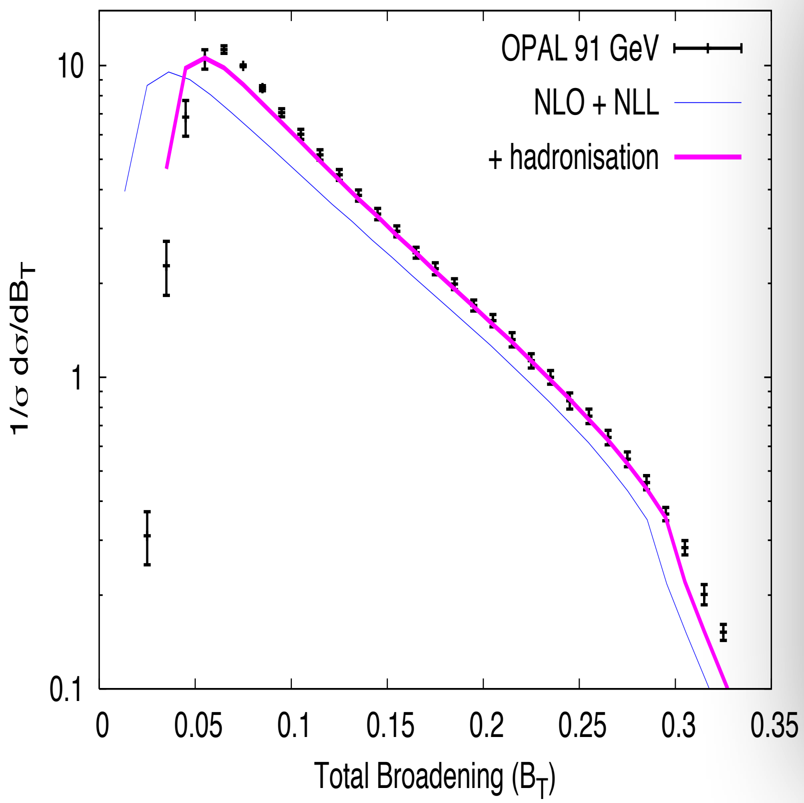
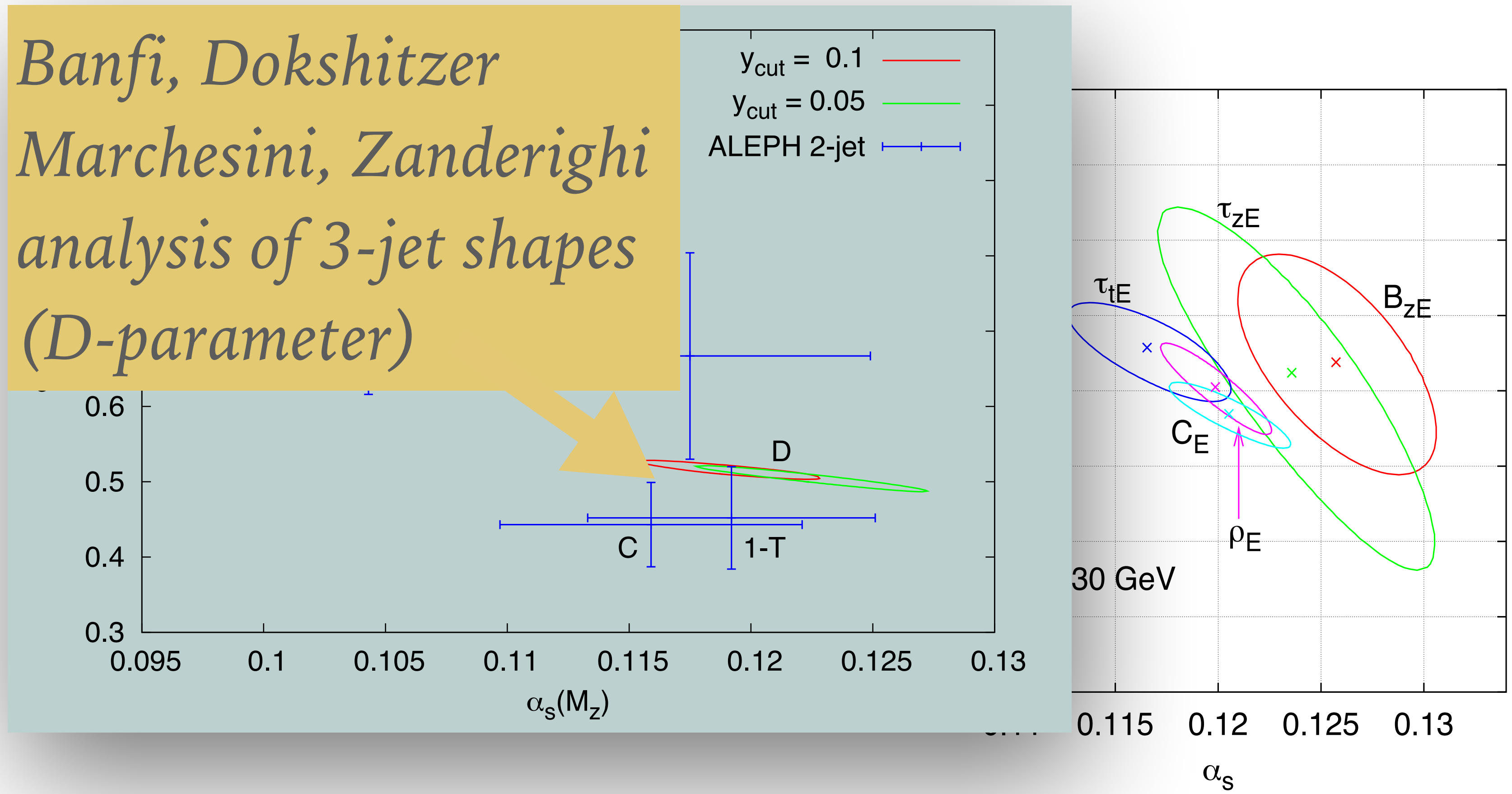
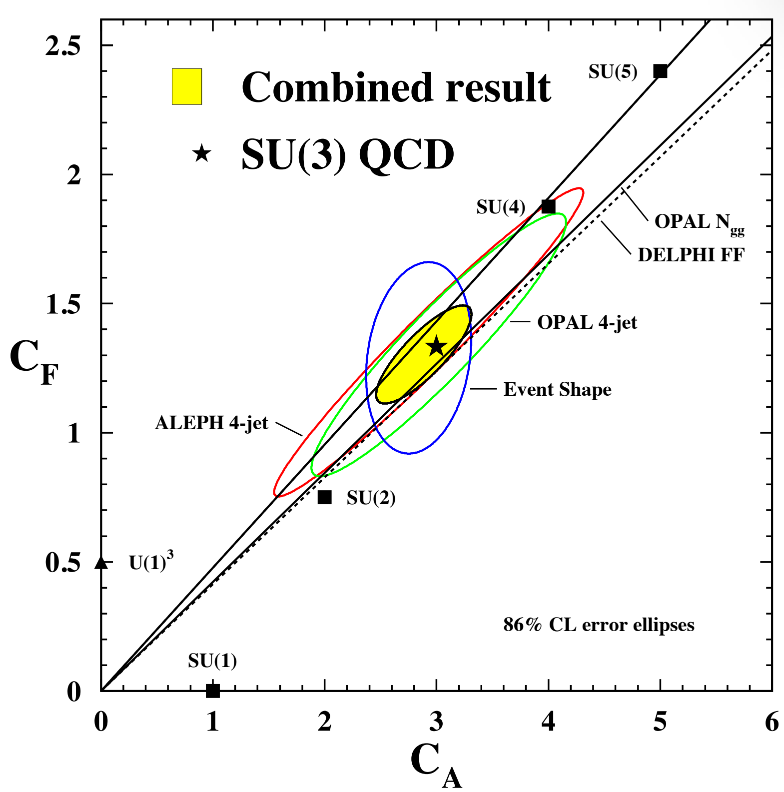
many other investigations







Overall, many analyses in late '90s and early '00s paint a picture of general success of the simple physical idea of probing NP physics with perturbative tools.

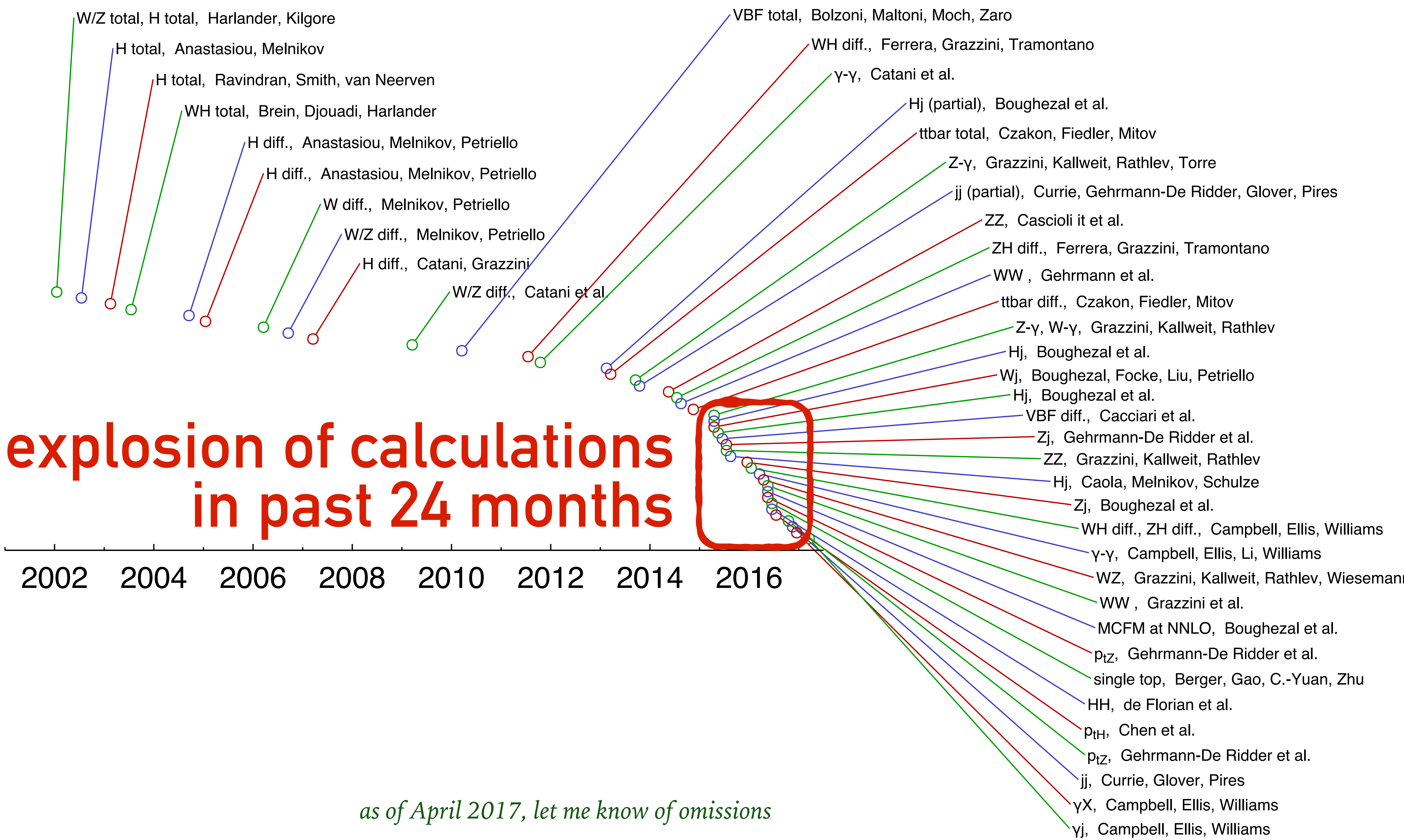
Even if there are "corners" where it doesn't work as well as we'd like. . .

