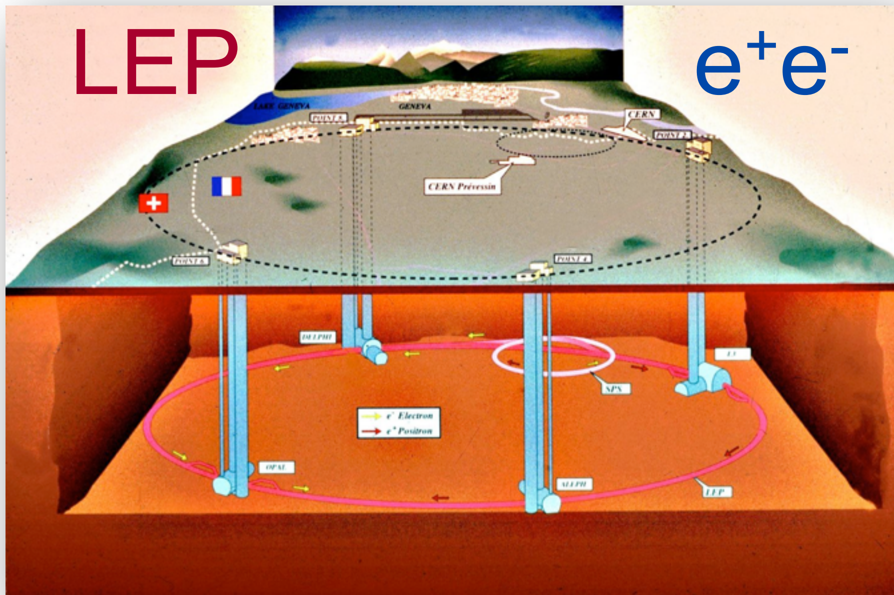
From LEP to the LHC

Günther Dissertori
ETH Zürich

10.6.2016

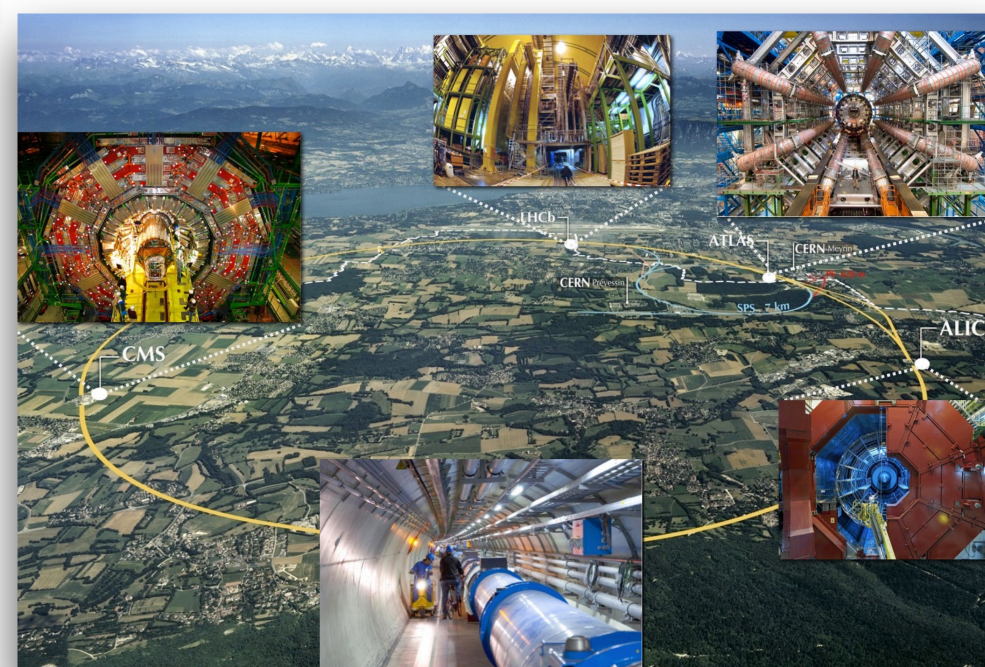
Outline



General intro

Monte Carlo generators

Measurements of the strong coupling

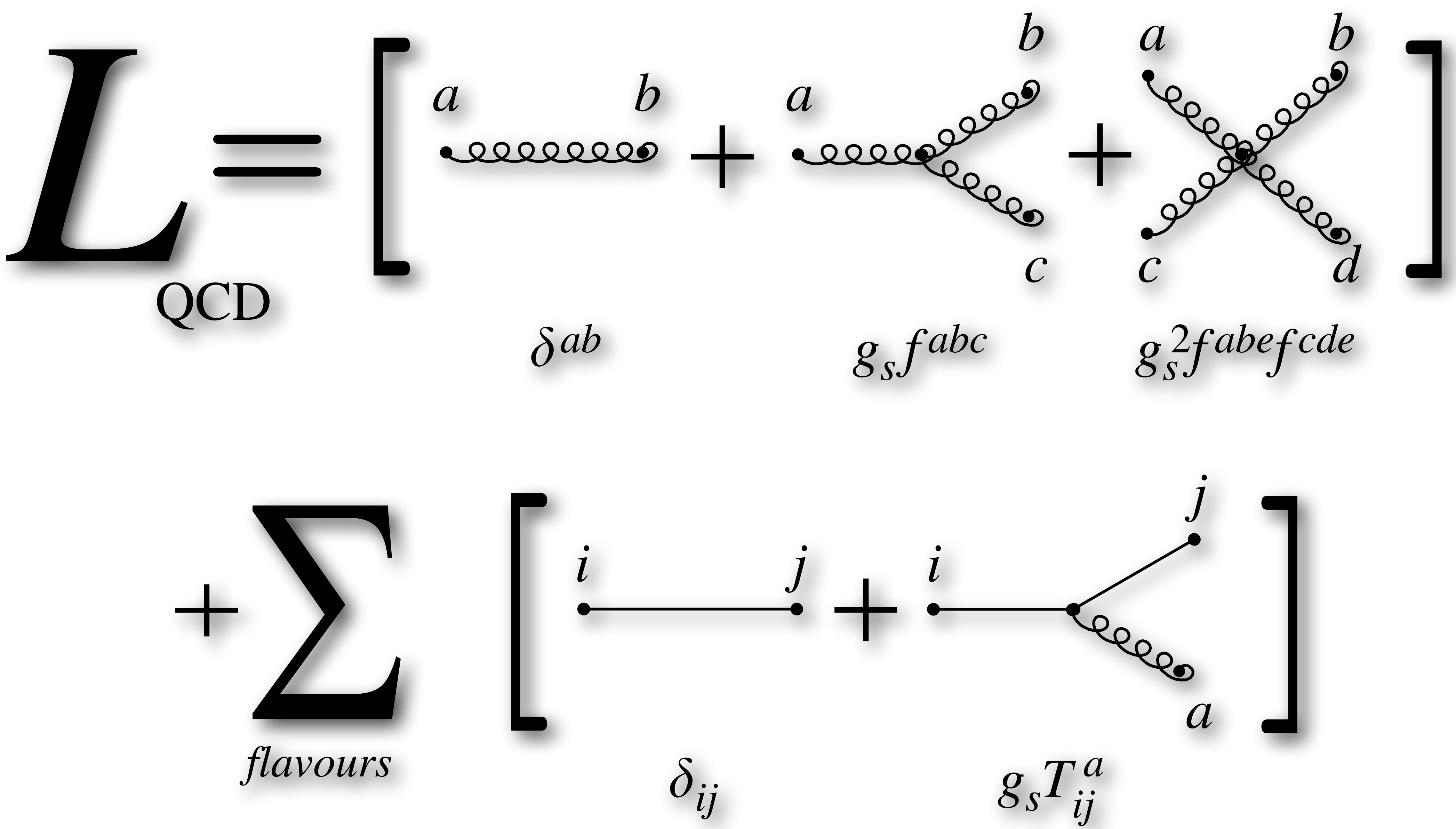


The (N)(N)NLO, Multi-Leg, NLO+PS revolutions…

Achievements at the LHC

Quantum Chromodynamics

ETH Institute for Particle Physics



$$\alpha_s = \frac{g_s^2}{4\pi}$$

in 1989....

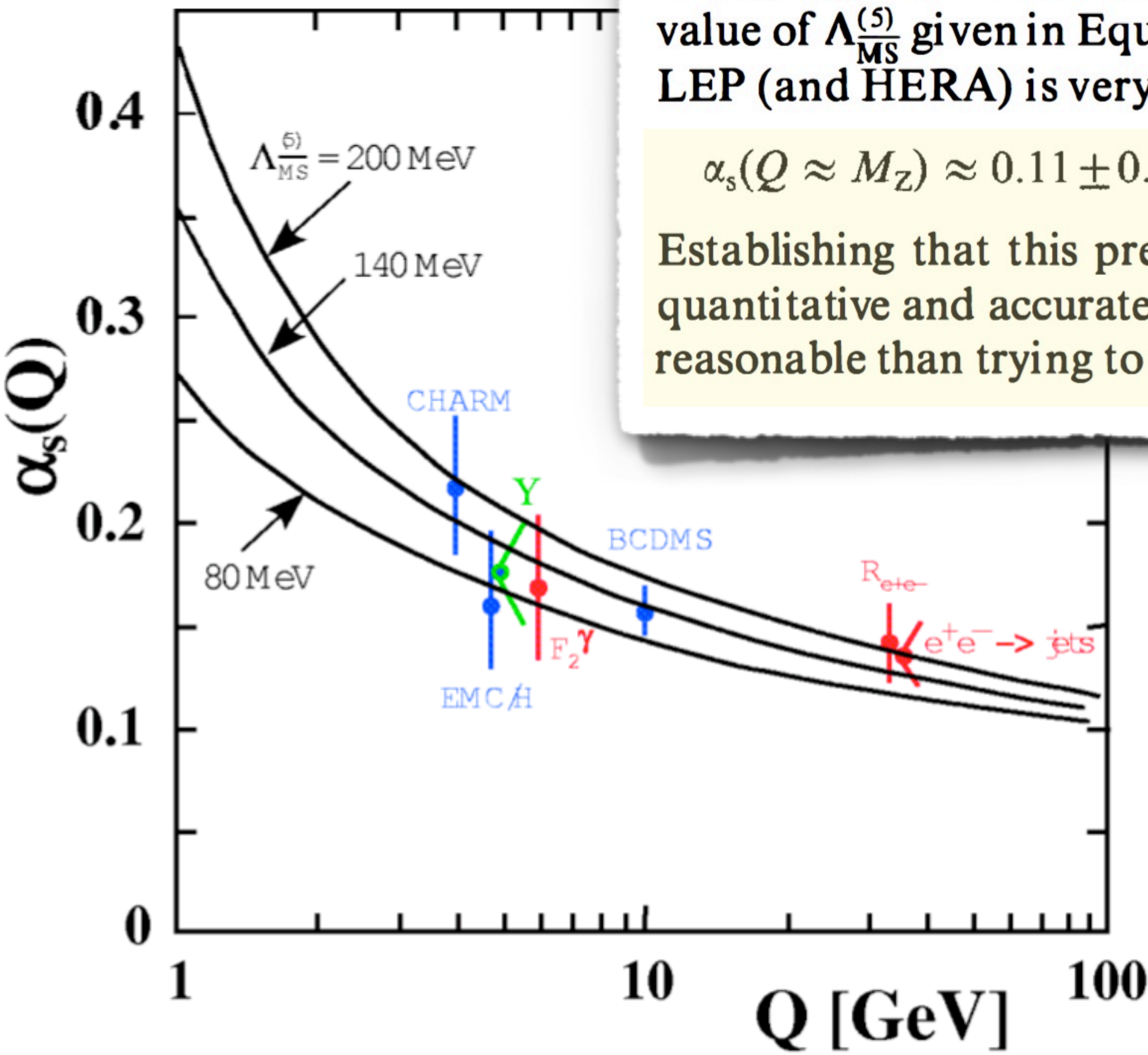


Figure 7. A relatively loose determination of $\alpha_s(Q)$ at $Q \approx 1$ GeV leads to a very tight determination of $\alpha_s(Q)$ at large Q. For example, from the value of $\Lambda^{(5)}_{\overline{MS}}$ given in Equation 58, the prediction for α_s to be measured at LEP (and HERA) is very precise:

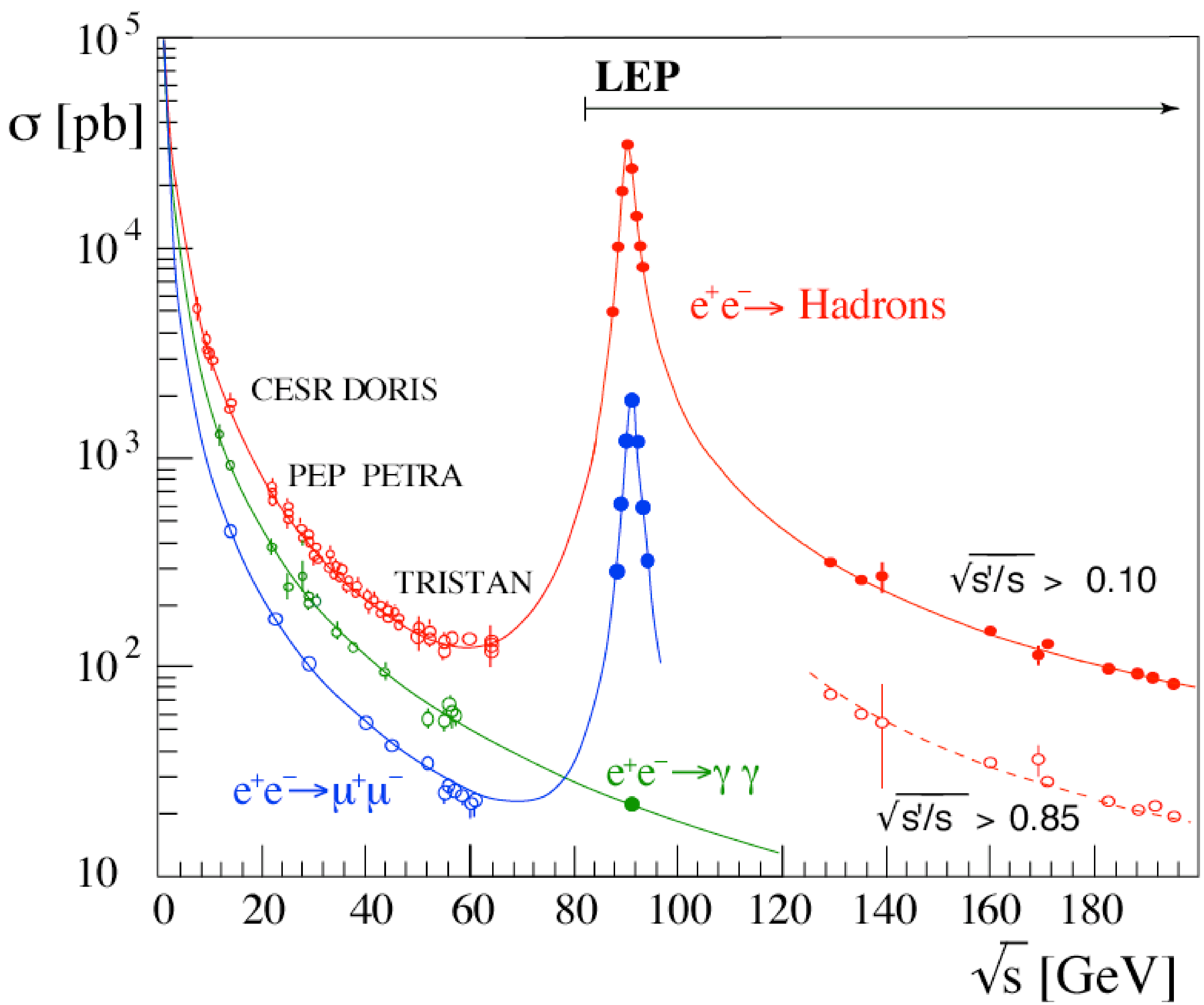
$$\alpha_s(Q \approx M_Z) \approx 0.11 \pm 0.01. \qquad 59.$$

Establishing that this prediction is experimentally true would be a very quantitative and accurate test of QCD, conceptually equivalent but more reasonable than trying to see the running in a given experiment.

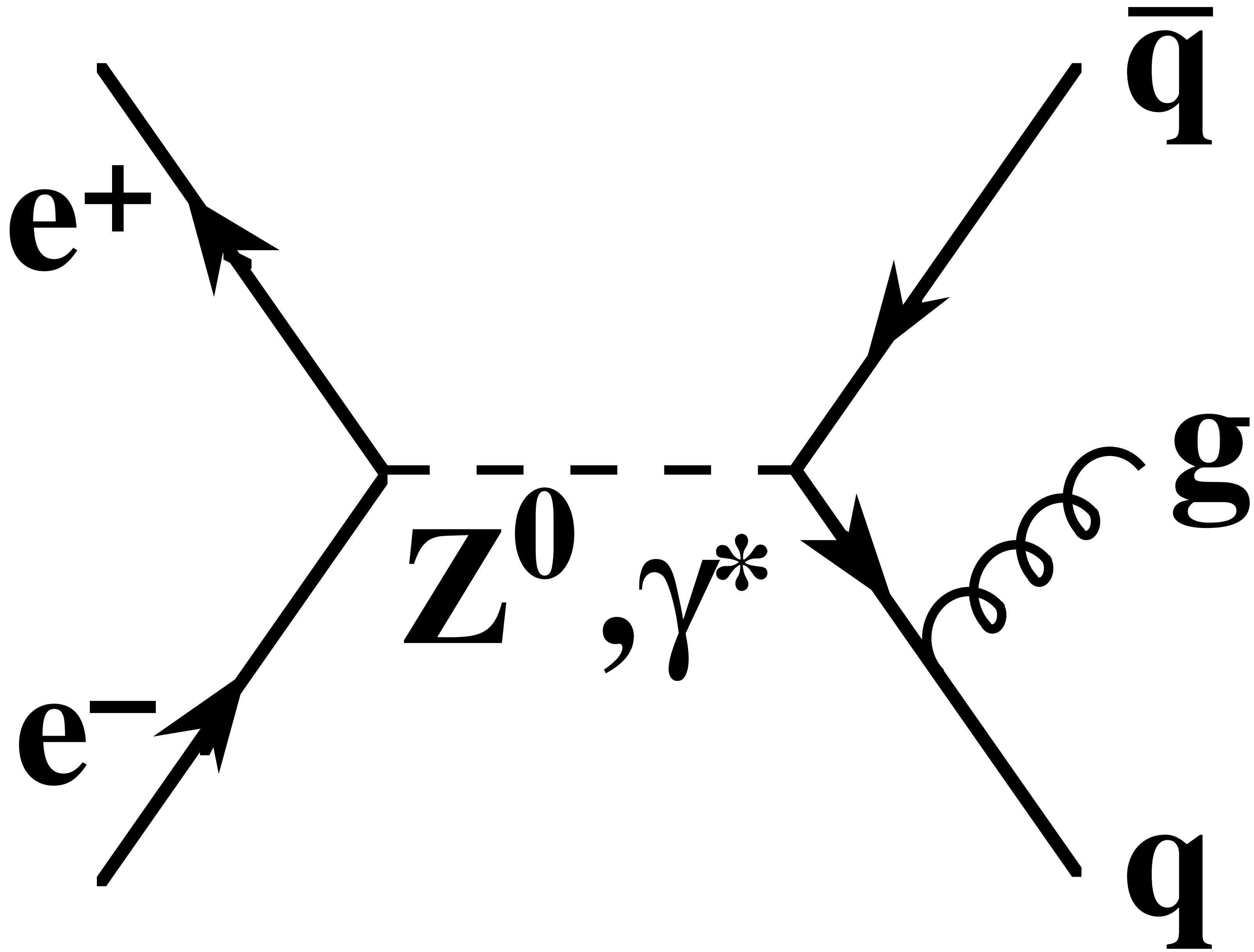
G. Altarelli, Ann. Rev. Nucl. Part. Sci. 39, 1989

LEP data

LEP statistics (4 million events per experiment):
a plethora of detailed studies of pert. and non-pert. QCD.



Anatomy of a LEP process



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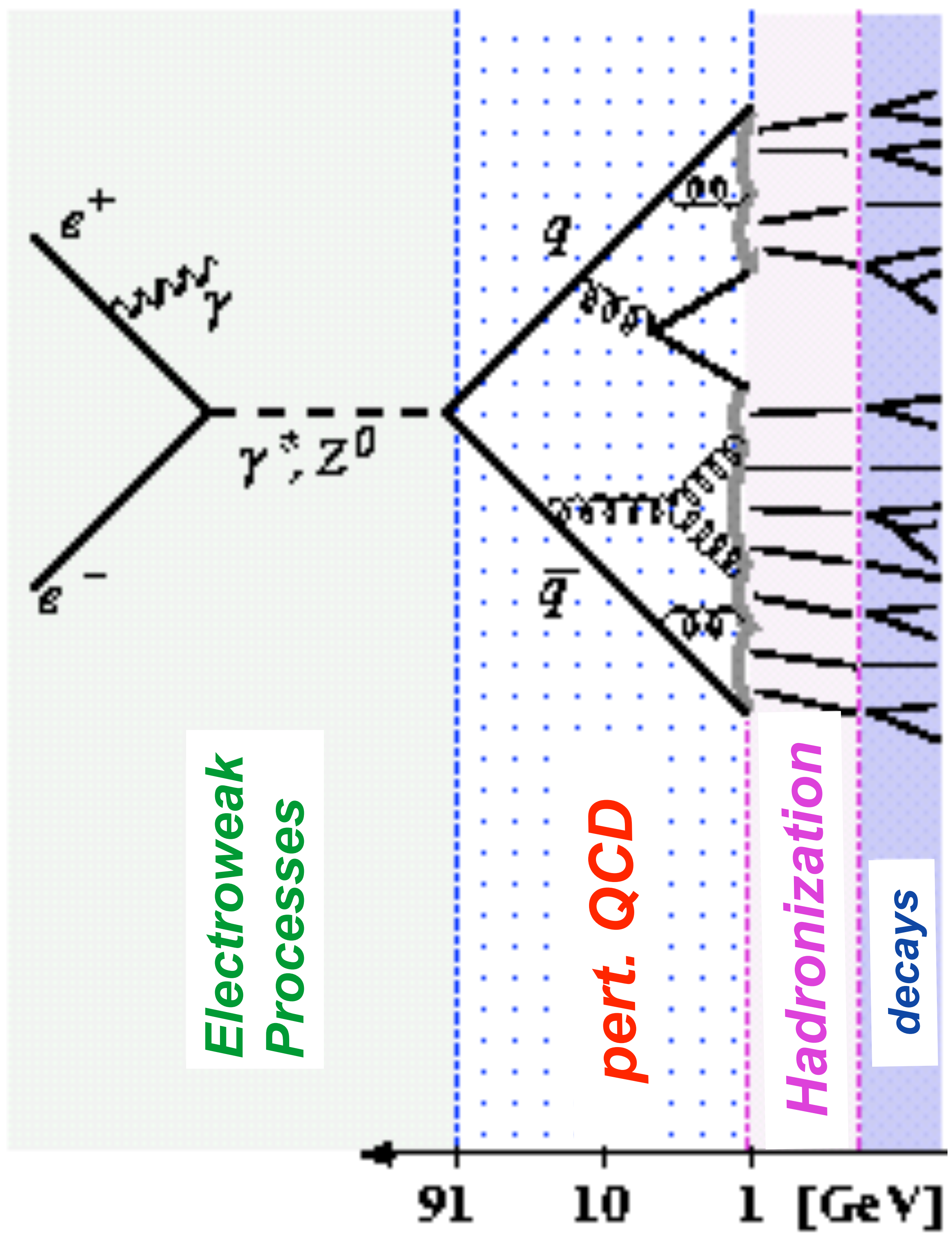
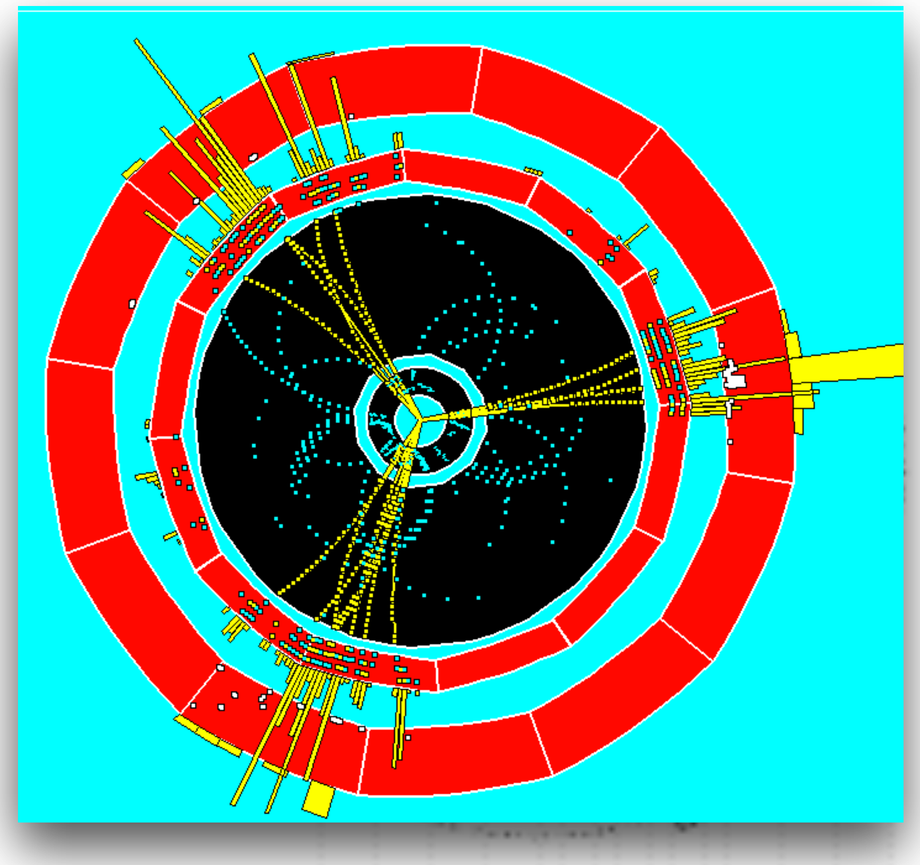
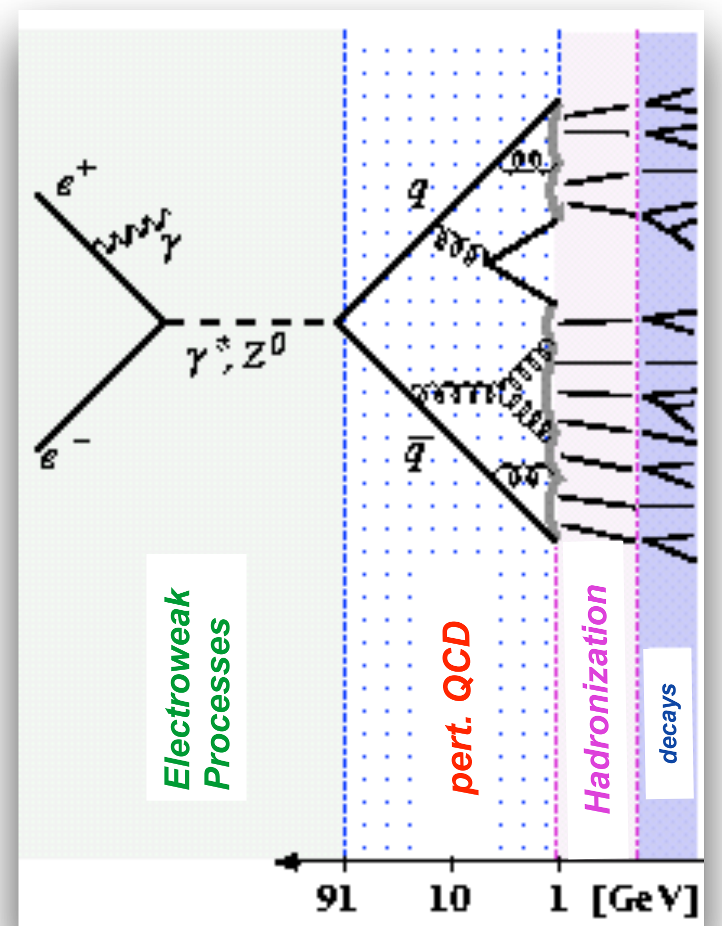




The workhorses of those days

PYTHIA / JETSET

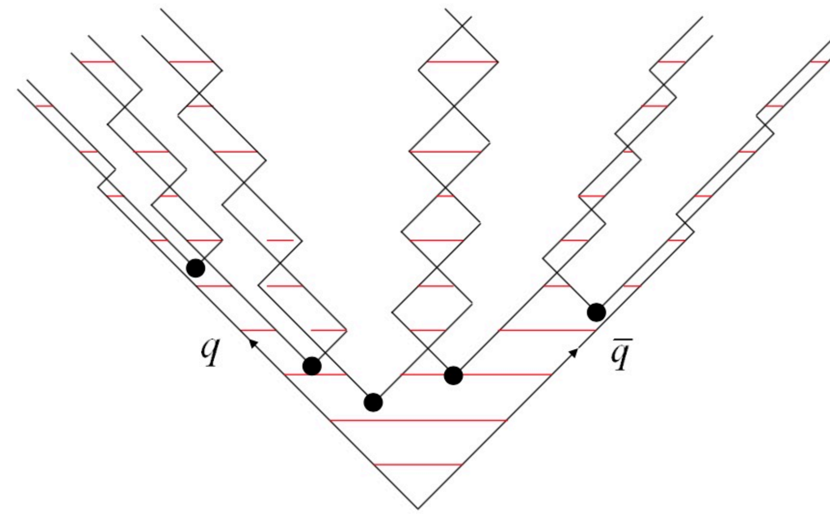


HERWIG

Leading Order (LO) Matrix Element

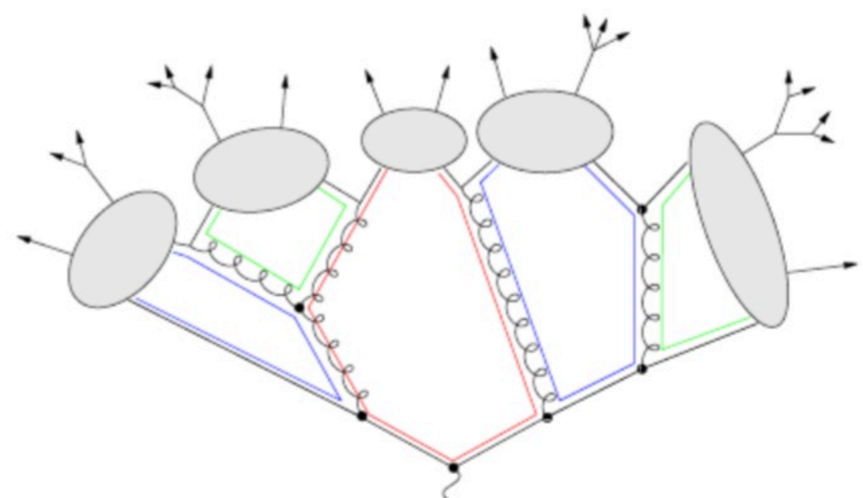
plus Parton Showers

ARIADNE



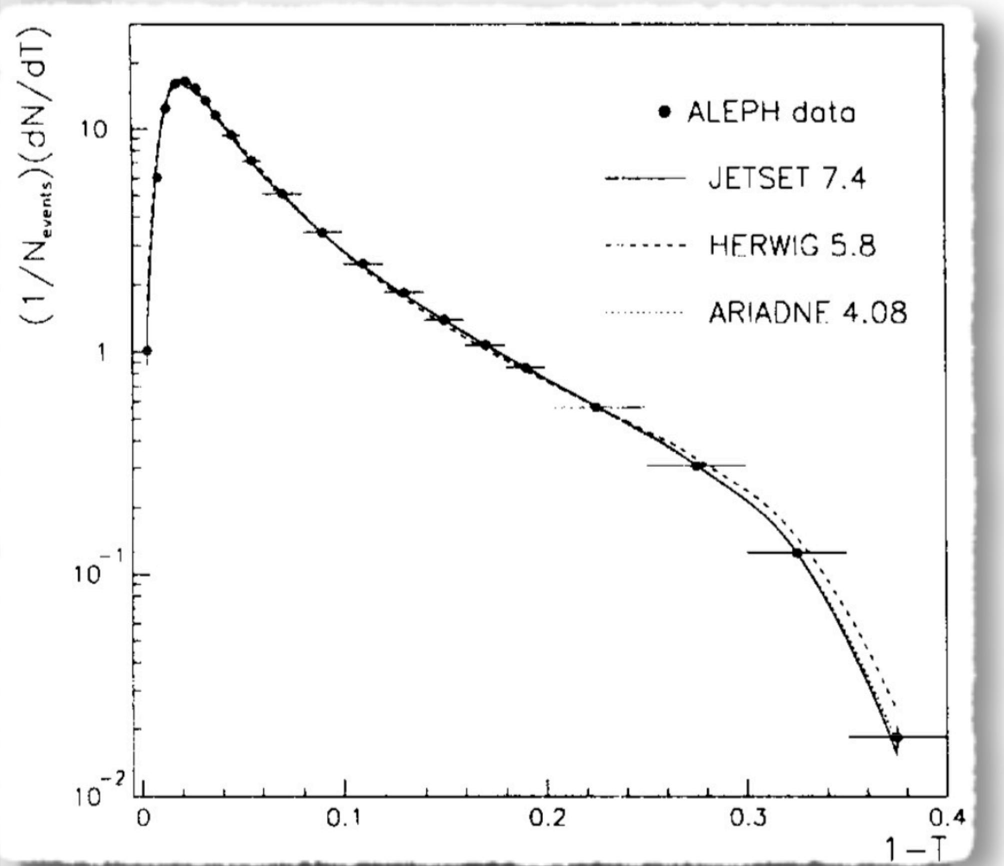
Lund String Model

Herwig Cluster Model



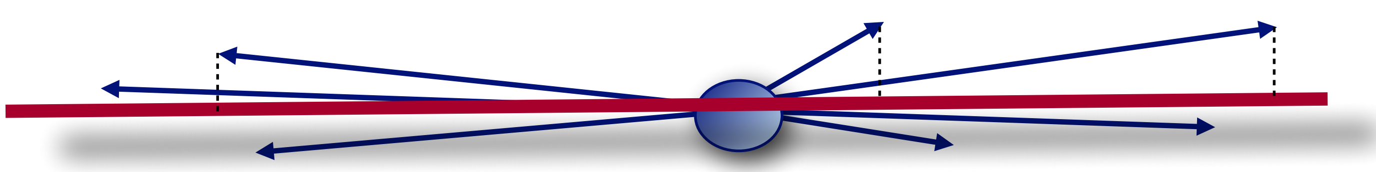
http://www.quantumdiaries.org/wp-content/uploads/2010/12/jets.png

