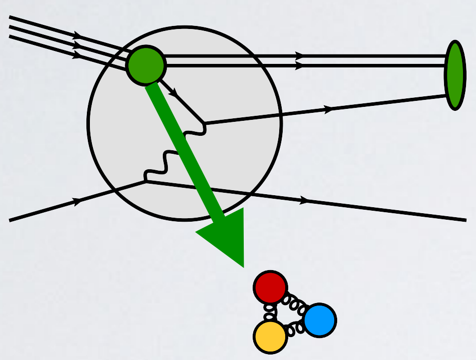
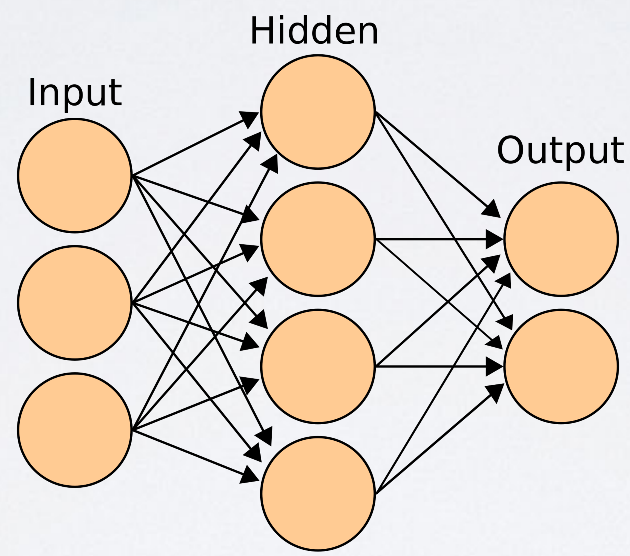
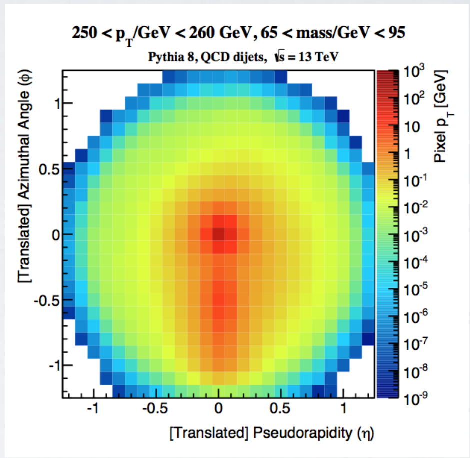
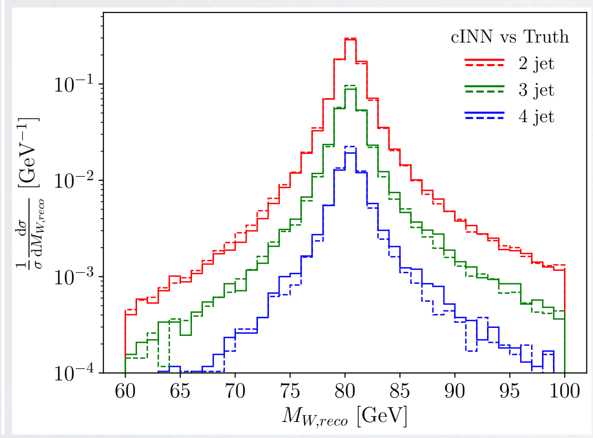
Machine Learning per la fisica applicata e la fisica delle alte energie

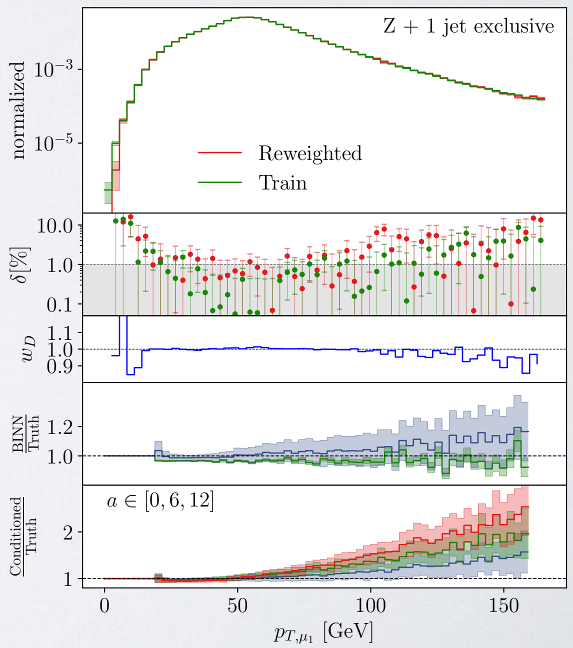








Prof. Simon Badger
Quinto piano EN 9
simondavid.badger at unito.it



Schema del corso

motivazione

Femenologia in collider ad alte energie

Dalle teorie di campi alle esperimenti

Simulazione teorica

l'alto costo della integrazione numerica

Machine Learning per fisica fondamentale

Come puo ML aiutarci a capire le legge di Natura?

Schema del corso

practica

Ottimizzazione di simulazioni

- Problemi di regressione (riepilogo)
- Reti neurali
- Ampiezza di scattering
- Errori?
- Event generation

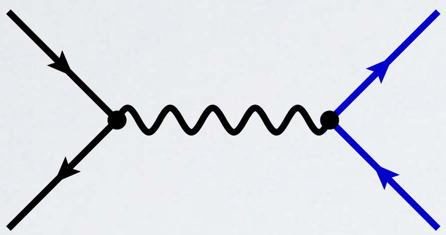
Scegliere i osservabili migliori

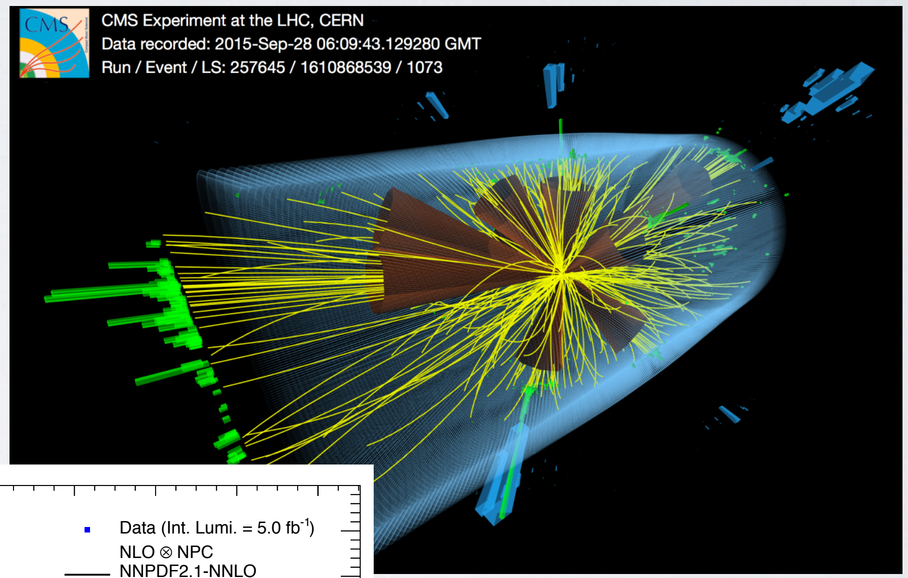
- Classification problems
- Jets and jet substructure

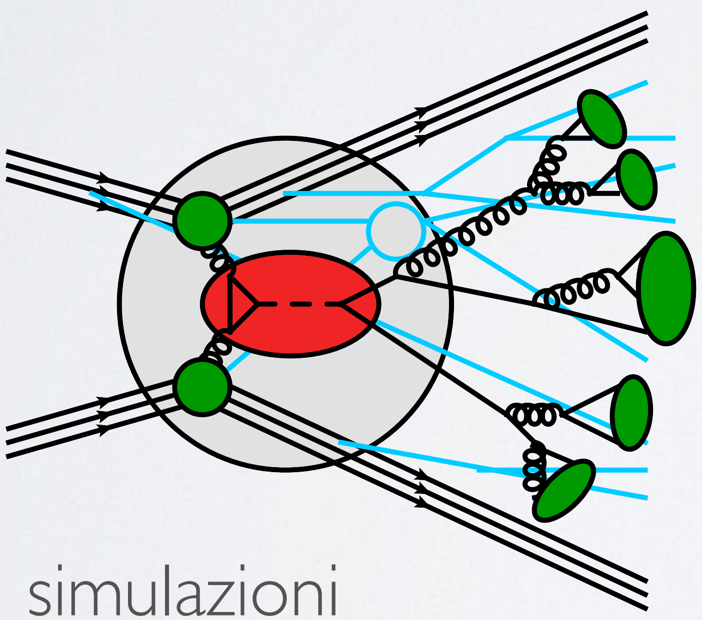
I. Introduzione alla fisica del collisore

rivelatori (detectors)