NOW MOVE FORWARDS 15–20 YEARS

many NNLO calculations have become available (for e^+e^-, DIS and pp)

LHC physics is reaching high precision, not just for QCD physics, but also e.g. today for "dark-matter" searches, & in the future for Higgs physics

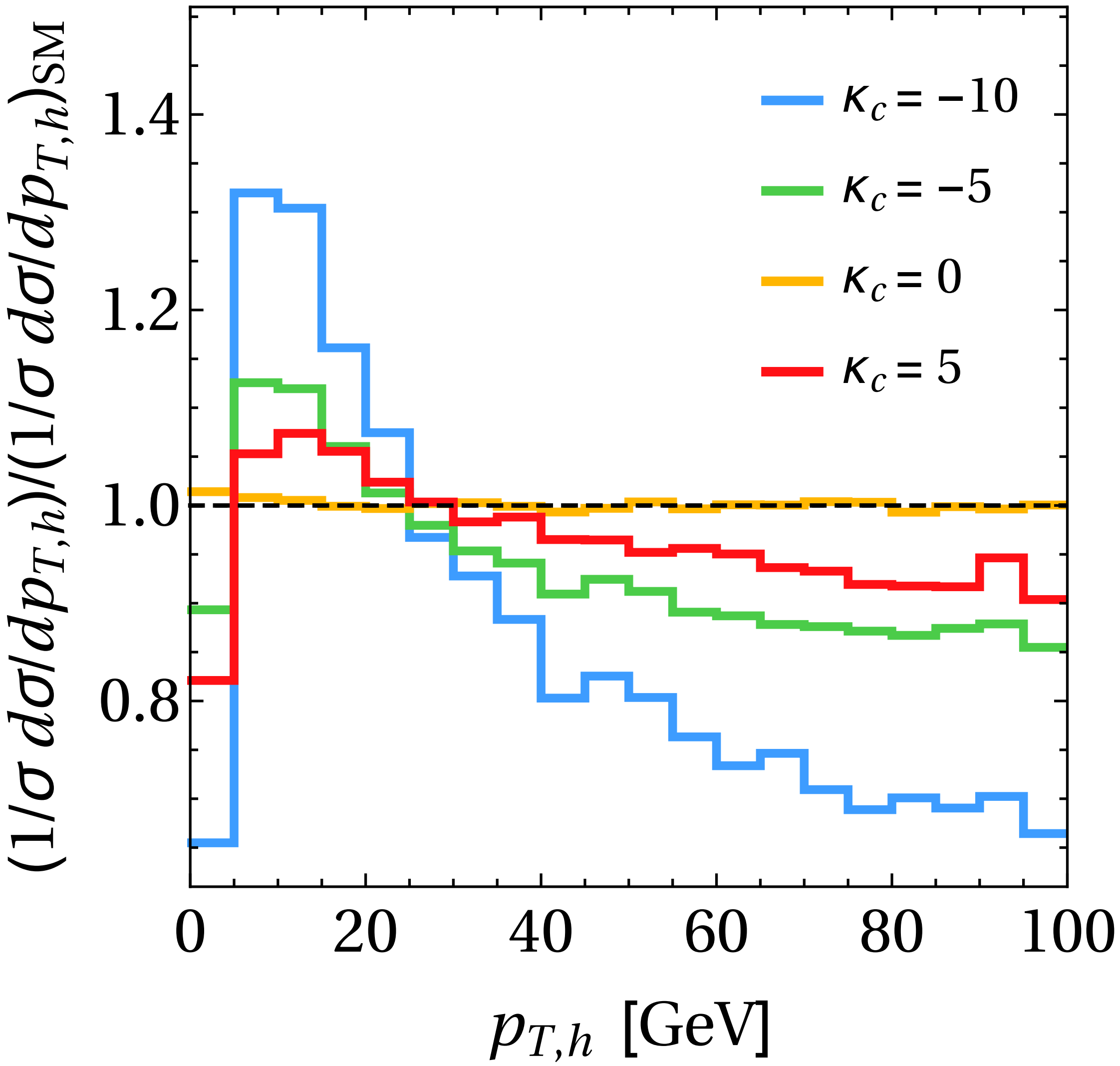
NNLO hadron-collider calculations v. time



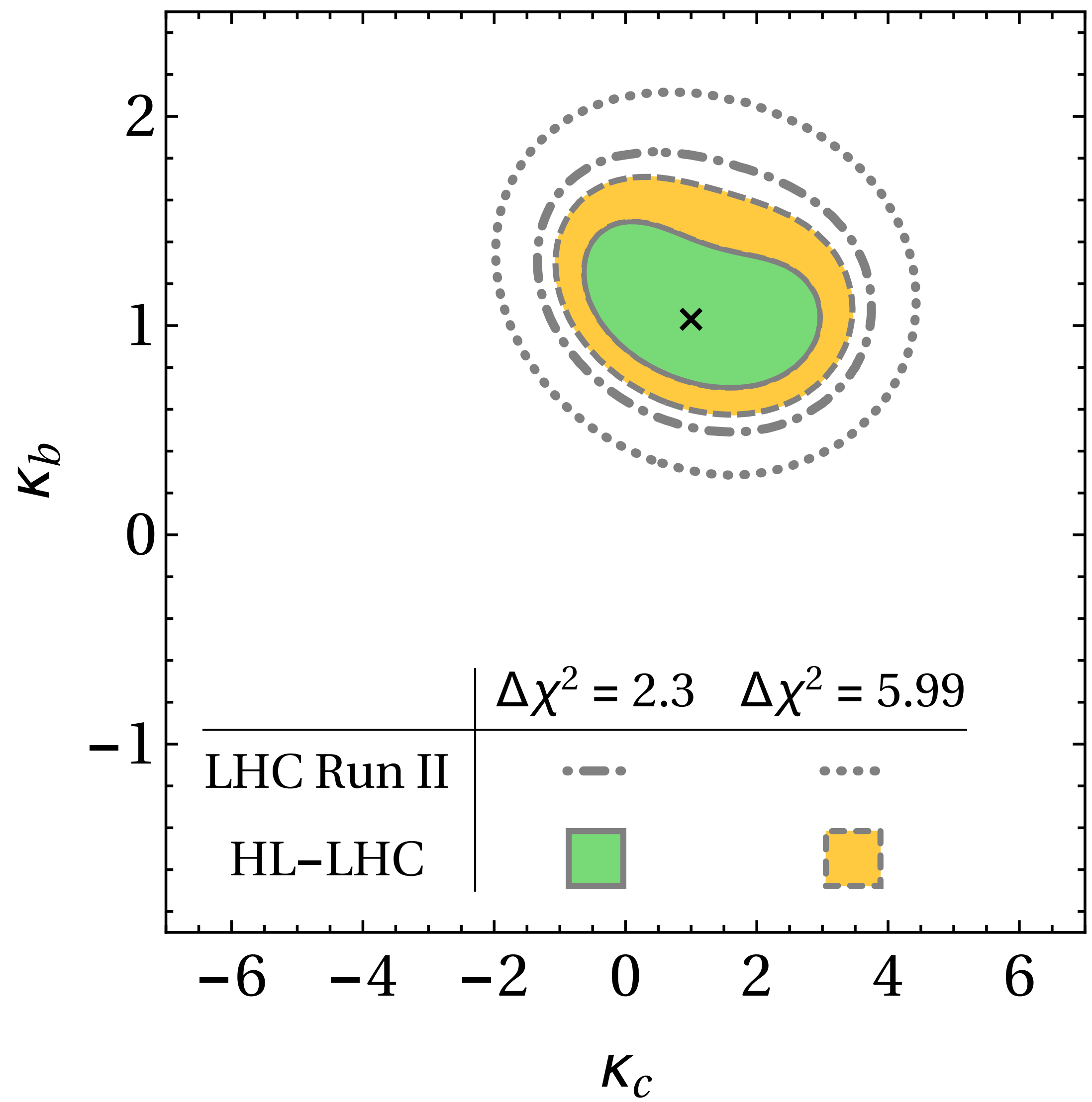
as of April 2017, let me know of omissions