The workhorses of those days



Thrust

$$T = \max_{\vec{n}} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|}$$



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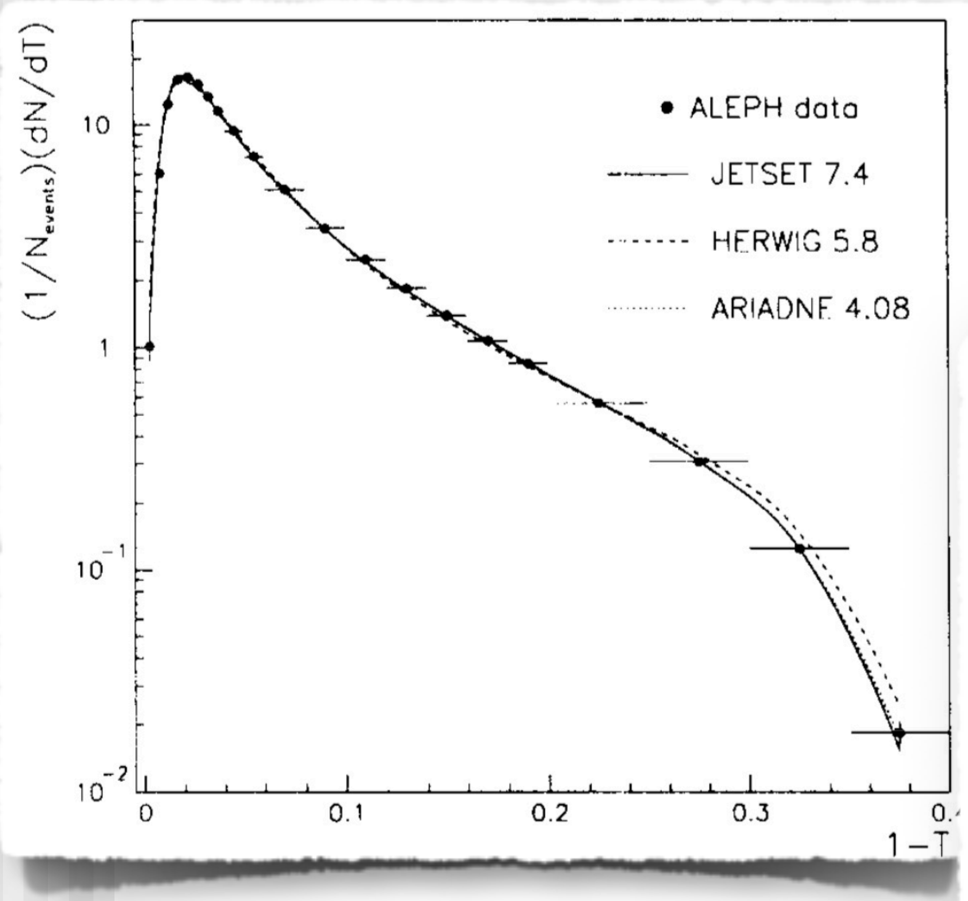
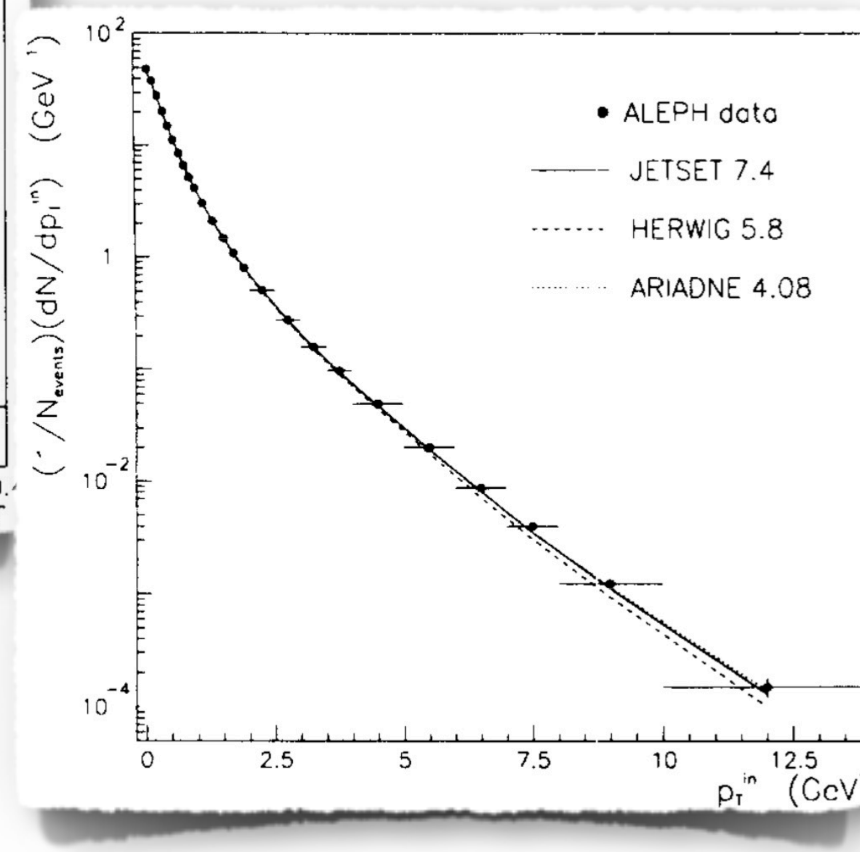


Thrust

Chg. tracks:
momentum component
in the event plane



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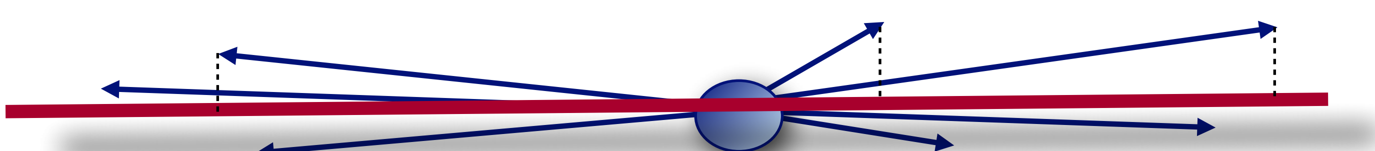

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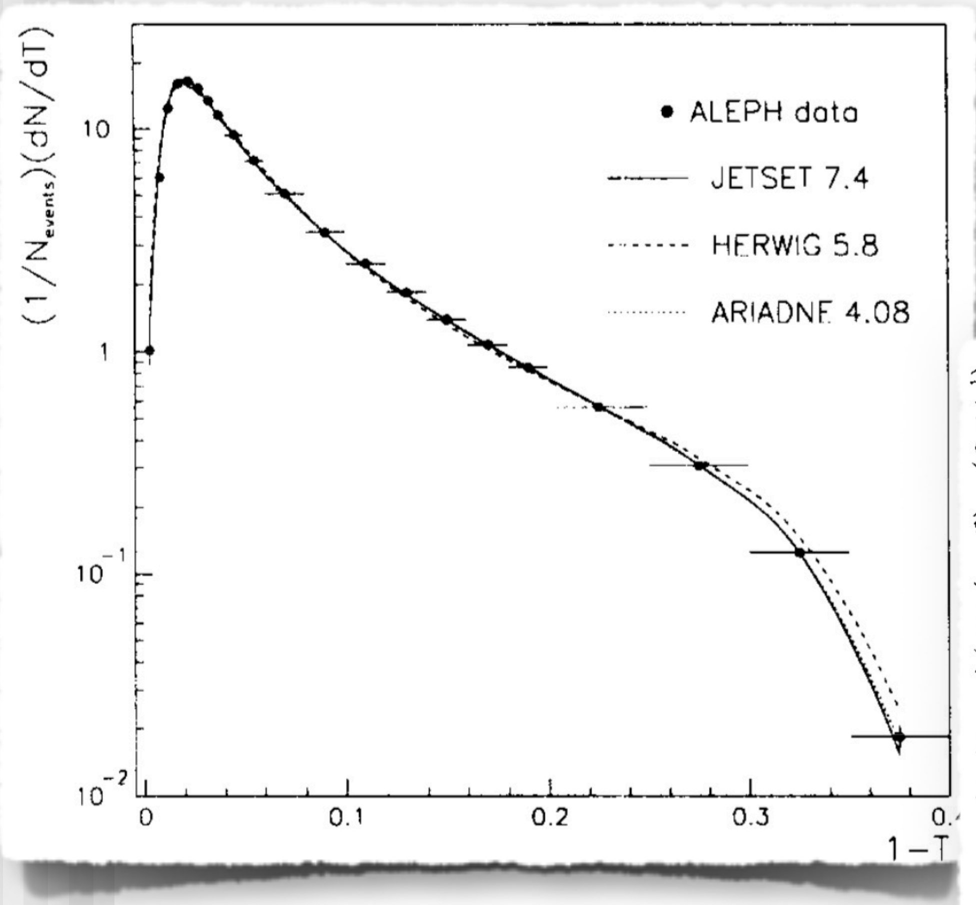
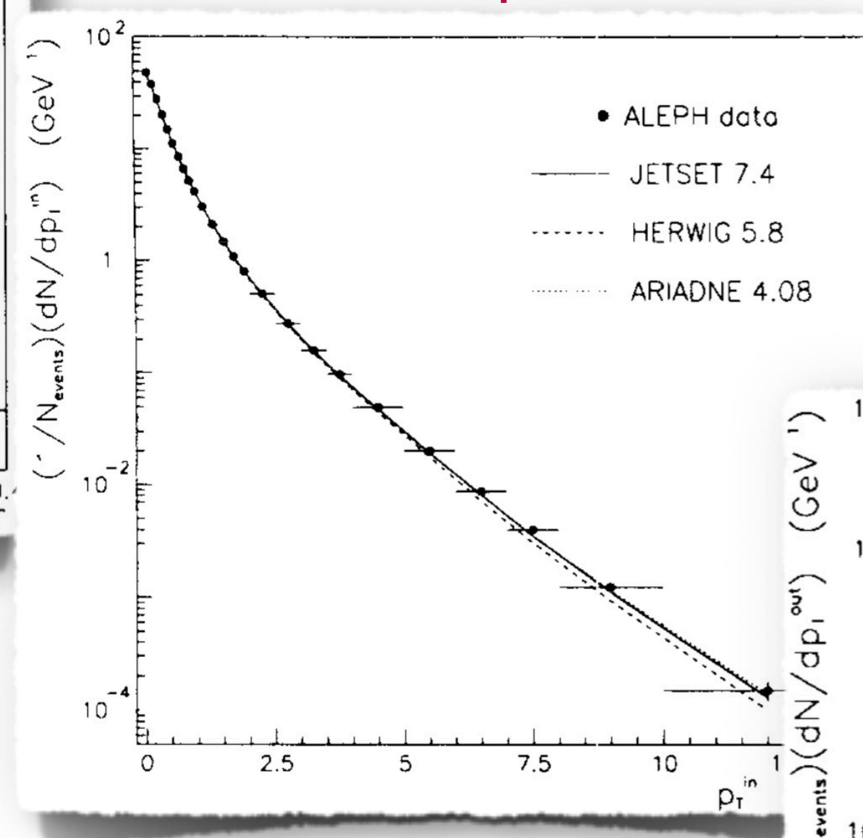
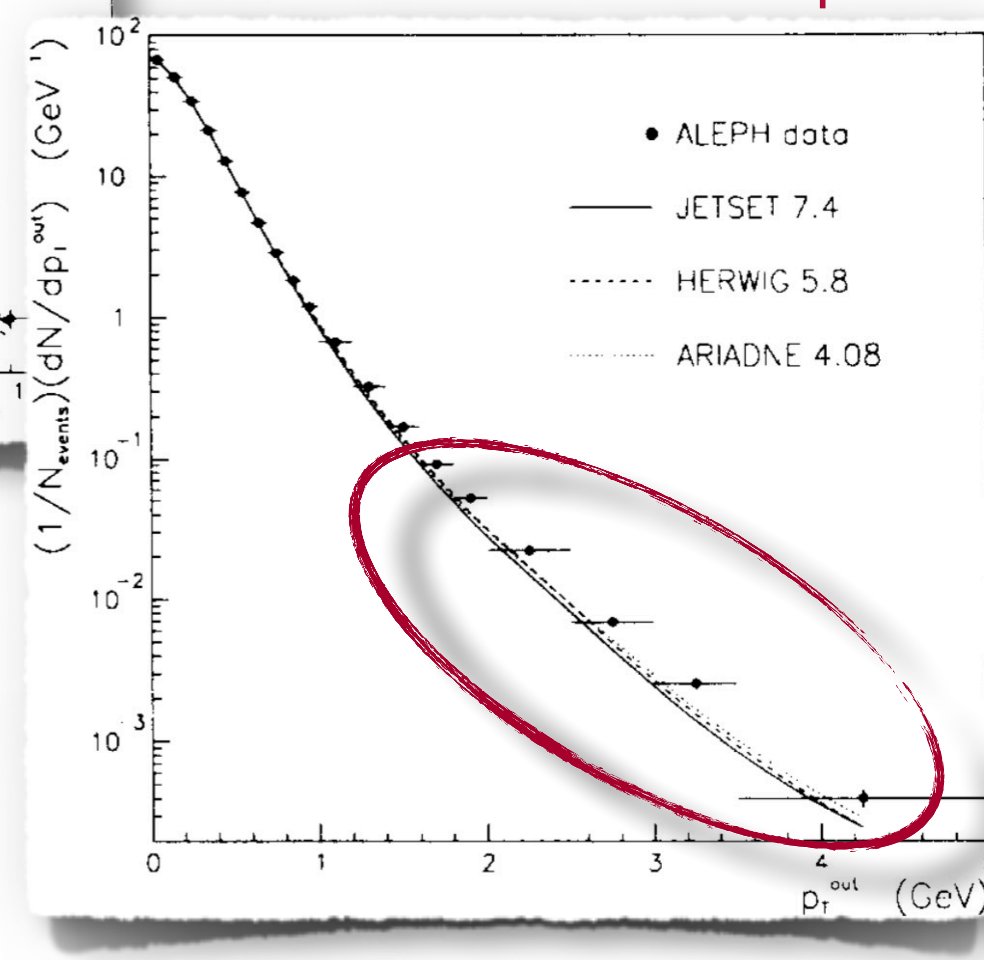


Chg. tracks:
momentum component
in the event plane



Chg. tracks:
momentum component
out of the event plane



Thrust

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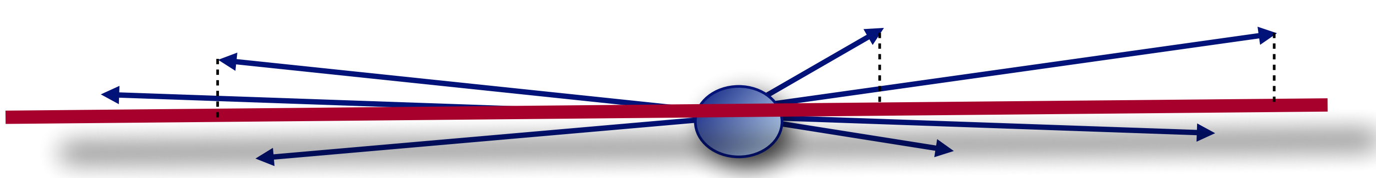
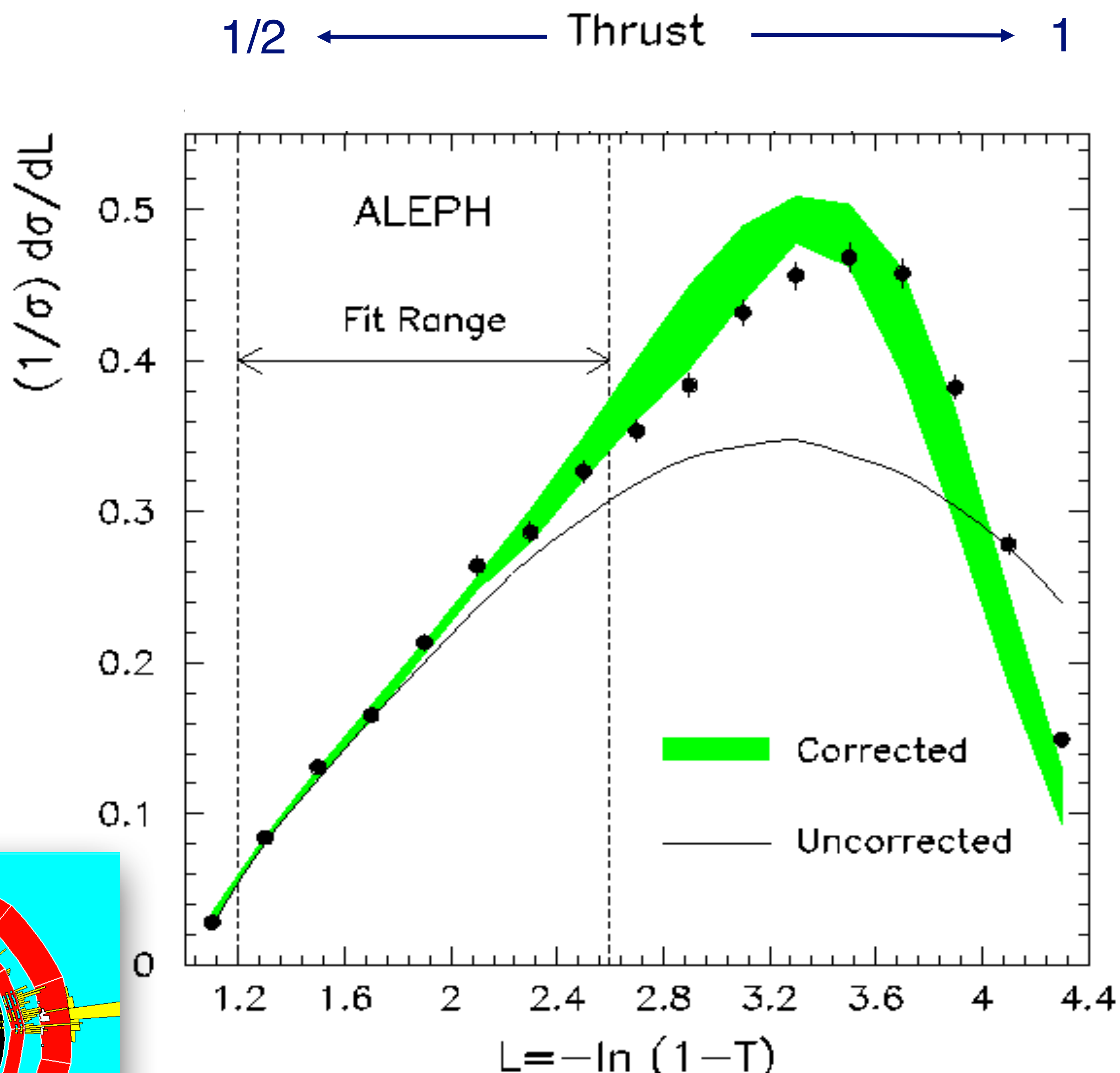
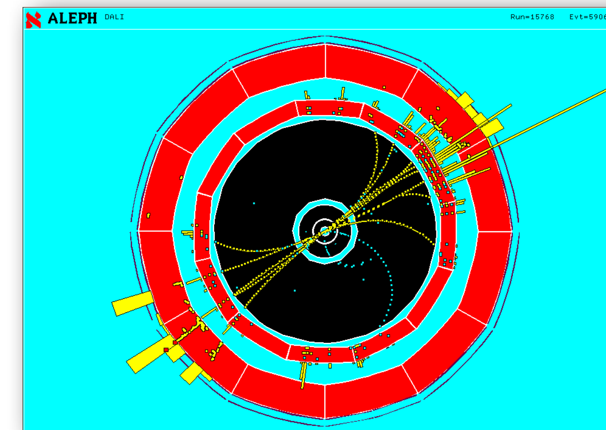
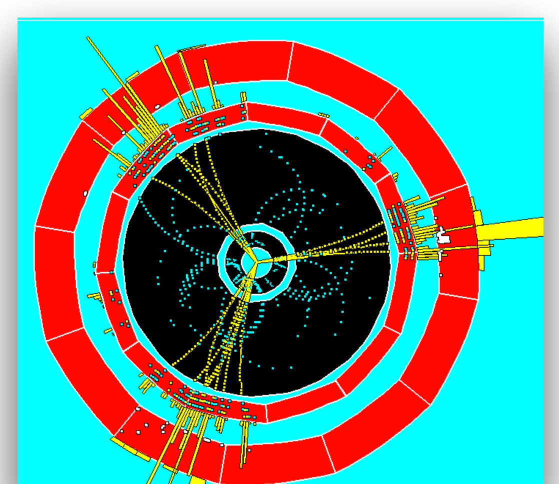


Measurements of α_s

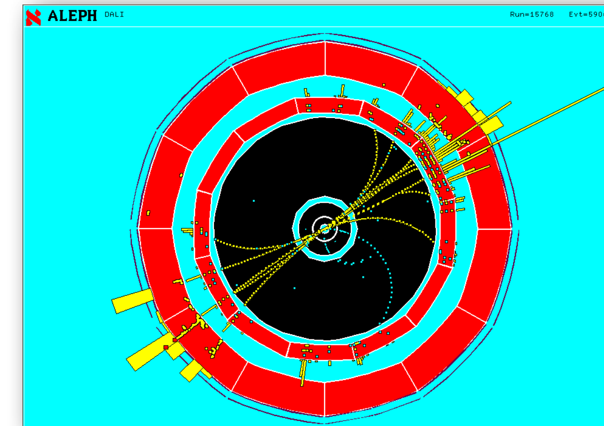


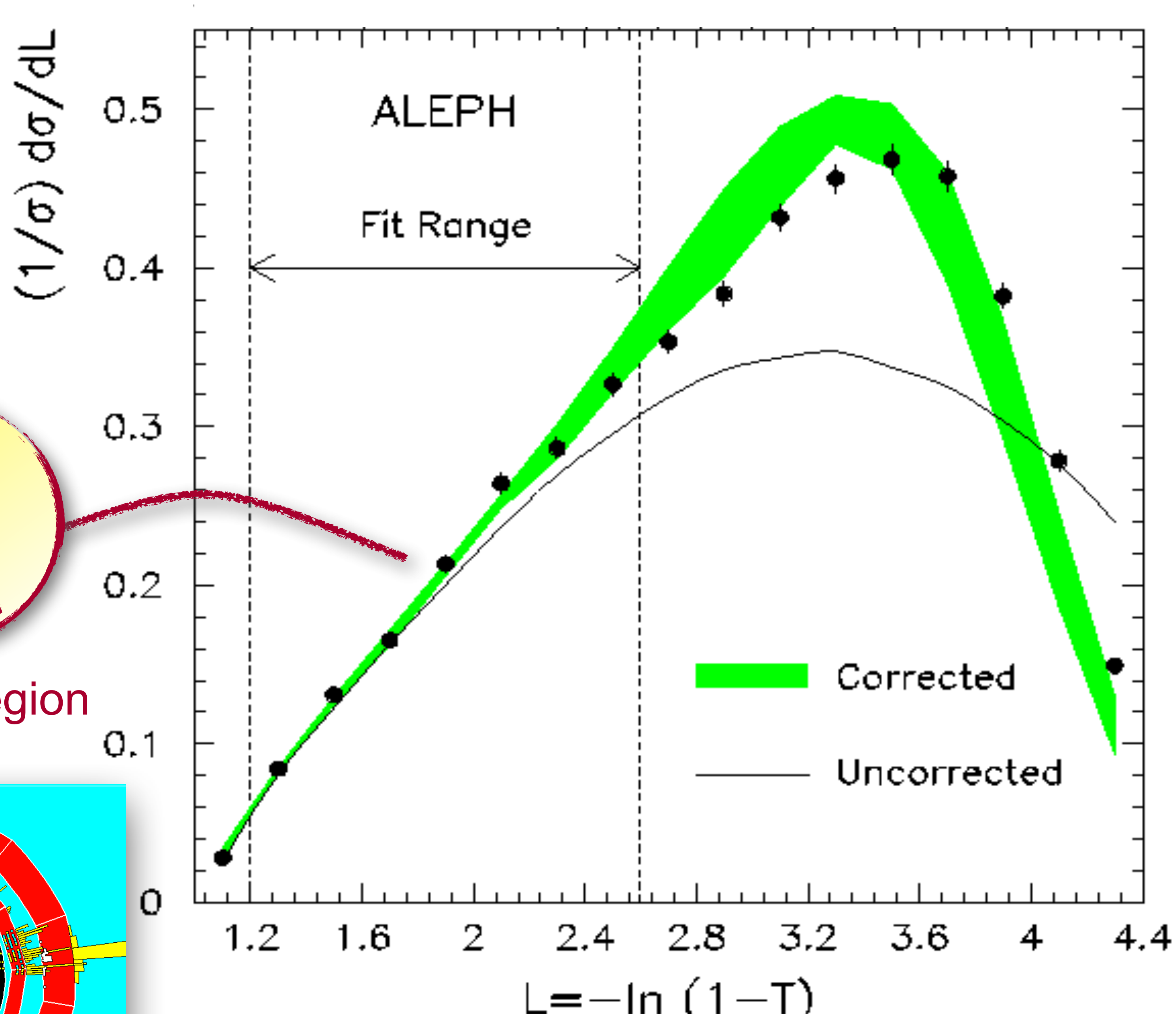


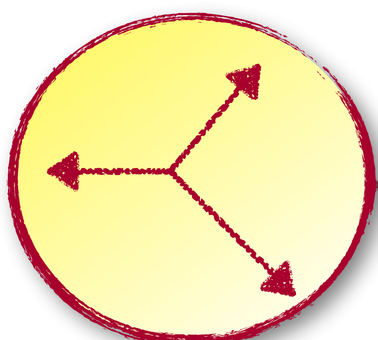


Measurements of α_s

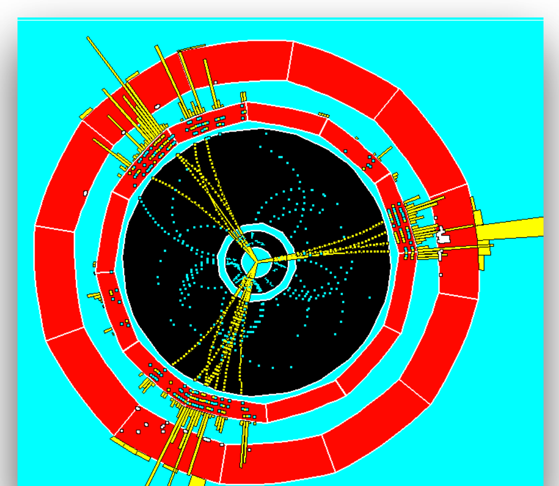
1/2 ← Thrust → 1



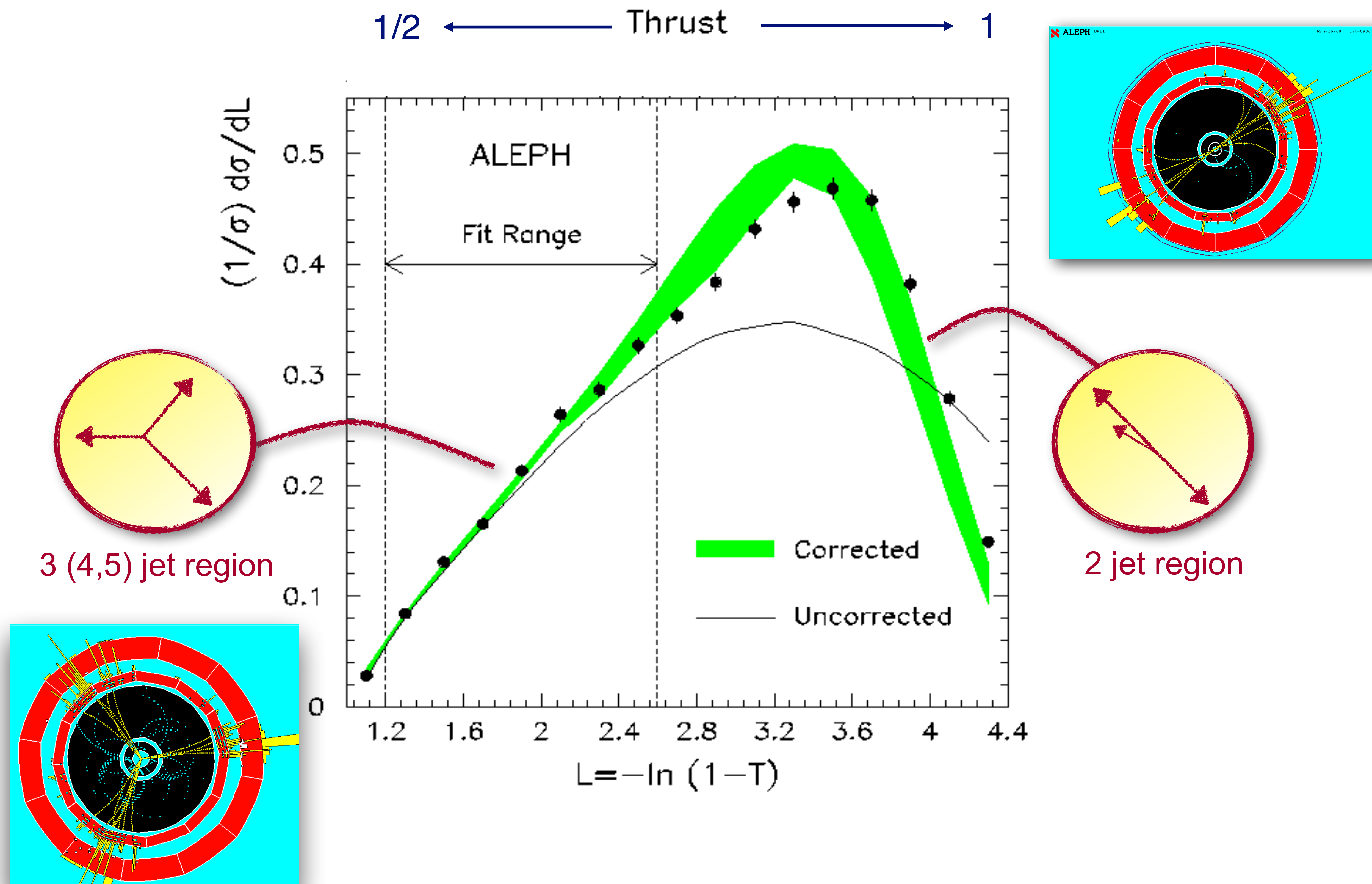




3 (4,5) jet region



Measurements of α_s



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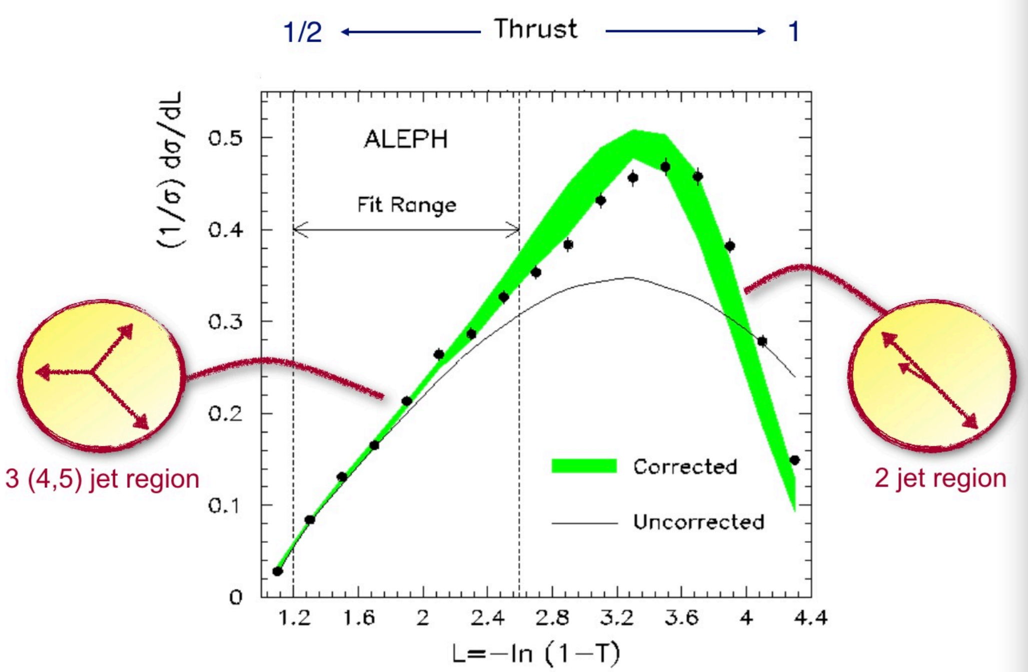
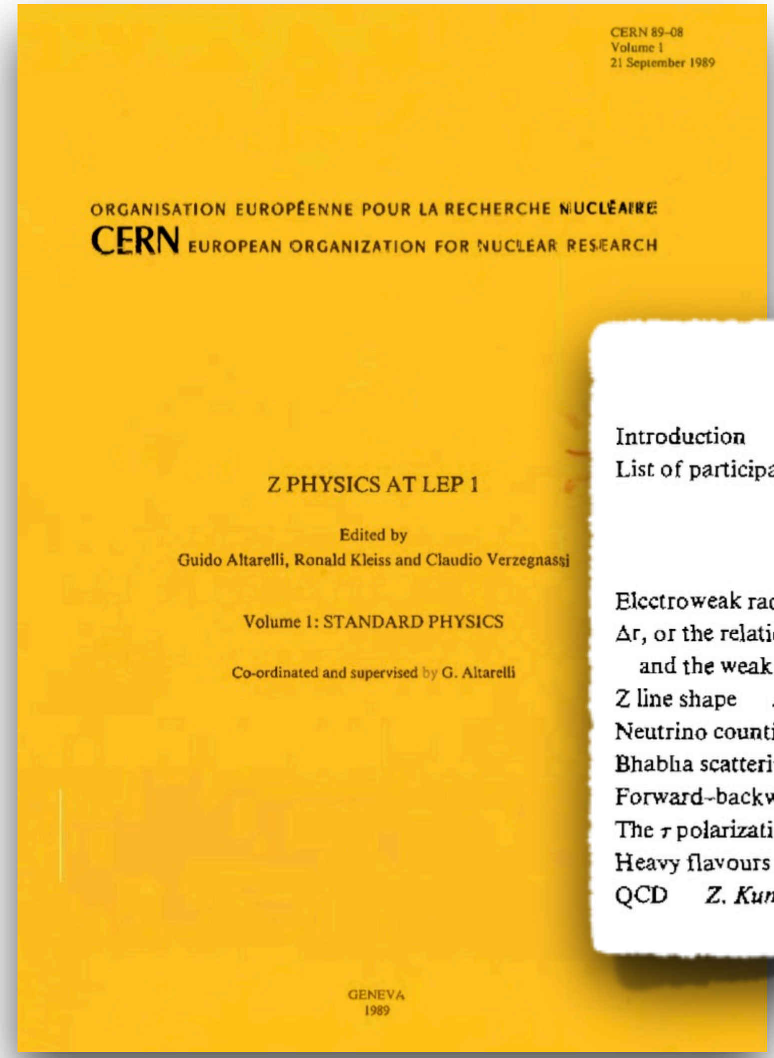