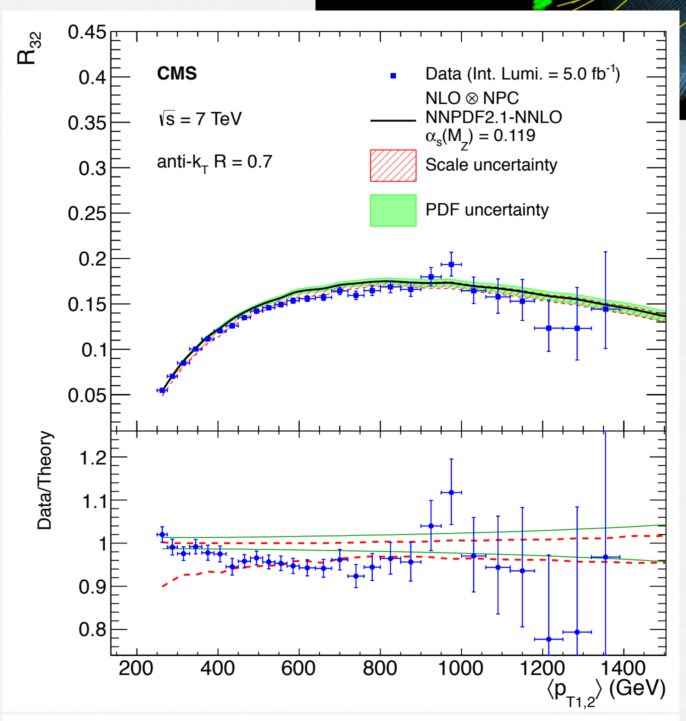
ampiezza

$\mathcal{A} =$ 



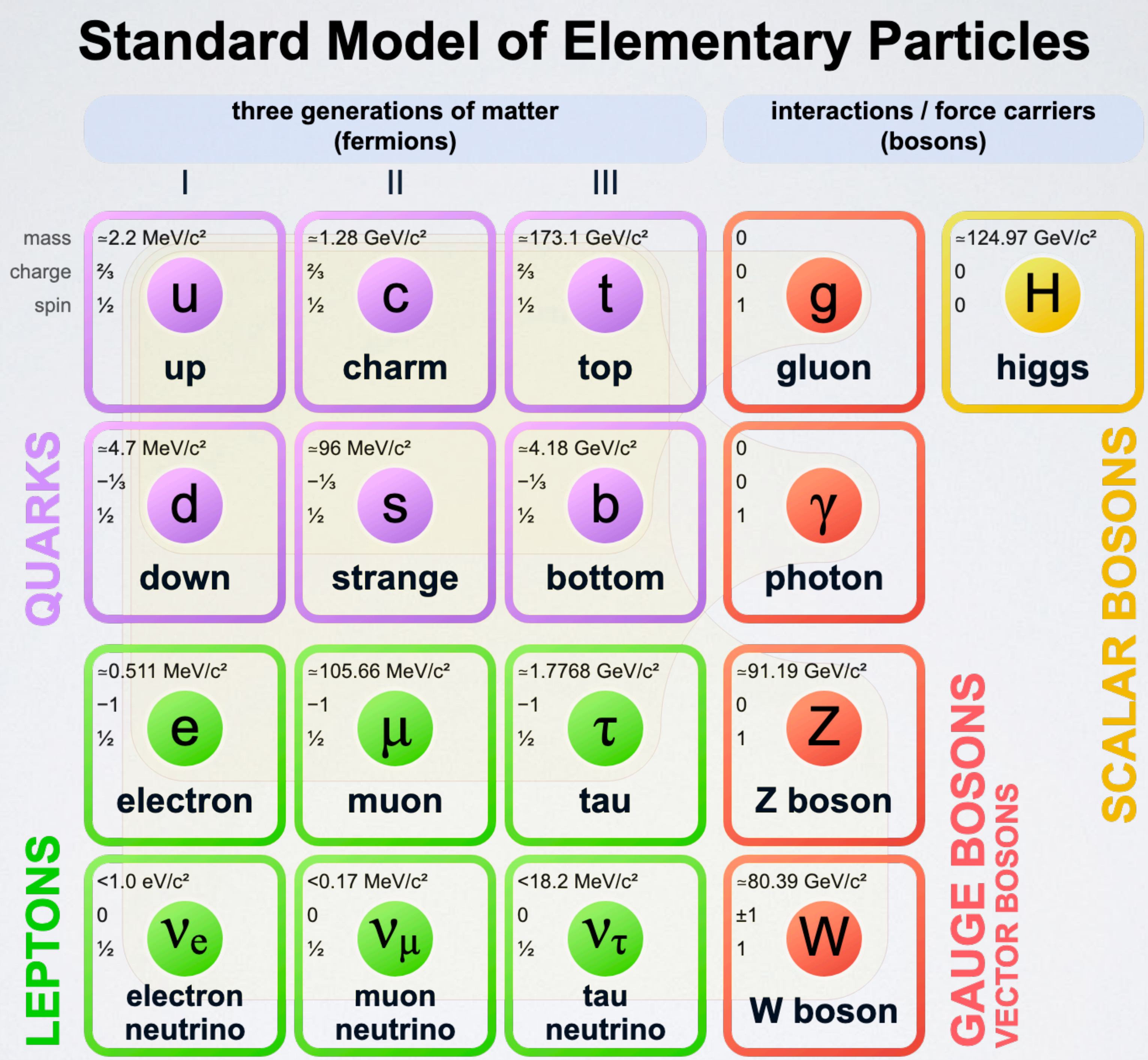


simulazioni

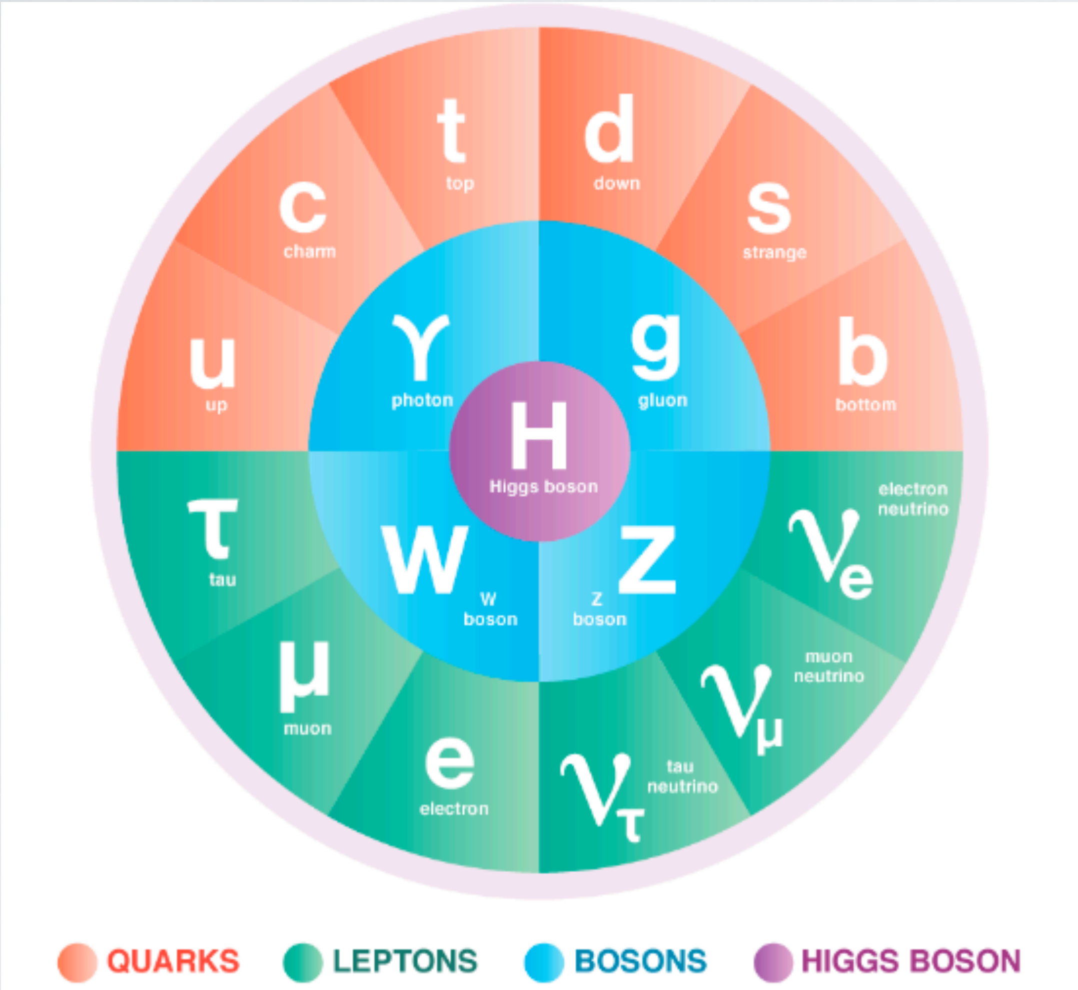


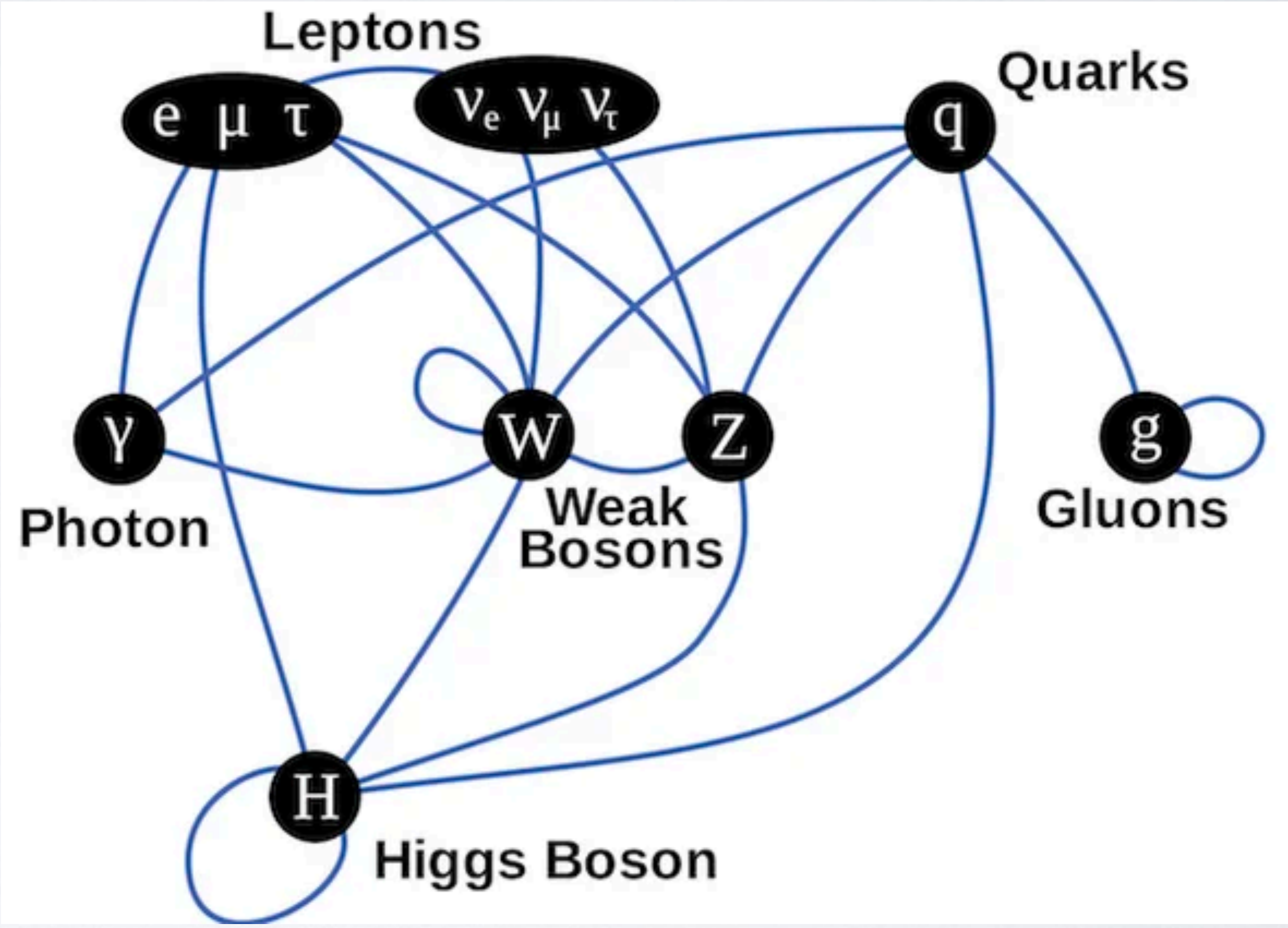
fenomenologia

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$



$SU(3)_C \times SU(2)_L \times U(1)_Y$

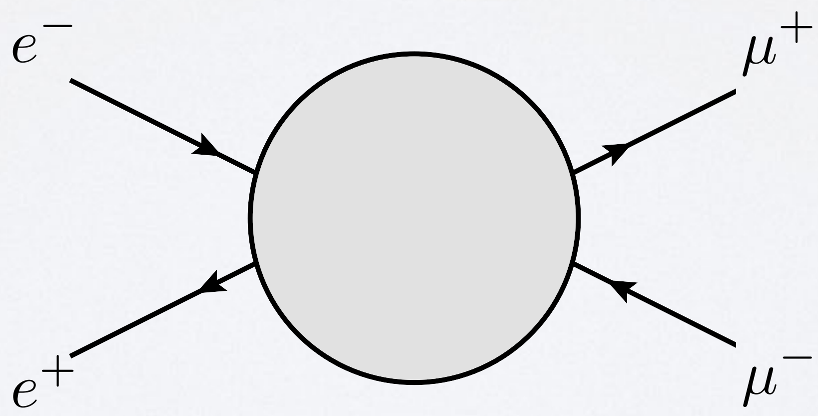




Scattering alle alte energie

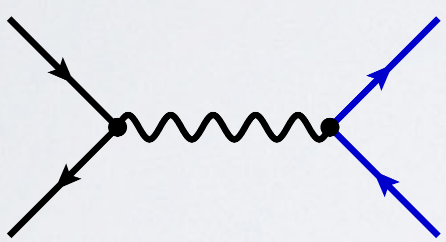
$$\sigma = \frac{1}{\text{flux}} \int \delta^{(4)}(Q - \sum_i p_i) \prod_i d^4p\delta^{(+)}(p_i^2 - m_i^2)\langle|\mathcal{A}|^2\rangle$$

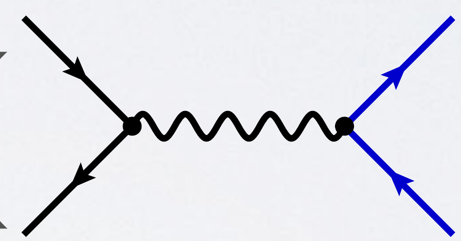
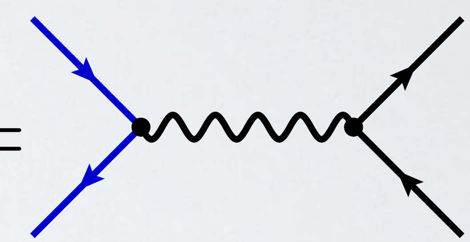
e.g.