indirect constraints on Hcc coupling

impact of modified Hcc coupling on Higgs+jet pT



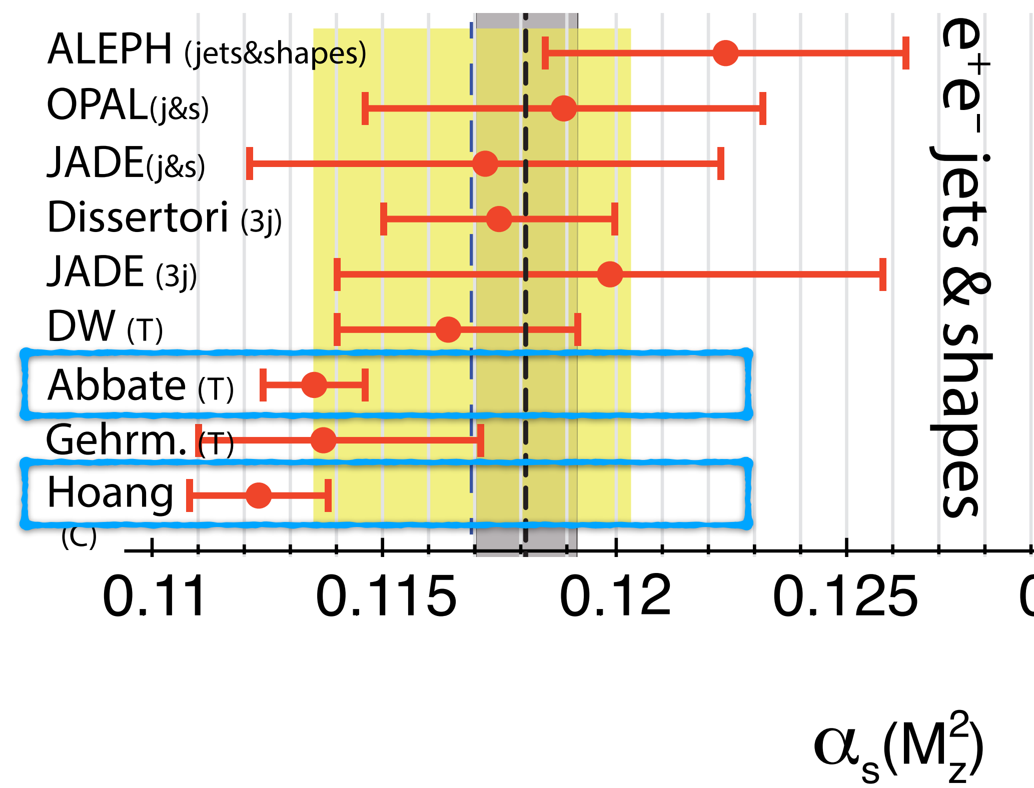
joint limits on κ_c & κ_b @ HL-LHC



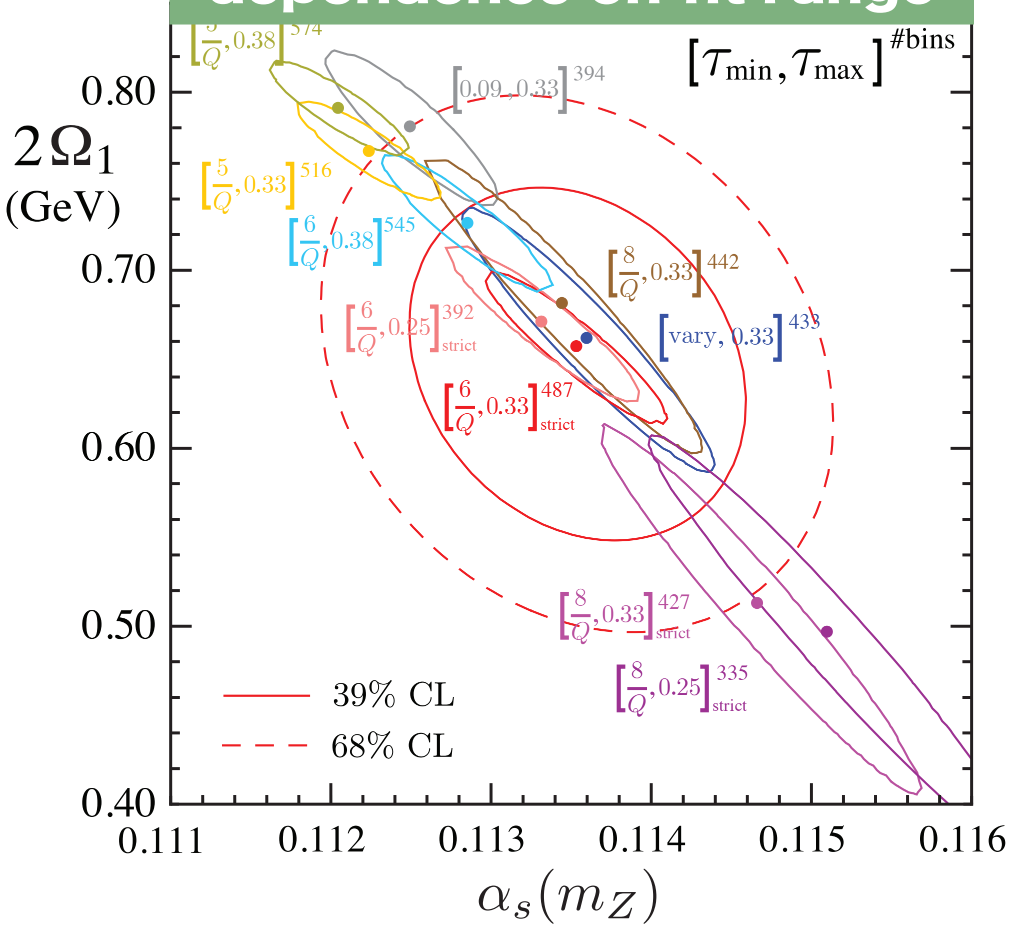
Fady Bishara, Ulrich Haisch, Pier Francesco Monni and Emanuele Re, arXiv:1606.09253
see also Y. Soreq, H. X. Zhu, and J. Zupan, JHEP 12, 045 (2016), 1606.09621

Extracting α_s from e+e- event shapes and jet rates

- Two "best" determinations are from same group
  (Hoang et al, 1006.3080,1501.04111)
  $\alpha_s(M_Z) = 0.1135 \pm 0.0010$ (0.9%) [thrust]
  $\alpha_s(M_Z) = 0.1123 \pm 0.0015$ (1.3%) [C-parameter]
- Similar result from Gehrmann, Luisoni & Monni (1210.6945)
  $\alpha_s(M_Z) = 0.1131 \pm 0.0028$ (2.5%) [thrust]
- lattice:
  $\alpha_s(M_Z) = 0.1183 \pm 0.0007$ (0.6%) [HPQCD]
  $\alpha_s(M_Z) = 0.1186 \pm 0.0008$ (0.7%) [ALPHA prelim.]