CERN 89-08
Volume 1
21 September 1989

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

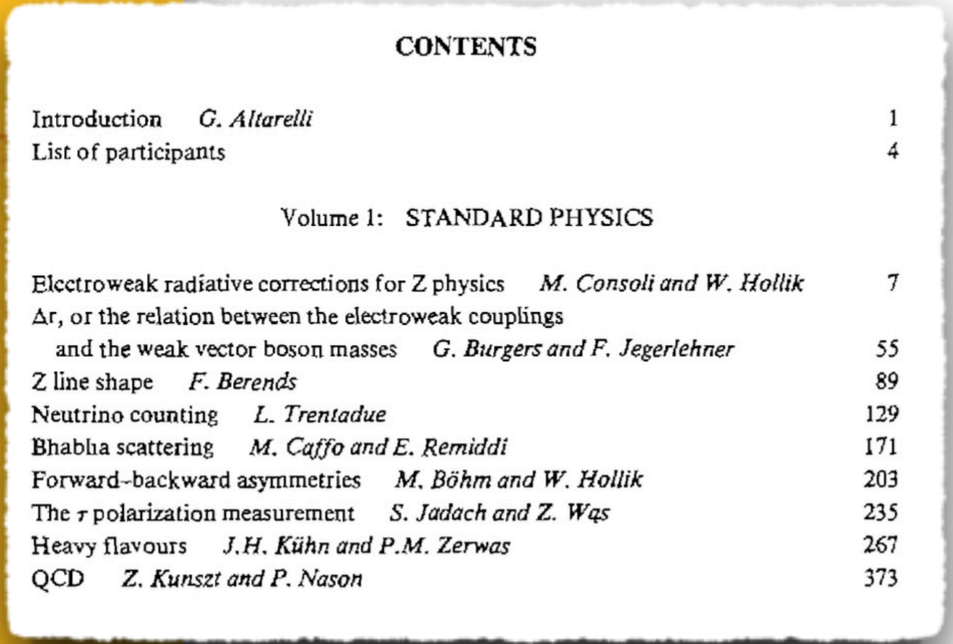
Z PHYSICS AT LEP 1

Edited by
Guido Altarelli, Ronald Kleiss and Claudio Verzegnassi

Volume 1: STANDARD PHYSICS

Co-ordinated and supervised by G. Altarelli

GENEVA
1989



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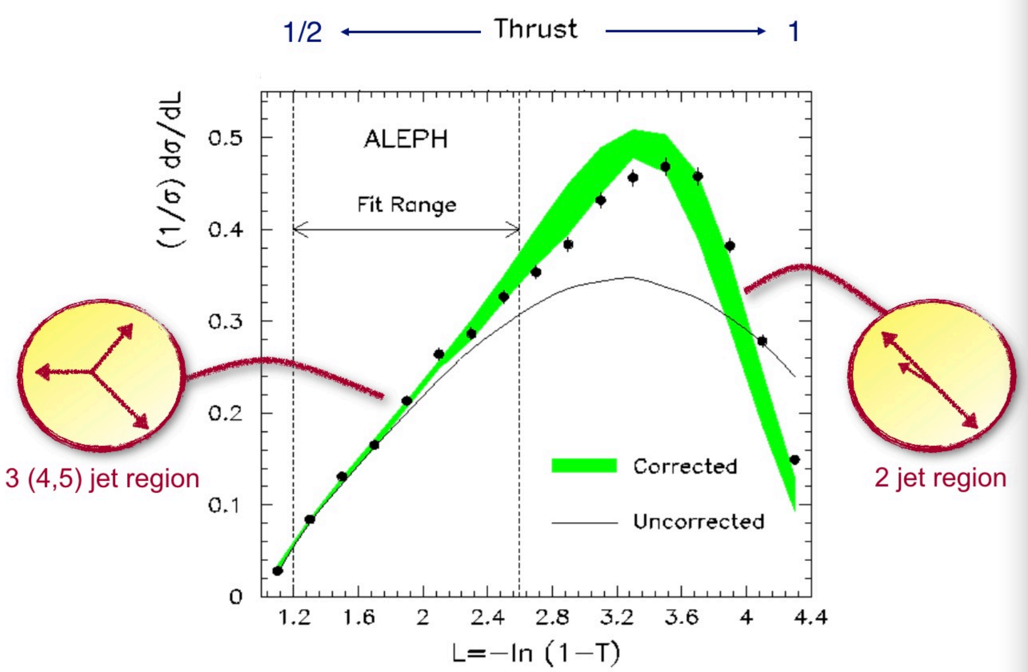

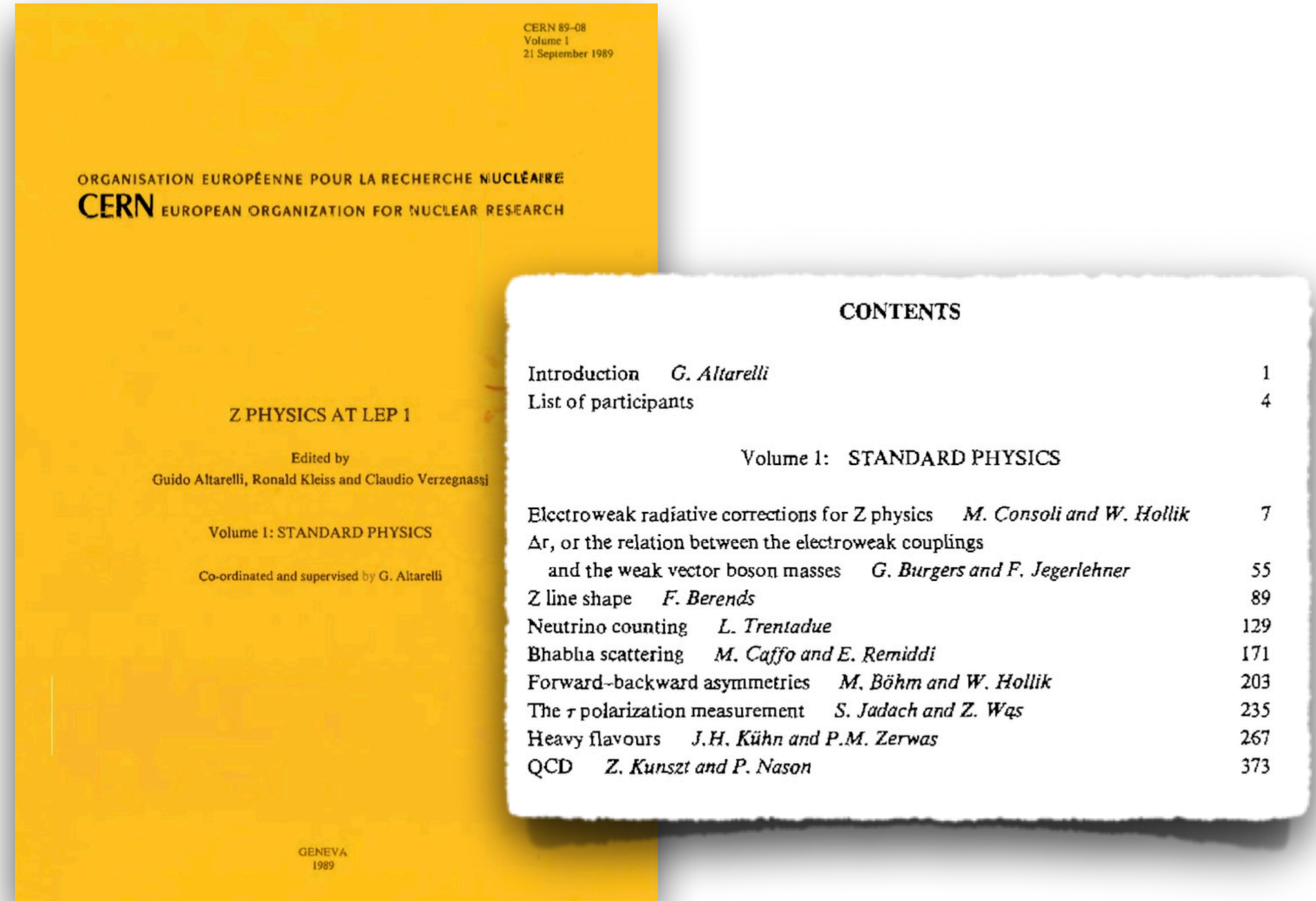

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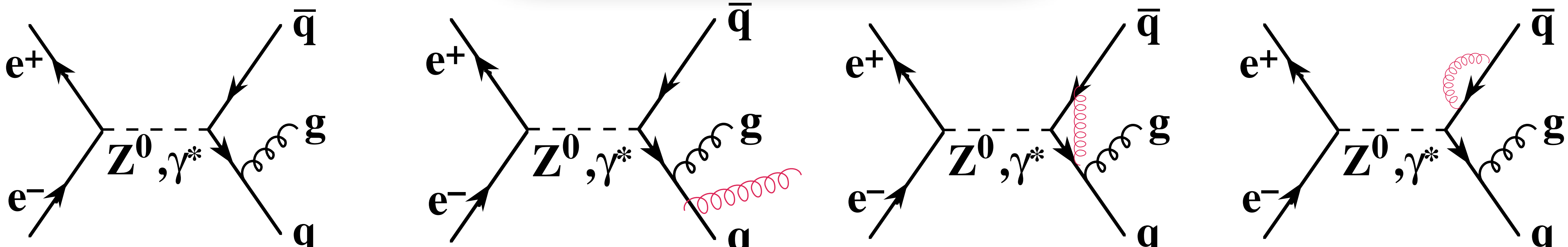
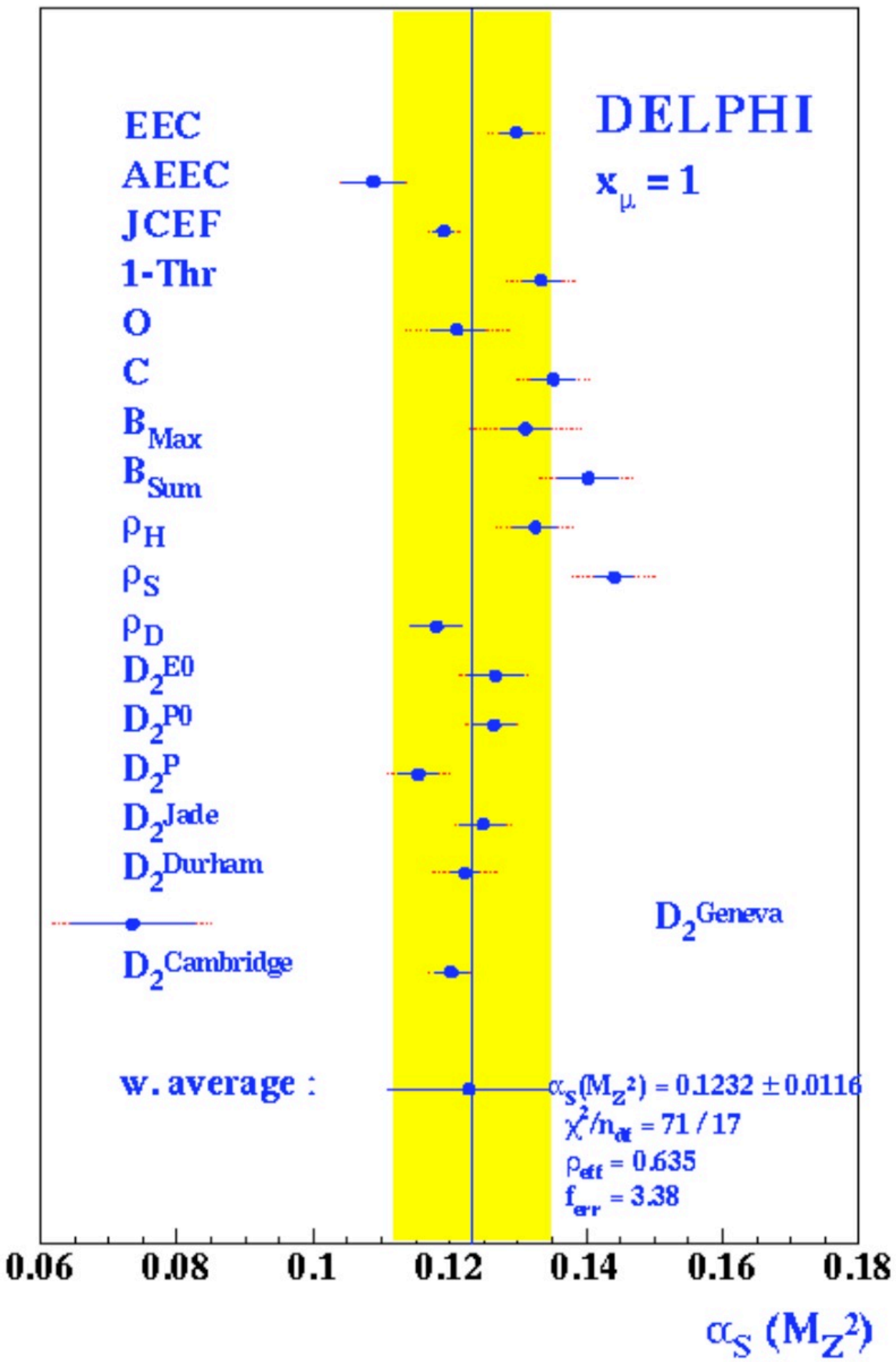


$$\sigma^{\rm pert}_{\rm NLO} = \alpha_s(\mu^2)\, A + \alpha_s^2(\mu^2)\left[B + \beta_0\, A \ln\frac{\mu^2}{Q^2}\right]$$

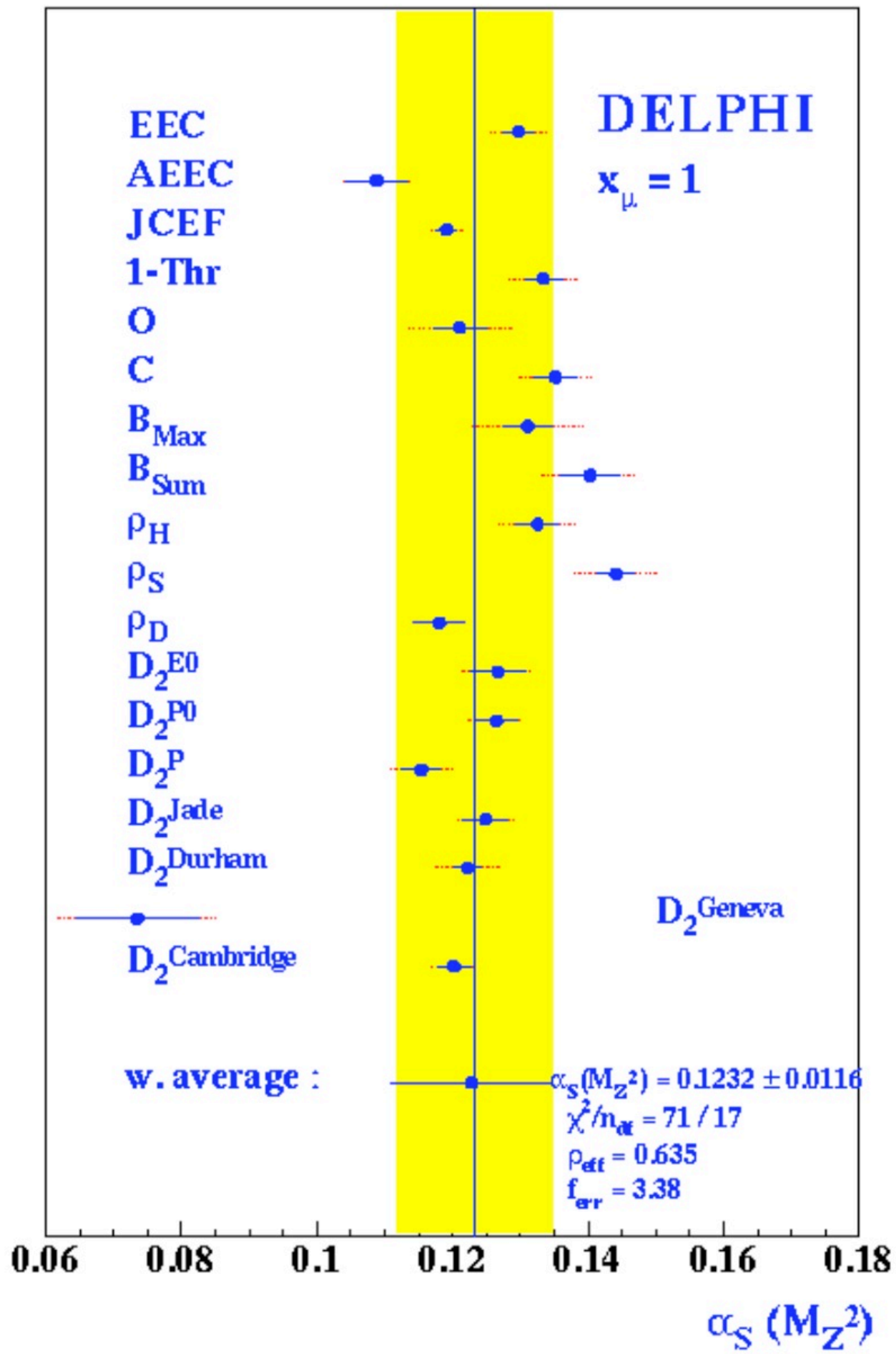
NLO ➠ Resummation

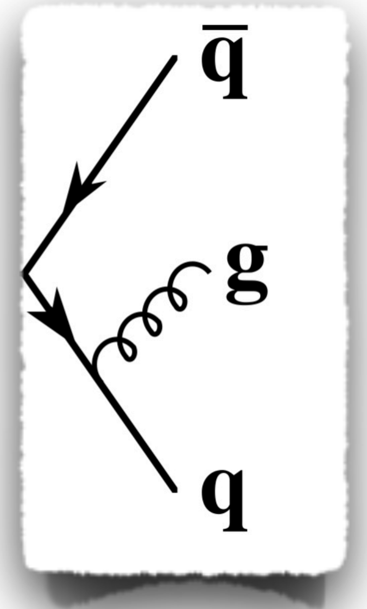


NLO only, typical results

$\alpha_s(M_Z) \approx 0.125 \pm \mathbf{0.010}$

NLO ➠ Resummation





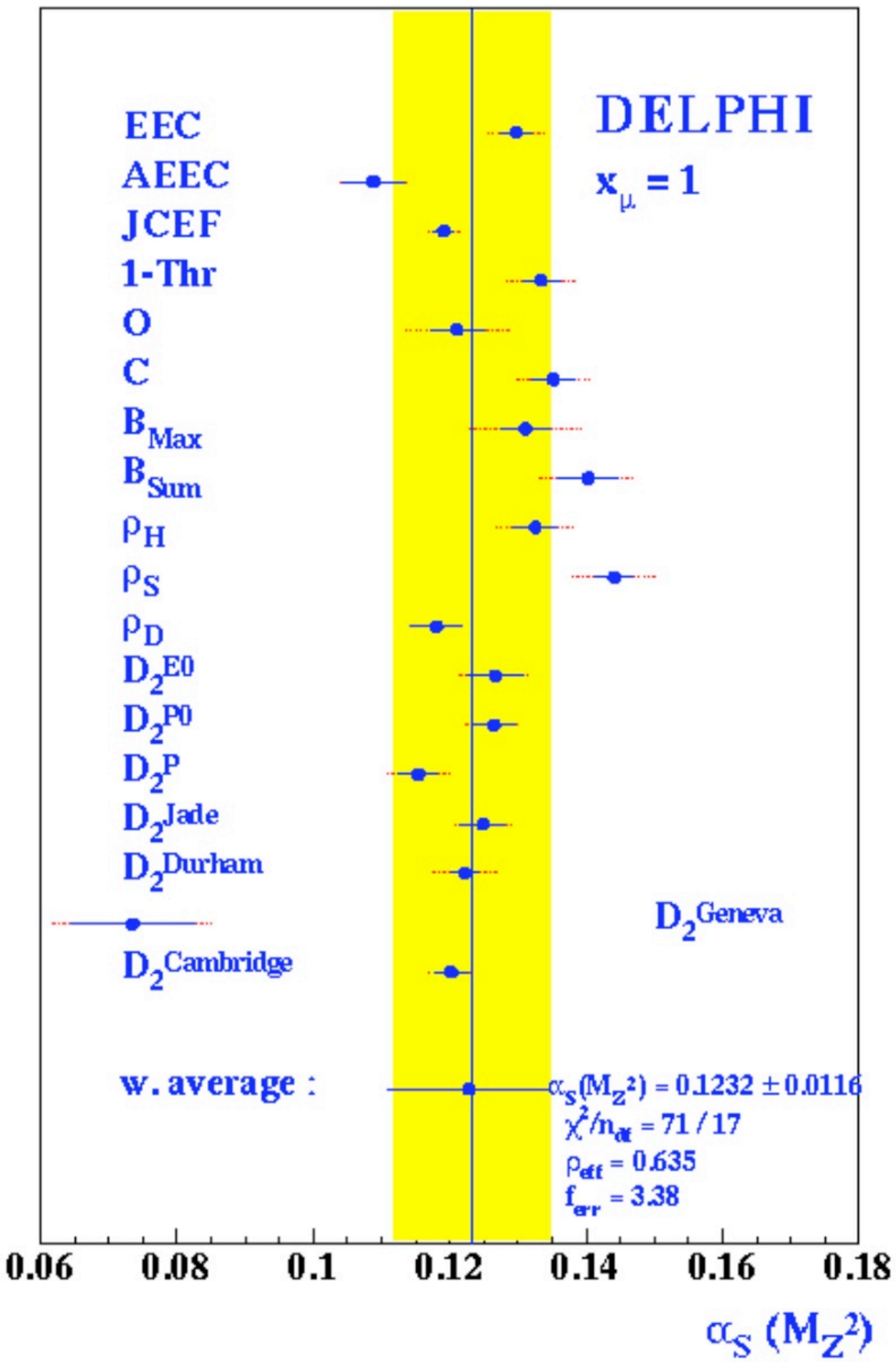
$$\frac{\alpha_s}{E_G(1-\cos\theta_{QG})}$$

$$\Rightarrow \alpha_s \ln^2 y_{cut}$$

NLO only, typical results

$\alpha_s(M_Z) \approx 0.125 \pm$ **0.010**

NLO ➠ Resummation



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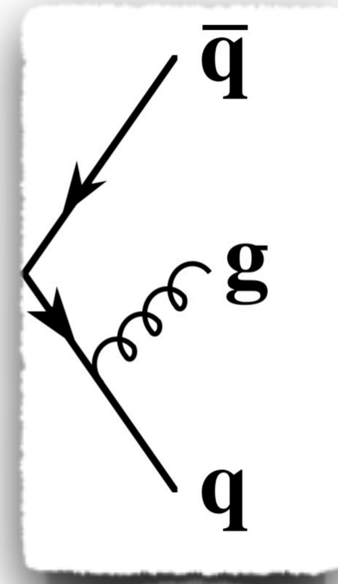

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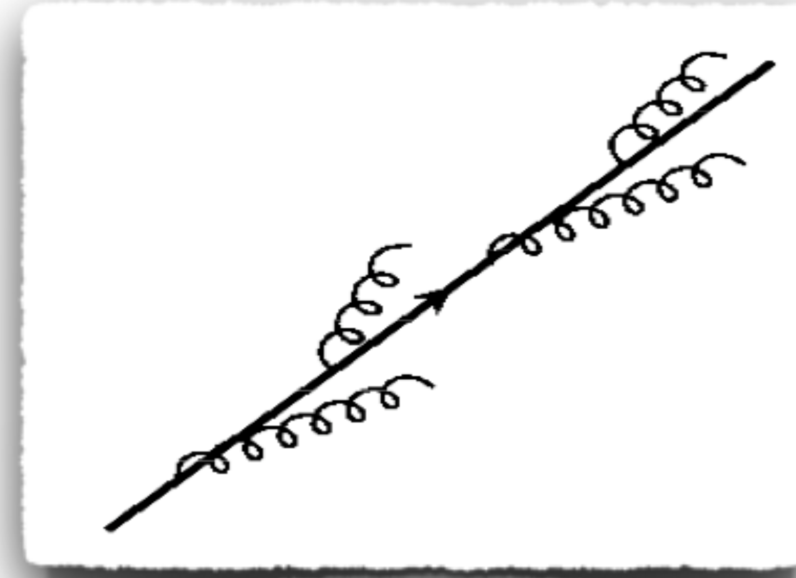
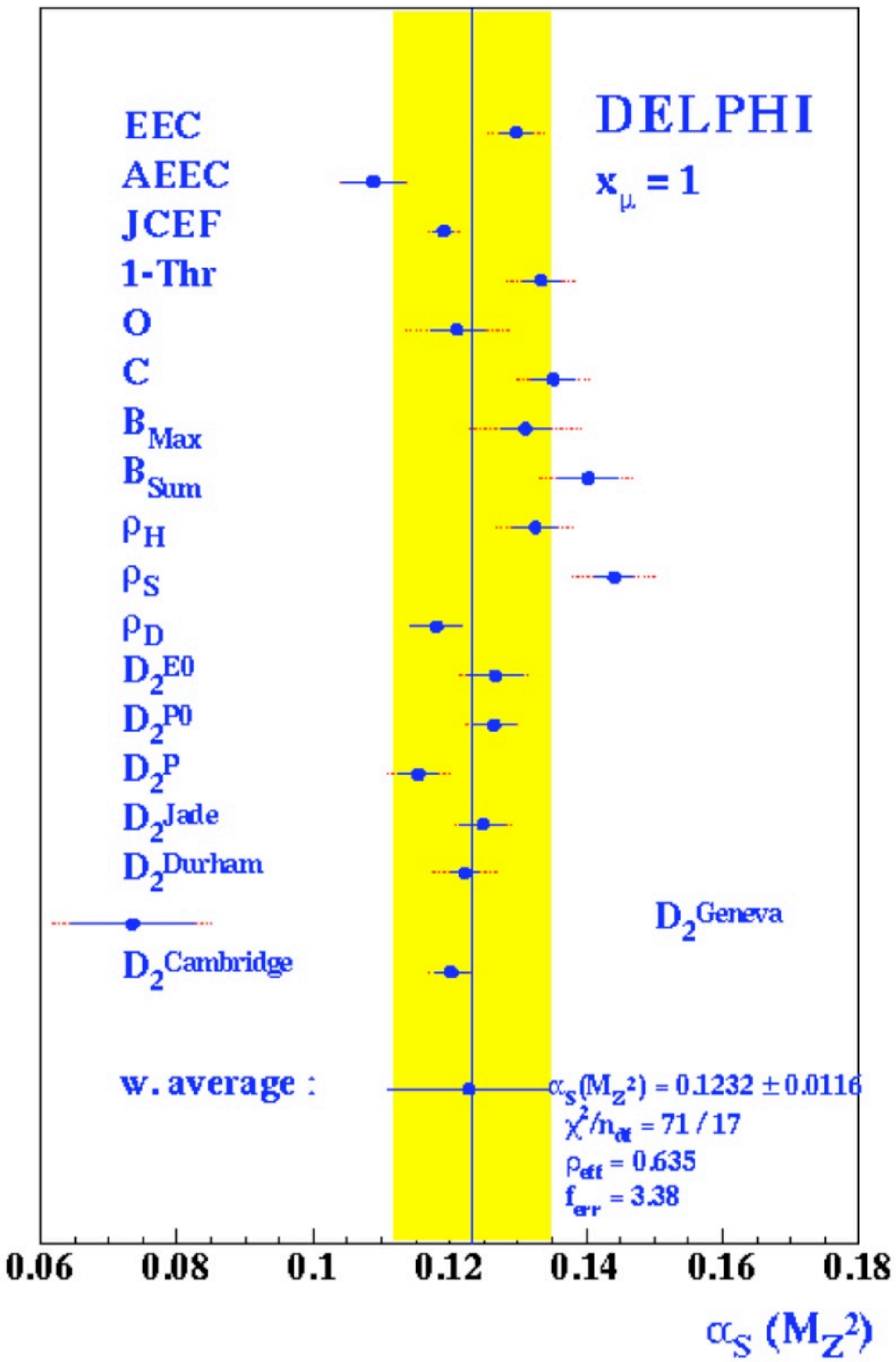


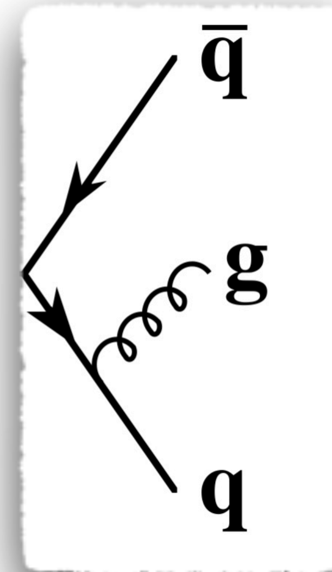
$$\alpha_s^n\ \ln^{2n}\ y_{cut}$$

NLO ➡ Resummation



NLO only, typical results

$\alpha_s(M_Z) \approx 0.125 \pm$ **0.010**



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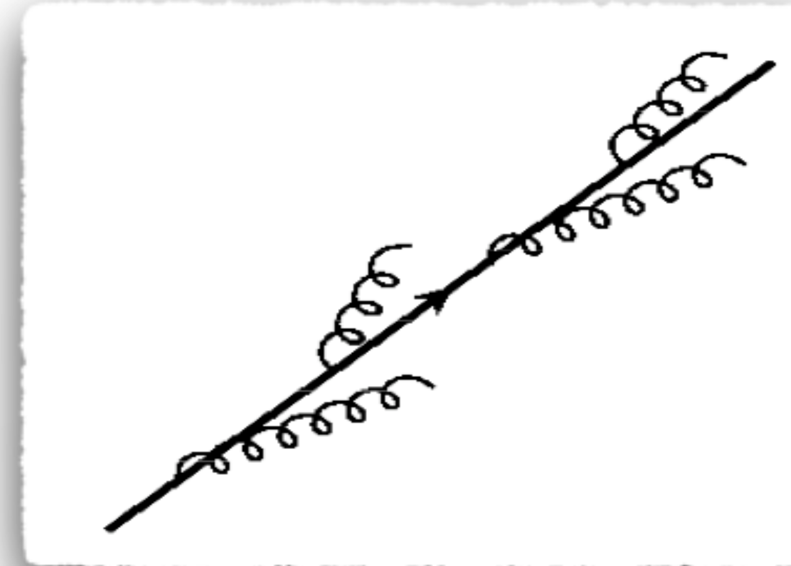
$$\Rightarrow \alpha_s \ln^2 y_{cut}$$