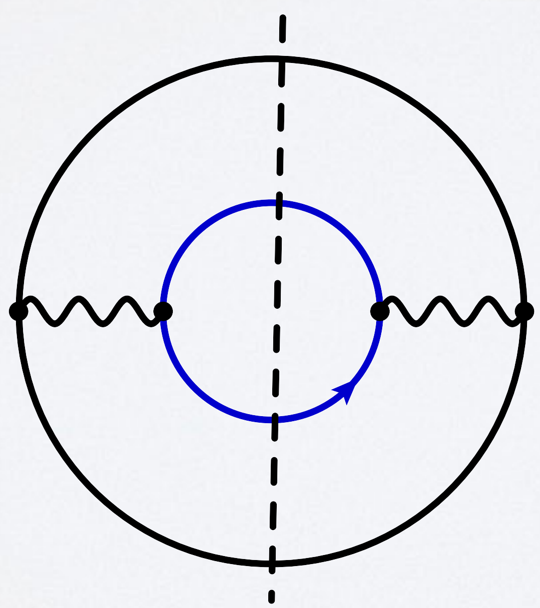


Ampiezza di scattering : probabilità dalla Lagrangiana

$$\langle |\mathcal{A}|^2 \rangle = \sum_{\text{spins}} \mathcal{A}^\dagger \mathcal{A}$$

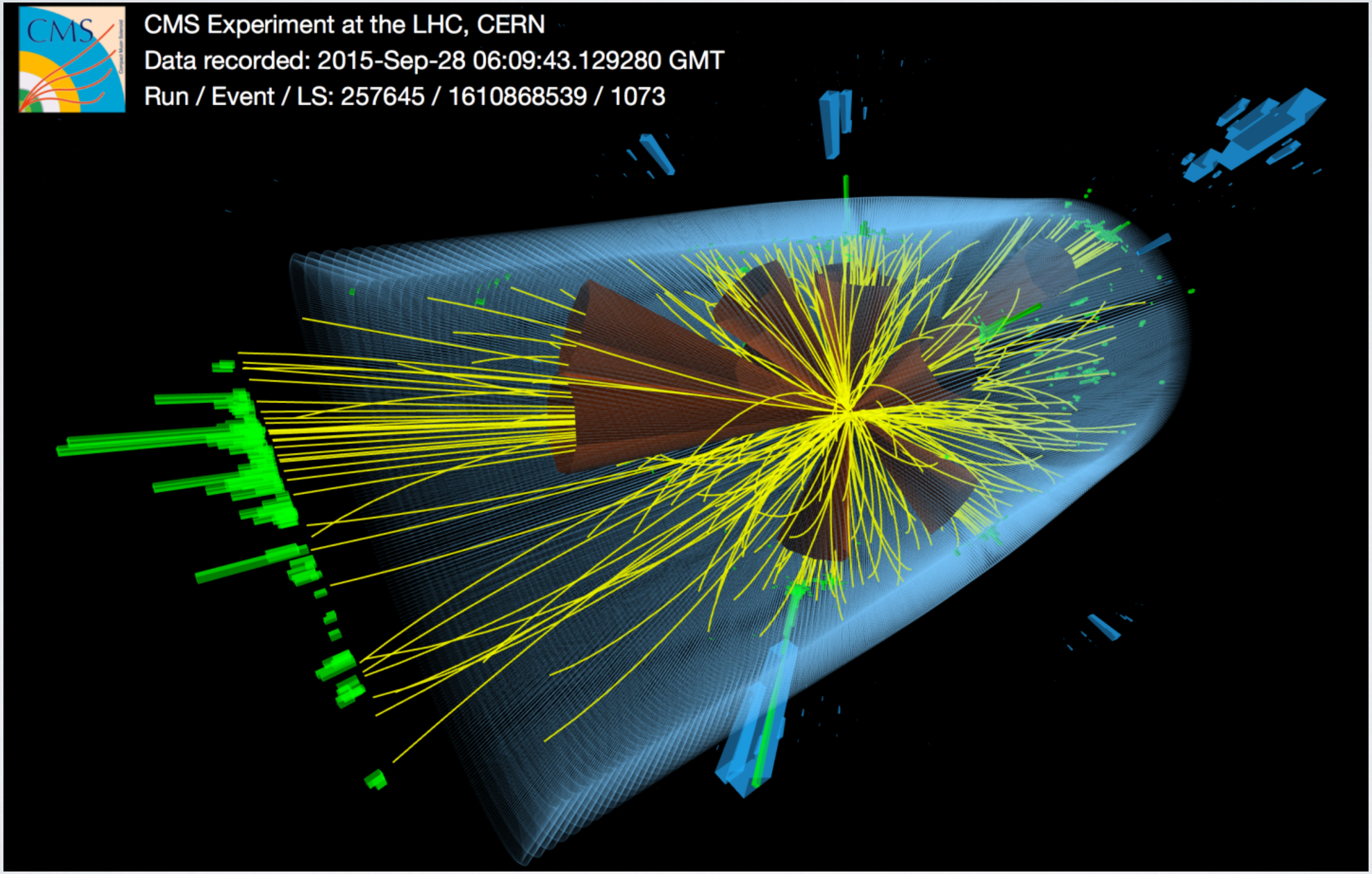
$\mathcal{A} =$ 

$\mathcal{A}^\dagger = \Big($  $\Big)^\dagger =$ 

$\langle |\mathcal{A}|^2 \rangle =$ 

diagrammatic
representation of the
squared amplitude

Cosa vedono i esperimenti?



Cosa vedono i esperimenti?

tracking detectors

calorimeters

exclusive particle identification

(see **π**, p, J/**ψ** **NOT** u,d,c,g)

unstable particle decay

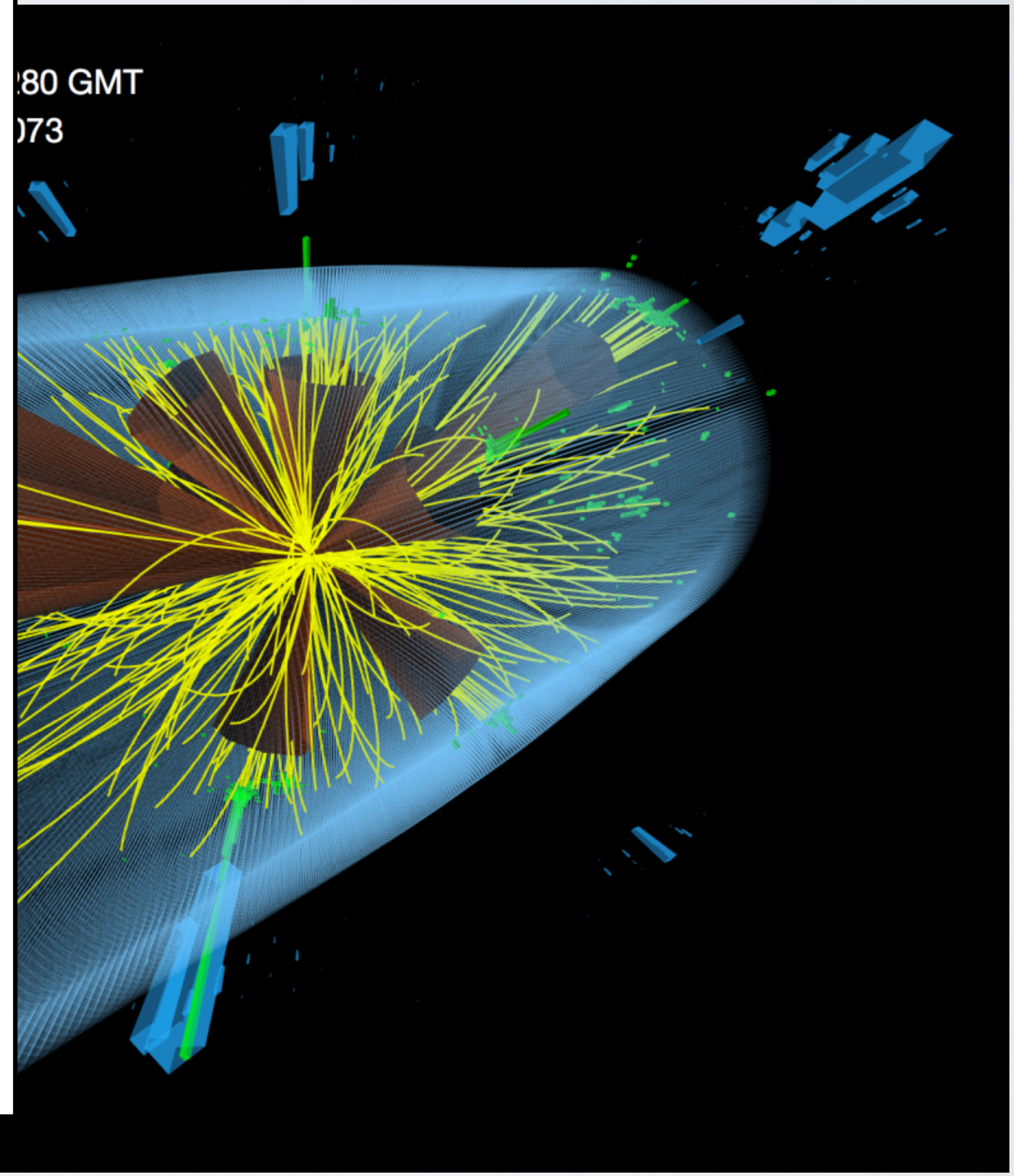
(see e,**μ**,b **NOT** W,Z,H,t)

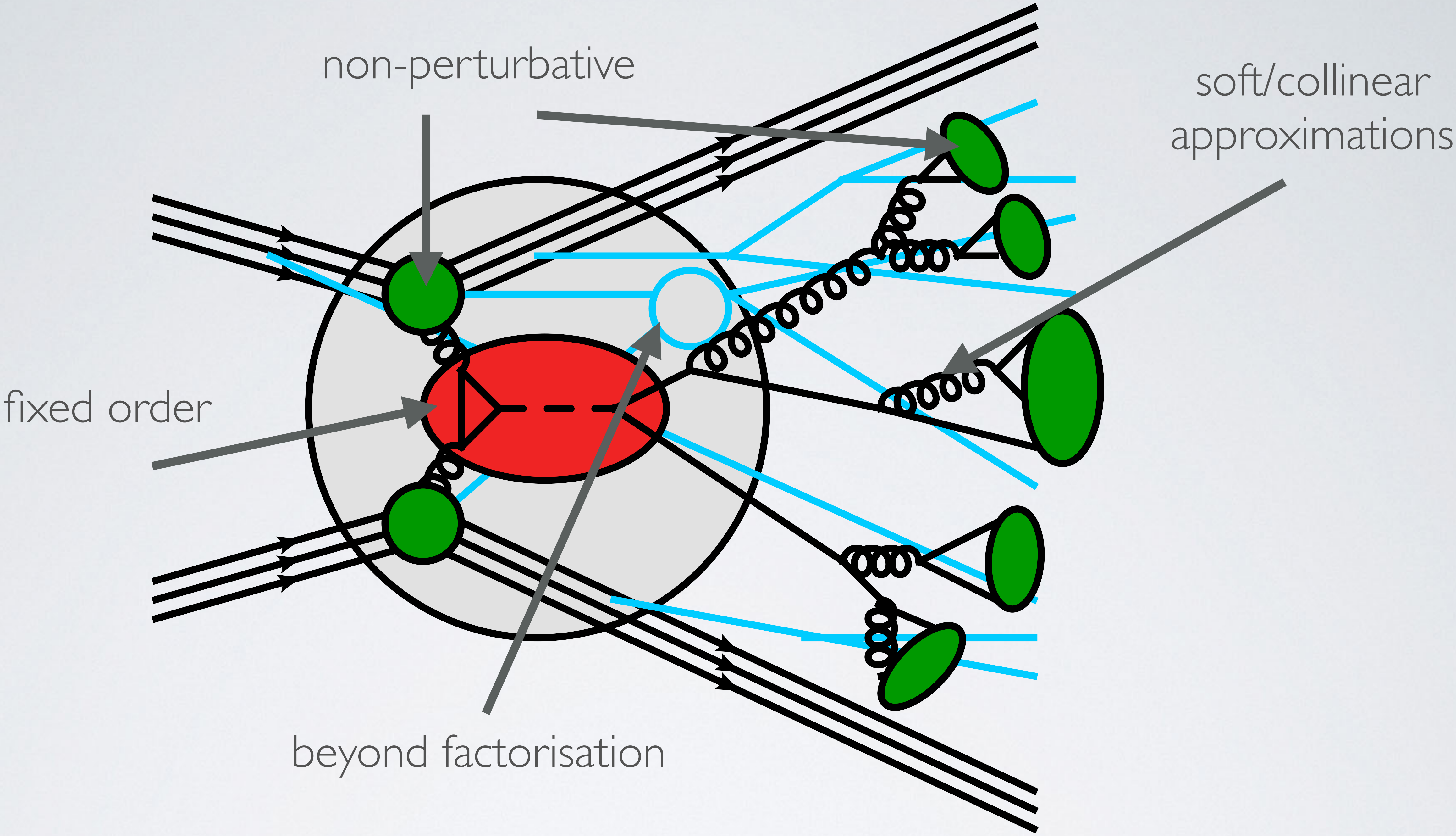
there will be missing energy

(can't see **ν**)

precise physical dimensions!