dependence on fit range

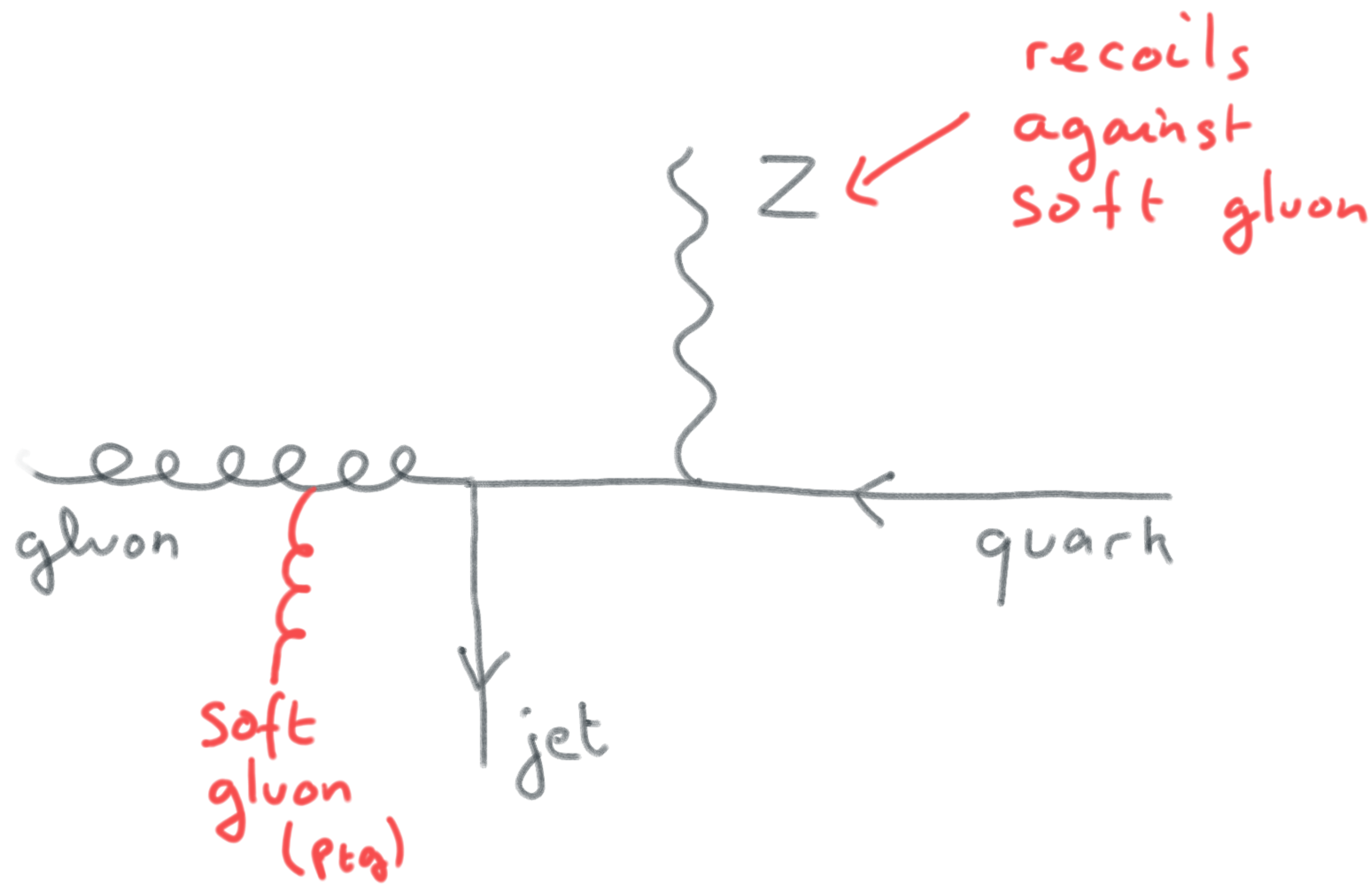


thrust & "best" lattice are 4-σ apart

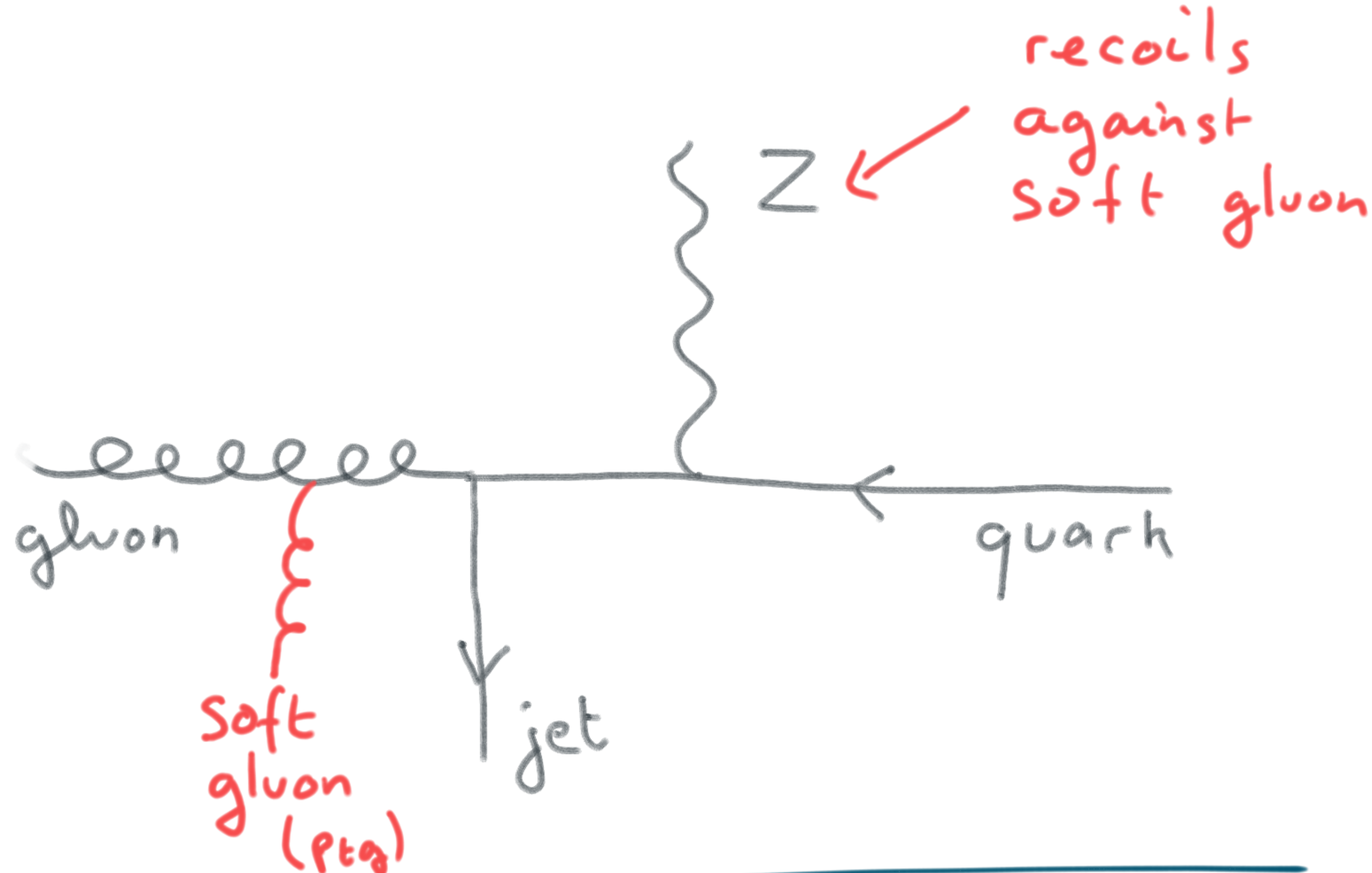
Comments:

- thrust & C-parameter are highly correlated observables
- Analysis valid far from 3-jet region, but not too deep into 2-jet region — at LEP, not clear how much of distribution satisfies this requirement
- **thrust fit shows noticeable sensitivity to fit region** (C-parameter doesn't)

Non-perturbative effects in Z p_T — (issues hold also for Higgs p_T)