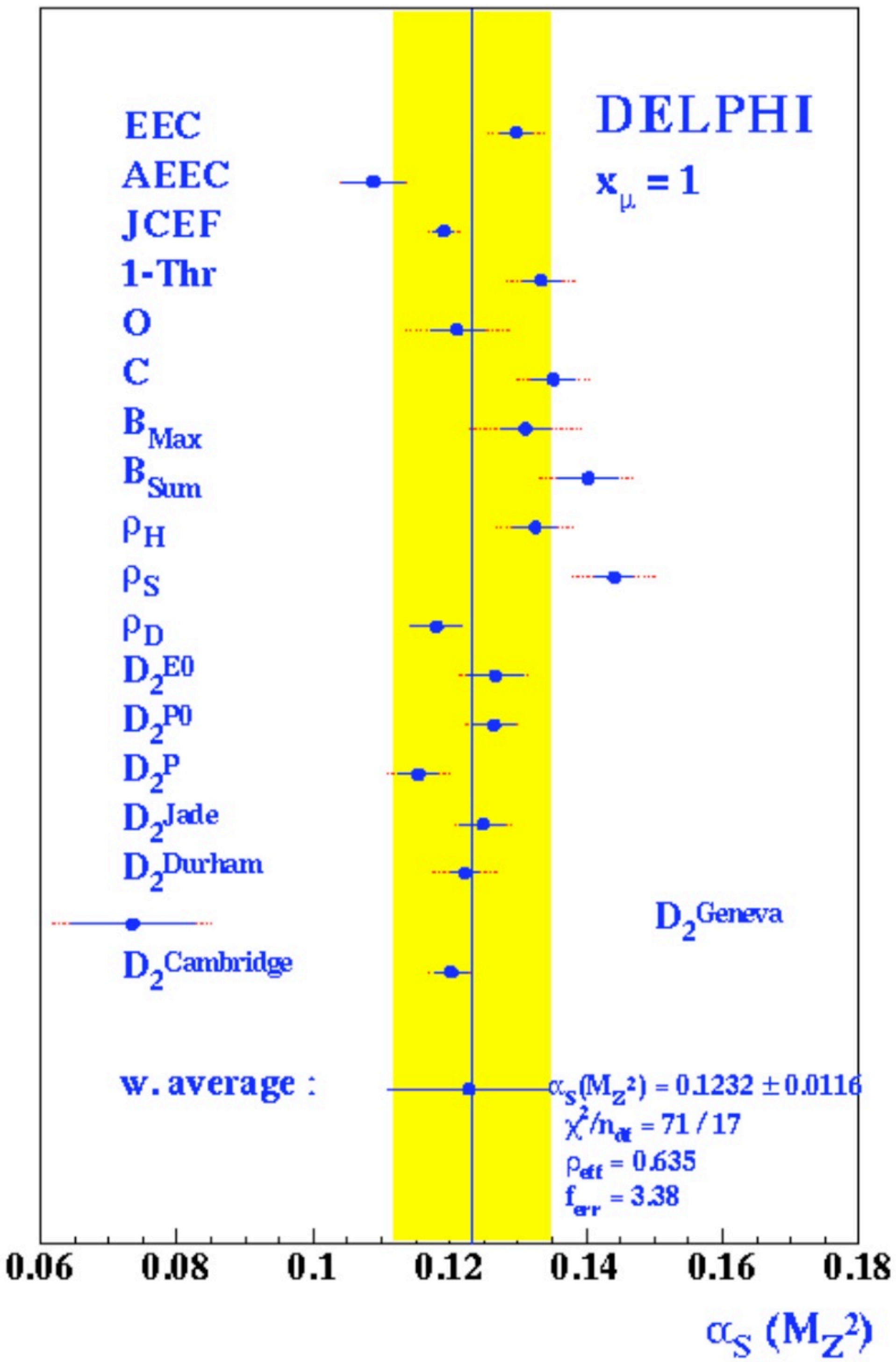


$$\alpha_s^n \ln^{2n} y_{cut}$$

$$\sigma \propto \sigma_{NLO} + \sum_{n,m} c_{n,m}\,\alpha_s^n \ln^m y_{cut}$$

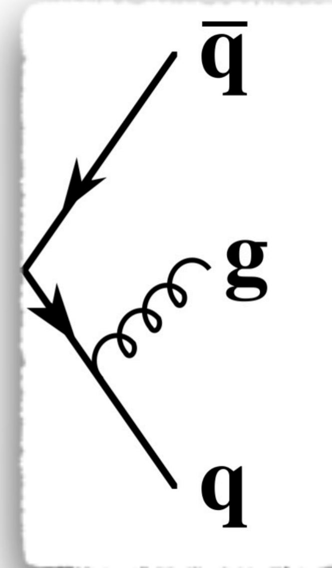
"industry of resummation"

NLO ➠ Resummation



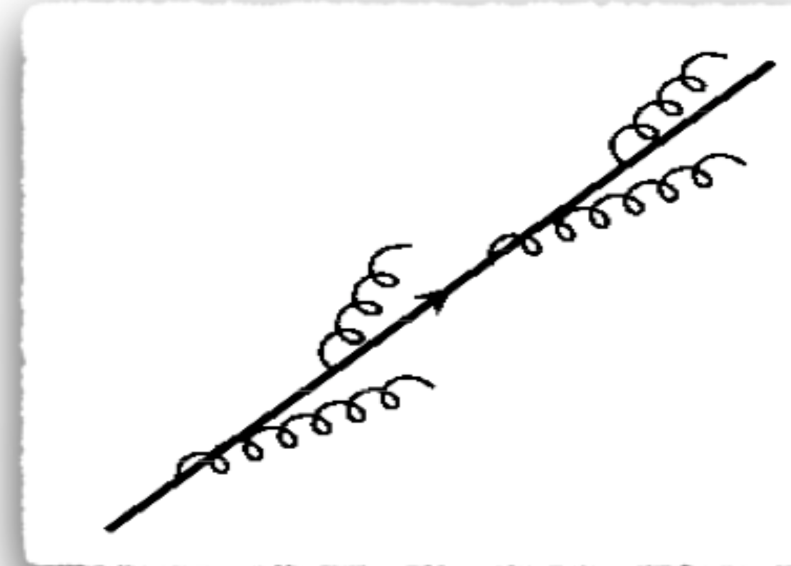
NLO only, typical results

$\alpha_s(M_Z) \approx 0.125 \pm \mathbf{0.010}$



$$\frac{\alpha_s}{E_G\,(1-\cos\theta_{QG})}$$

$$\Rightarrow \alpha_s \ln^2 y_{\rm cut}$$



$$\alpha_s^n \ln^{2n} y_{\rm cut}$$

$$\sigma \propto \sigma_{\rm NLO} + \sum_{n,m} c_{n,m}\, \alpha_s^n \ln^m y_{\rm cut}$$

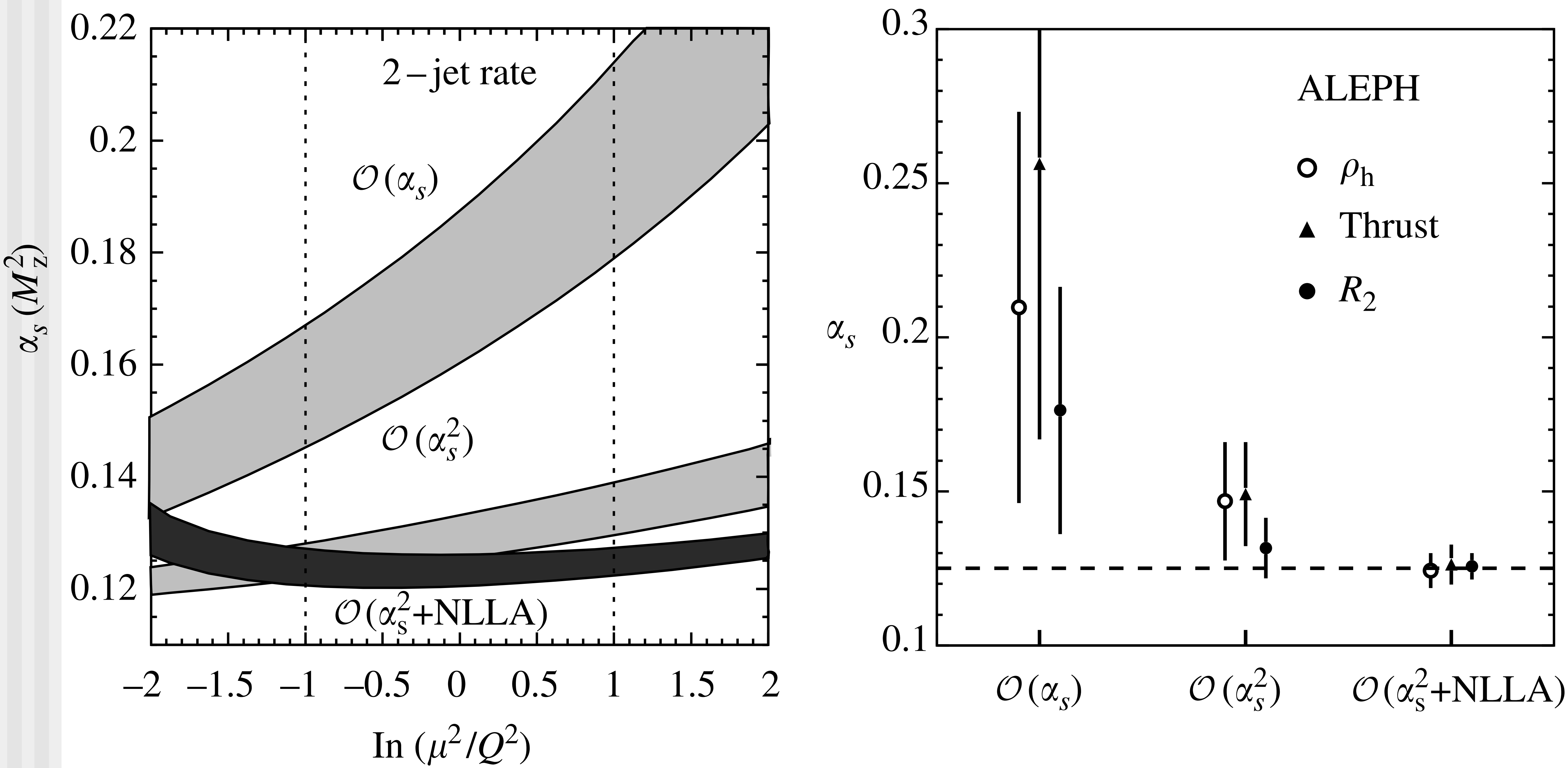
"industry of resummation"

$$y_{ij} = \frac{2\,\min(E_i^2, E_j^2)\,(1-\cos\theta_{ij})}{E_{\rm cm}^2} \approx \frac{k_\perp^2}{E_{\rm cm}^2}$$

Durham Jet Algo

NLO ➠ Resummation

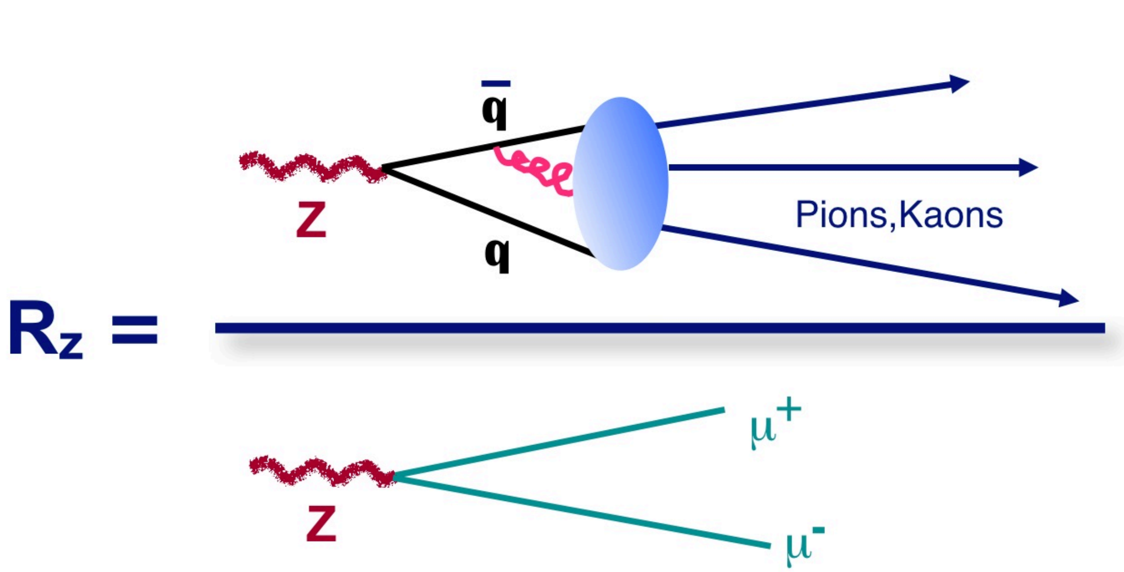
ETH Institute for Particle Physics

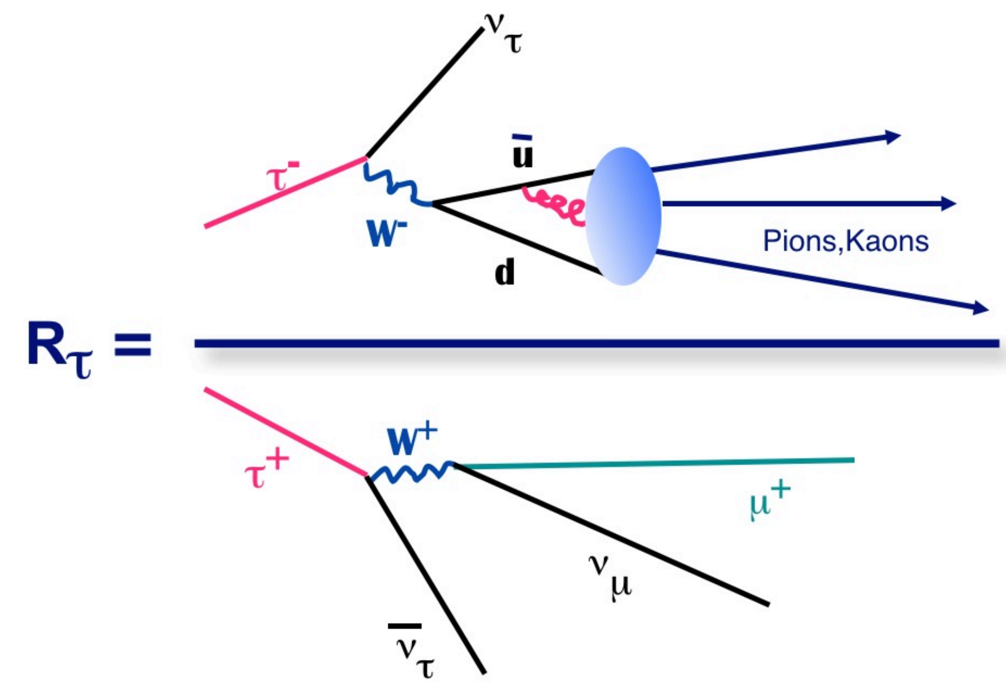


Resummation matched to NLO, typical results

$\alpha_s(M_Z) \approx 0.120 \pm \mathbf{0.005}$

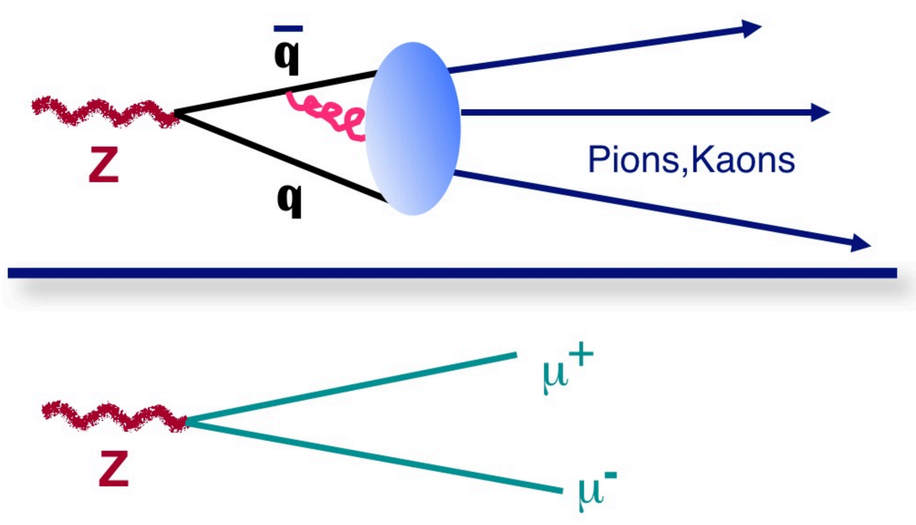
α_s from inclusive Z or Tau Decays



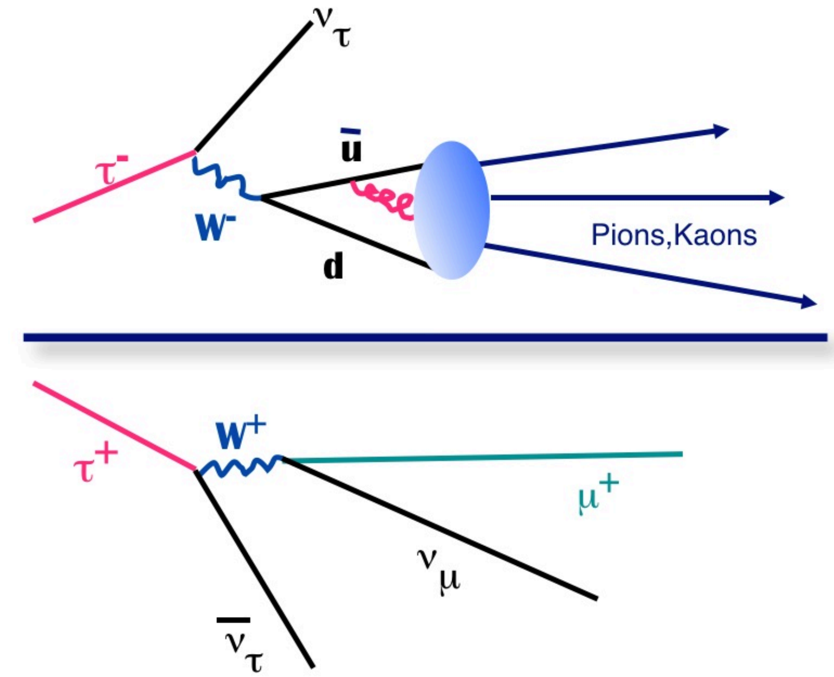


α_s from inclusive Z or Tau Decays

R_Z =



R_τ =

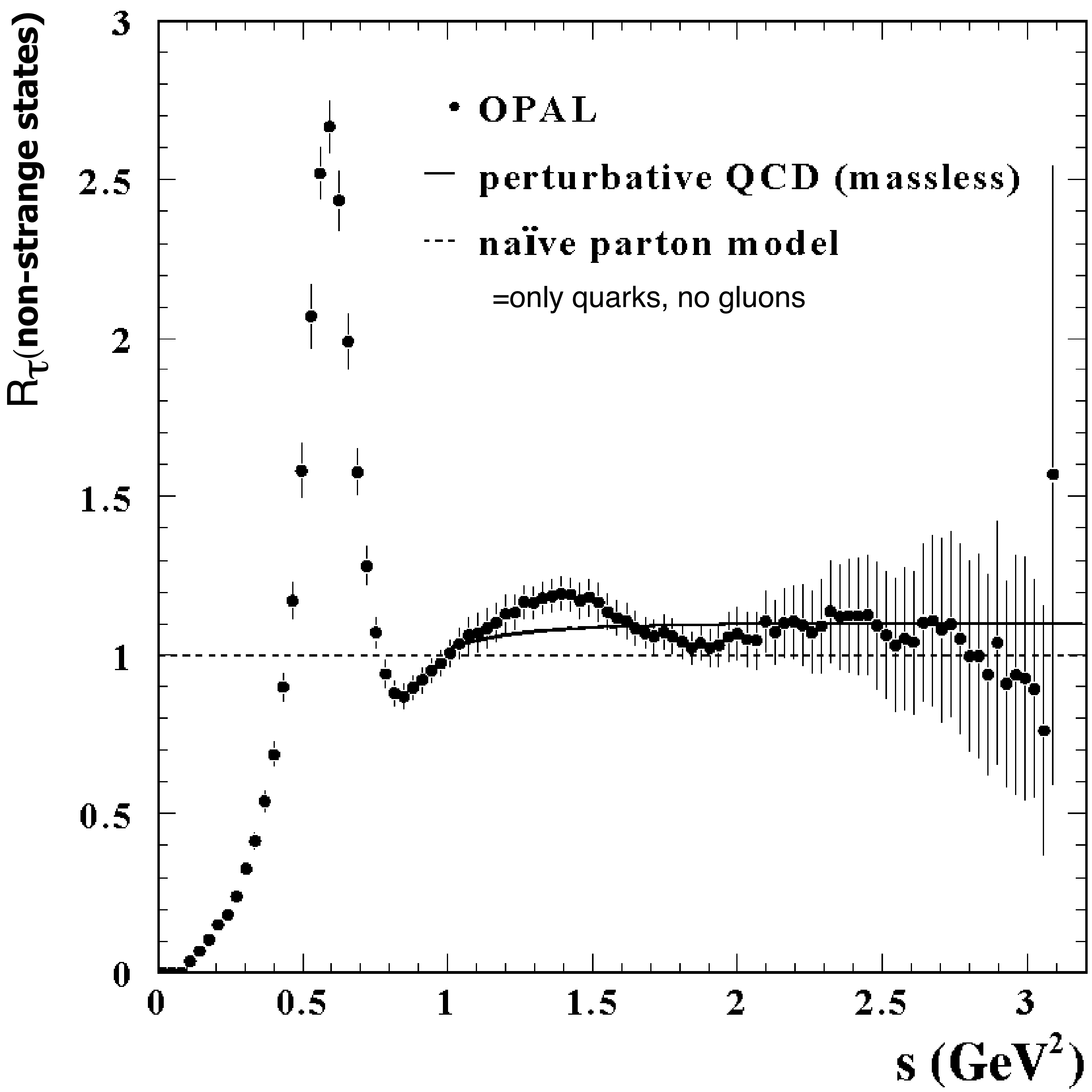


$$R = \frac{\Gamma(Z,\tau \rightarrow Hadrons)}{\Gamma(Z,\tau \rightarrow Leptons)} = R_X^{EW}(1 + \delta_{QCD} + \delta_{mass} + \delta_{np})$$

$$\delta_{QCD} = c_1 \frac{\alpha_s}{\pi} + c_2 \left(\frac{\alpha_s}{\pi}\right)^2 + c_3 \left(\frac{\alpha_s}{\pi}\right)^3 + \ldots \quad \mathcal{O}\left(\frac{\Lambda^4}{Q^4}\right)$$

quarks ((N)NNLO) → hadrons : " x 1"

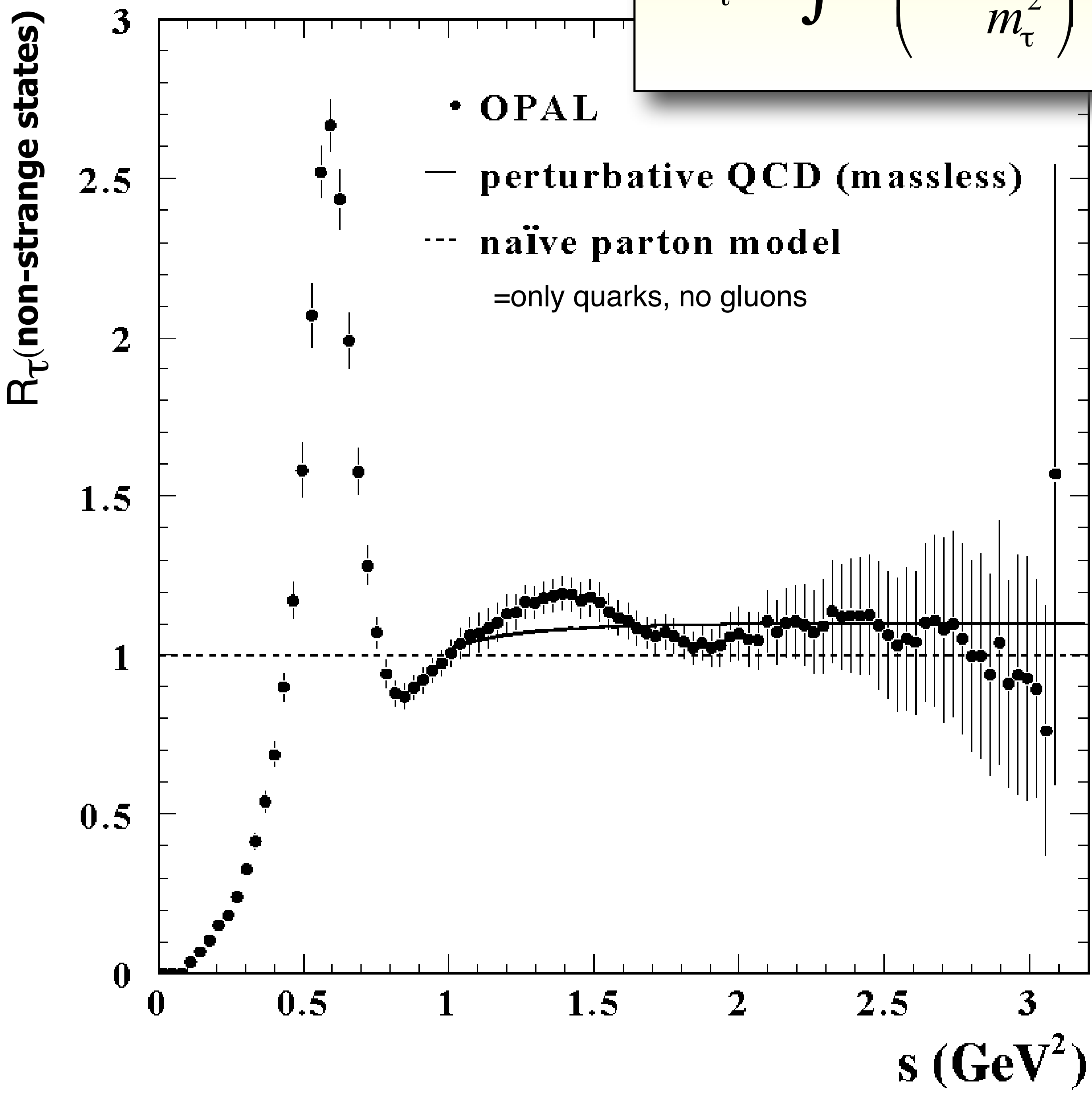
The Beauty of a Moment...



The Beauty of a Moment...

take moments, in order to average out resonances:

$$R_\tau^{kl} = \int ds \left(1 - \frac{s}{m_\tau^2}\right)^k \left(\frac{s}{m_\tau^2}\right)^l \frac{dR_\tau}{ds} \propto 3\,(1 + \delta_{QCD} + \delta_{mass} + \delta_{NP})$$



$$O\left(\frac{<O>}{M_\tau^4}\right)$$

"suprisingly" small, O(1%)

The Beauty of a Moment...

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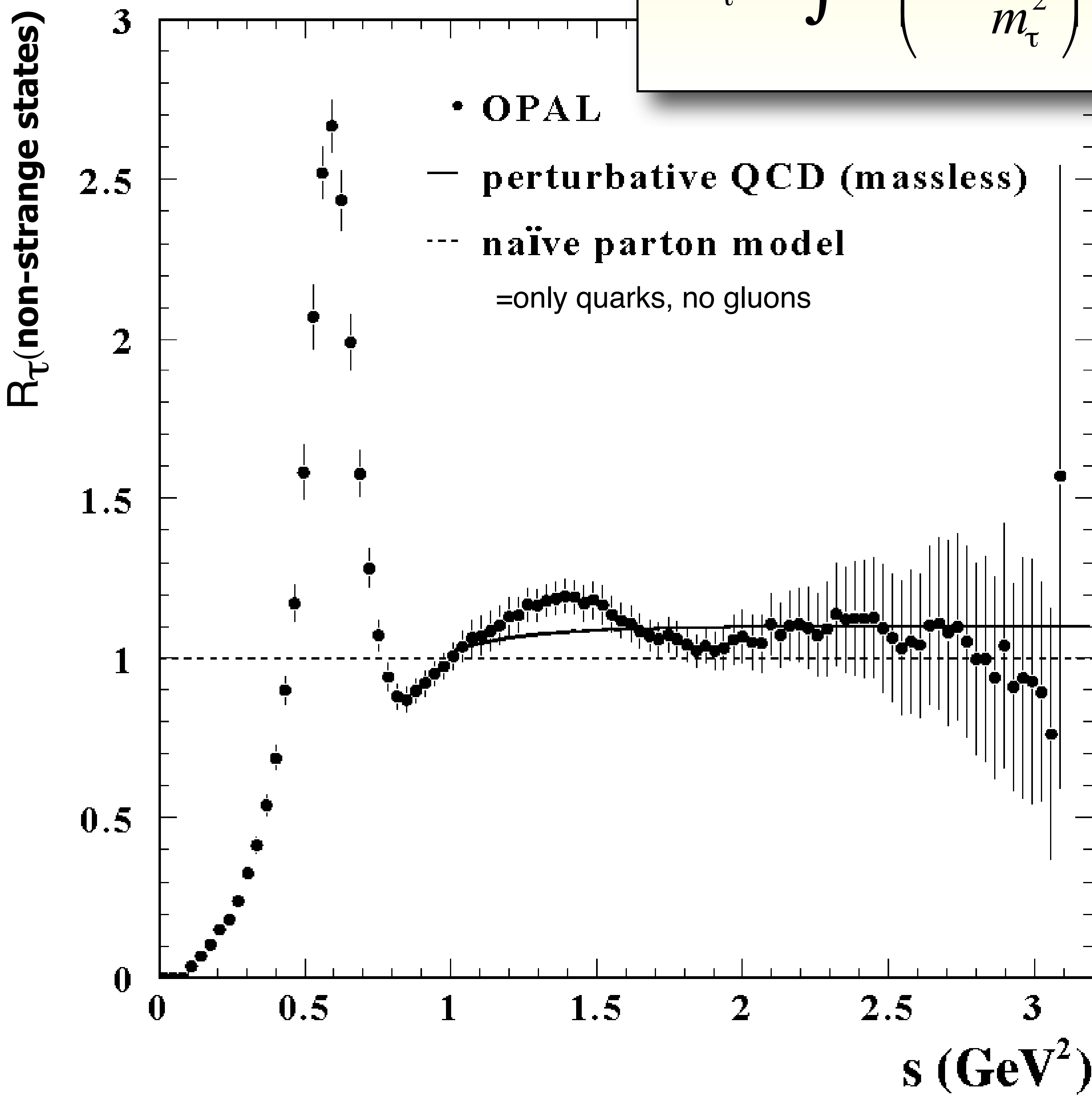
$$R_\tau^{kl} = \int ds \left(1 - \frac{s}{m_\tau^2}\right)^k \left(\frac{s}{m_\tau^2}\right)^l \frac{dR_\tau}{ds} \propto 3\,(1 + \delta_{QCD} + \delta_{mass} + \delta_{NP})$$



$$O\left(\frac{<O>}{M_\tau^4}\right)$$

"suprisingly" small, O(1%)

Bethke, Dissertori, Salam (PDG, 2016, prelim)

$$\alpha_s(M_\tau^2) = 0.325 \pm 0.015$$

$$\downarrow$$

$$\alpha_s(M_Z^2) = 0.1192 \pm 0.0018$$

compare to, e.g. Pich, Rodriguez-Sanchez, 2016

$$\alpha_s(M_Z^2) = 0.1197 \pm 0.0014$$

Guido’s take on it…

arXiv:1303.6065v1 [hep-ph] 25 Mar 2013

The QCD Running Coupling and its Measurement

Guido Altarelli[*†]
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INFN, Sezione di Roma Tre, I-00146 Rome, Italy

and
CERN, Department of Physics, Theory Division
CH-1211 Geneva 23, Switzerland

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In this lecture, after recalling the basic definitions and facts about the running coupling in QCD, I present a critical discussion of the methods for measuring α_s and select those that appear to me as the most reliably precise

Guido’s take on it…

ETH Institute for Particle Physics

The QCD Running Coupling and its Measurement

Guido Altarelli[*†]
Dipartimento di Fisica ‘E. Amaldi’, Università di Roma Tre
INFN, Sezione di Roma Tre, I-00146 Rome, Italy

mination). In my opinion one should select few theoretically simplest processes for measuring α_s and consider all other ways as tests of the theory. Note that this is what is usually done in QED

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Guido’s take on it…

The QCD Running Coupling and its Measurement

Guido Altarelli[*†]
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In any case, one can discuss the error, but what is true and remarkable, is that the central value of α_s from τ decay, obtained at very small Q^2, is in good agreement with all other precise determinations of α_s at more typical LEP values of Q^2.

The rise of (diff.) NNLO

https://www.tes.com/lessons/k1Ba06GZasKO3g/sunrise

Beginning of this millenium:

Out of heoric efforts, the first **differential NNLO** calculations appear, not only for e^+e^-, but also for DY and Higgs prod. at hadron colliders !