(need fully differential theory predictions)





numerical simulations using Monte Carlo integration

‘Monte Carlo Event Generators’

Scattering ad alte energie ancora; factorisation per collisore adronico (LHC)

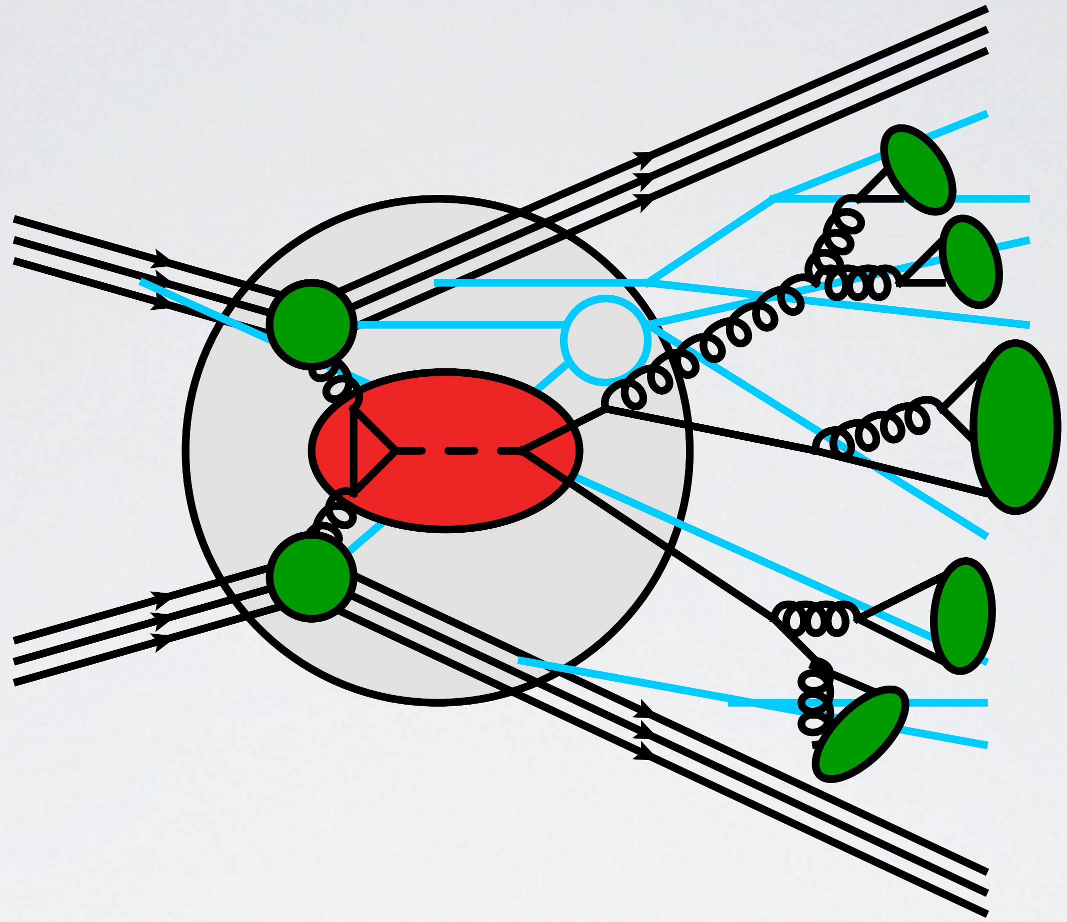
$$\widehat{\sigma} = \frac{1}{\text{flux}} \int \delta^{(4)}(Q - \sum_i p_i) \prod_i d^4p\delta^{(+)}(p_i^2 - m_i^2) \langle |\mathcal{A}|^2 \rangle$$

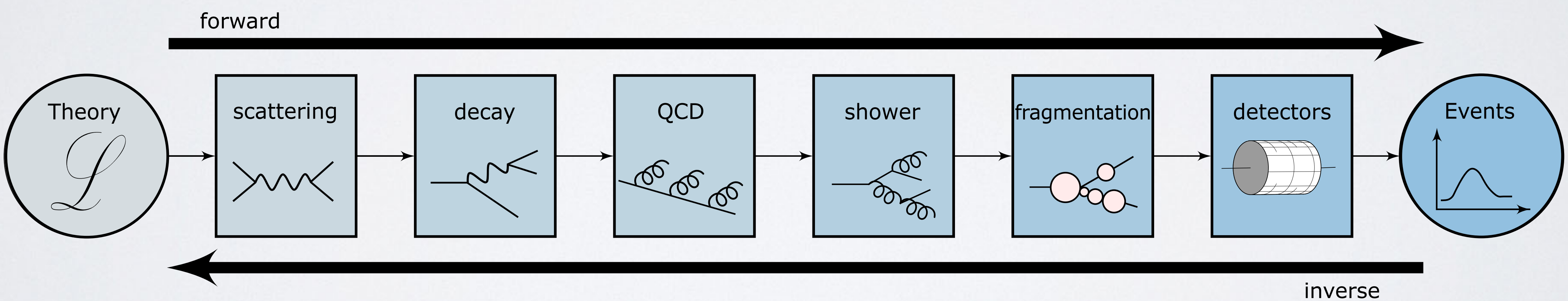
$$\sigma \sim \int dx_1 dx_2 f_i(x_1, Q^2) f_j(x_2, Q^2) \hat{\sigma}(ij \to \{p\}) \Theta + \mathcal{O}(Q/\Lambda)$$

PDF
parton distribution function

observable
(very broad definition)

beyond leading
order factorisation




forward
Theory
scattering
decay
QCD
shower
fragmentation
detectors
Events
inverse

what precision do we need?

determination of SM parameters

a lot!

general searches for BSM resonances

less…

e.g. Drell-Yan with ATLAS (2019)

Many experimental measurements approach 1% precision

	Data
$\sigma\ (W^+ \to \mu^+\nu)$ [pb]	3110 ± 0.5 (stat.) ± 28 (syst.) ± 59 (lumi.)
$\sigma\ (W^- \to \mu^-\bar{\nu})$ [pb]	2137 ± 0.4 (stat.) ± 21 (syst.) ± 41 (lumi.)
Sum [pb]	5247 ± 0.6 (stat.) ± 49 (syst.) ± 100 (lumi.)
Ratio	1.4558 ± 0.0004 (stat.) ± 0.0040 (syst.)

QCD is the largest coupling and so dominates the pertubative expansion

$$\alpha_s(M_z^2) = 0.117 \pm 0.0009$$

PDG world average (2021)

c.f. $\alpha^{(-1)}(0) = 137.035999150(33)$

$$\boxed{d\sigma = \boxed{d\sigma^{\mathrm{LO}}} + \boxed{\alpha_s d\sigma^{\mathrm{NLO}}} + \boxed{\alpha_s^2 d\sigma^{\mathrm{NNLO}}}}$$

~10-30 % **~1-10 %**

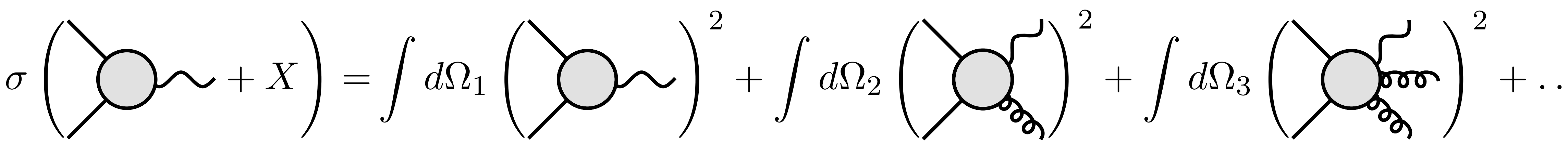
remember: RG improved PT is asymptotic

differentially many effects play a role: EW corrections, mass effects etc.

Making Precision Predictions

As mentioned before QFT contains divergences in both UV and IR

observables such as (differential) cross sections must be **inclusive** over the phase-space in order to capture the cancellations from **unresolved** radiation configurations



now consider the perturbative expansion of these amplitudes

Making Precision Predictions

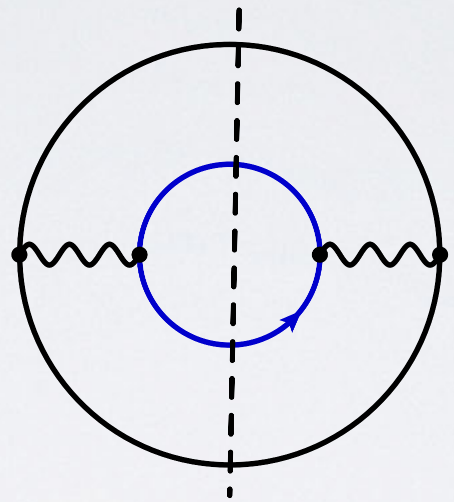
QCD corrections to $e^+e^- \to q\bar{q}$

IR divergences cancel between real and virtual corrections to physical observables.

Kinoshita-Lee-Nauenberg (KLN) theorem

LO

$d\Phi_2$

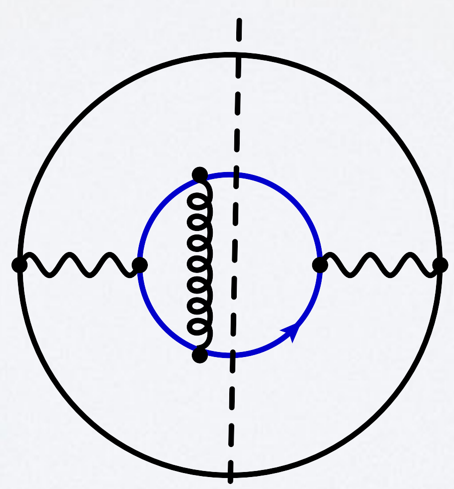


'Born'

NLO

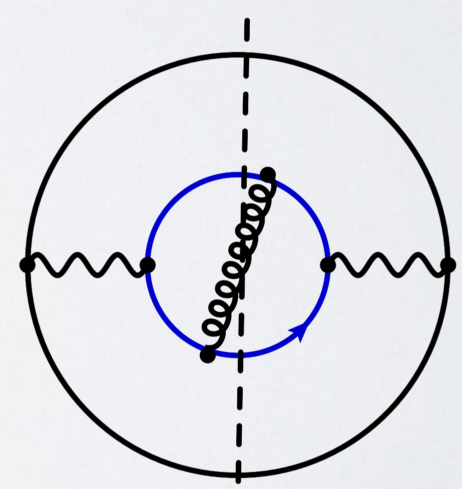
$d\Phi_2 d^4 l$

loop integration



'Virtual'

$+ \quad d\Phi_3$



'Real'