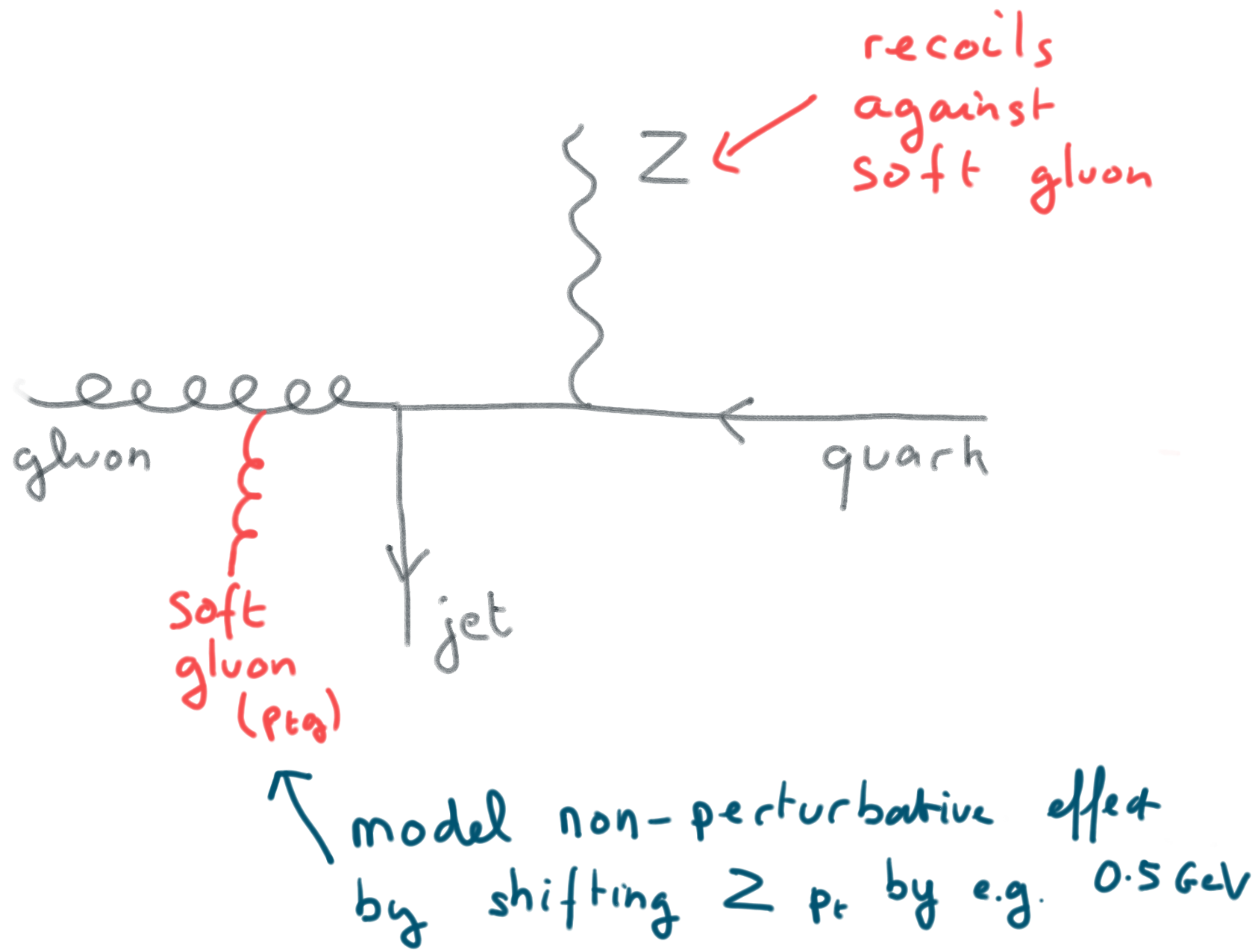
Non-perturbative effects in Z p_T



$$\text{recoil} \sim \int_0 \frac{dp_{tg}}{p_{tg}} \alpha_s(p_{tg})$$

integral over low p_t emissions is non-perturbative

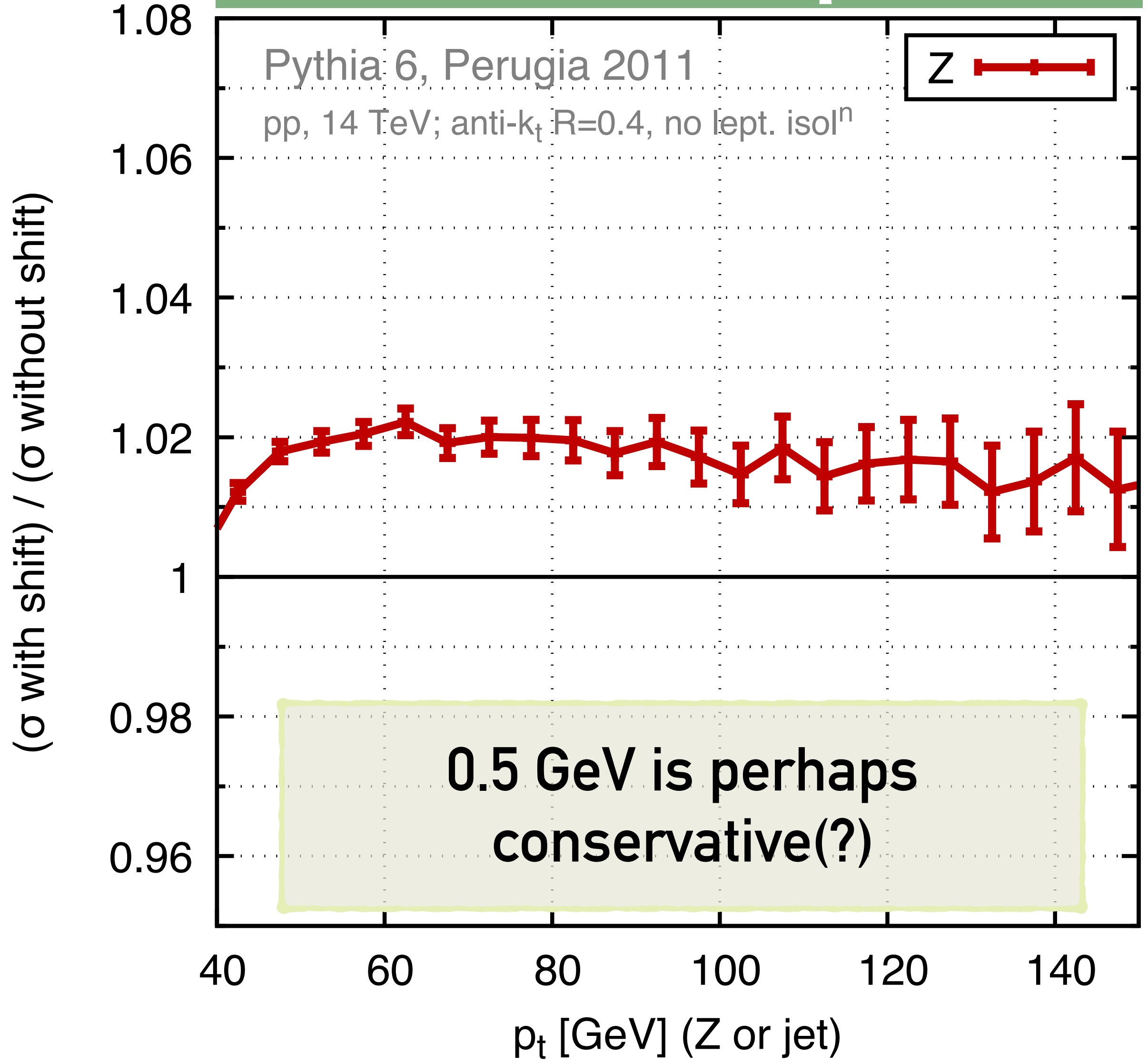
Non-perturbative effects in Z p_T



Non-perturbative effects in Z p_T

- Inclusive Z cross section should have $\sim\Lambda^2/M^2$ corrections ($\sim10^{-4}$?)
- Z p_T is **not inclusive** so corrections can be $\sim\Lambda/M$.
- Size of effect can't be probed by turning MC hadronisation on/off [maybe by modifying underlying MC parameters?]
- Shifting Z p_T by a finite amount illustrates what could happen

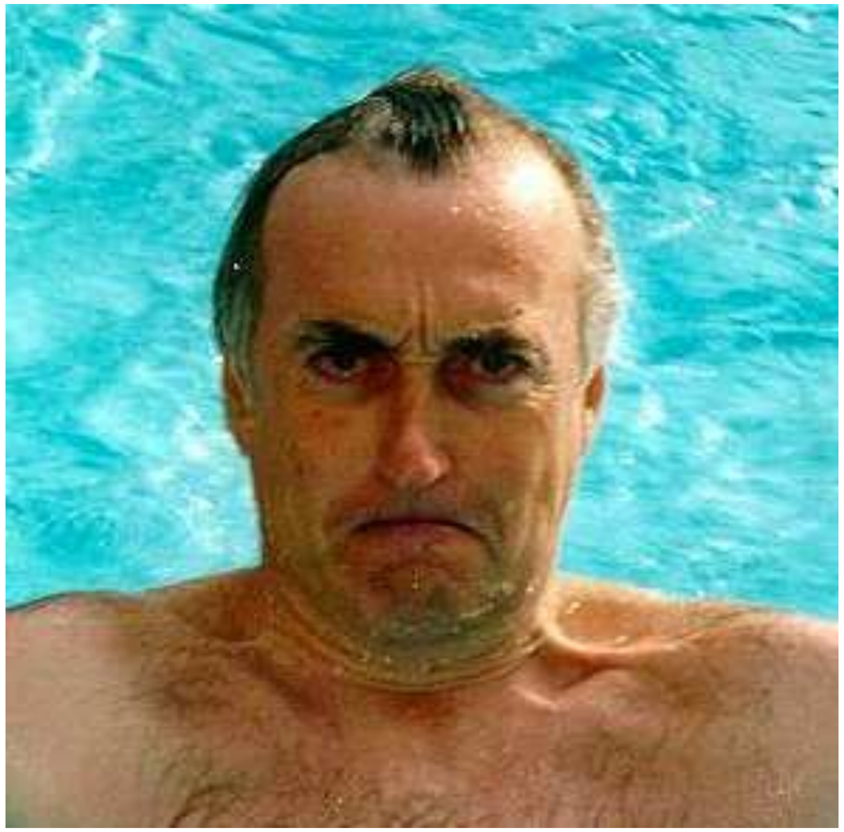
impact of 0.5 GeV shift of Z p_T



A conceptually similar problem is present for the W momentum in top decays

This is just one of several fun physics topics that were pushed forwards in the late '90s with Pino in Milan.

small x, resummations were others



Pino wrote $\sim$ 15 articles with the students and postdocs then (including Banfi, Dasgupta, GPS, Smye, Zanderighi)

Many of the collaborations that formed between them then have continued to this day, easily having produced another $\sim$ ~~15~~ **24** articles.

EXTRAS

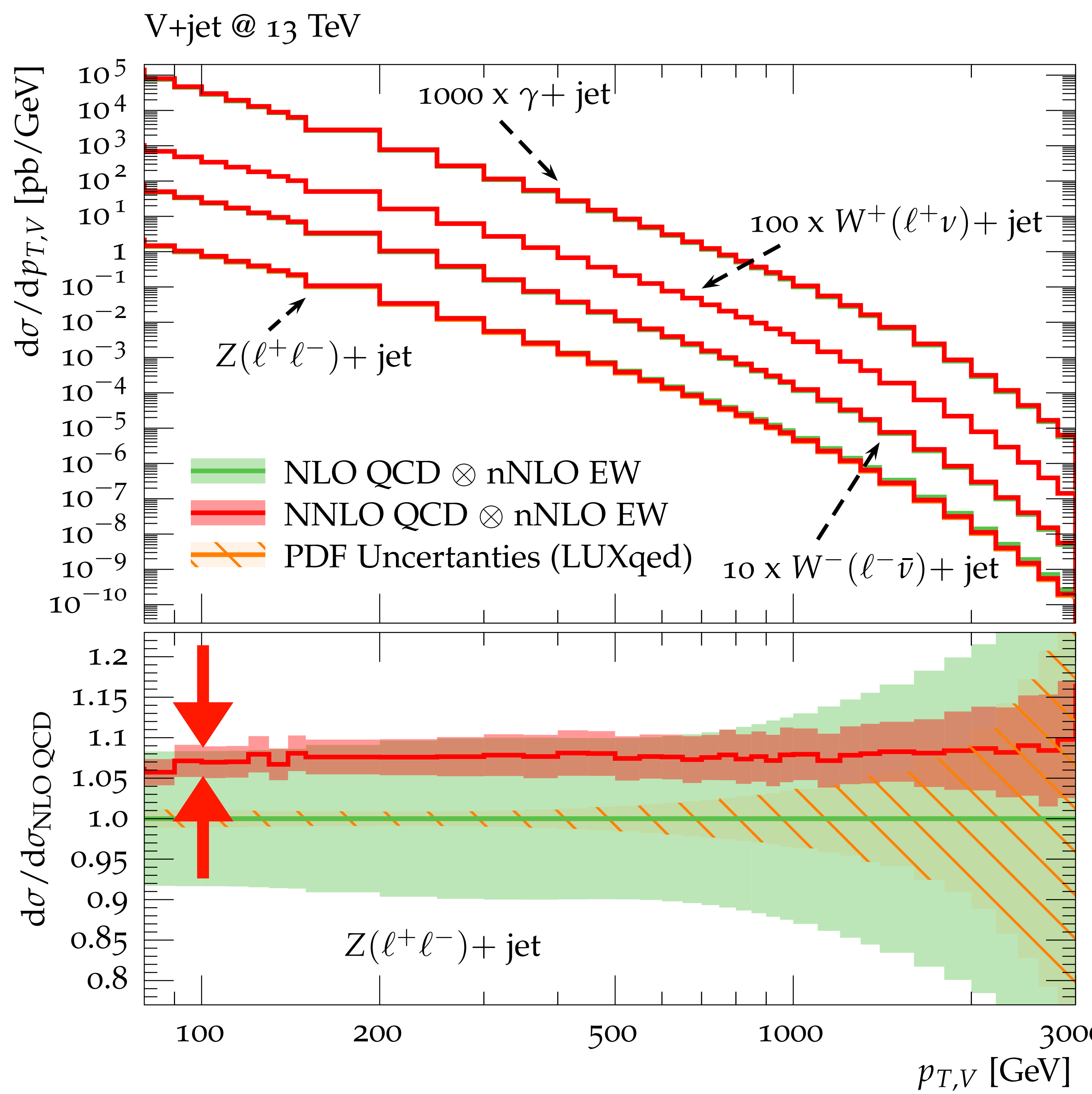
LHC PRECISION: PERTURBATION THEORY

Z+jet process is main background for LHC dark-matter searches.

And powerful input for PDF fits.