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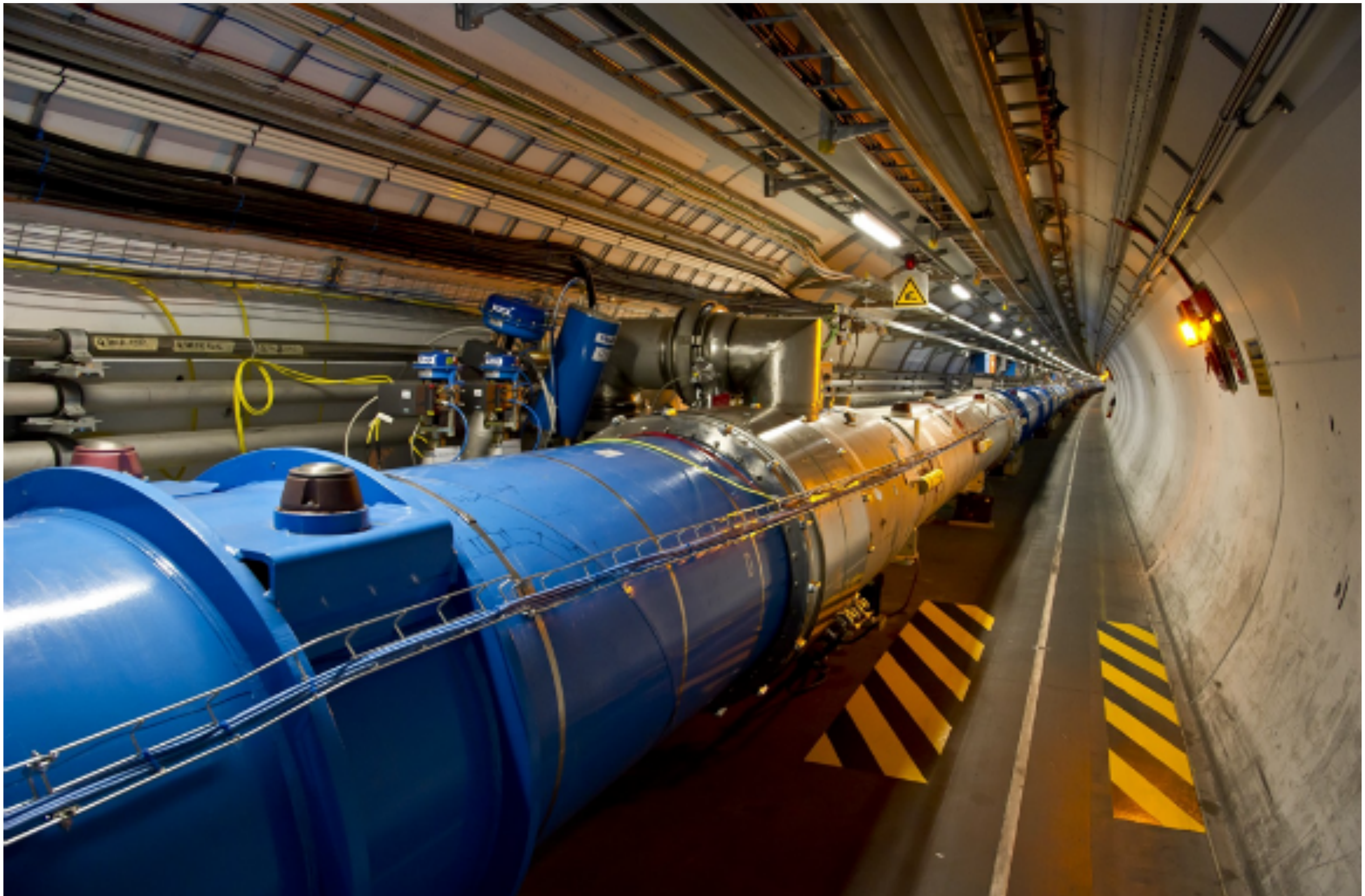
eg. very first α_s measurement at NNLO, 3-jet rate, in 2009: $\alpha_s(M_Z) \approx 0.1175 \pm \mathbf{0.0025}$

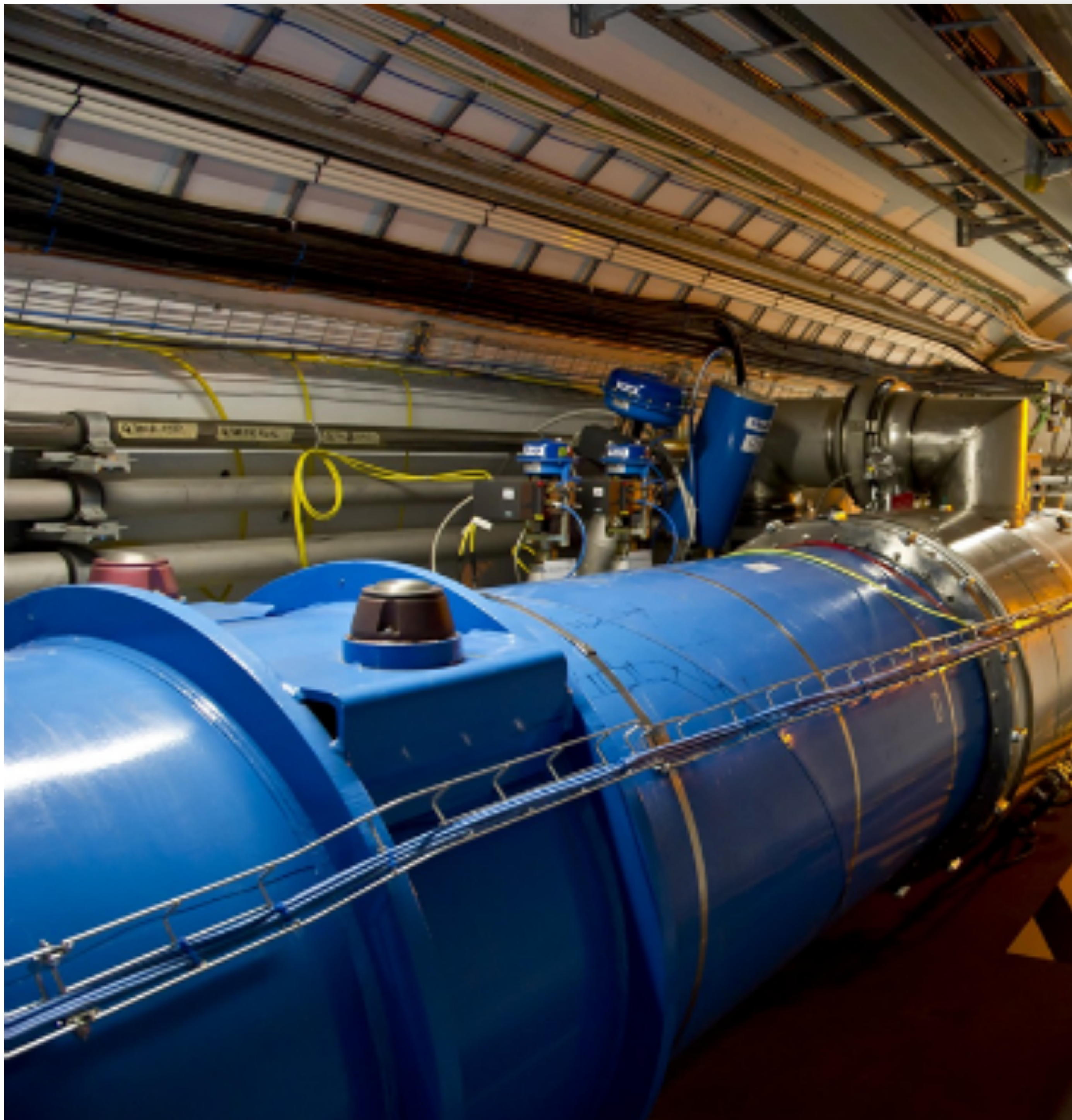
Dissertori et al

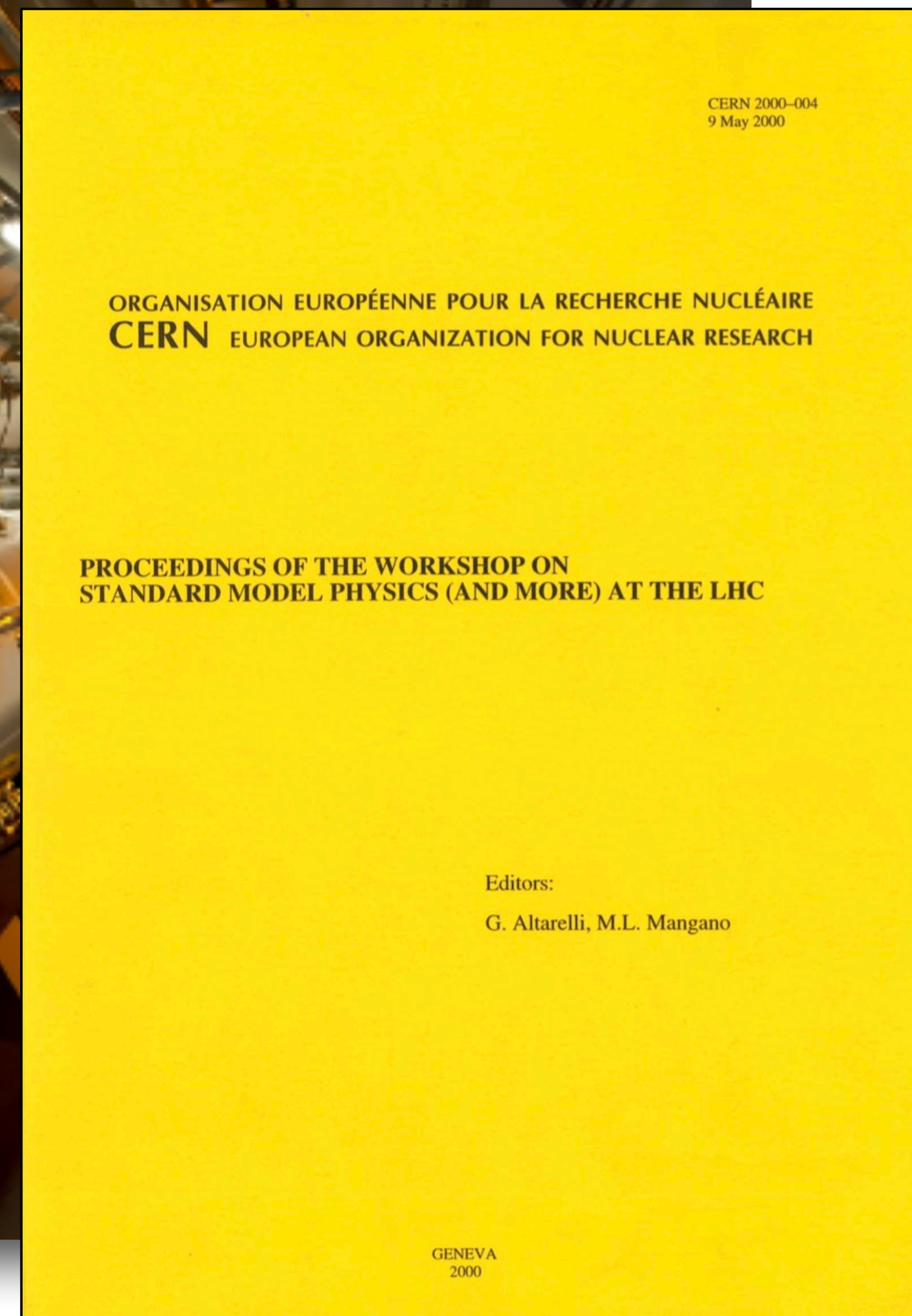
LEP ➠ LHC

LEP ➠ LHC



LEP ➠ LHC





CERN 2000–004
9 May 2000

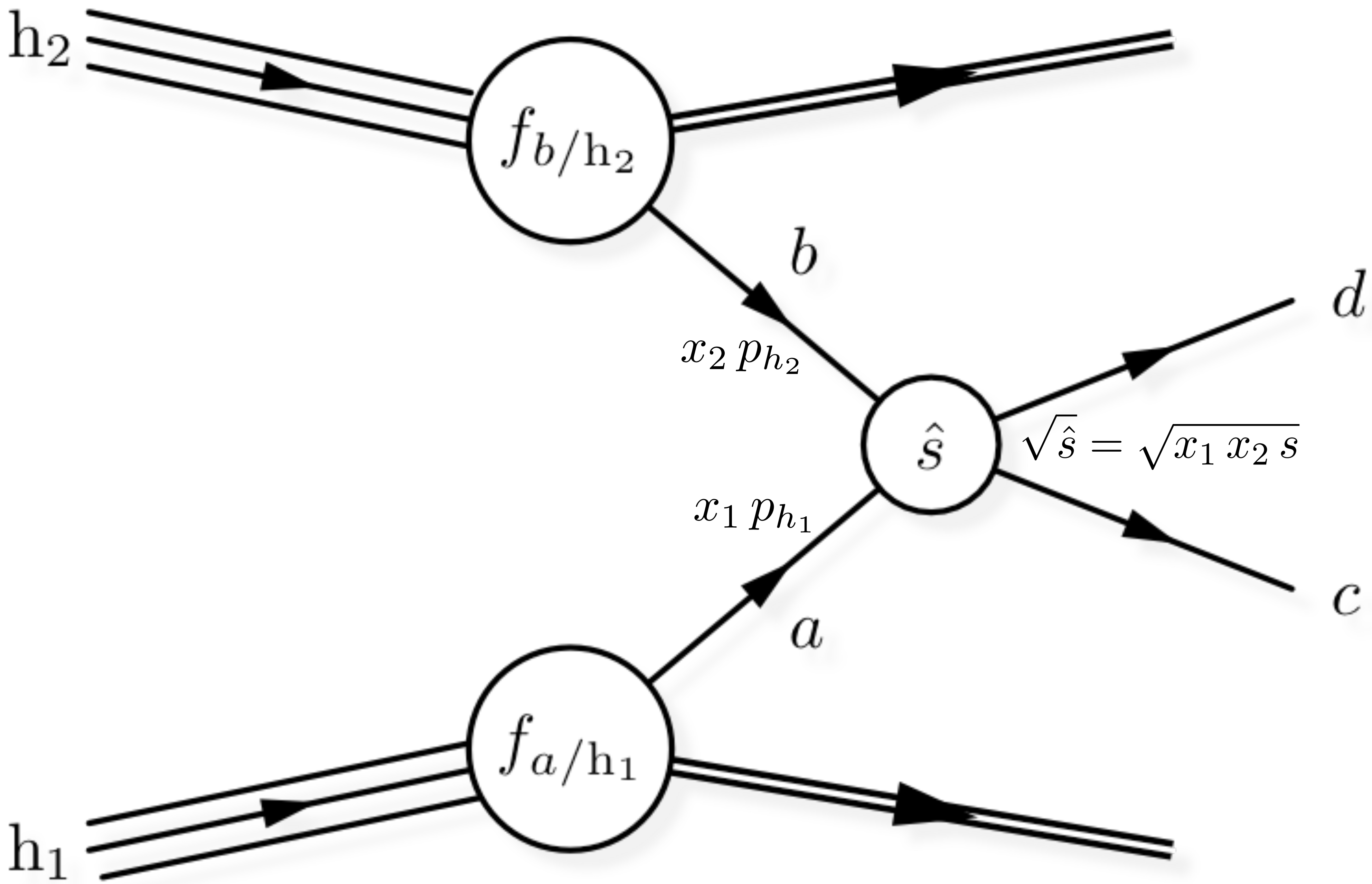
ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PROCEEDINGS OF THE WORKSHOP ON
STANDARD MODEL PHYSICS (AND MORE) AT THE LHC

Editors:
G. Altarelli, M.L. Mangano

GENEVA
2000

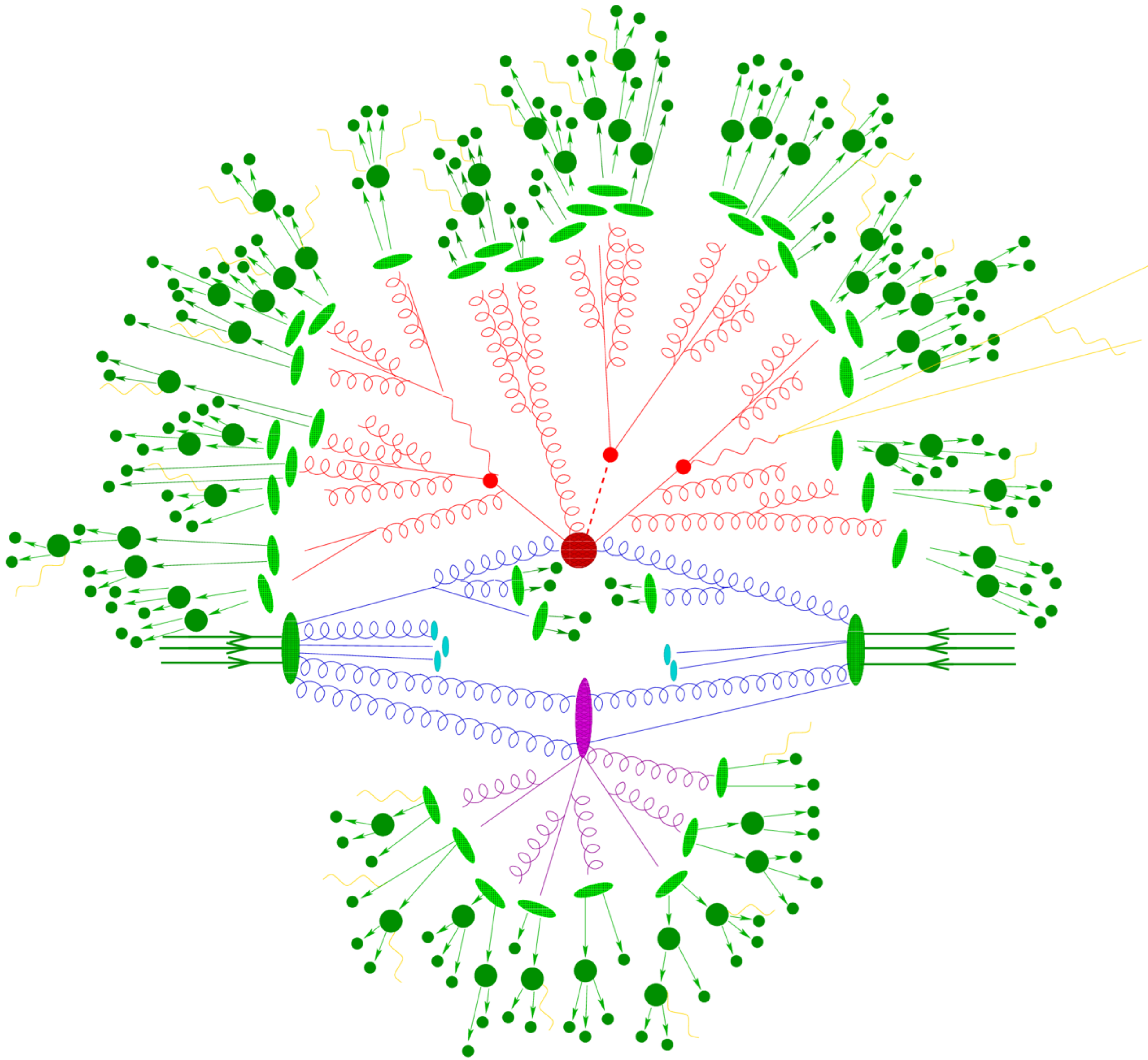
Anatomy of a hadron-hadron collision



$$\mathrm{d}\sigma(\mathrm{h}_1\mathrm{h}_2 \to cd) = \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 \sum_{a,b} f_{a/\mathrm{h}_1}(x_1, \mu_F^2) f_{b/\mathrm{h}_2}(x_2, \mu_F^2) \mathrm{d}\hat{\sigma}^{(ab\to cd)}(Q^2, \mu_F^2)$$

Anatomy of a hadron-hadron collision

Guido's Memorial Symposium

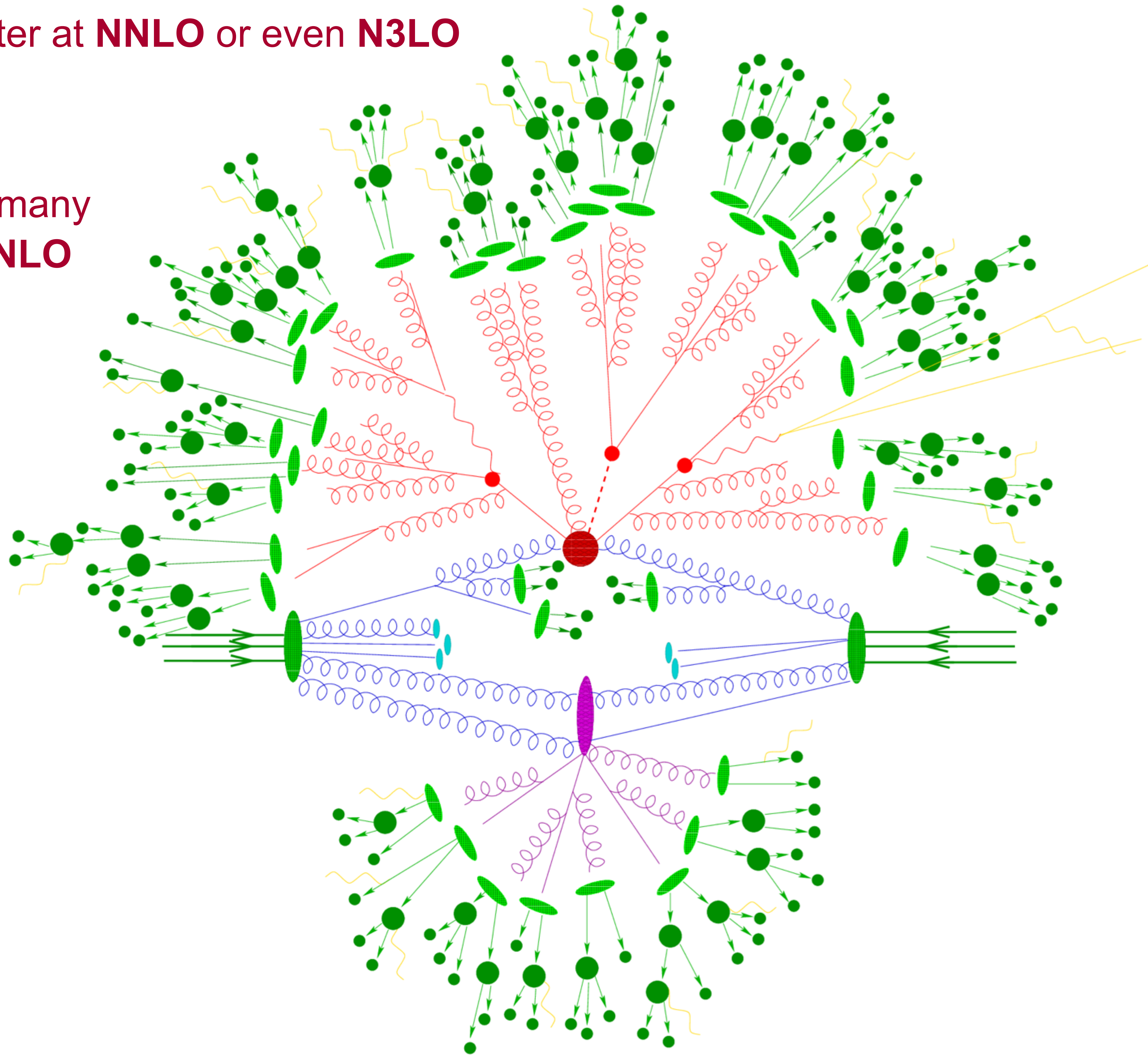


https://inspirehep.net/record/1328513/plots

Anatomy of a hadron-hadron collision

hard scatter at **NNLO** or even **N3LO**

some to many legs at **NLO**



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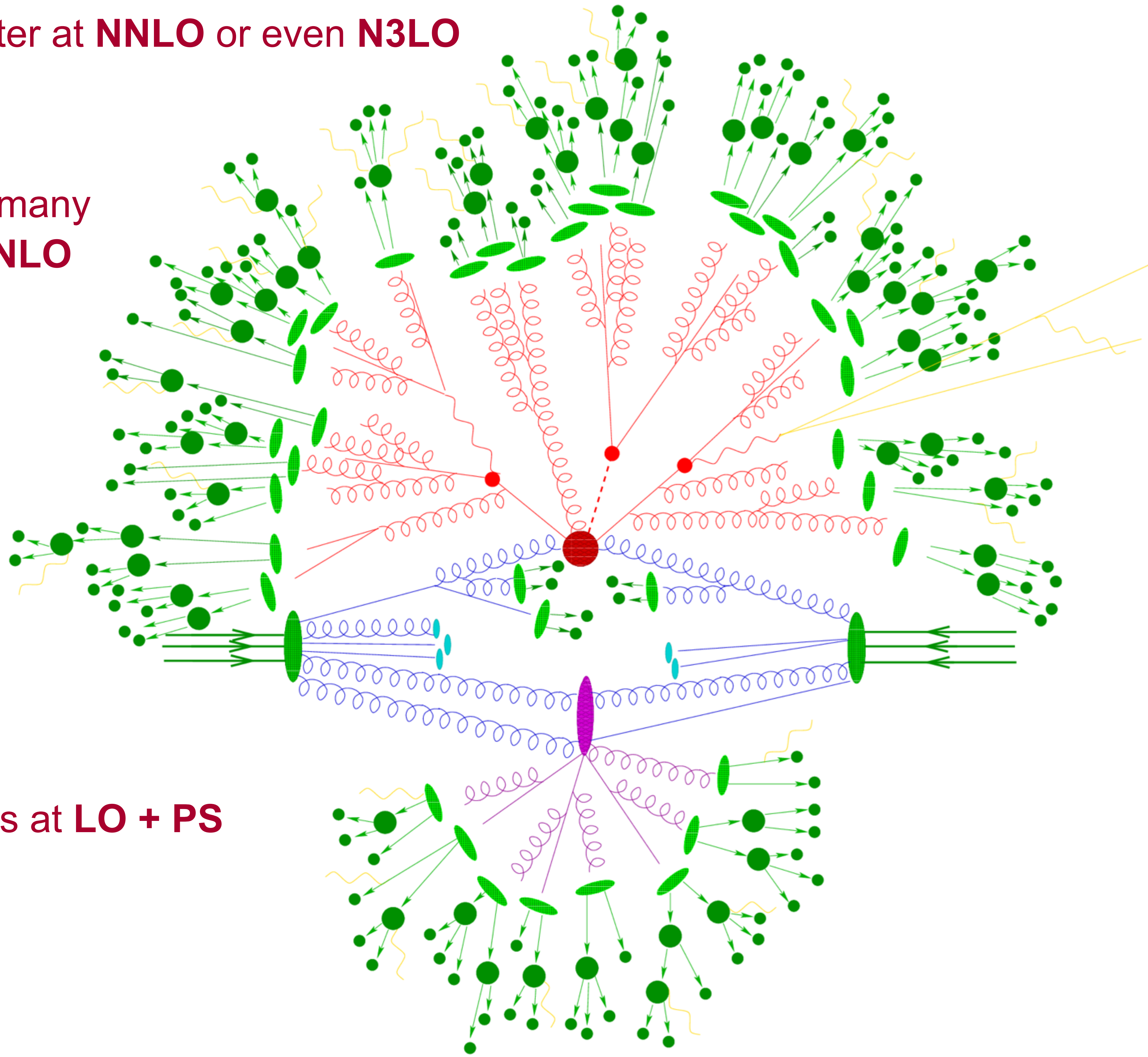

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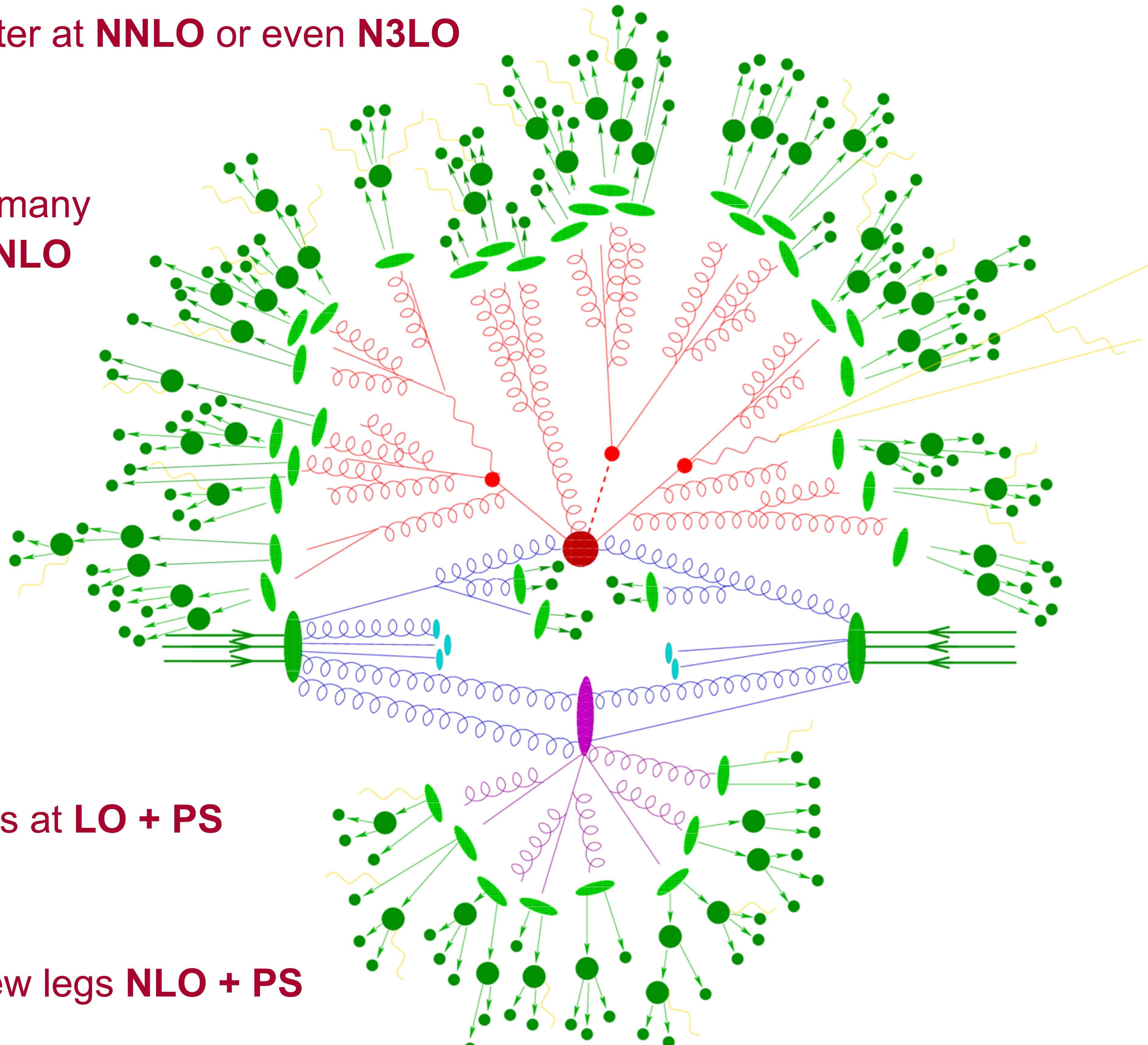

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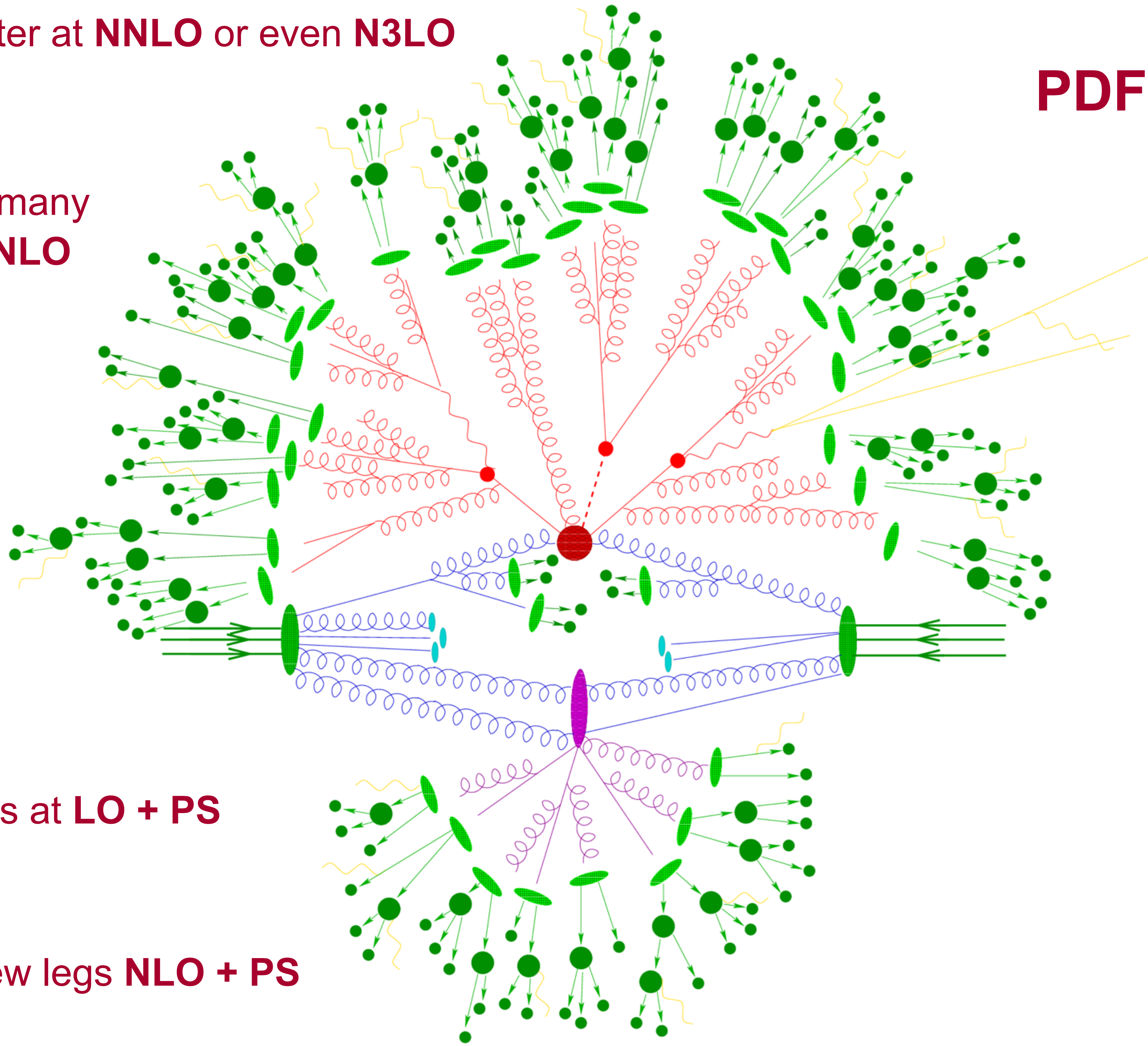