Making Precision Predictions

The full calculation involves many steps and techniques…

$$\sigma^B(e^+e^- \to q\bar{q}) = \frac{4N_c\,\alpha^2\,q_q^2}{3\pi s}$$

$$\sigma^V(e^+e^- \to q\bar{q}) = \sigma^B C_F \frac{\alpha_s}{2\pi}\mathcal{H}(\epsilon)\left(-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} - 7 - \delta^{CDR} + \pi^2\right)$$

$$\sigma^R(e^+e^- \to q\bar{q}) = \sigma^B C_F \frac{\alpha_s}{2\pi}\mathcal{H}(\epsilon)\left(\frac{2}{\epsilon^2} + \frac{3}{\epsilon} + 17/2 + \delta^{CDR} - \pi^2\right)$$

$$R = N_c \sum_{q=\{u,d,s,\dots\}} \Theta(\sqrt{s} - 2m_q)q_q^2\left(1 + C_F\frac{3\alpha_s}{4\pi}\right)$$

can use this to extract α_s from data $\Rightarrow \alpha_s(m_Z) = 0.1226 \pm 0.0038$

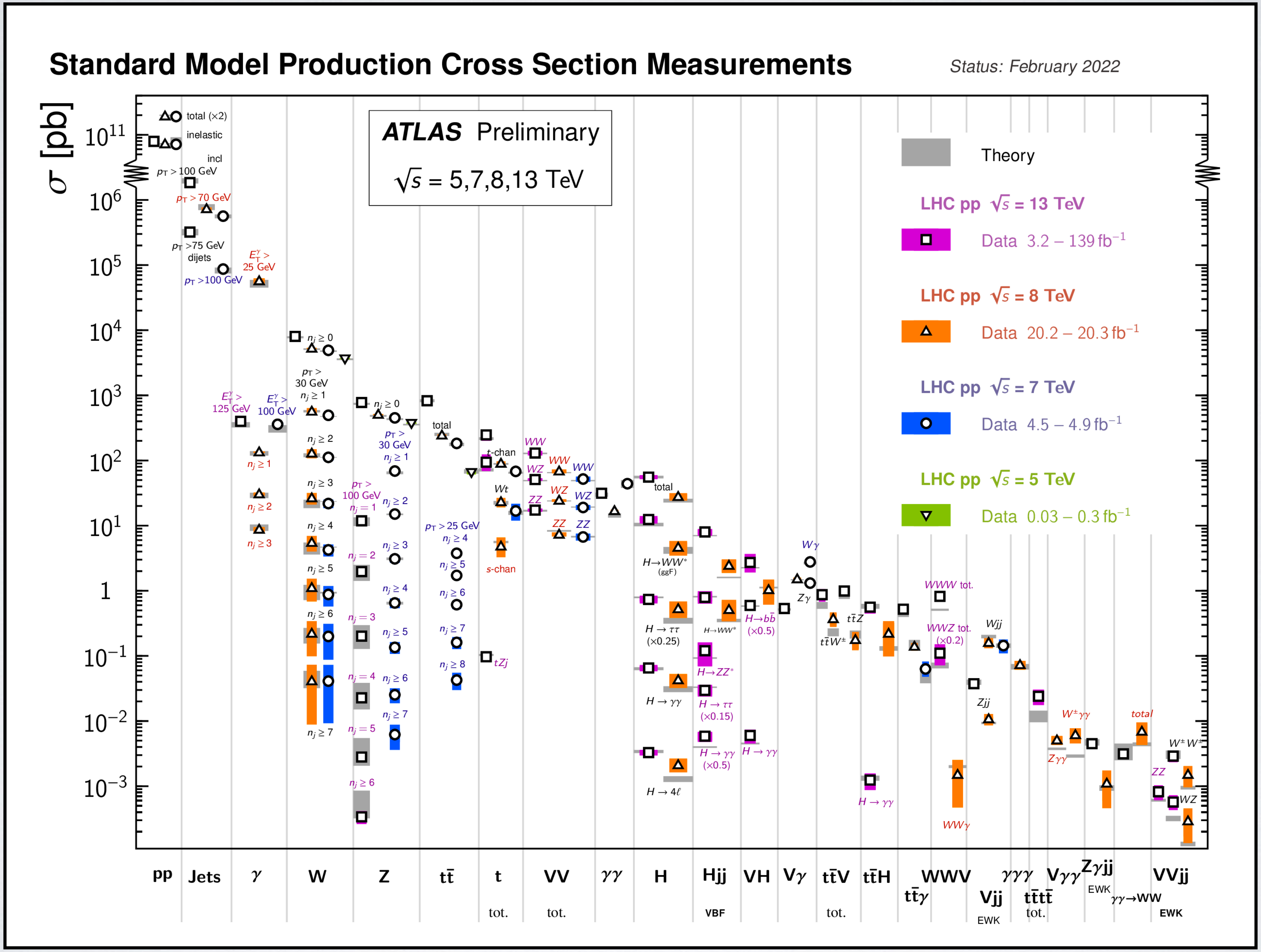
dimensional regularisation

$$d = 4 - 2\epsilon$$

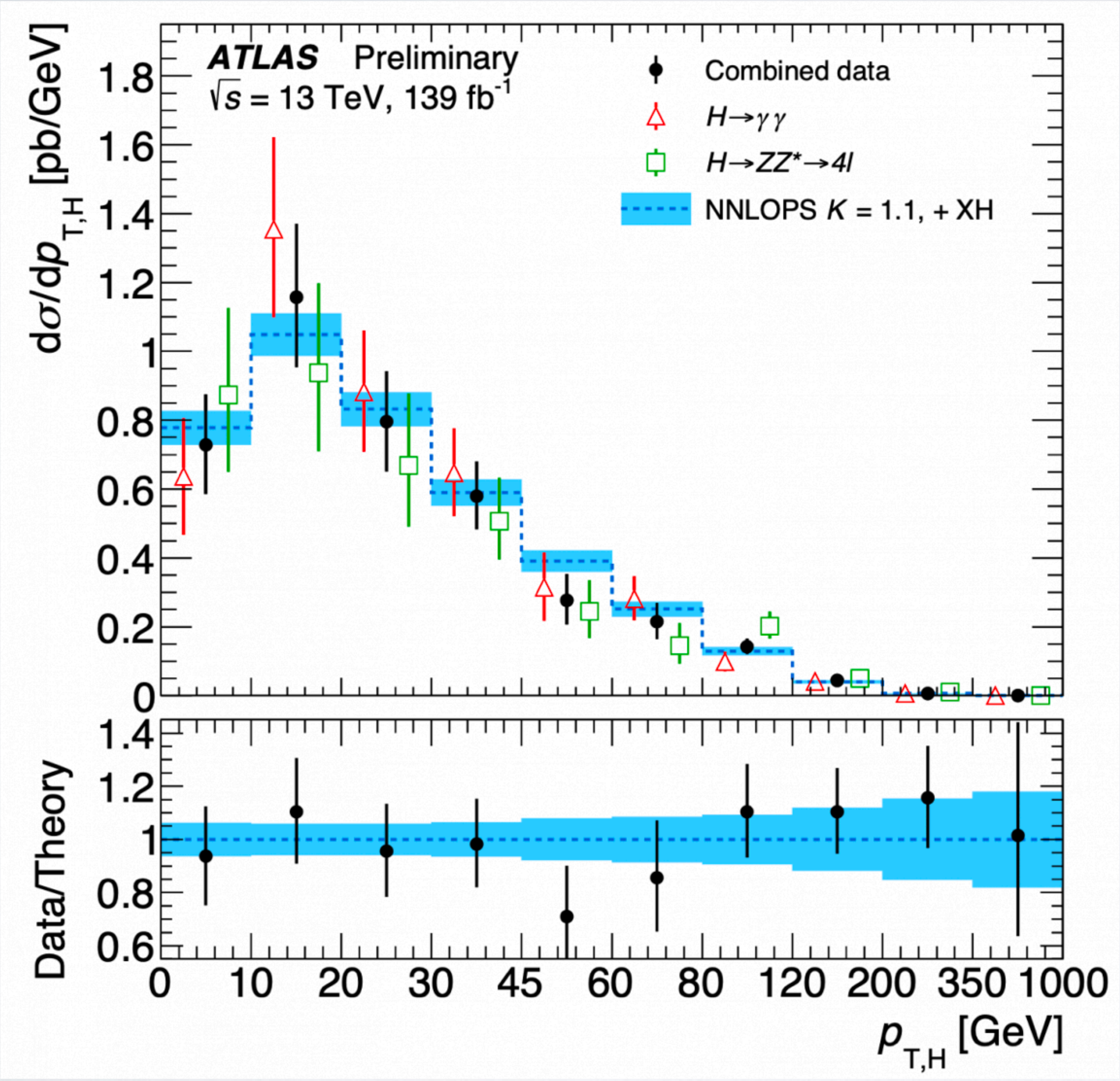
scheme dependence

$$C_F = \frac{N_c^2 - 1}{2N_c}$$

Current Standard Model Tests

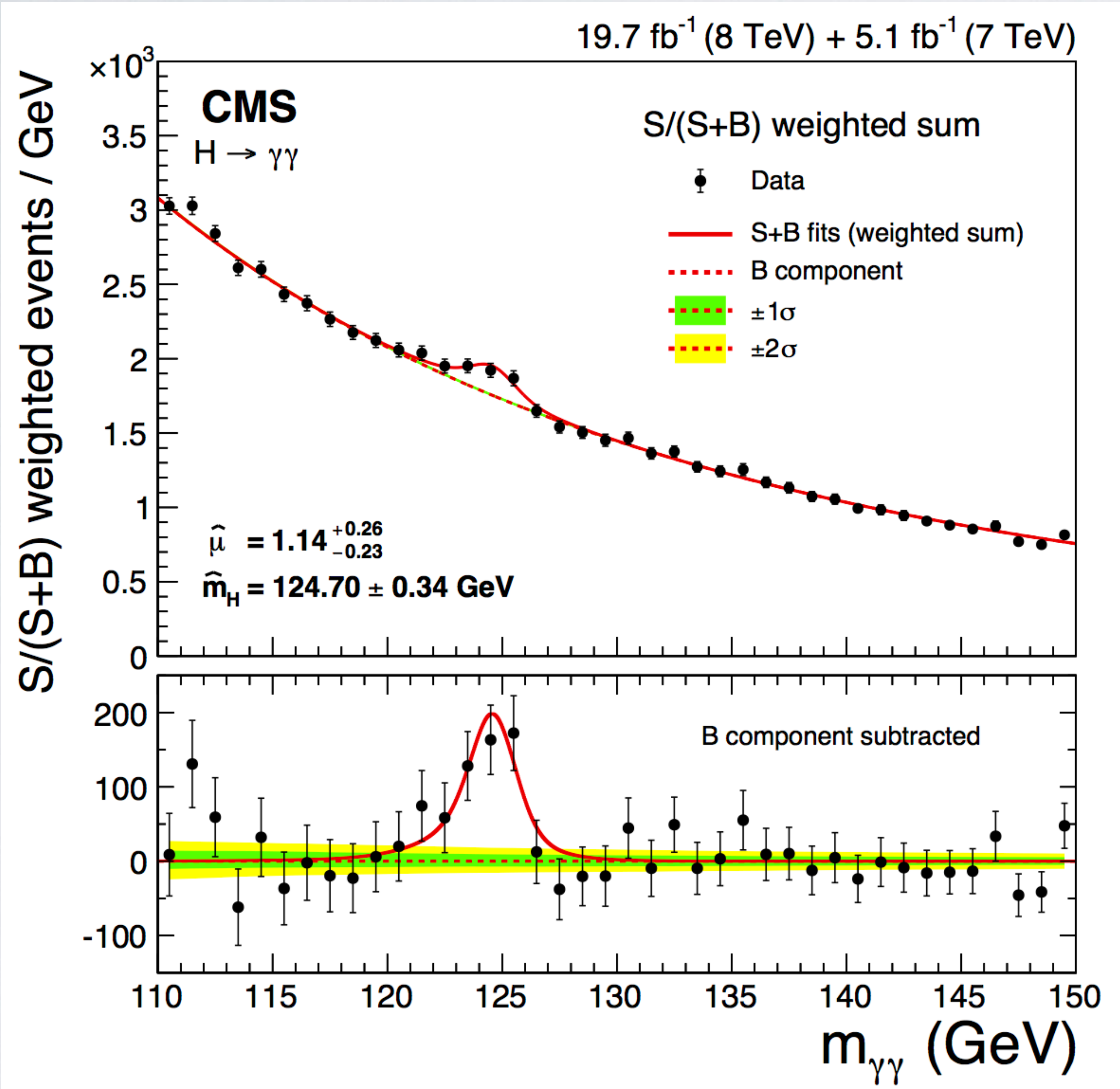


Differential tests offer more information



area under the curve is the cross section (Sezione d'urto)