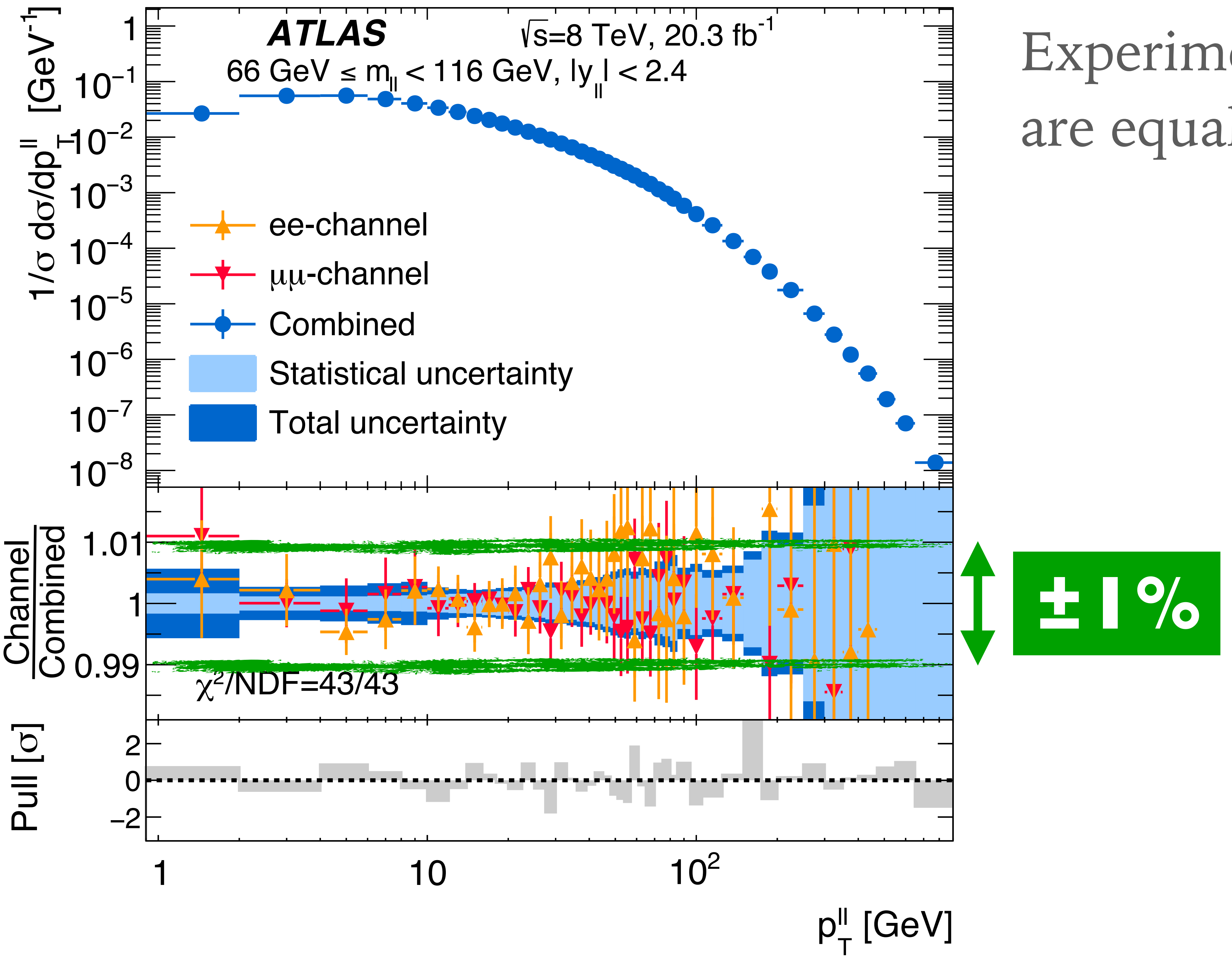
Perturbative results are very precise…

±2%



Lindert, Pozzorini et al, 1705.04664

LHC PRECISION: EXPERIMENT

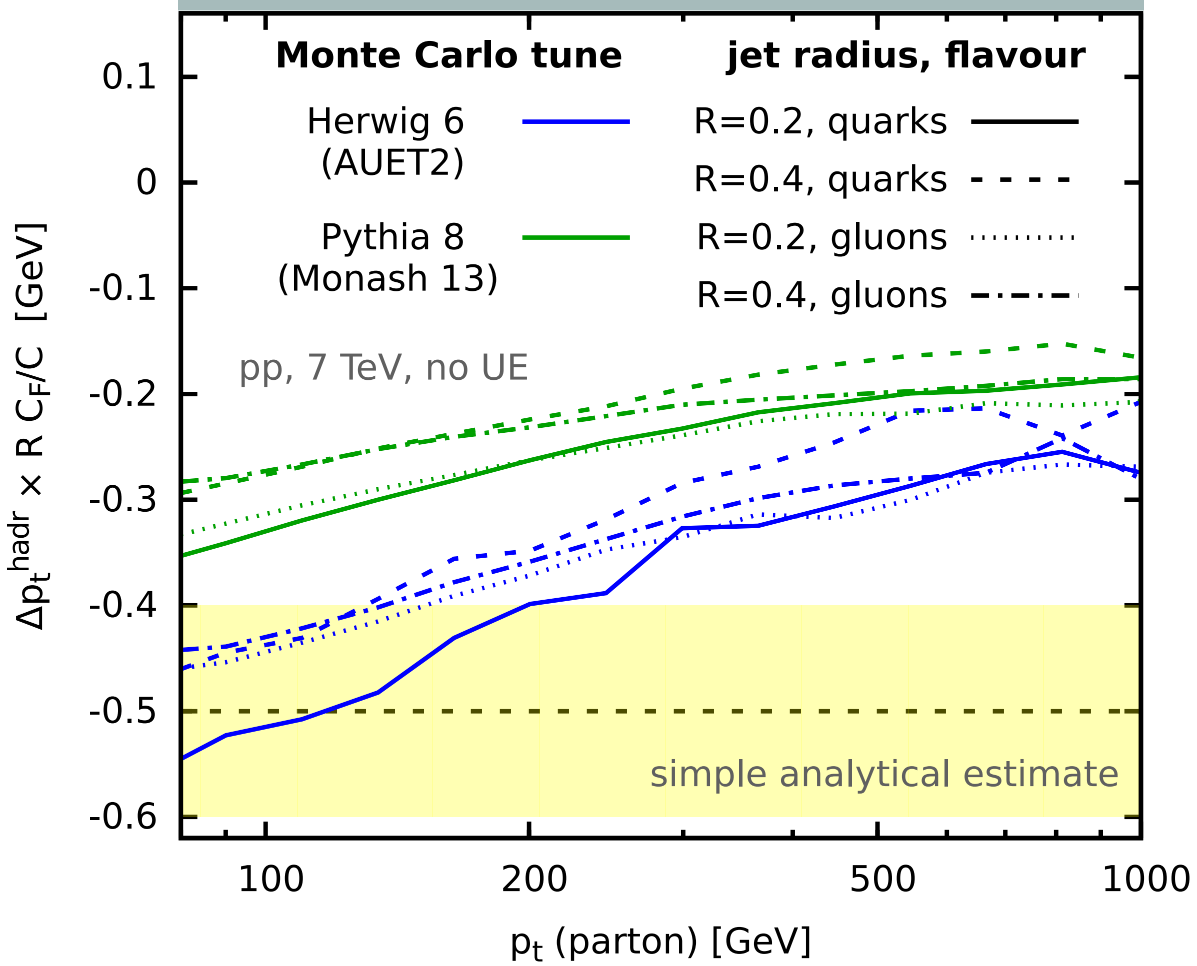


Experimental results are equally precise.

REMARKS

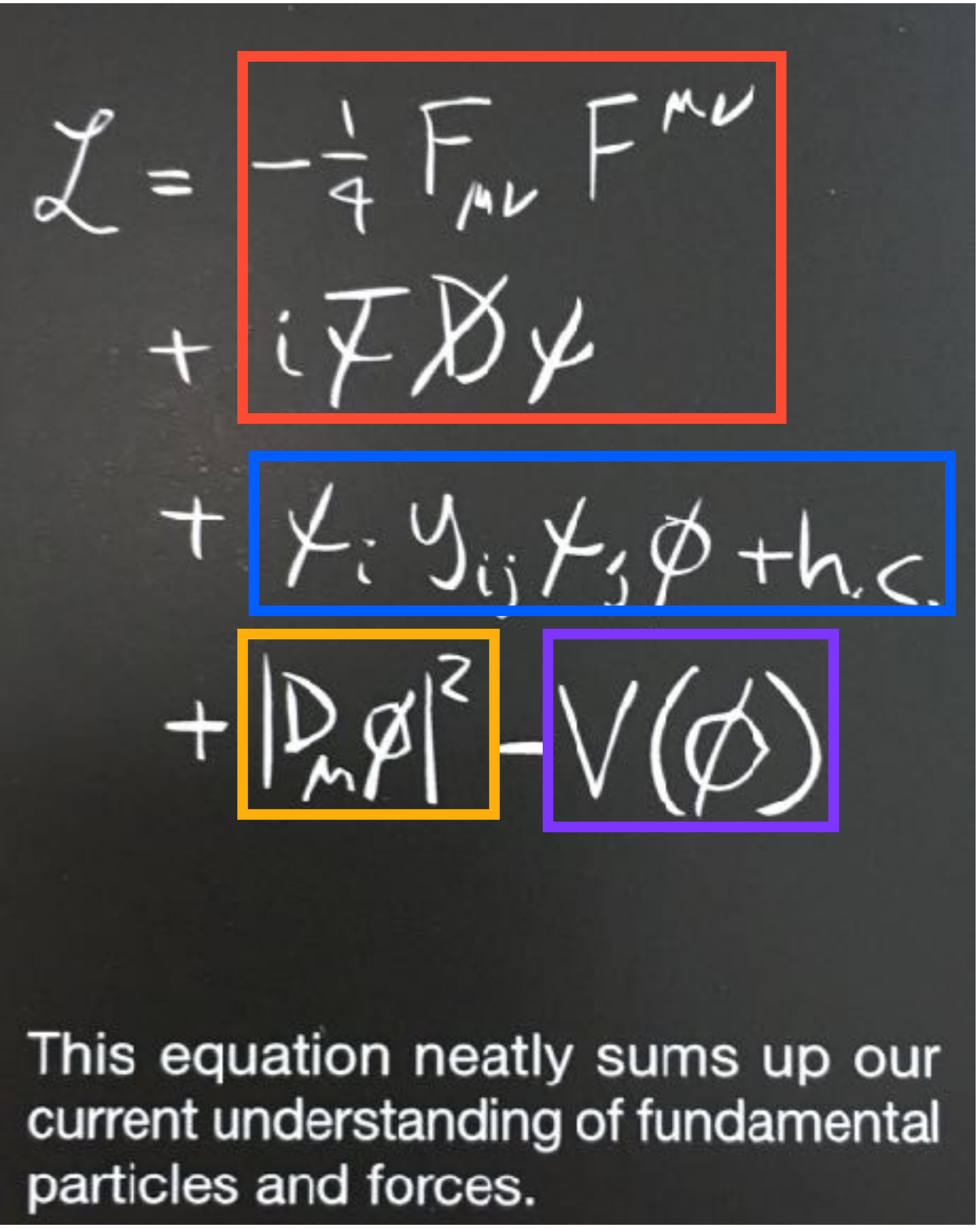
- Non-pert. effects are always relevant at accuracies we're interested in
- Watch out for cancellation between "hadronisation" and MPI/UE (separate physical effects)
- Definition of perturbative / non-perturbative is ambiguous
- Alternative to MC: analytical estimates.
  MC's have strong pT dependence, missing in analytical estimates