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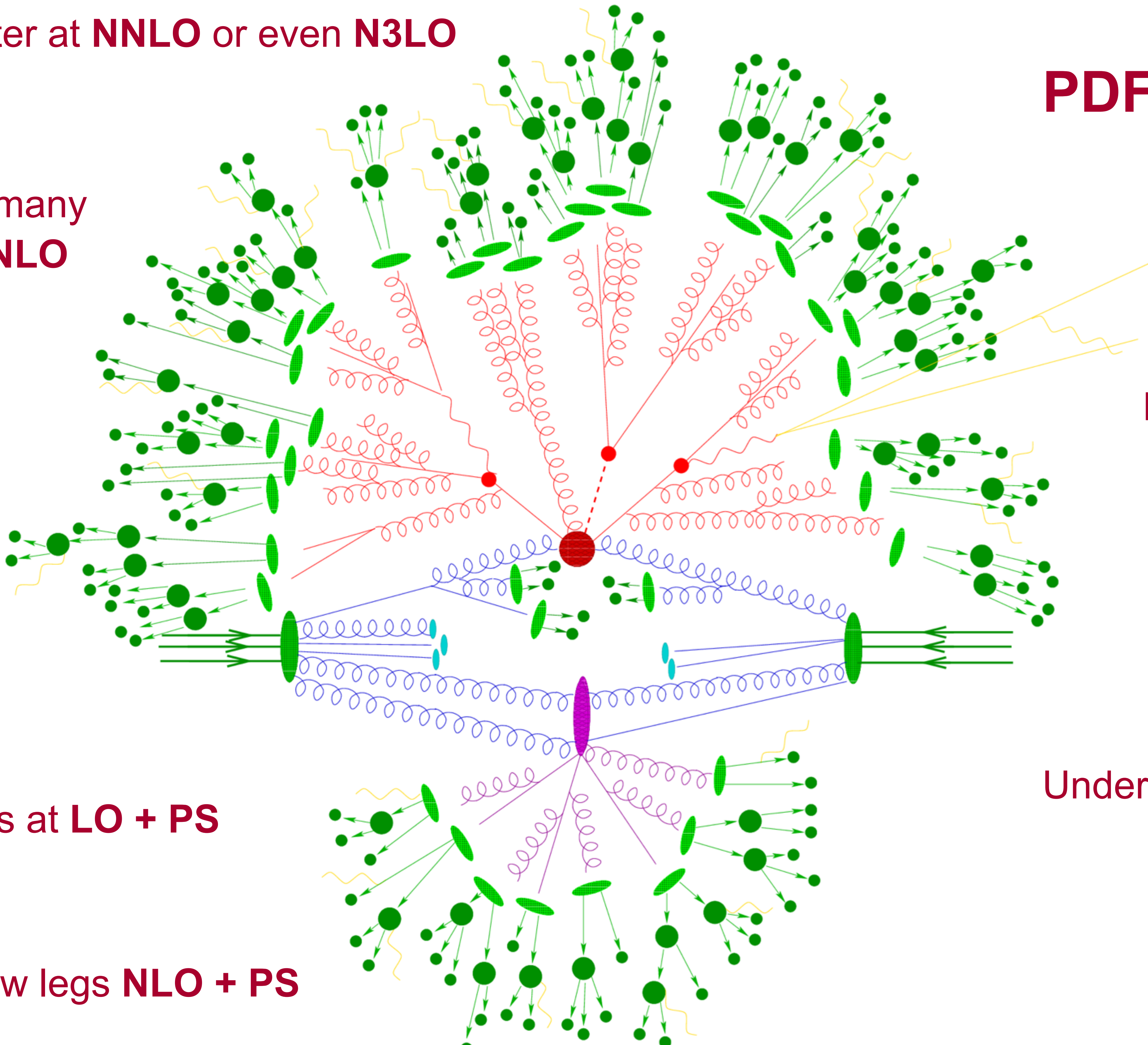
PDFs

Multi-Parton Interactions



ISR

Underlying Event

many legs at **LO + PS**

a few legs **NLO + PS**

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Anatomy of a hadron-hadron collision

ETH Institute for Particle Physics

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PDFs

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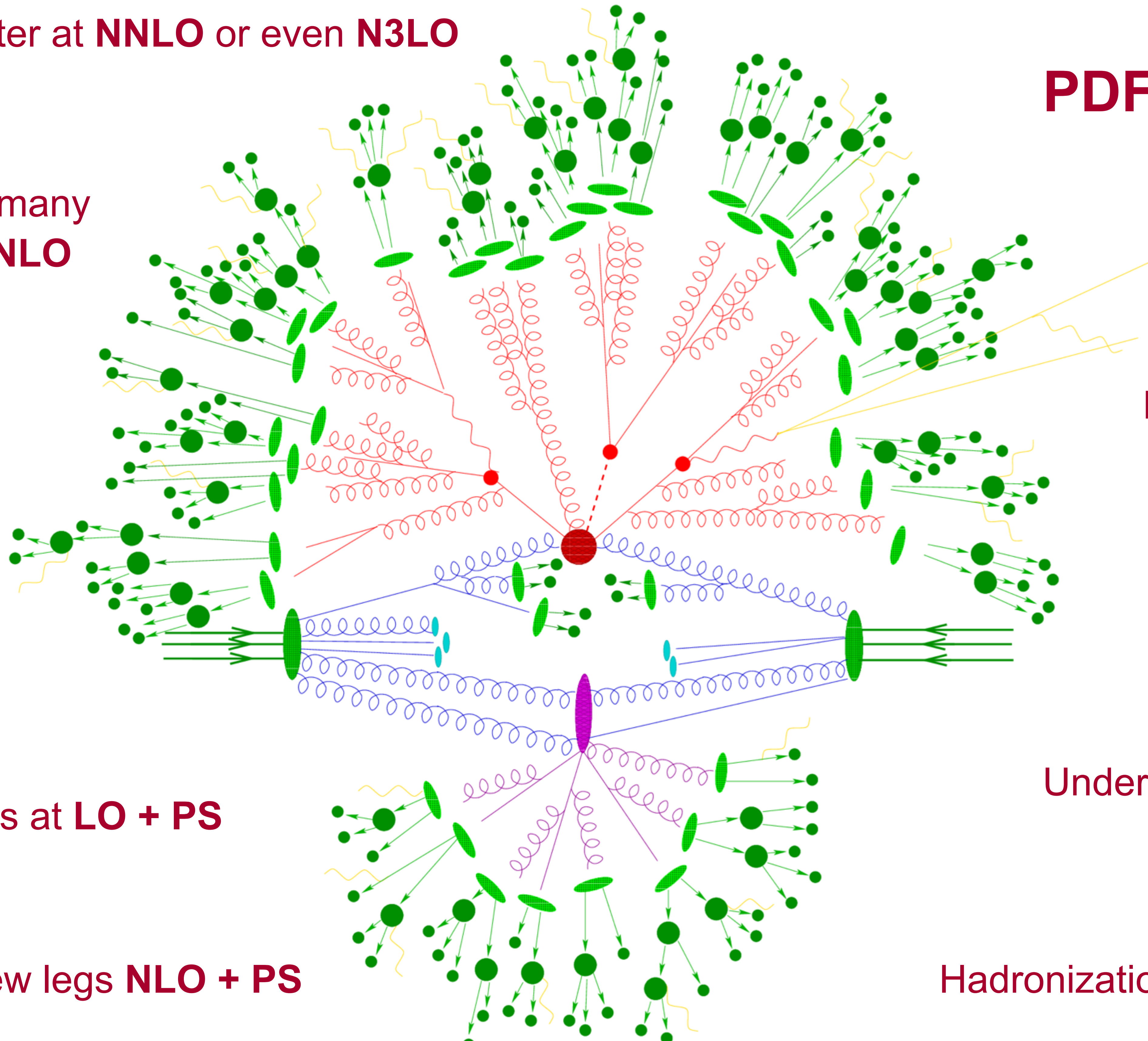


Multi-Parton Interactions

ISR

many legs at **LO + PS**

Underlying Event

a few legs **NLO + PS**

Hadronization

The rise of automated tools, multi-leg generators, MC @ NLO, …., N3LO

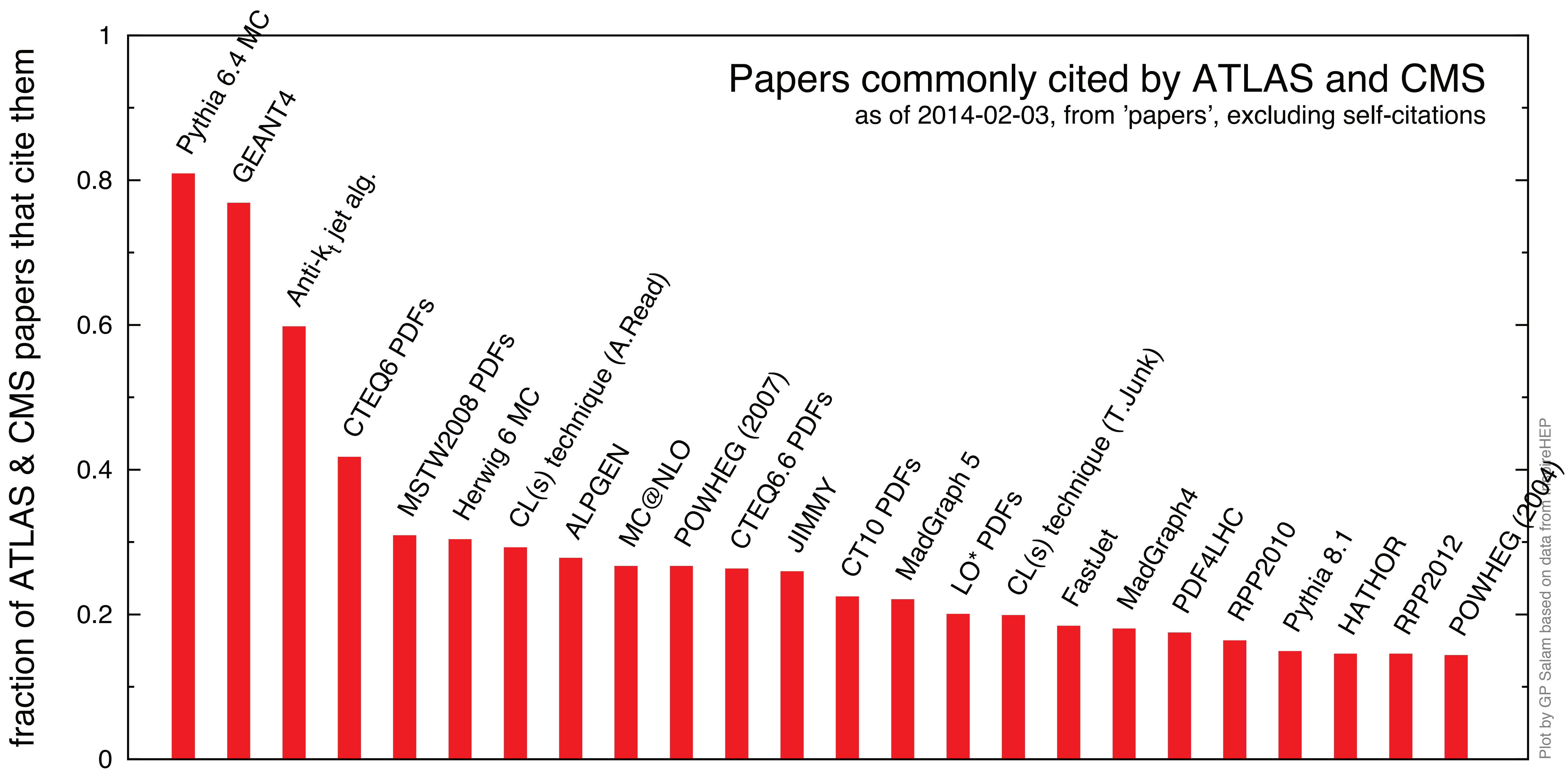
During the last ~decade:

A real explosion in the content of our tool-box;

again, thanks to many heroic efforts!

Giulia Zanderighi compared some of them to the 7 wonders of the world……… (Moriond 2016)

The Toolbox gives citations…



courtesy G. Salam,
see also http://www.lpthe.jussieu.fr/~salam/talks/repo/2012-LaThuile-collider-QCD-Salam-SILAFAE.pdf

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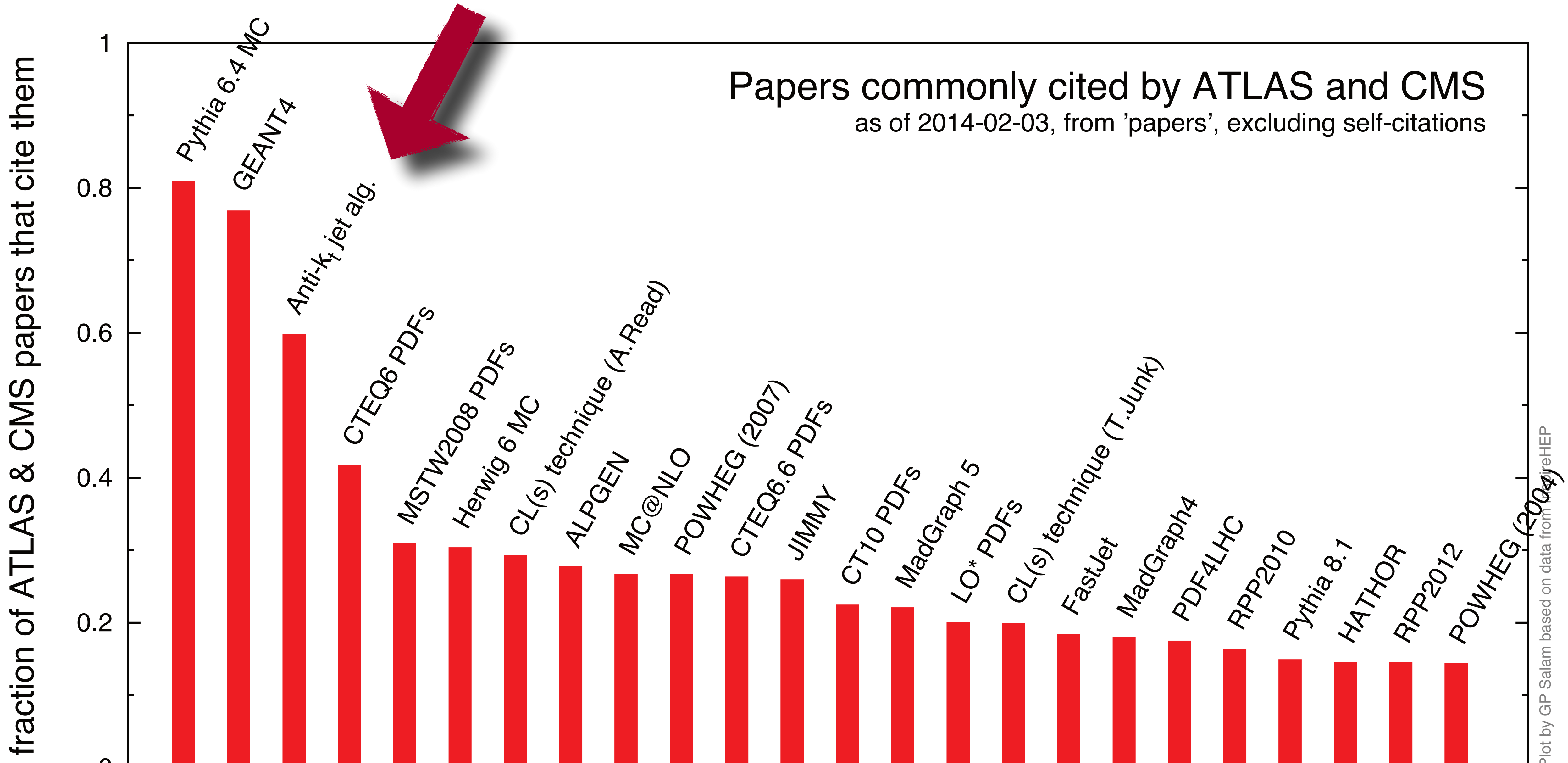

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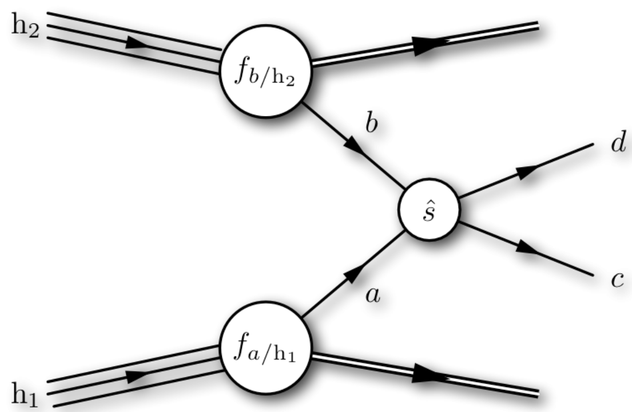
And the experiments don’t do badly, either …



some examples

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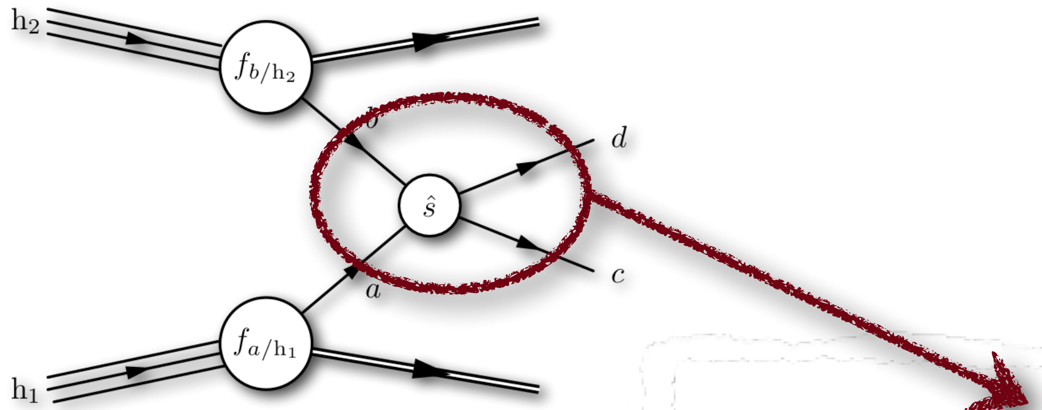
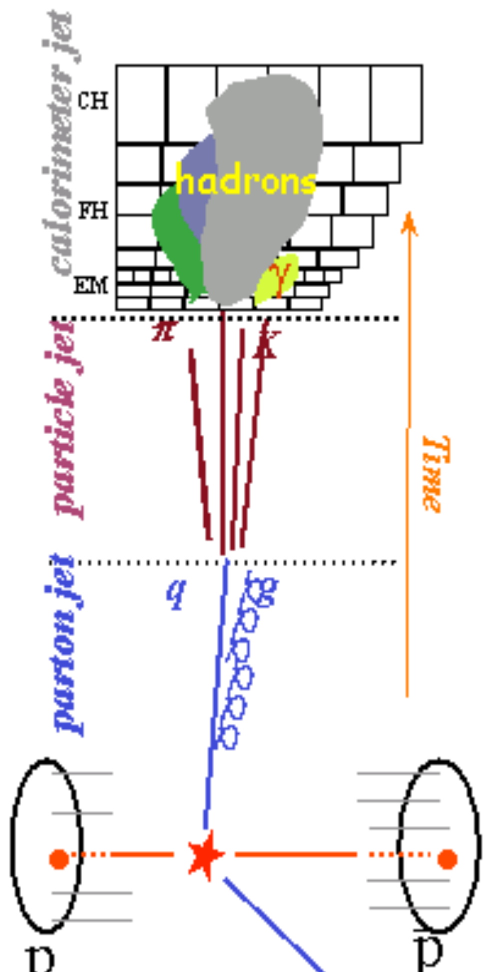
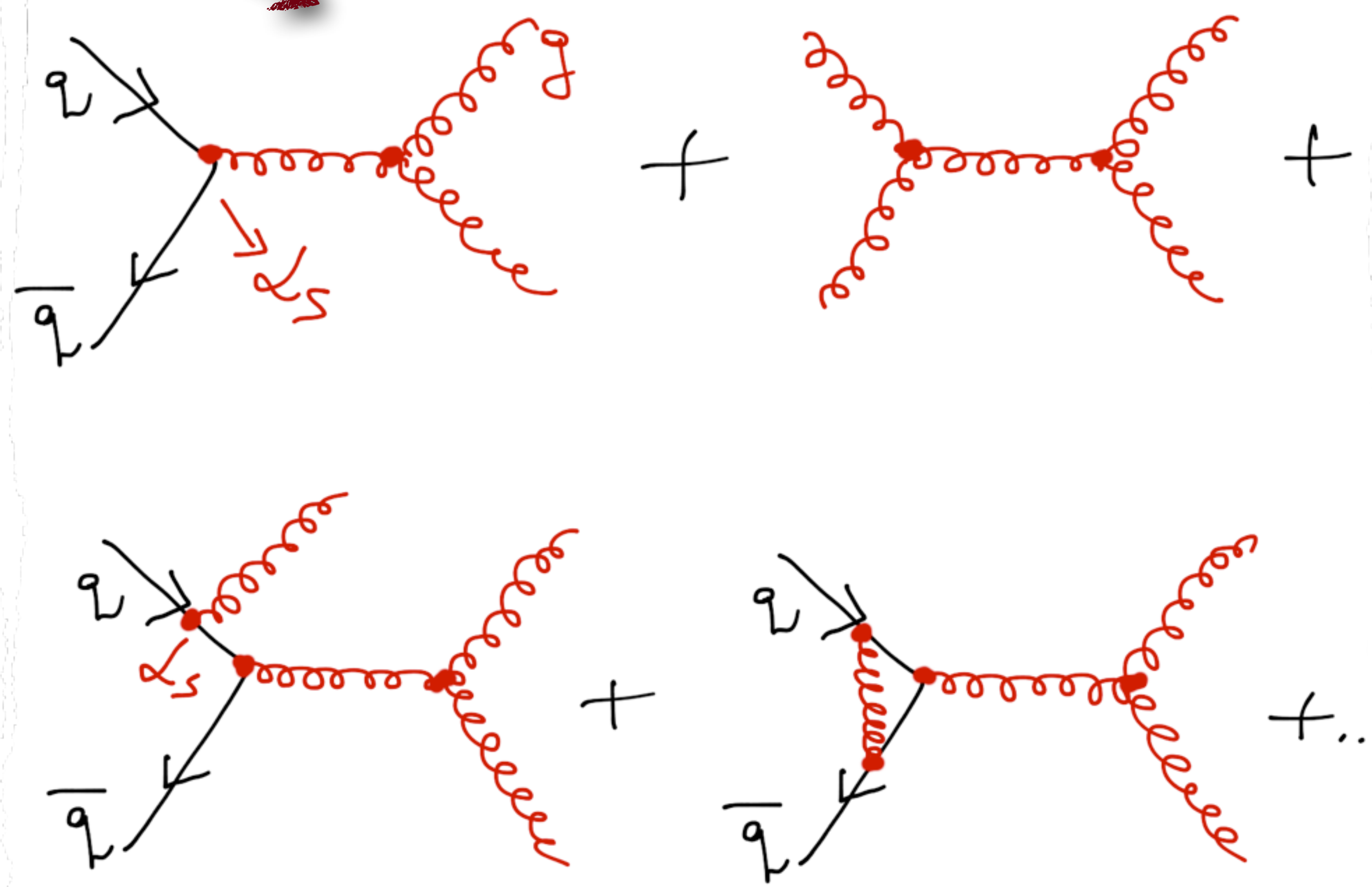




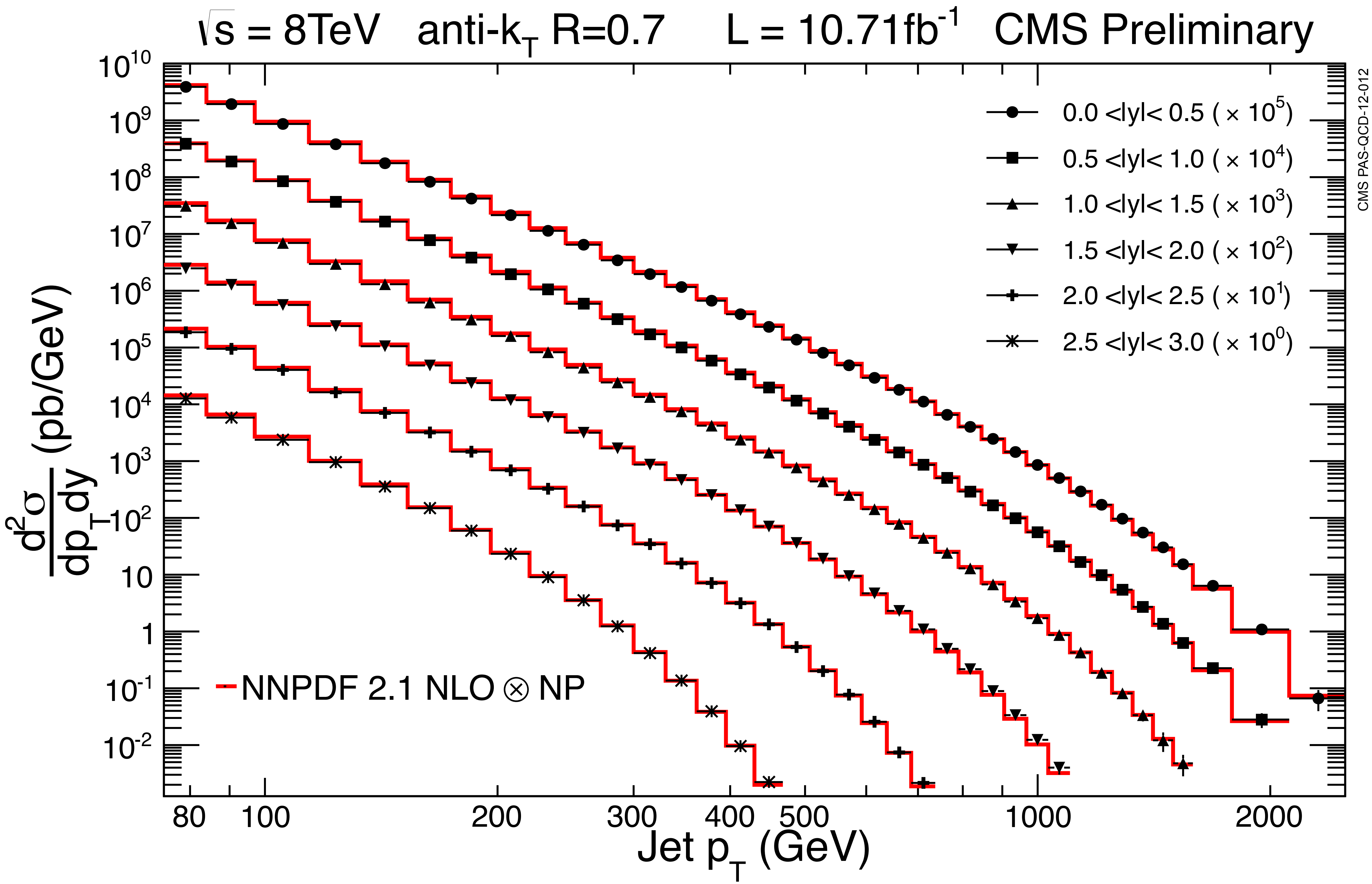


$$\sigma = \alpha_s^n C_{\rm LO} + \alpha_s^{n+1} C_{\rm NLO} + \alpha_s^{n+2} C_{\rm NNLO} + \cdots$$

LO=Leading Order
NLO=Next-to-Leading Order
NNLO=Next-to-Next-to-....

Incl. Jet Production

ETH Institute for Particle Physics



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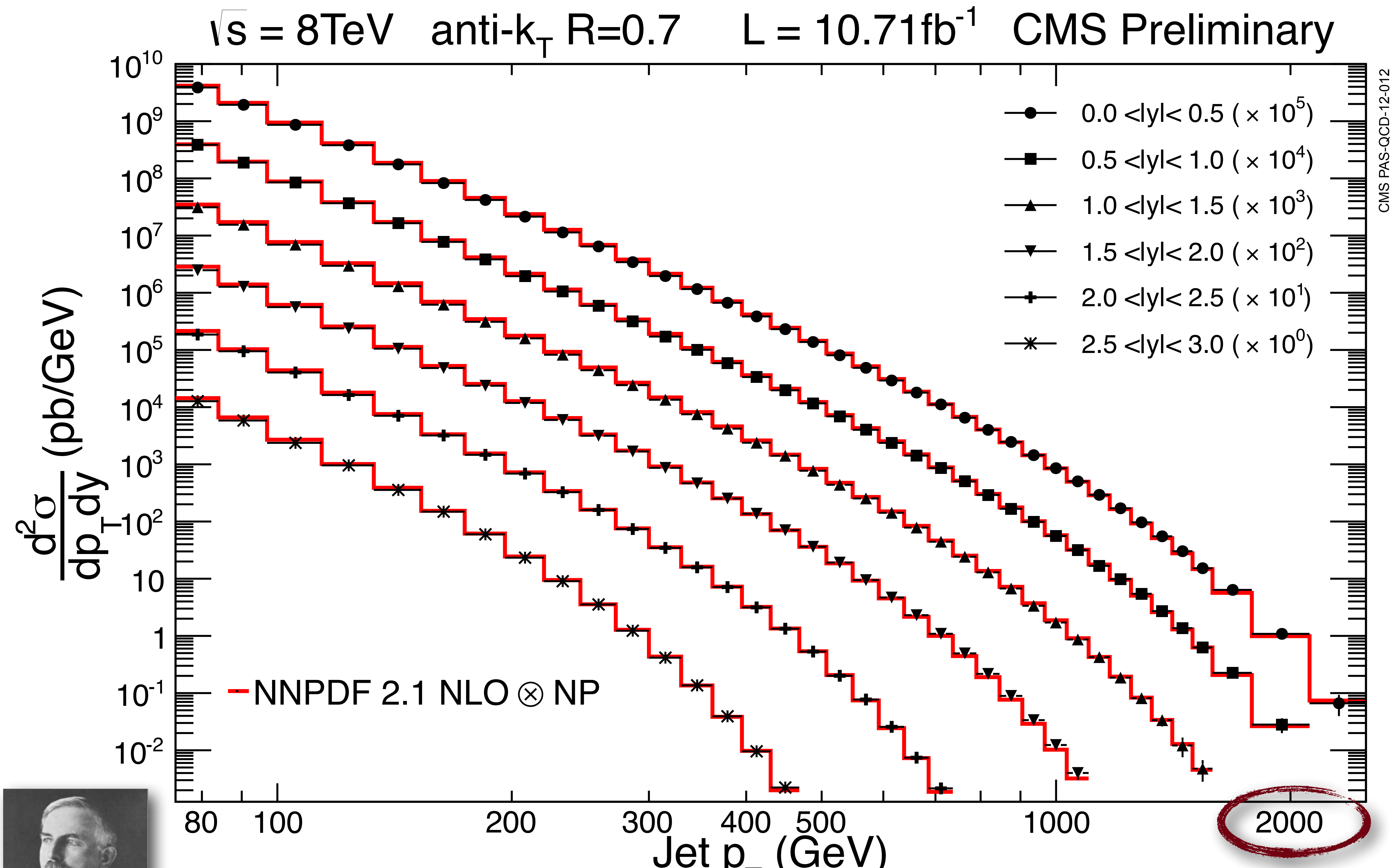
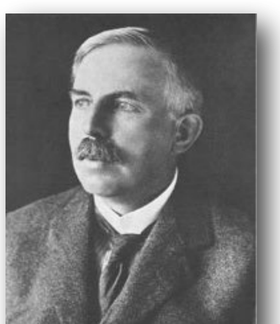
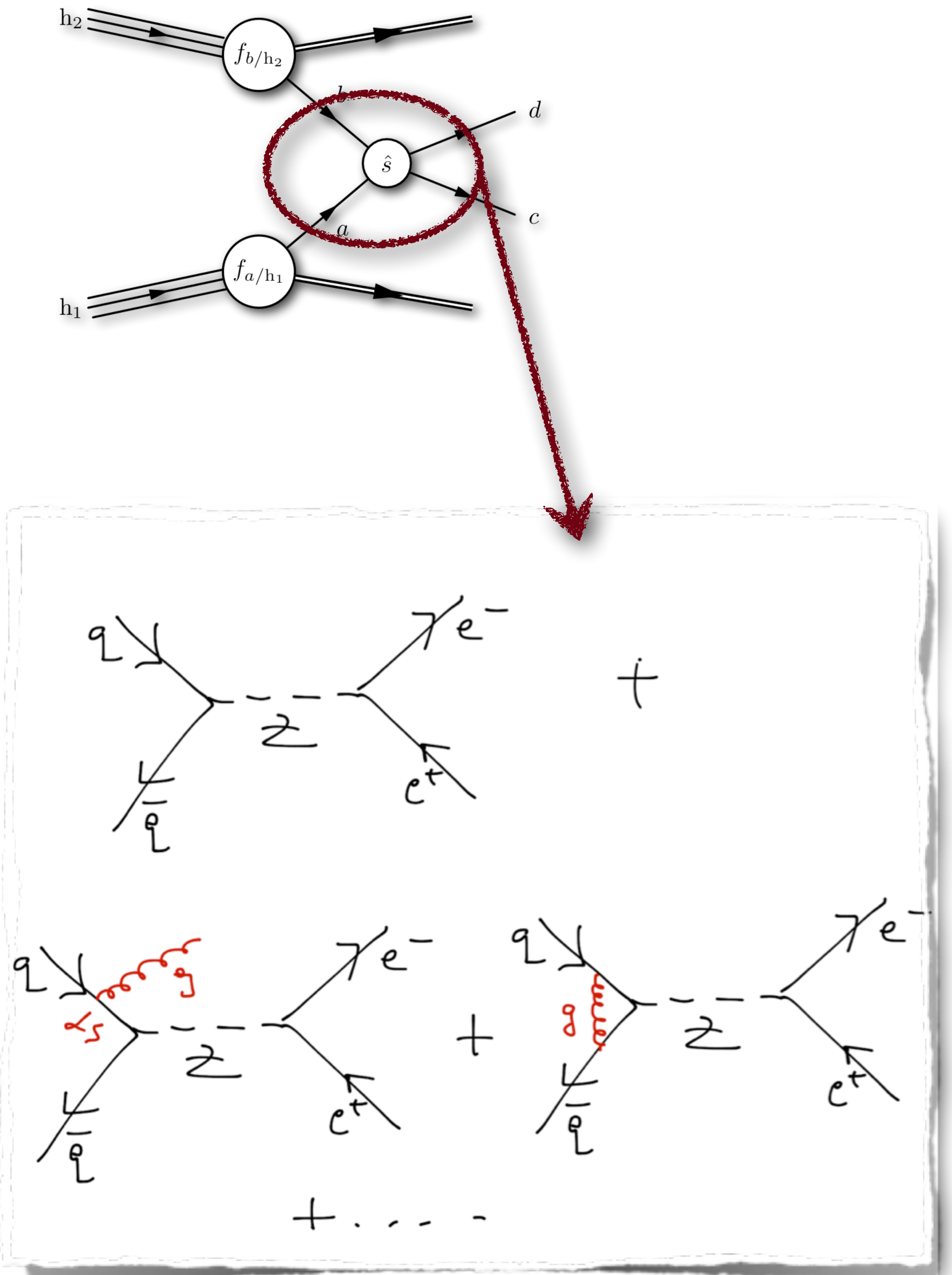
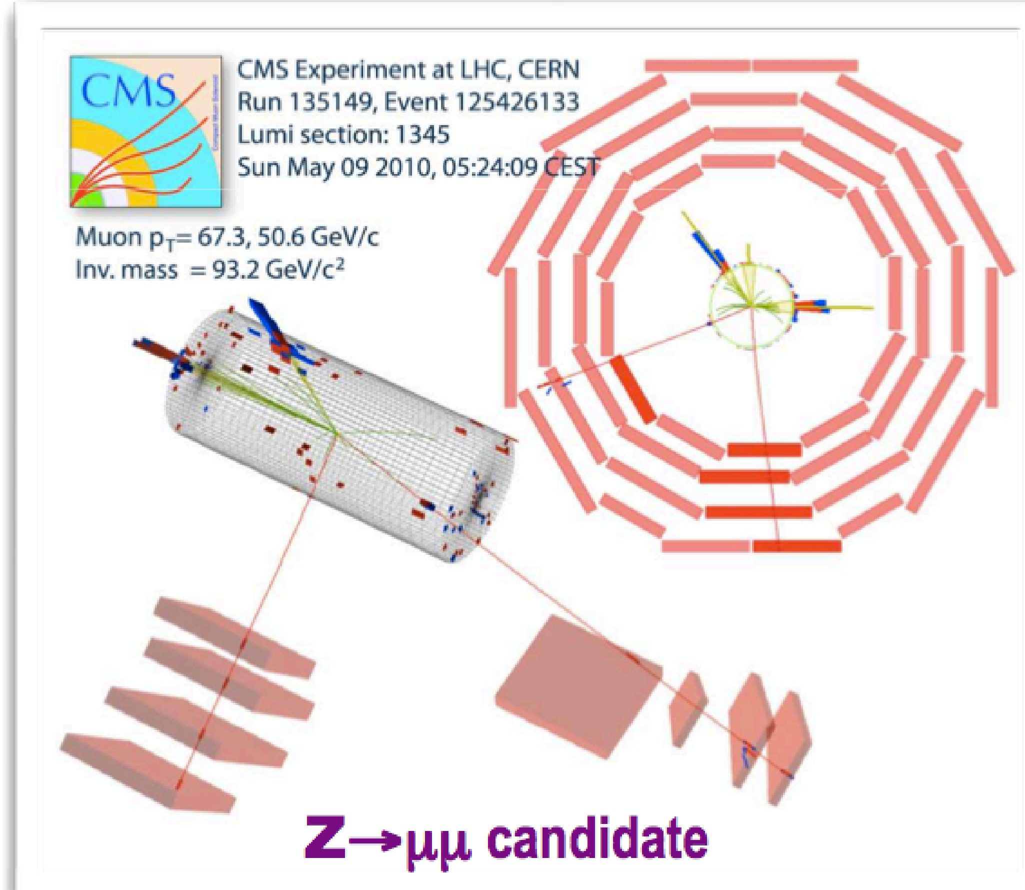