Finding new particles



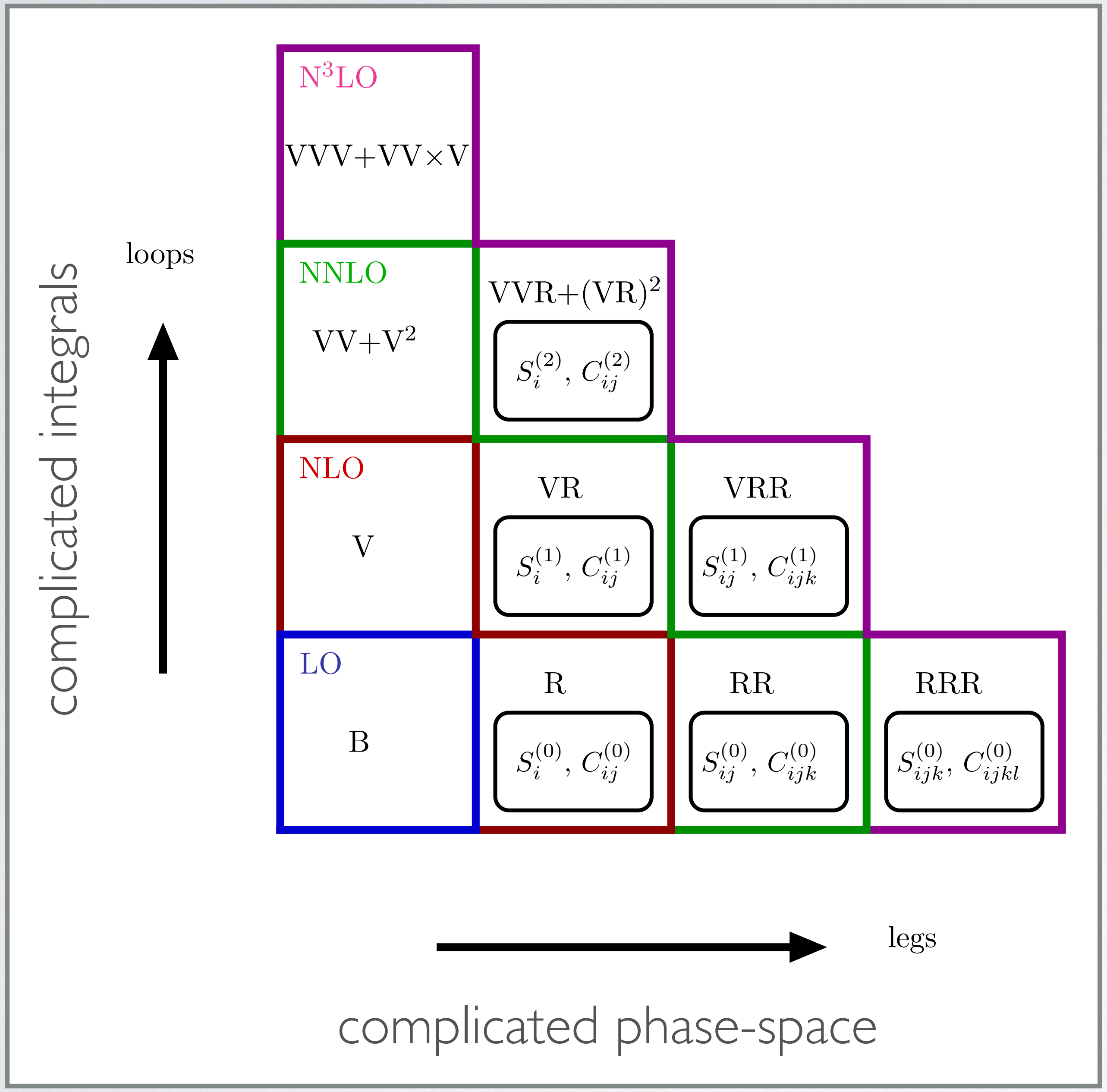
bump hunting is relatively easy

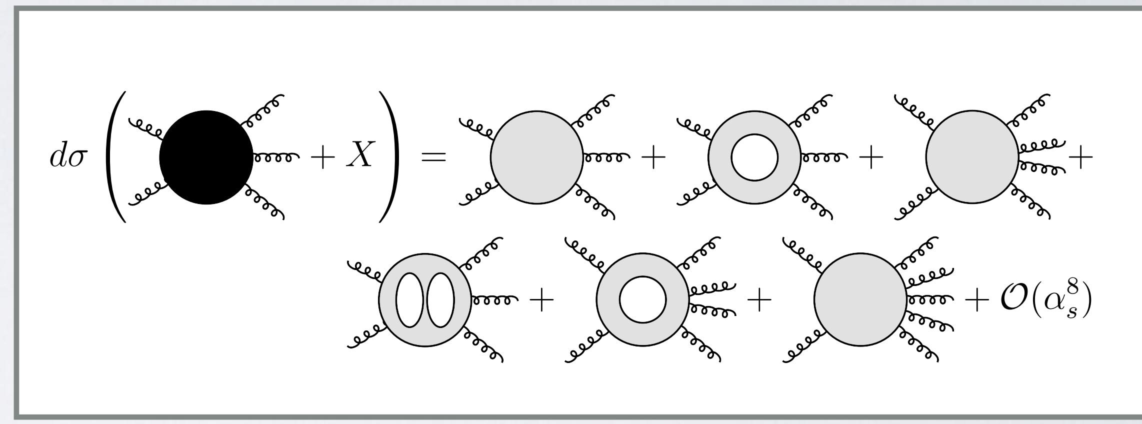
$$\mathcal{A} \sim \frac{1}{p^2 - m_h^2 - i m_h \Gamma_h}$$

leads to the
Breit-Wigner distribution

$\Gamma_h =$ decay width

Precision fixed order calculations



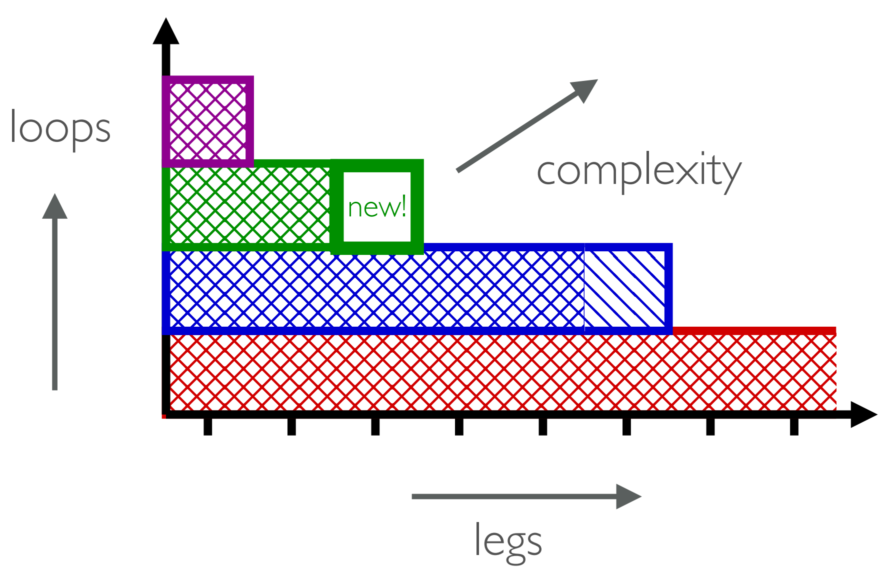


keeping theory in line with experiments takes **years** of dedicated effort

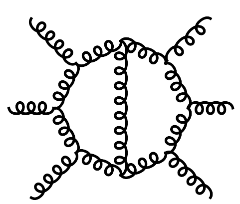
Growing Complexity

loops	1	2	3	4	5
diagrams	5	30	450	$50,000$	1.5×10^6
year	1973	1974	1980/1993	1997/2005	2016

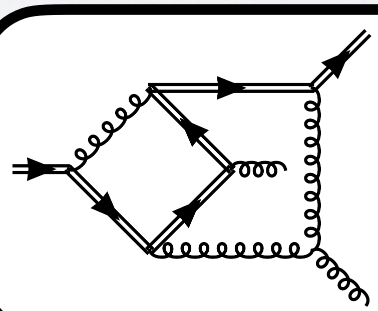
Diagrams contributiing to QCD β function up to 5 loops



more scales = more complicated



algebraic complexity
e.g. six-gluon scattering

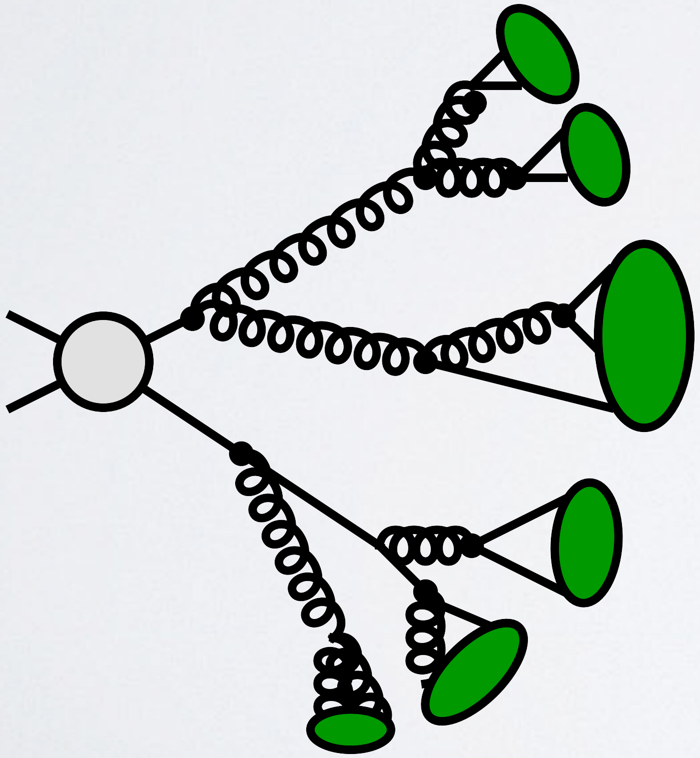


analytic complexity
e.g. pp⟶tt

More radiation: e.g. parton showers

The cancellation of IR divergences is connected to the universal singular behaviour of QCD