Analytic v. MC hadronisation



non-perturbative effects may become a key limitation at 1%

Standard Model today

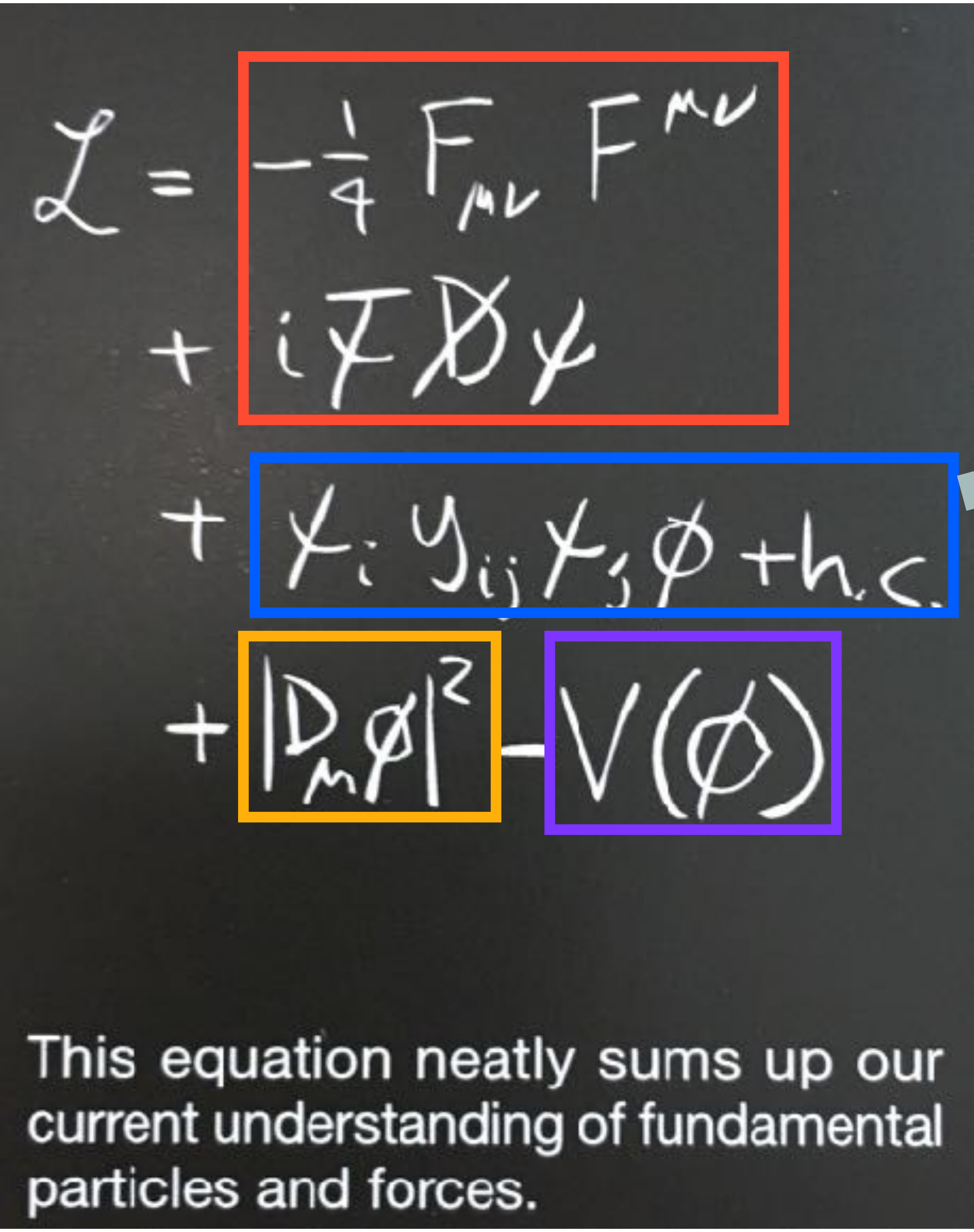


Gauge interactions well tested.

Higgs sector mostly an assumption

ASSUMPTION KNOWLEDGE

Standard Model today



t	b	τ
c	s	μ
u	s	e

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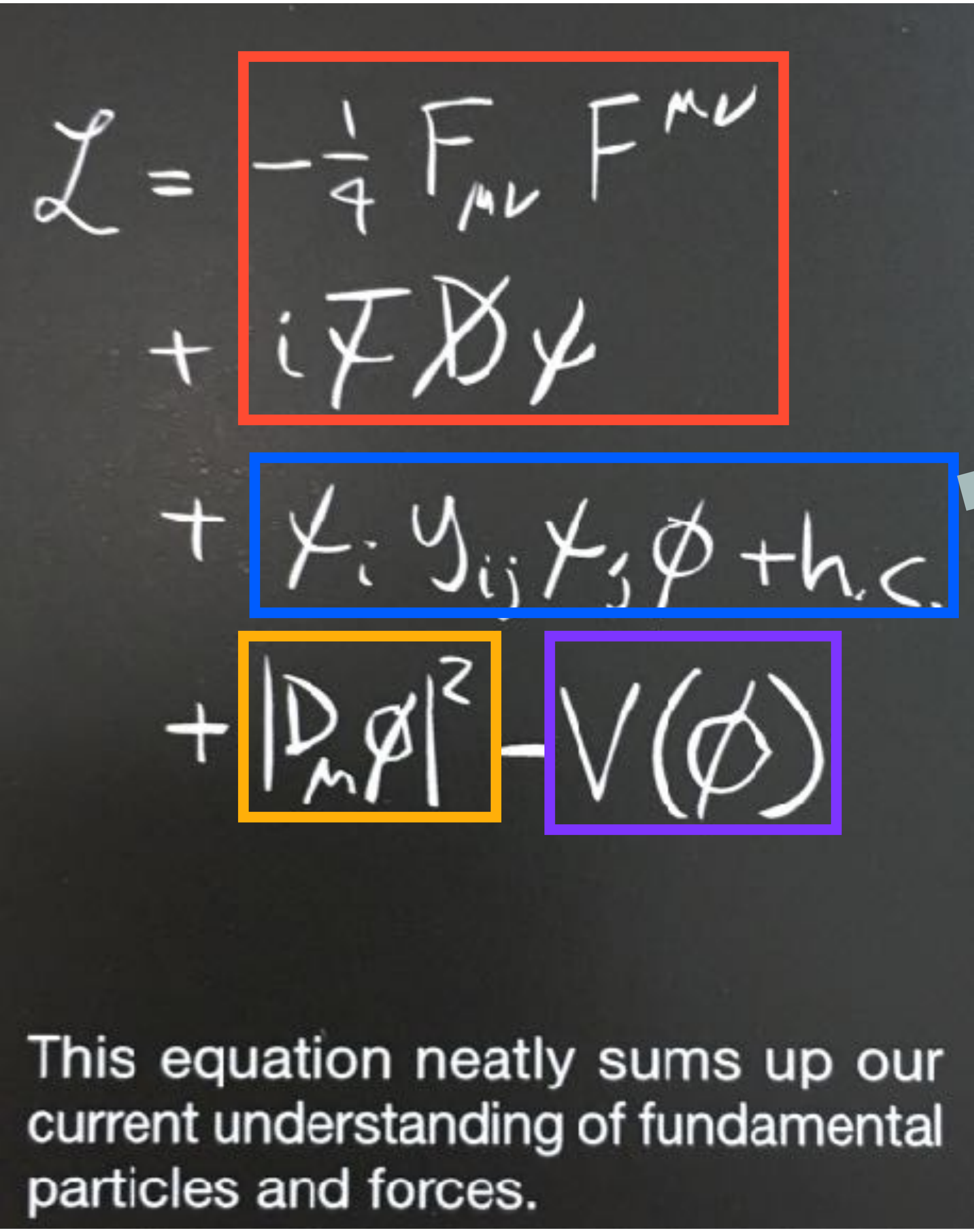
ASSUMPTION KNOWLEDGE

Standard Model by end of LHC (~2035)