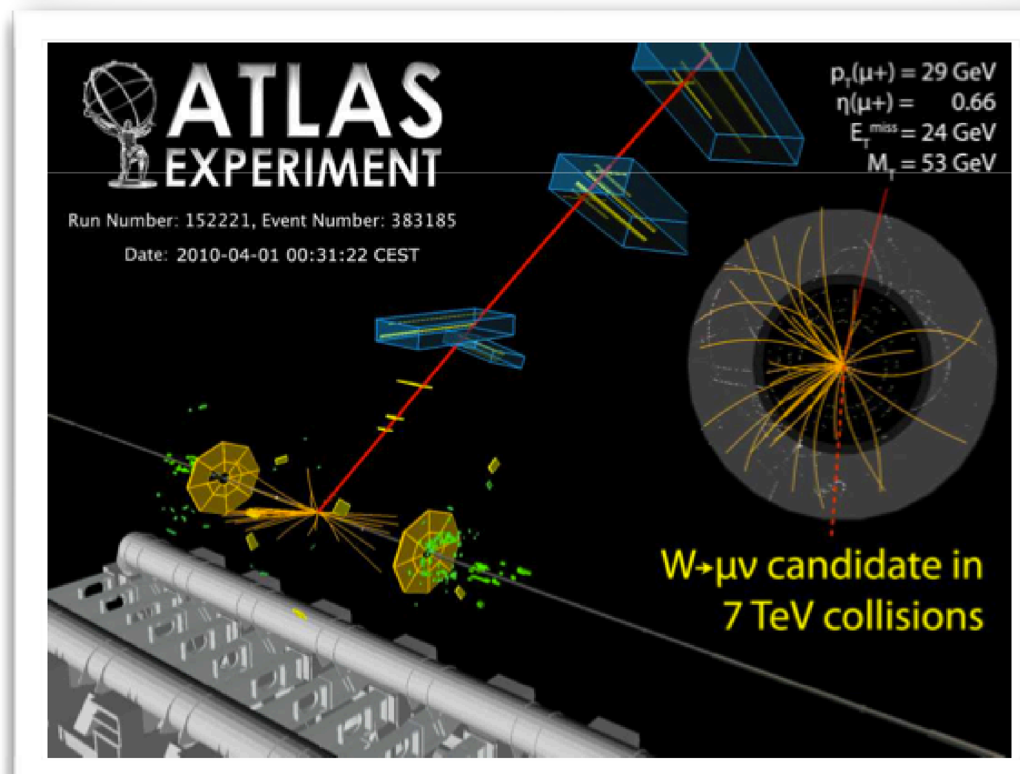


probing distance scales of 10^{-19} m !

Z and W boson production







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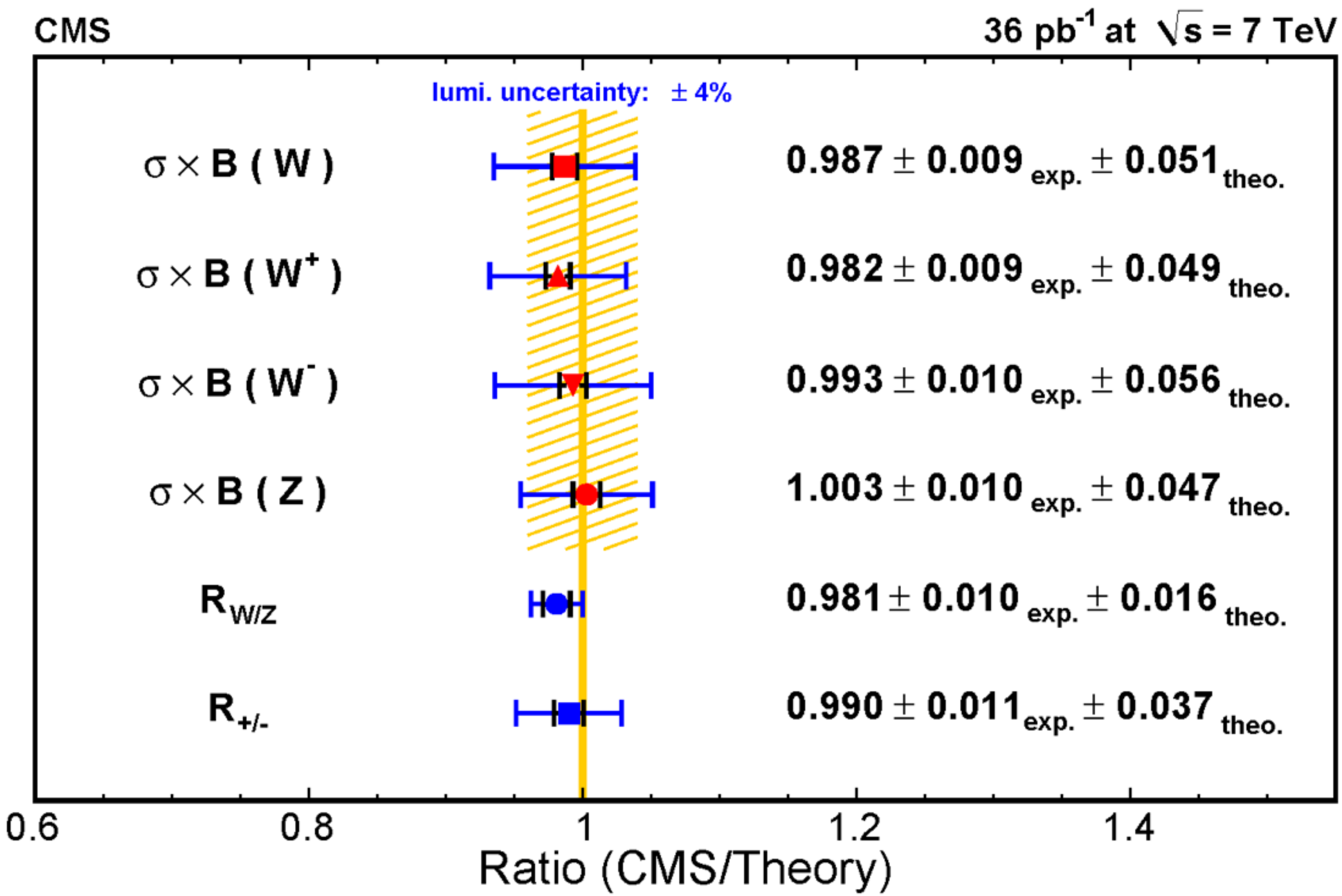
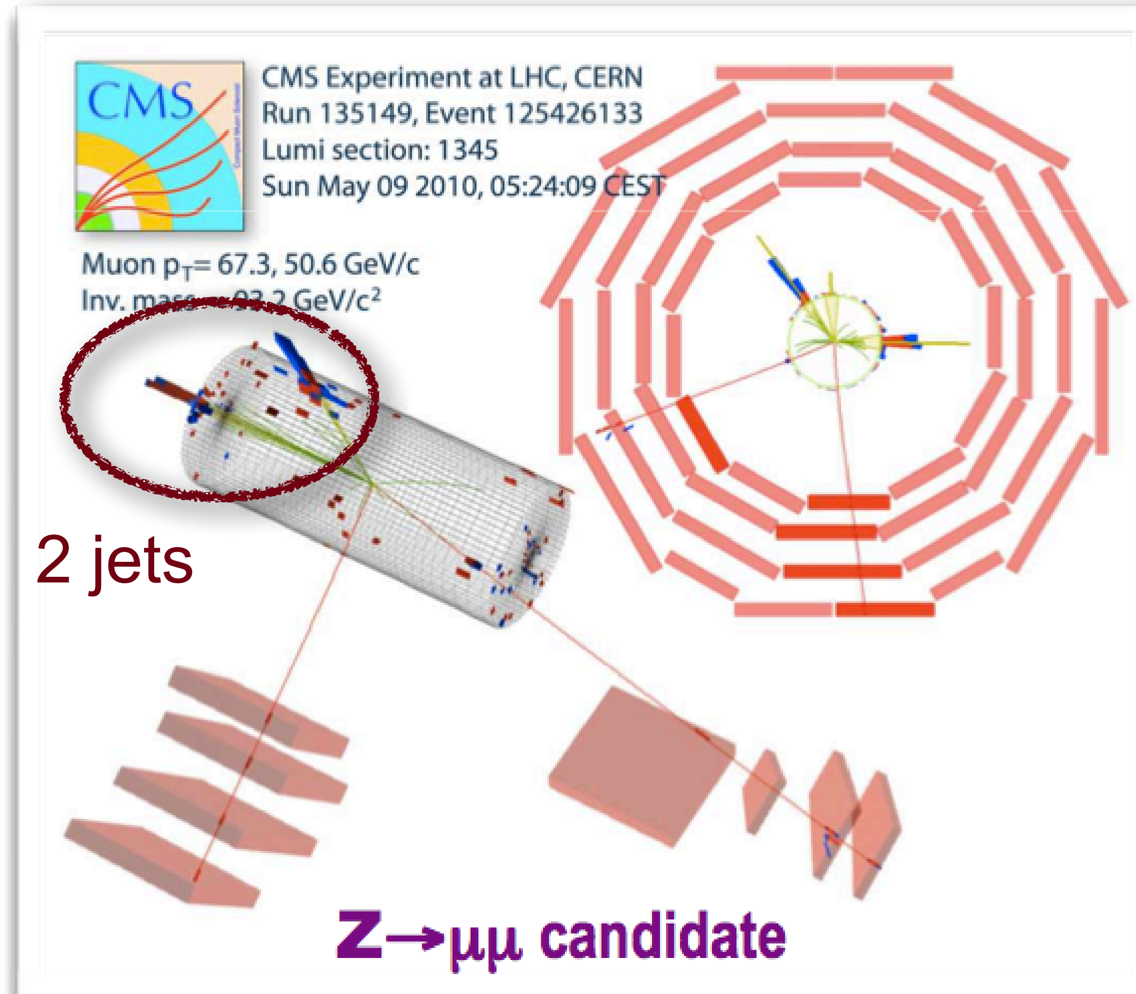


JHEP 10 (2011) 132

Amazing precision reached (~1% experimental !)
put important constraints on theory (NNLO, **PDFs**)

Vector Bosons + jets



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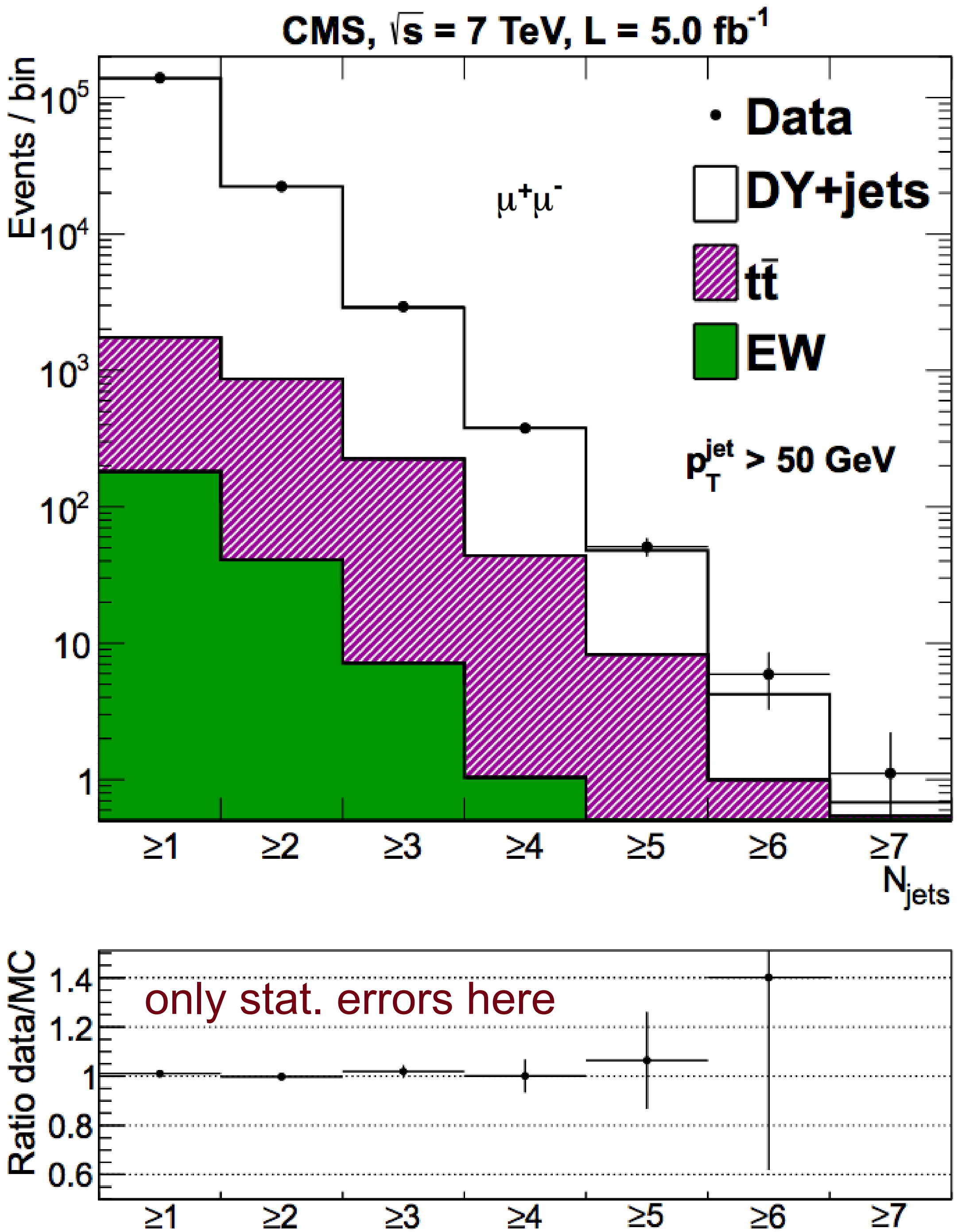
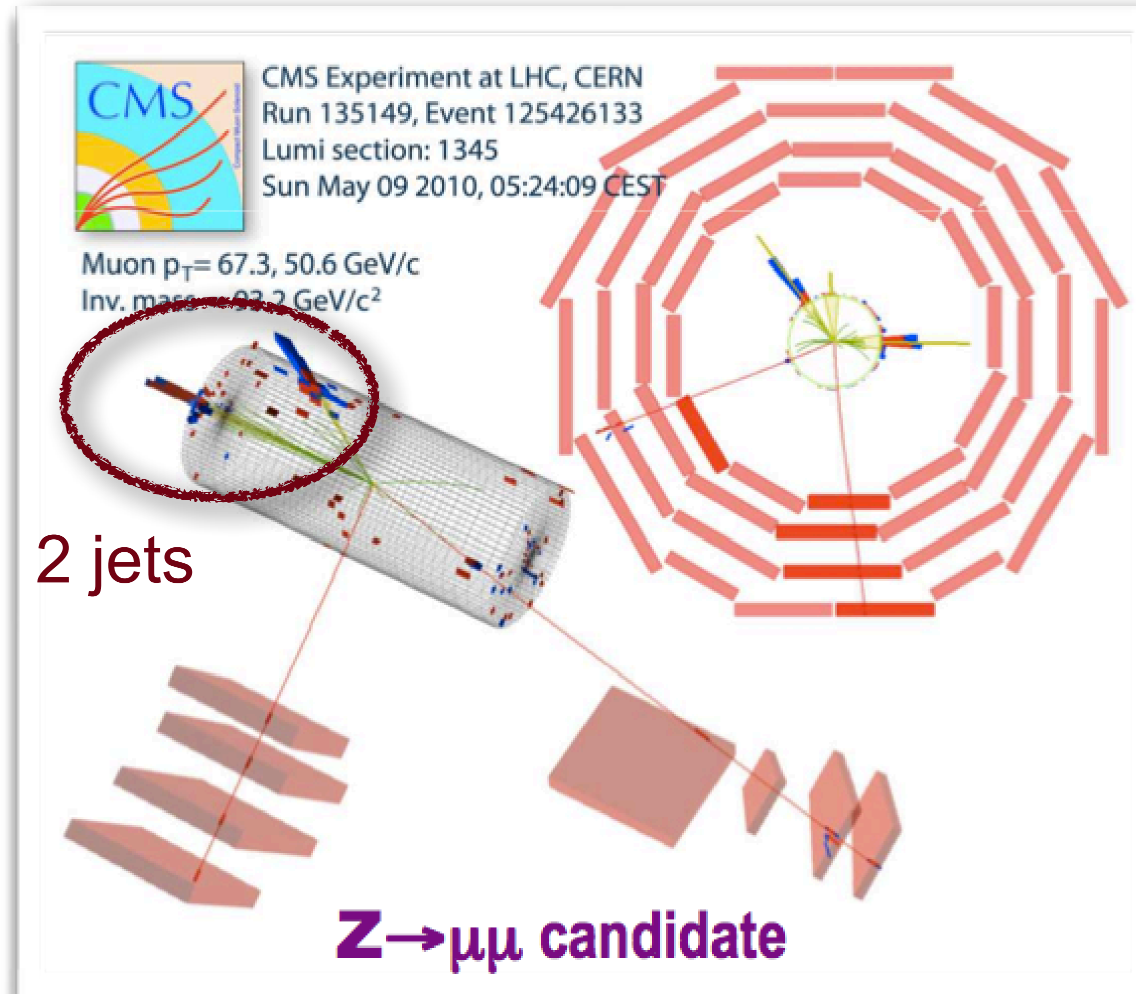


DY + jets: MADGRAPH (version 5.1.1.0), CTEQ6L1, normalized to incl. DY NNLO (FEWZ)

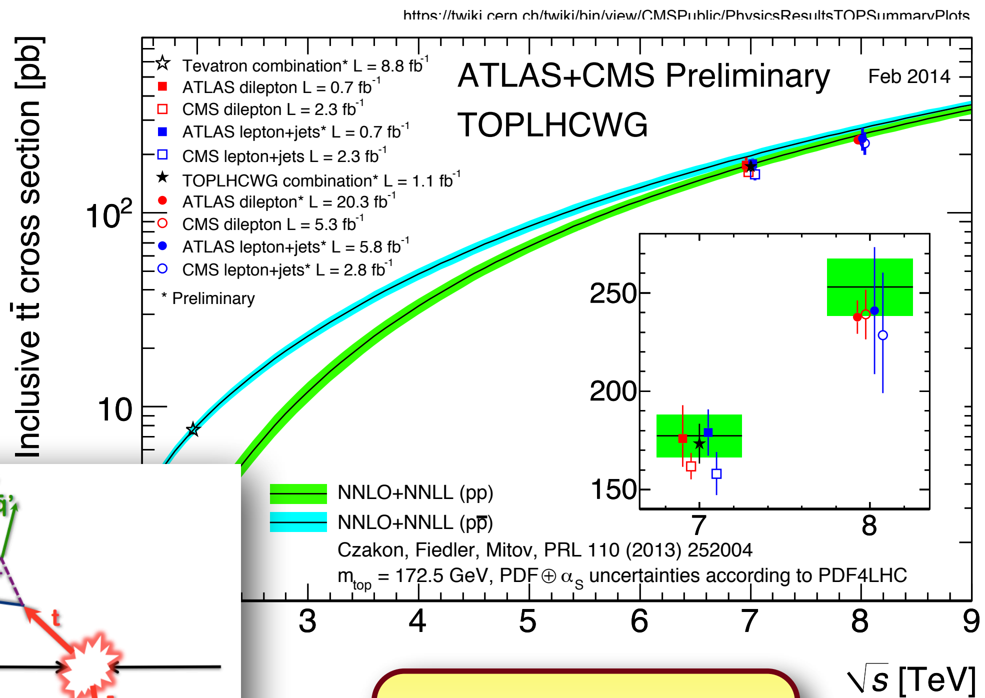
EW : WW, ZZ, WZ, W+jets, normalized to NLO (MCFM); ttbar normalized to NNLL incl. xsec

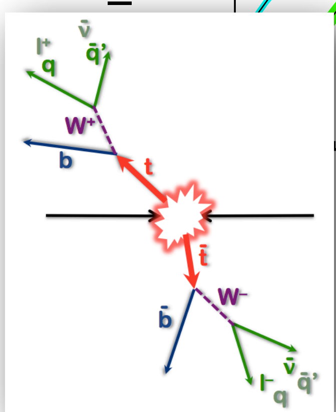


Very good agreement with QCD pred., such as LO (NLO) + PS matched calculations.

Also important for searches for new physics, where this is a background.

Probing the SM at high prec.





experimental uncert.
~ 4% (!)
~ theo. unc.

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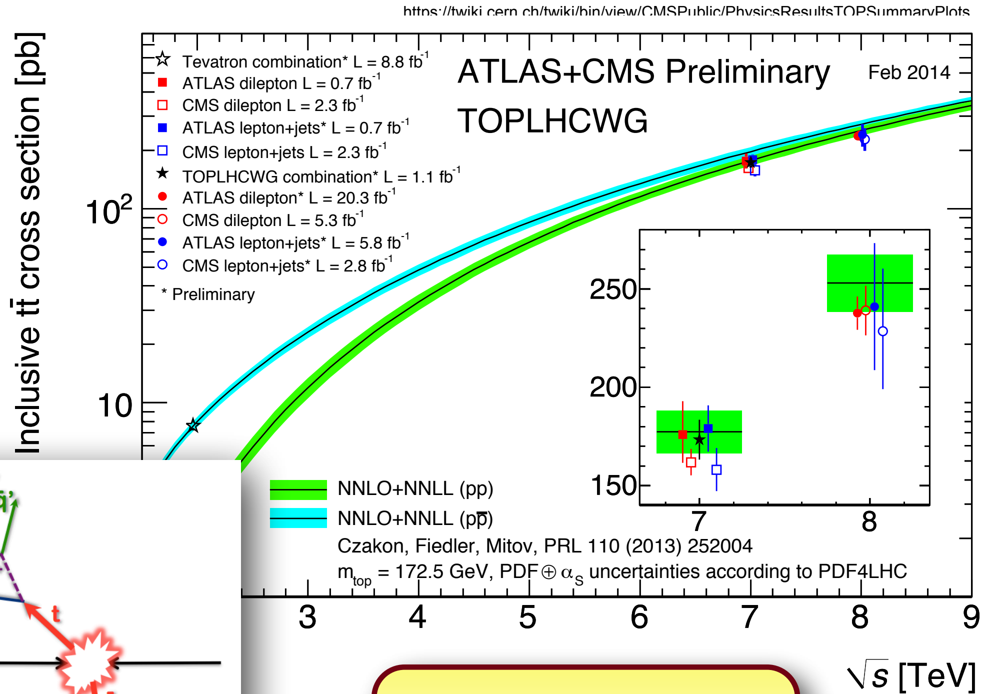

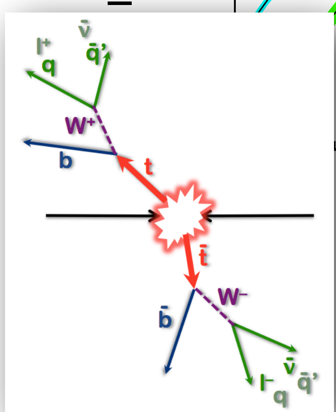

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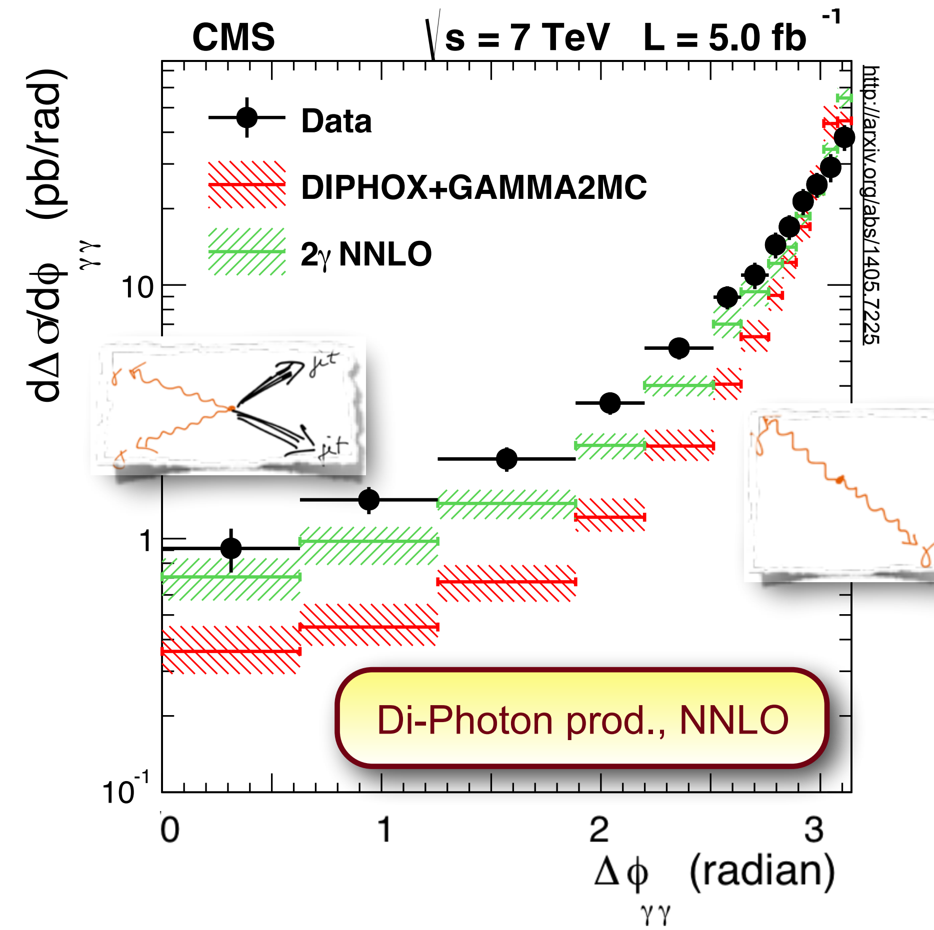
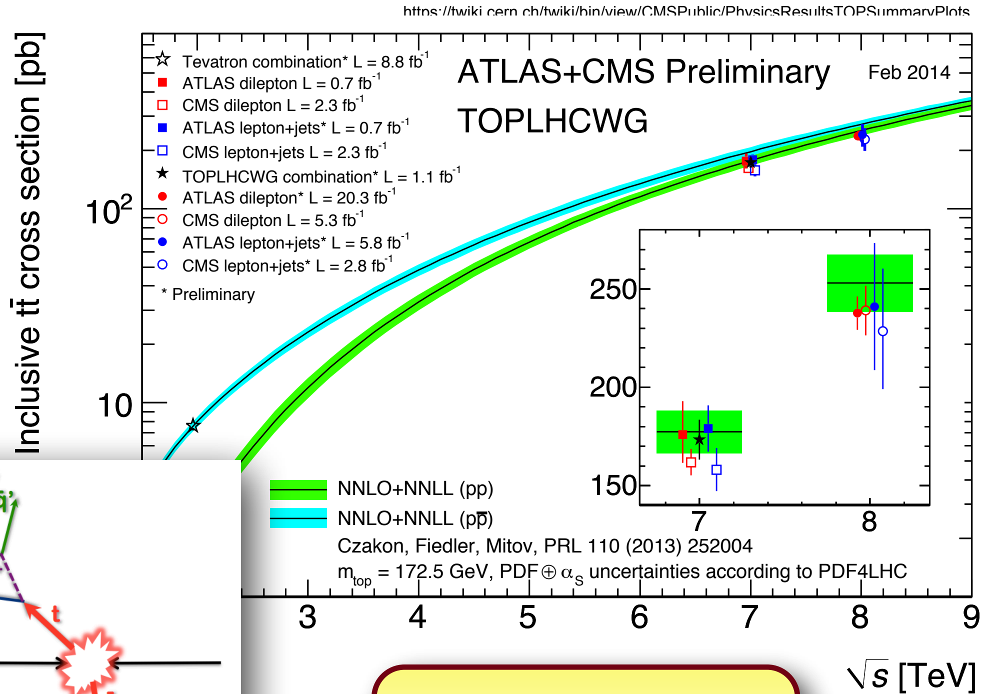
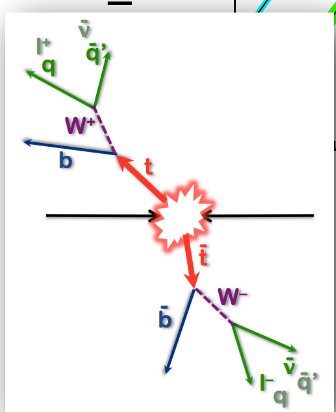


Di-Photon prod., NNLO

Probing the SM at high prec.