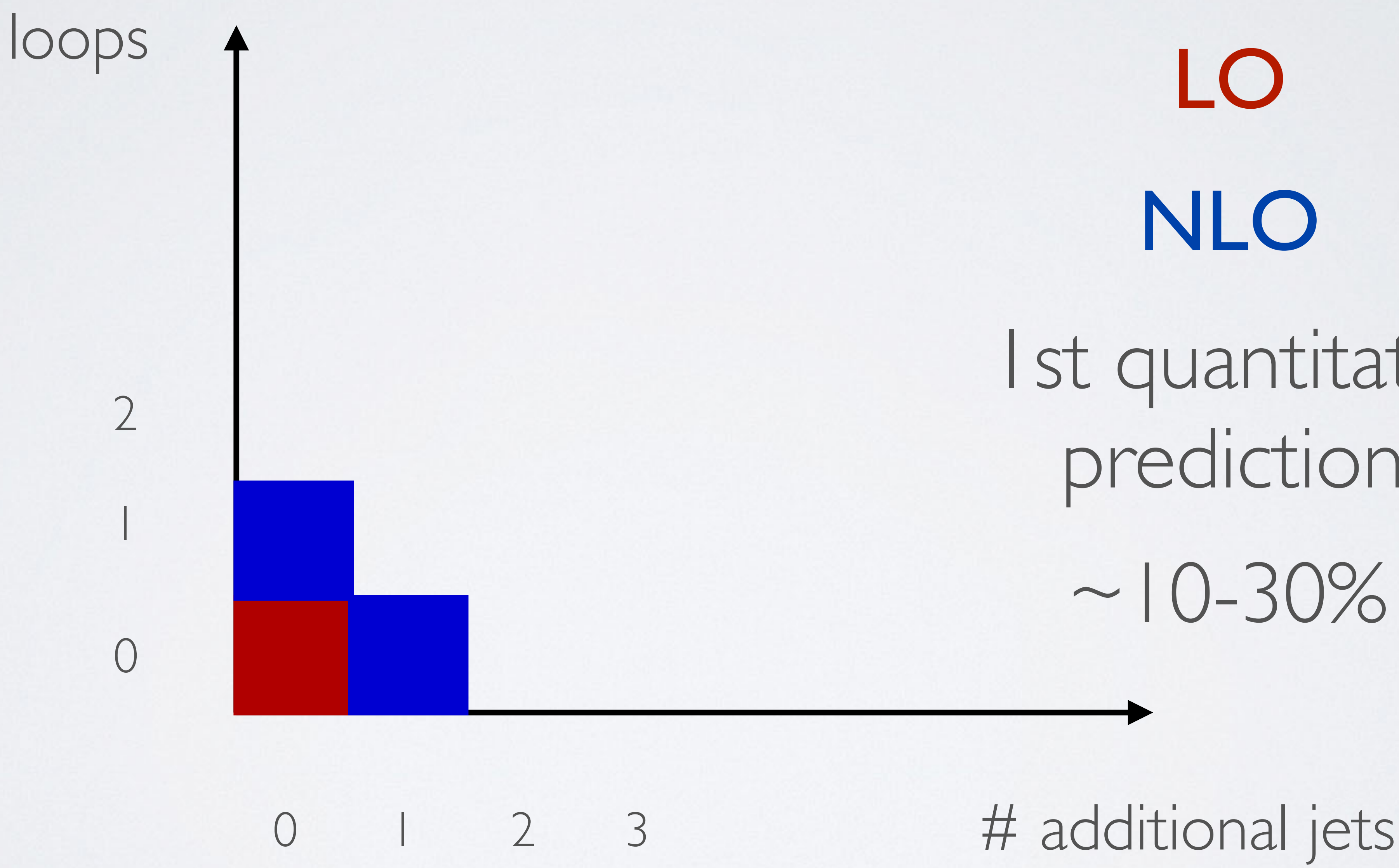
The probability of a parton emitting a soft or collinear gluon is independent of the hard scattering process



parton showers give a statistical evolution of the hard scattering process until the hadronisation scale is reached

the effect is an explicit re-summation of soft emissions **beyond fixed order** perturbation theory