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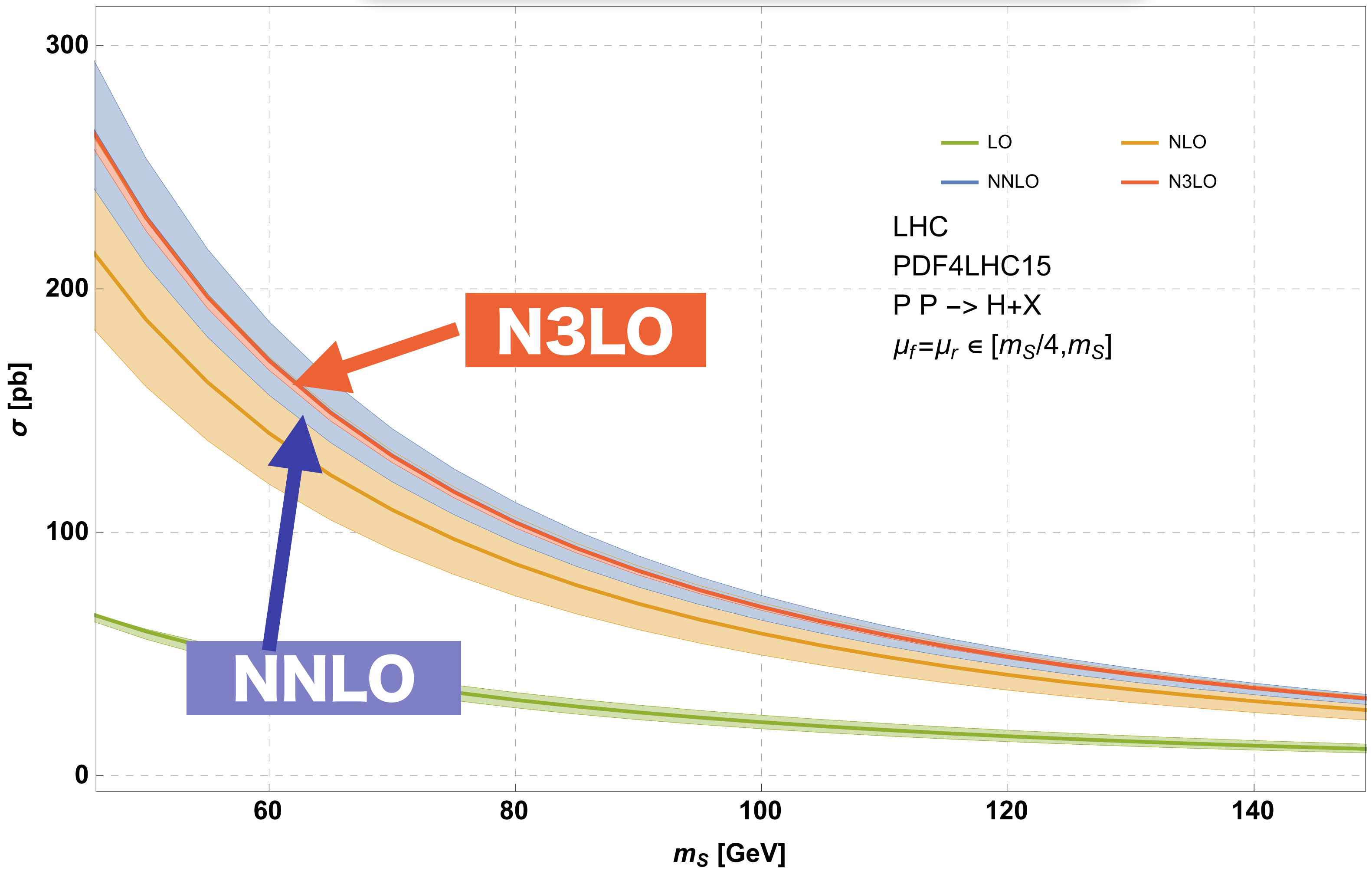
ASSUMPTION KNOWLEDGE

N3LO

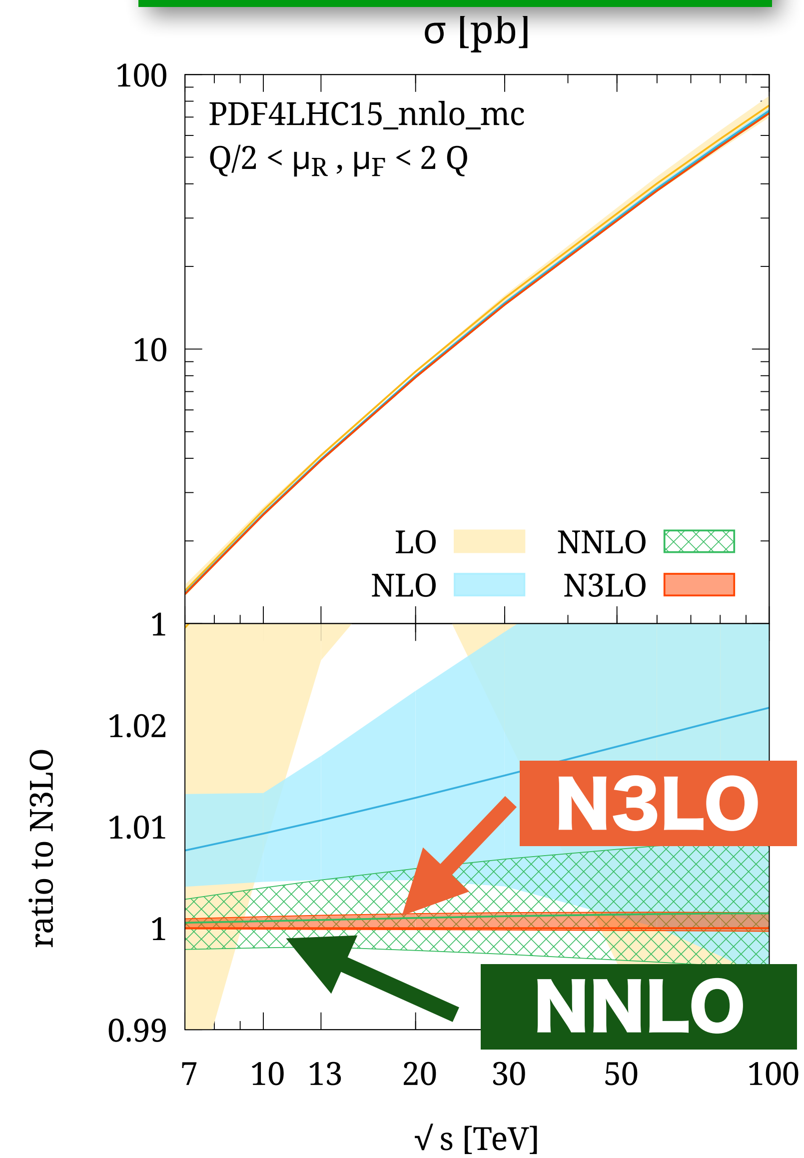
Anastasiou et al, 1602.00695

N3LO ggF Higgs

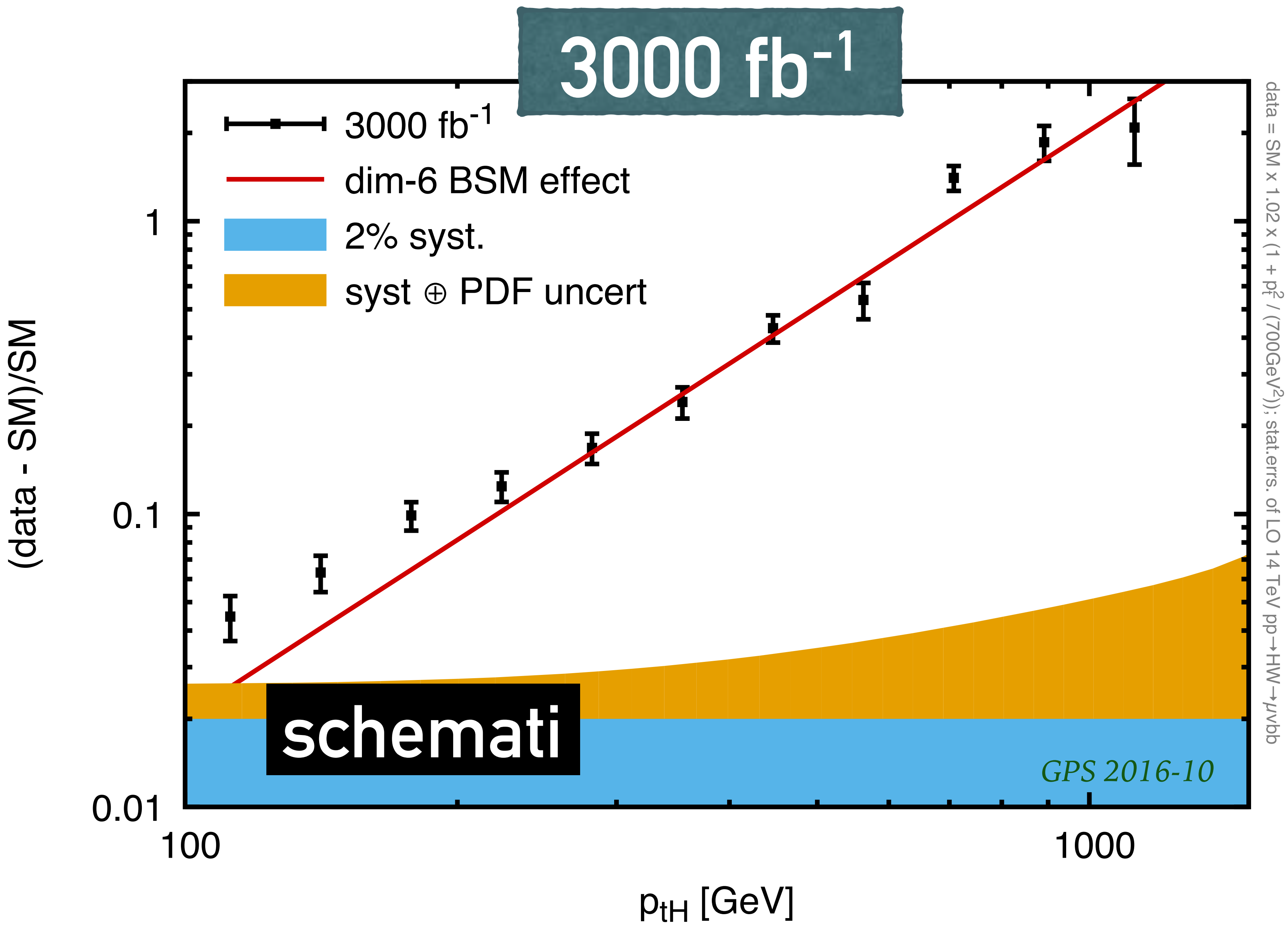


Dreyer & Karlberg, 1606.00840

N3LO VBF Higgs



WH at large Q^2 with dim-6 BSM effect



new physics isn't just a single number that's wrong (think g-2)

but rather a distinct scaling pattern of deviation ($\sim p_T^2$)

moderate and high p_T's have similar statistical significance — so it's useful to understand whole p_T range