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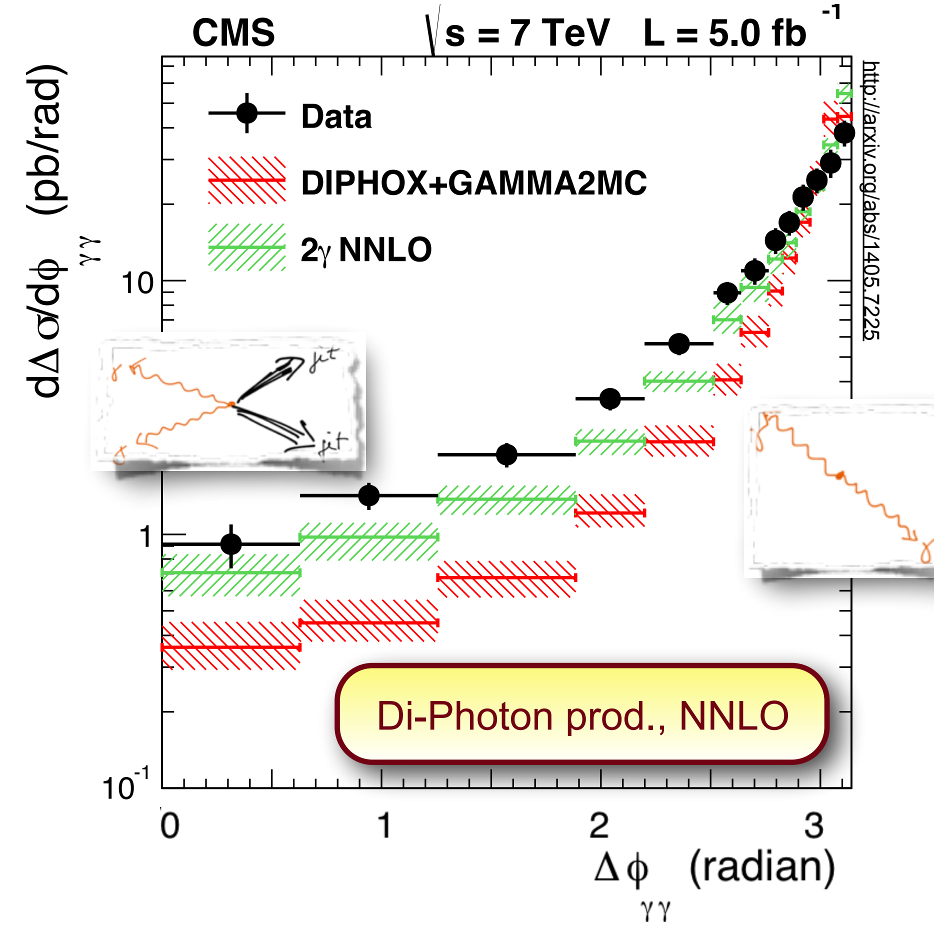

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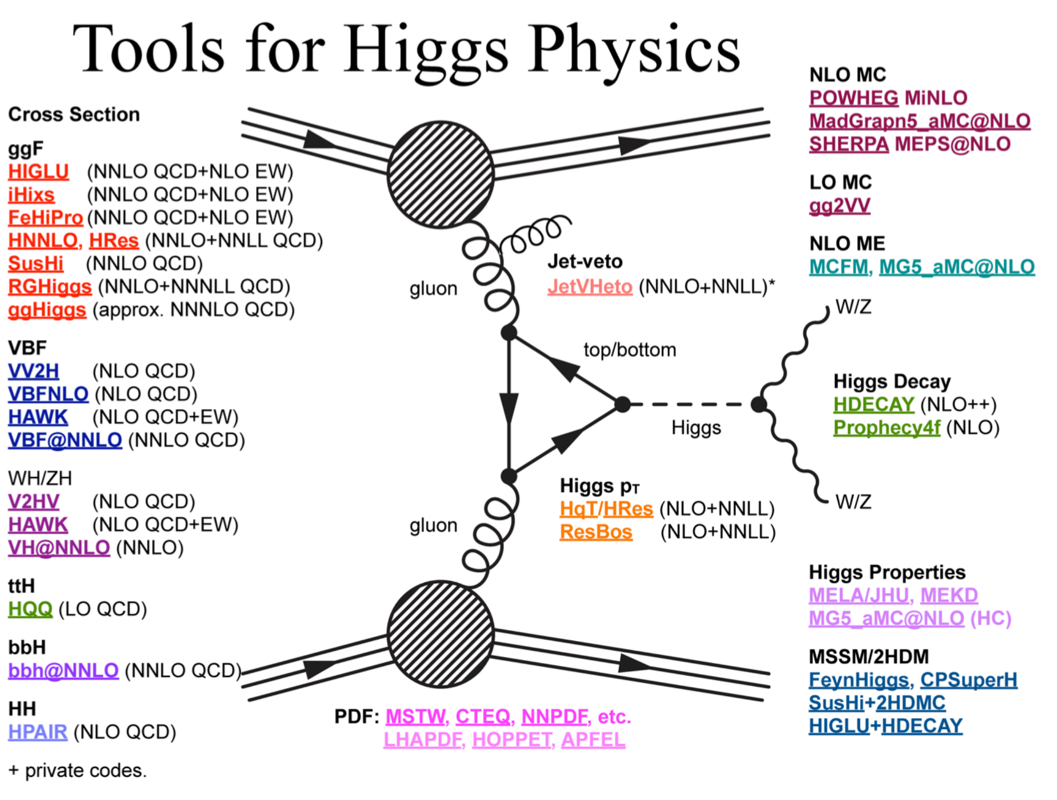
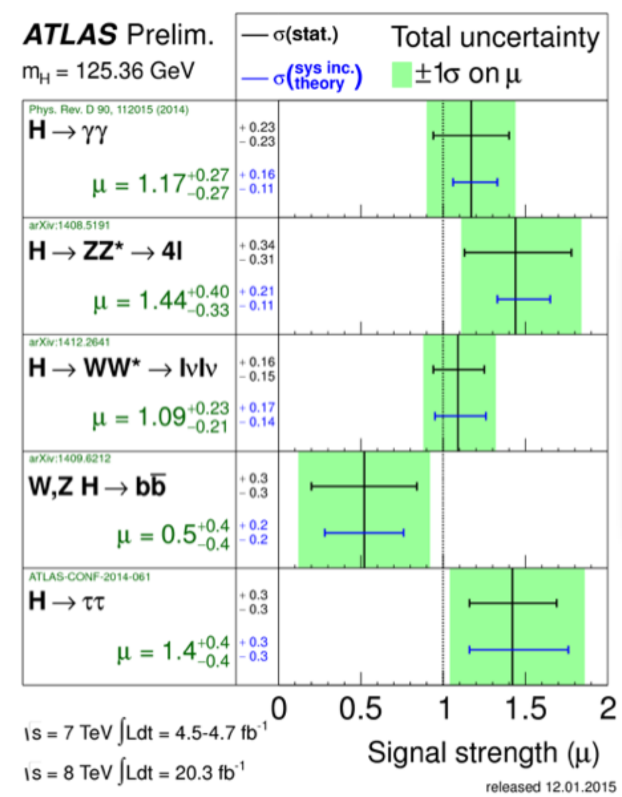
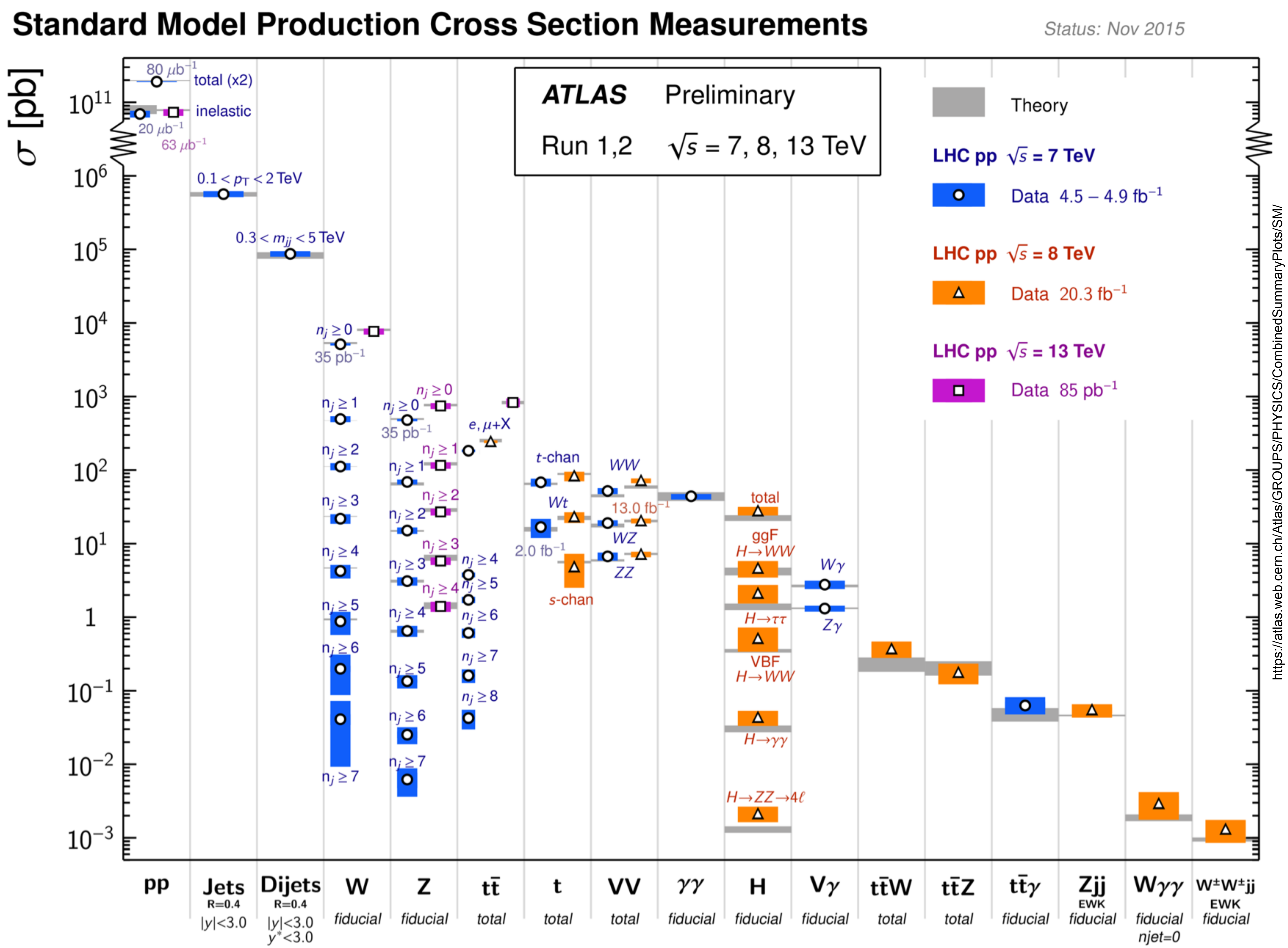


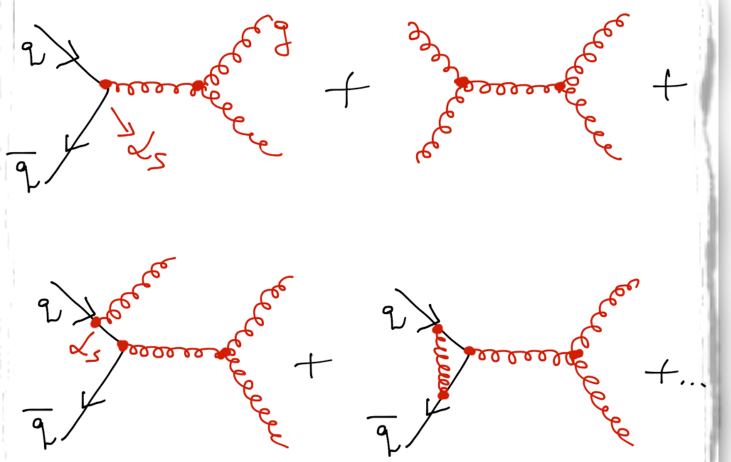


Higgs prod: understood at the 15-20% level already

The big picture

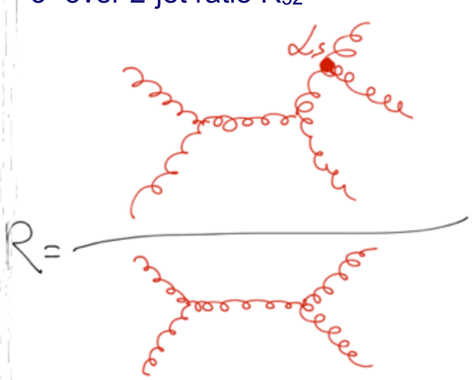


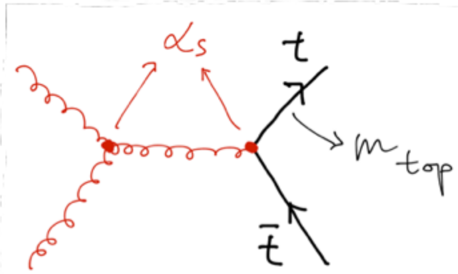
α_s at the LHC



inclusive jet production

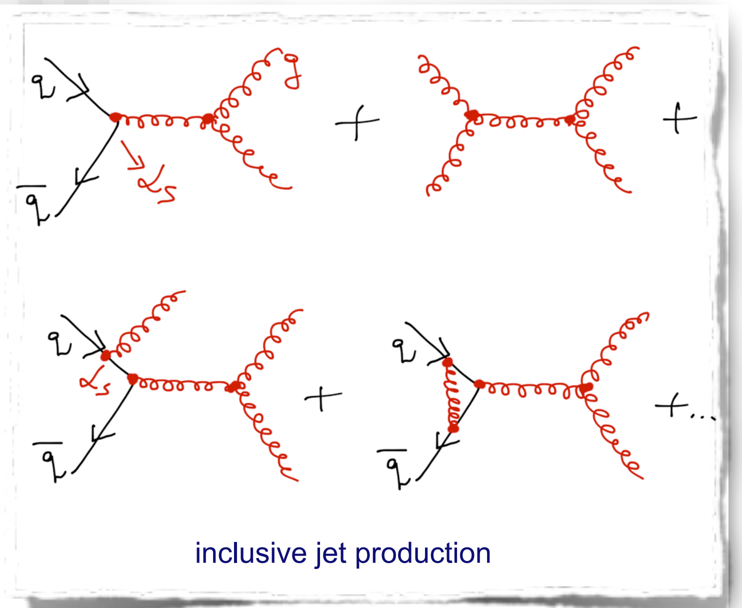
3- over 2-jet ratio R_{32}

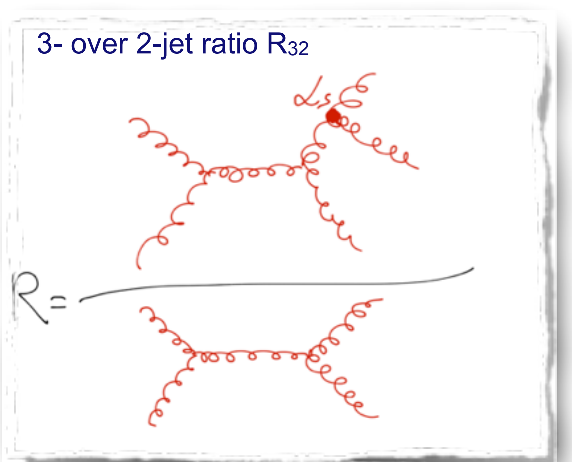


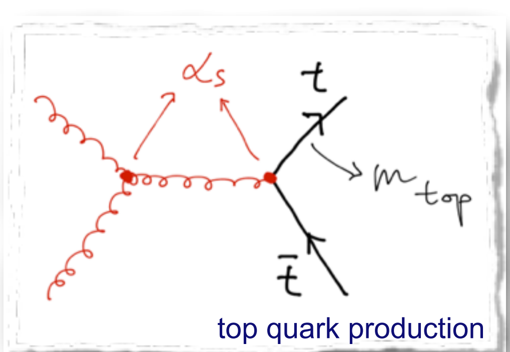


top quark production

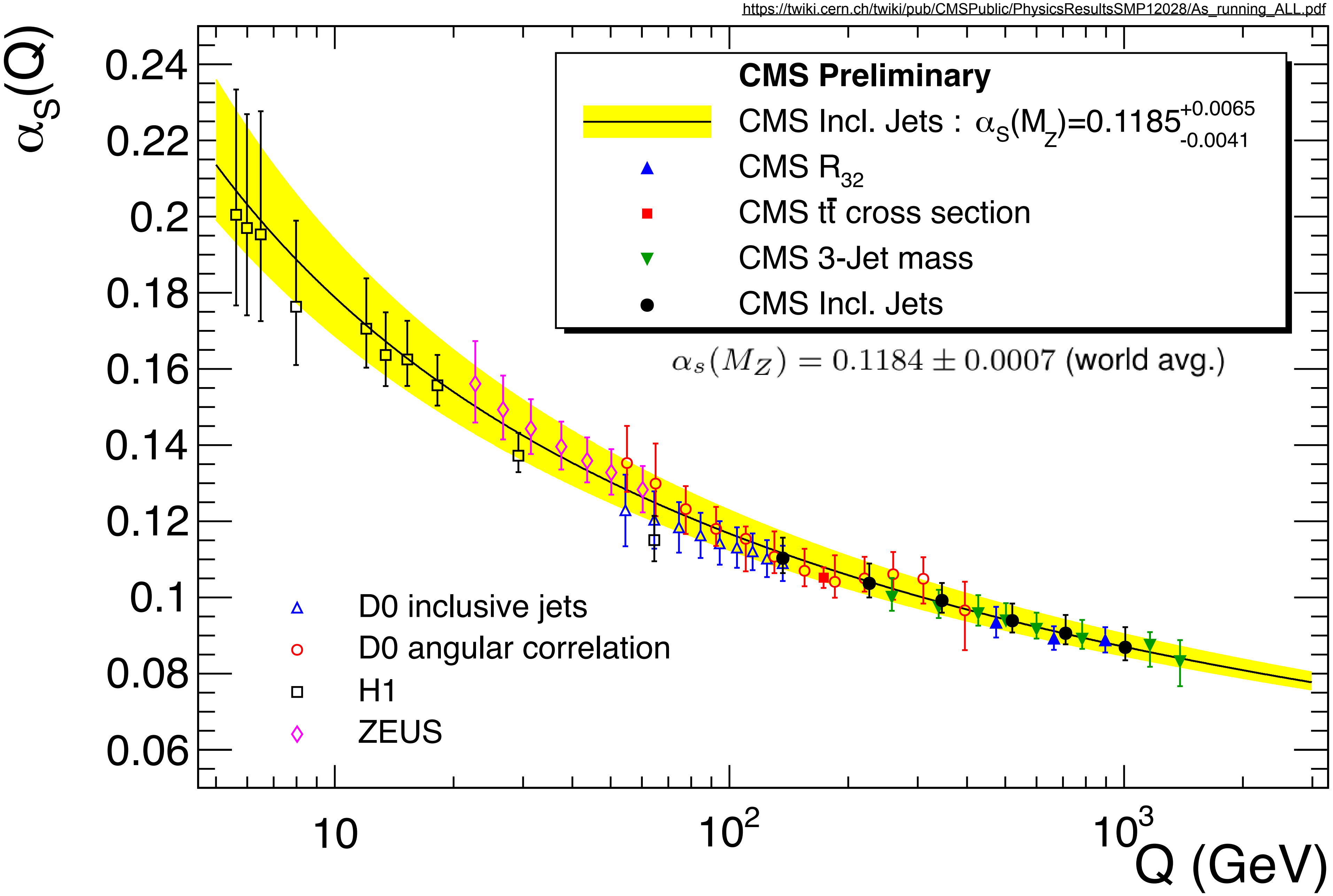
α_s at the LHC







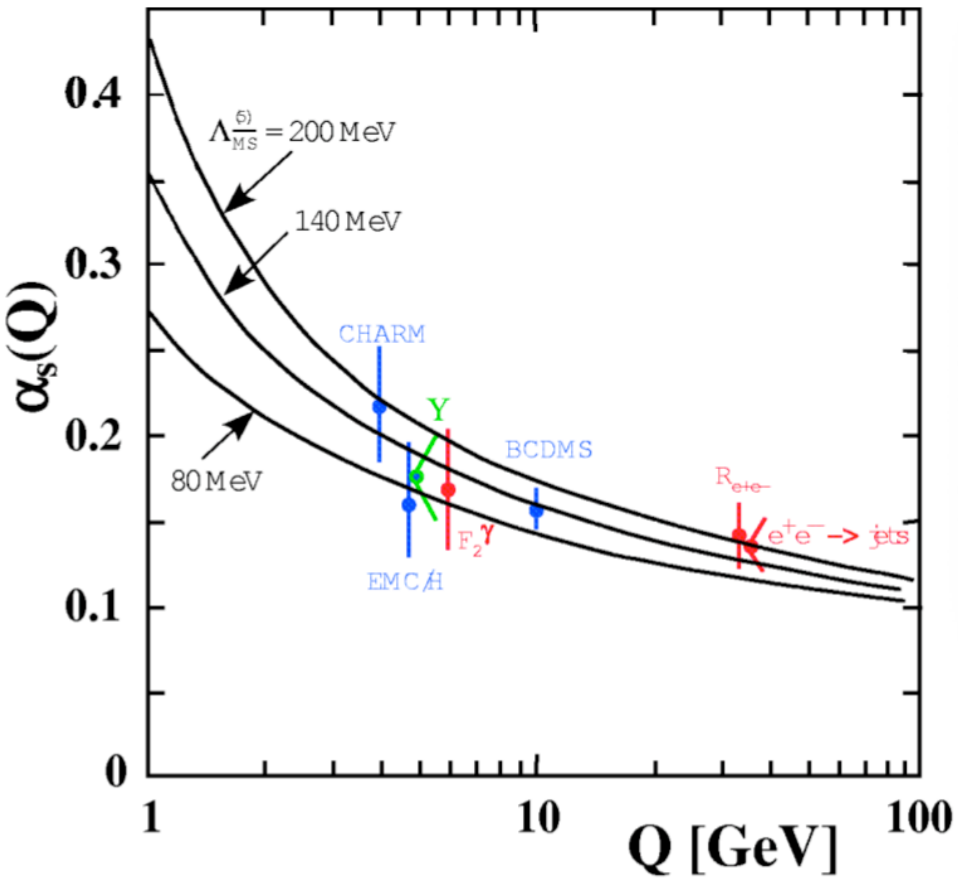
https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsSMP12028/As_running_ALL.pdf



Guido’s Memorial Symposium

Summary

ETH Institute for Particle Physics



G. Altarelli, Ann. Rev. Nucl. Part. Sci. 39, 1989

Figure 7. A relatively loose determination of $\alpha_s(Q)$ at $Q \approx 1$ GeV leads to a very tight determination of $\alpha_s(Q)$ at large Q. For example, from the value of $\Lambda^{(5)}_{\overline{MS}}$ given in Equation 58, the prediction for α_s to be measured at LEP (and HERA) is very precise:

$$\alpha_s(Q \approx M_Z) \approx 0.11 \pm 0.01. \qquad 59.$$

Establishing that this prediction is experimentally true would be a very quantitative and accurate test of QCD, conceptually equivalent but more reasonable than trying to see the running in a given experiment.

Guido's Memorial Symposium

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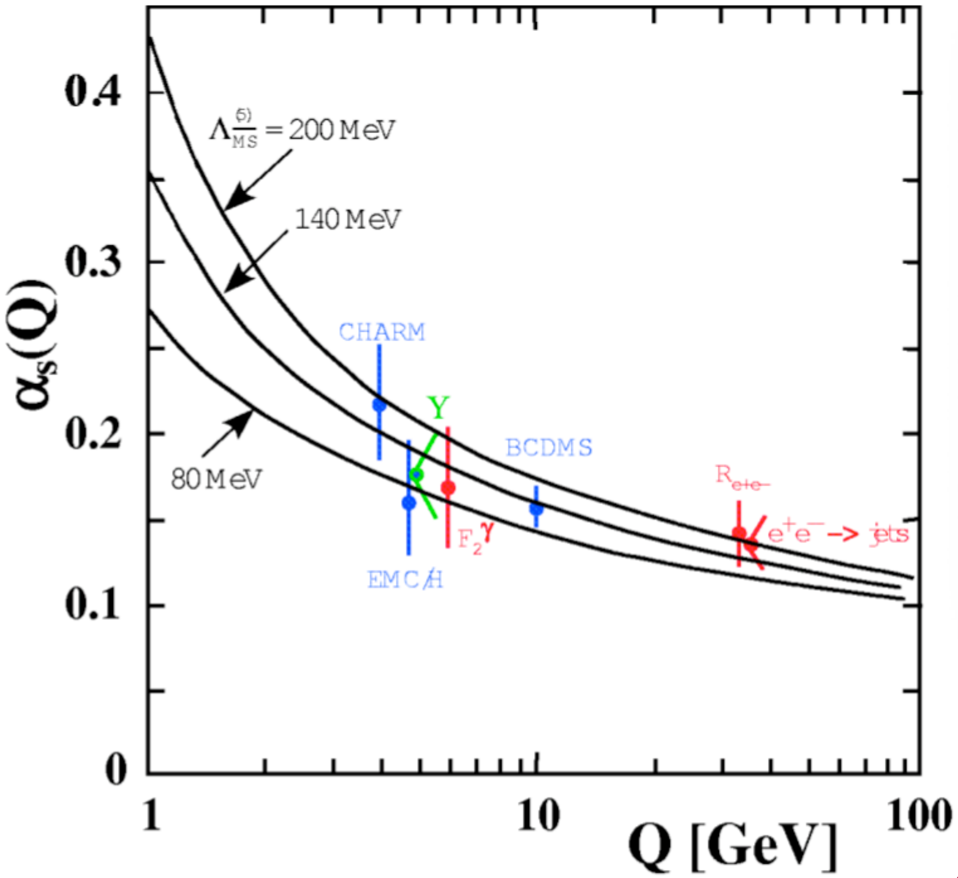

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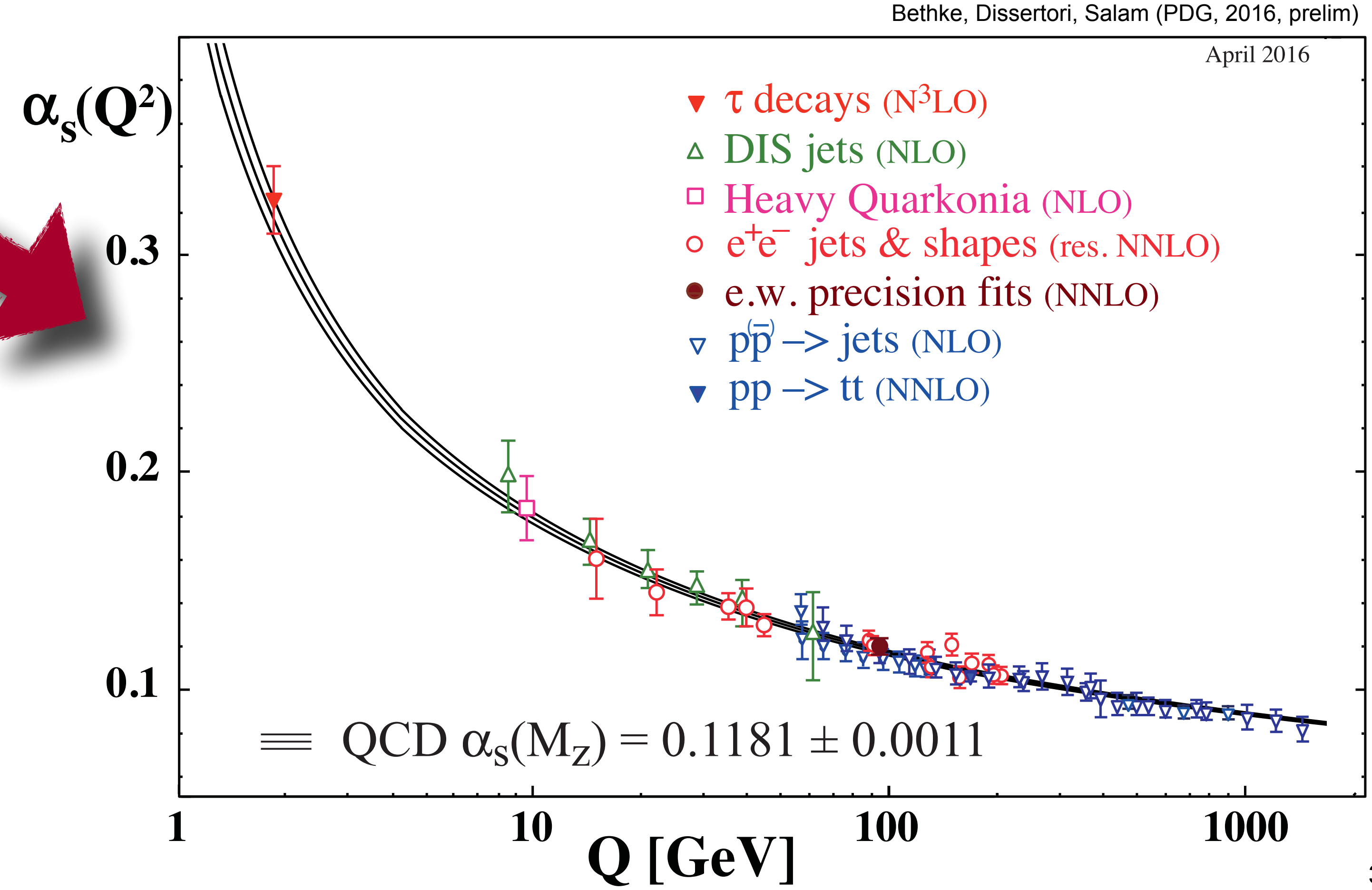
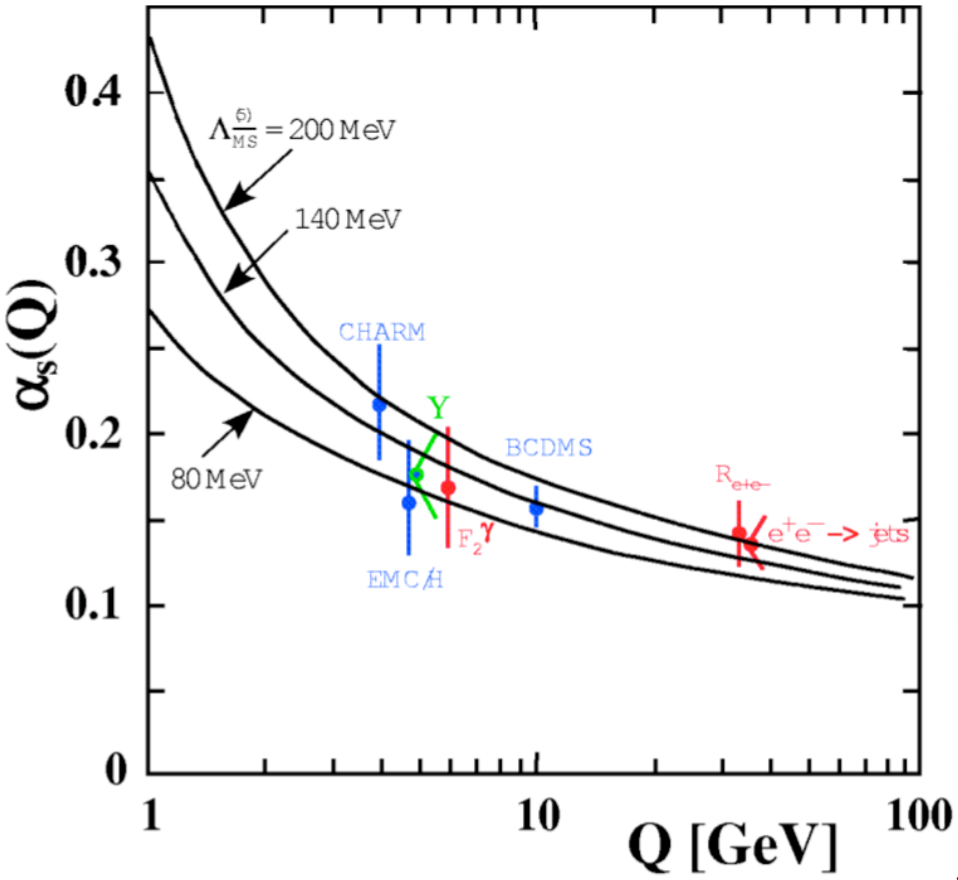
Establishing that this prediction is experimentally true would be a very quantitative and accurate test of QCD, conceptually equivalent but more reasonable than trying to see the running in a given experiment.

Bethke, Dissertori, Salam (PDG, 2016, prelim)



Summary



G. Altarelli, Ann. Rev. Nucl. Part. Sci. 39, 1989

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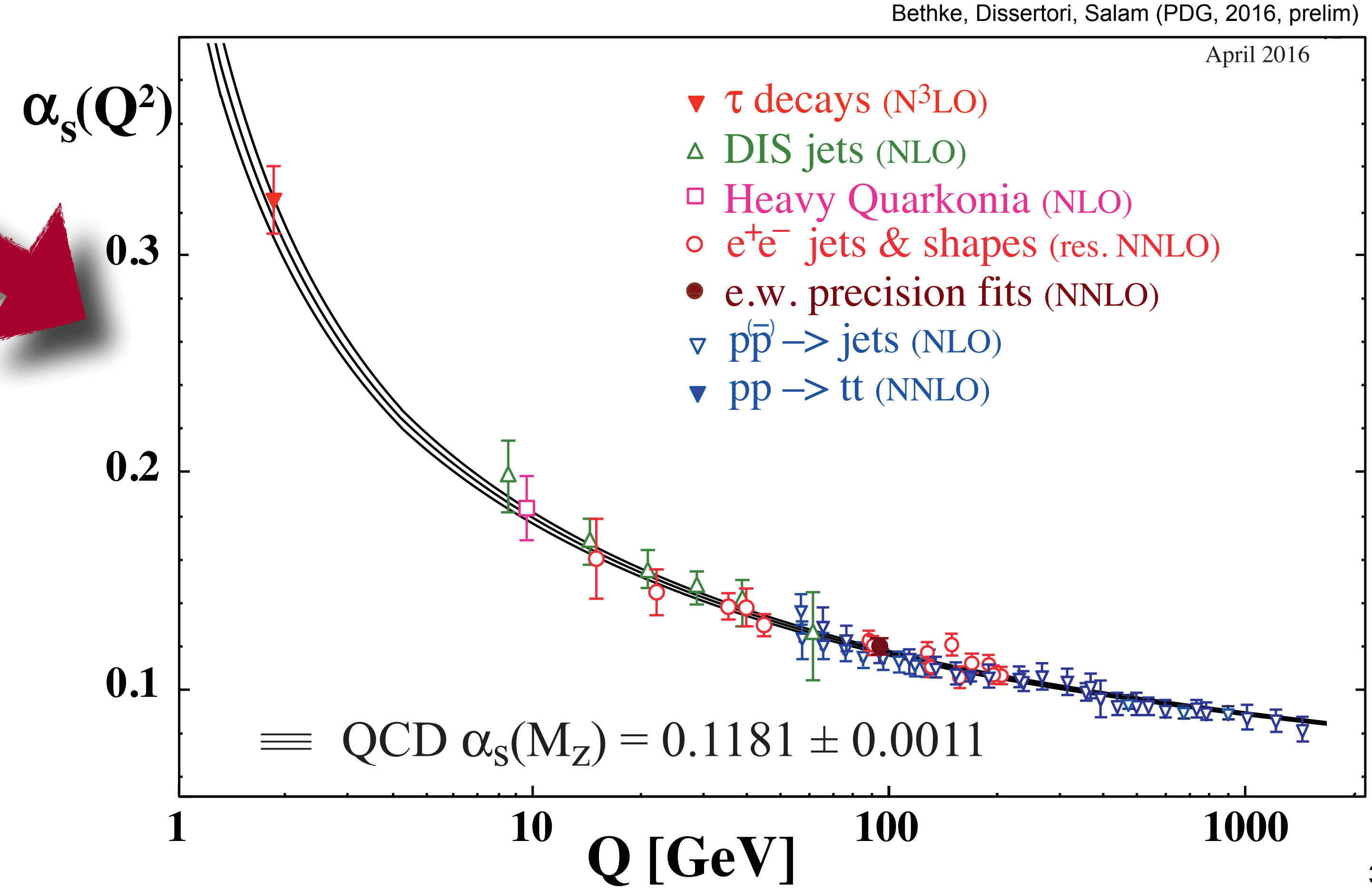

THANK YOU !