Ingredients for precision



LO

NLO

1st quantitative predictions

~10-30%

Ingredients for precision

LO

NLO

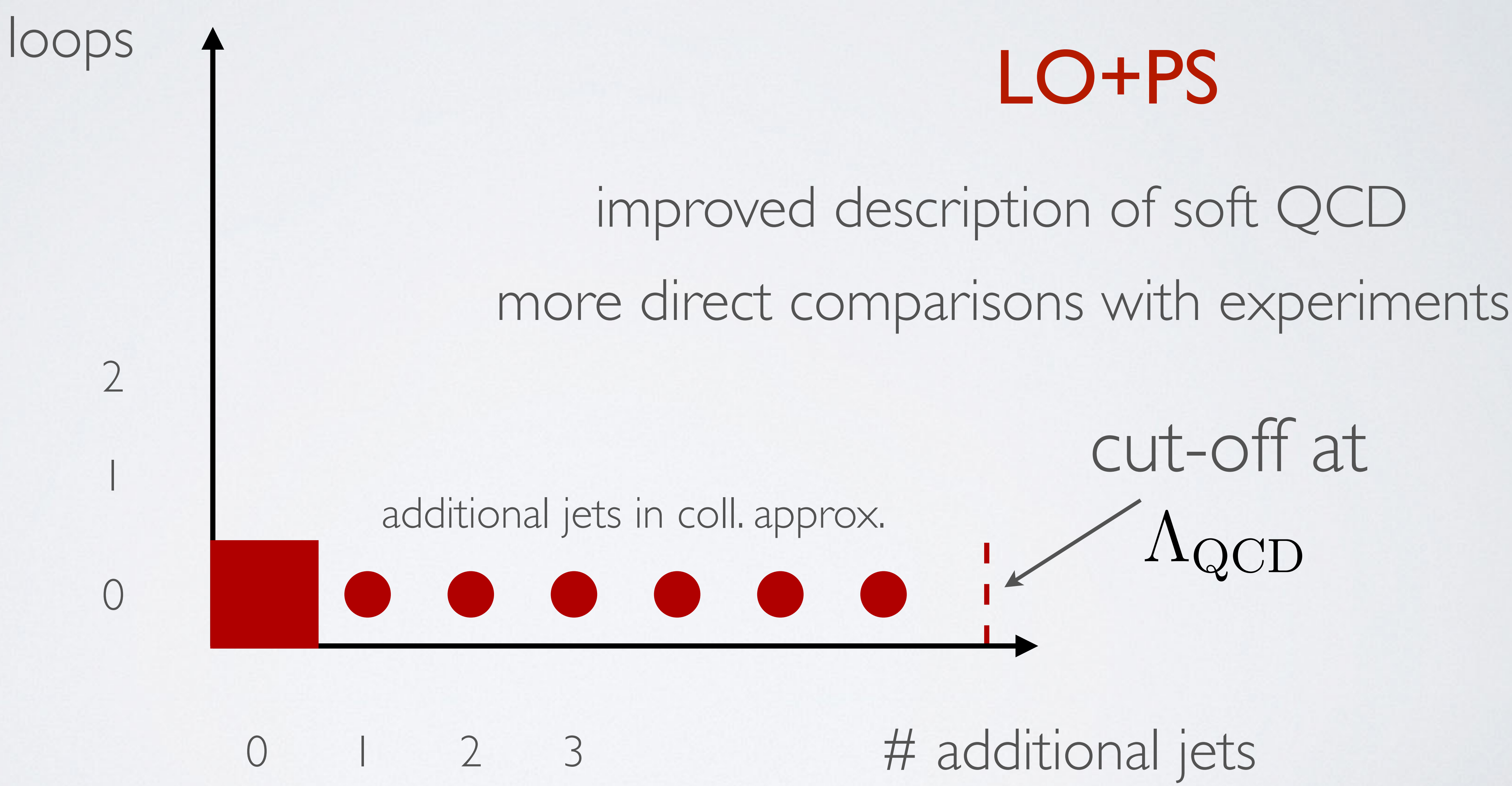
NNLO

~5%

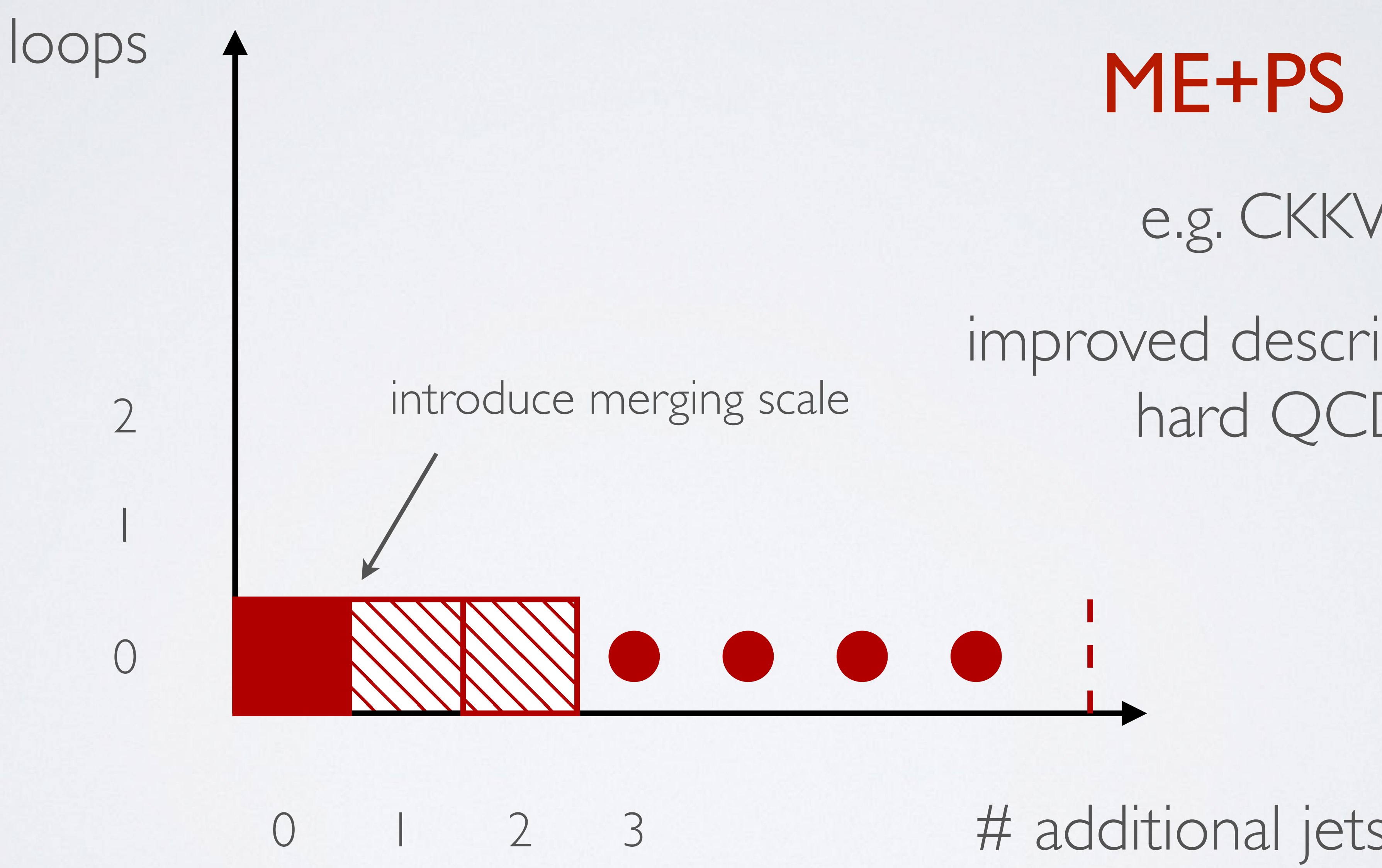
pdf uncertainties
becoming bottleneck

Ingredients for precision

fixed order not good for all regions



Ingredients for precision

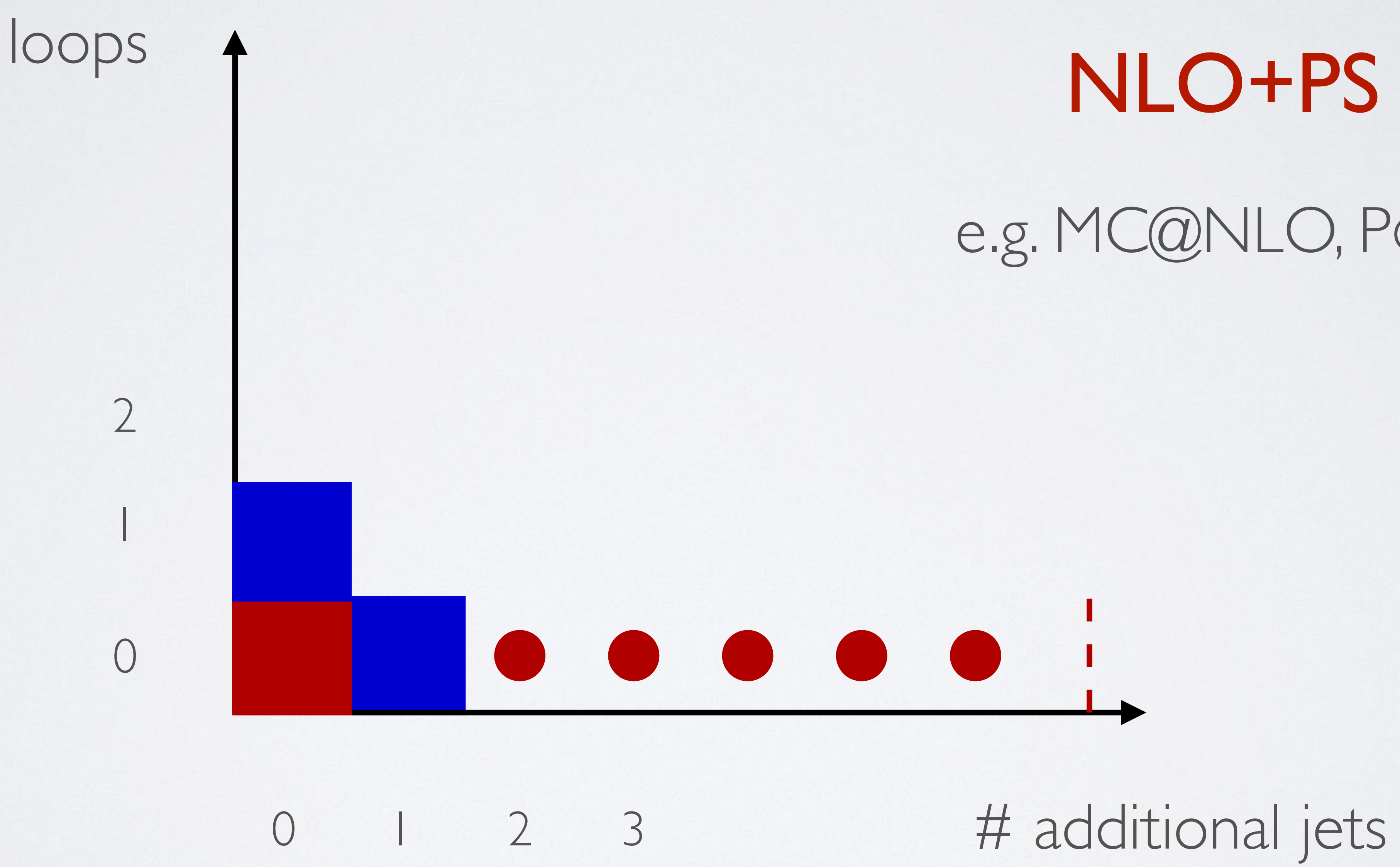


ME+PS

e.g. CKKW-L, MLM

improved description of hard QCD

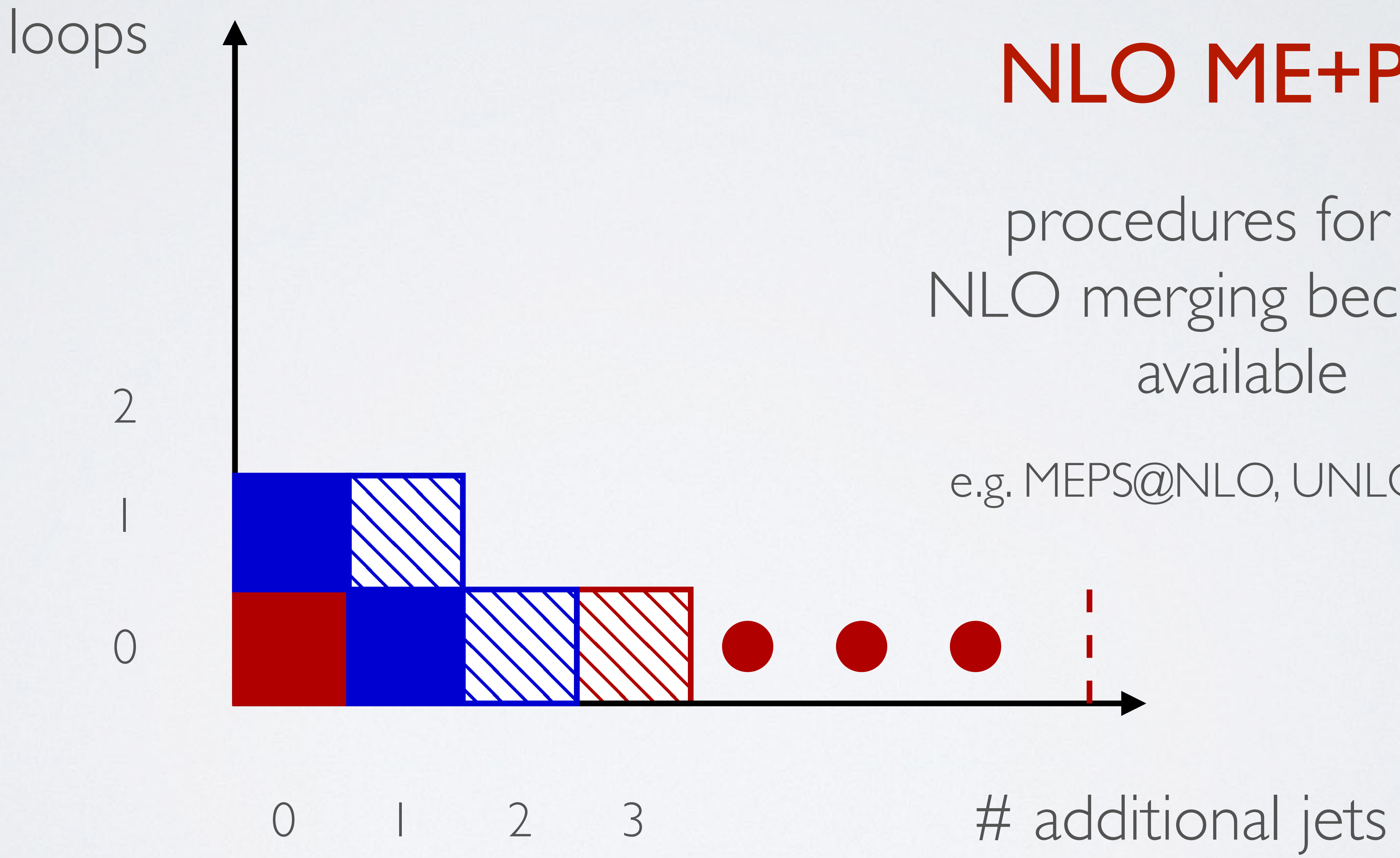
Ingredients for precision



NLO+PS

e.g. MC@NLO, POWHEG

Ingredients for precision



NLO ME+PS

procedures for full NLO merging becoming available

e.g. MEPS@NLO, UNLOPS, FxFx, ...

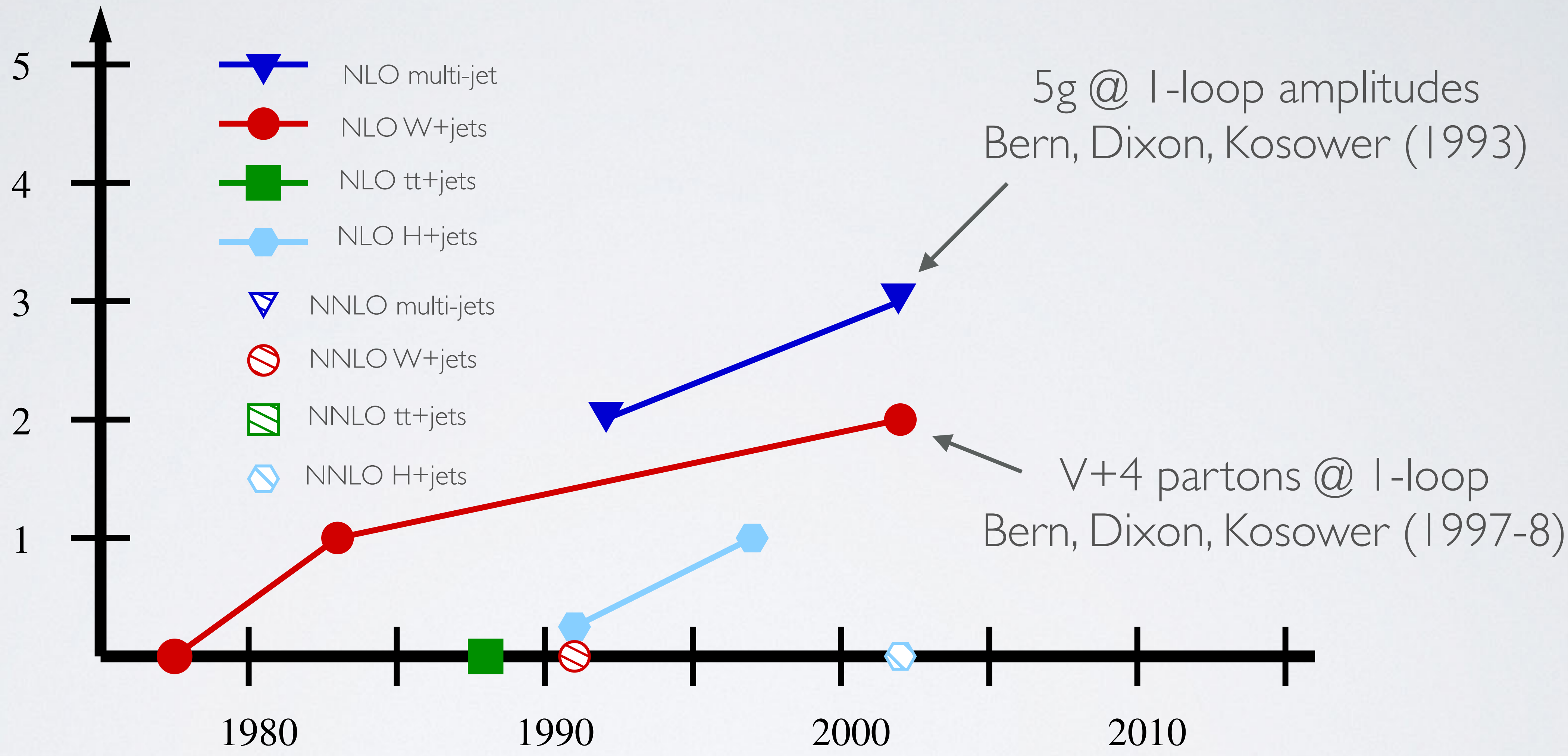
General purpose event generators (long term projects)

Pythia (1982-)
Herwig (1986-)
Sherpa (2002-)
Powheg (2004-)
MadGraph (1994-)

collect large numbers of different models (hadronisations, parton showers etc.) and interface with specialsed codes for PDFs, amplitudes etc.

Chi ha usato uno di questi generatori prima?

a bit of history

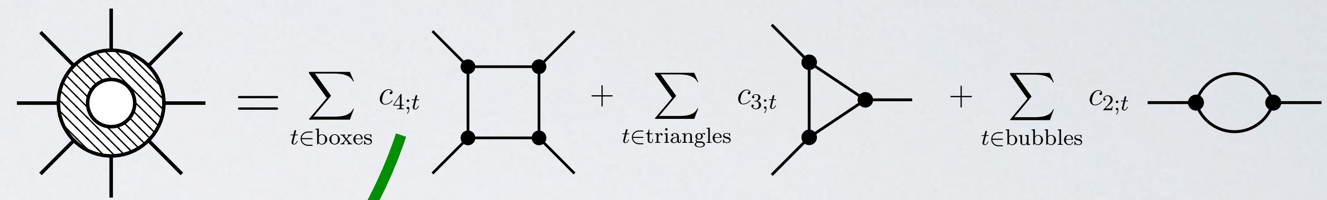


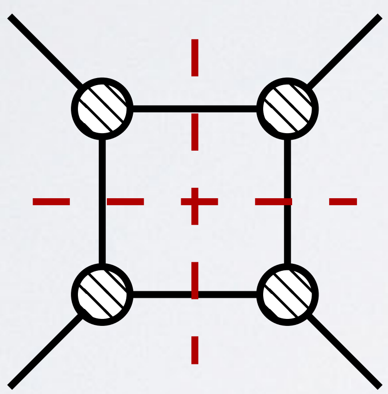
Loop corrections not the only issue: another breakthrough in mid 90's was IR subtraction technique of Catani and Seymour

new theoretical methods

~2005 one-loop basis integrals were known

't'Hooft, Veltman, Denner, Dittmaier, Bern, Dixon, Kosower, Ellis, Zanderighi, van Hameren,…





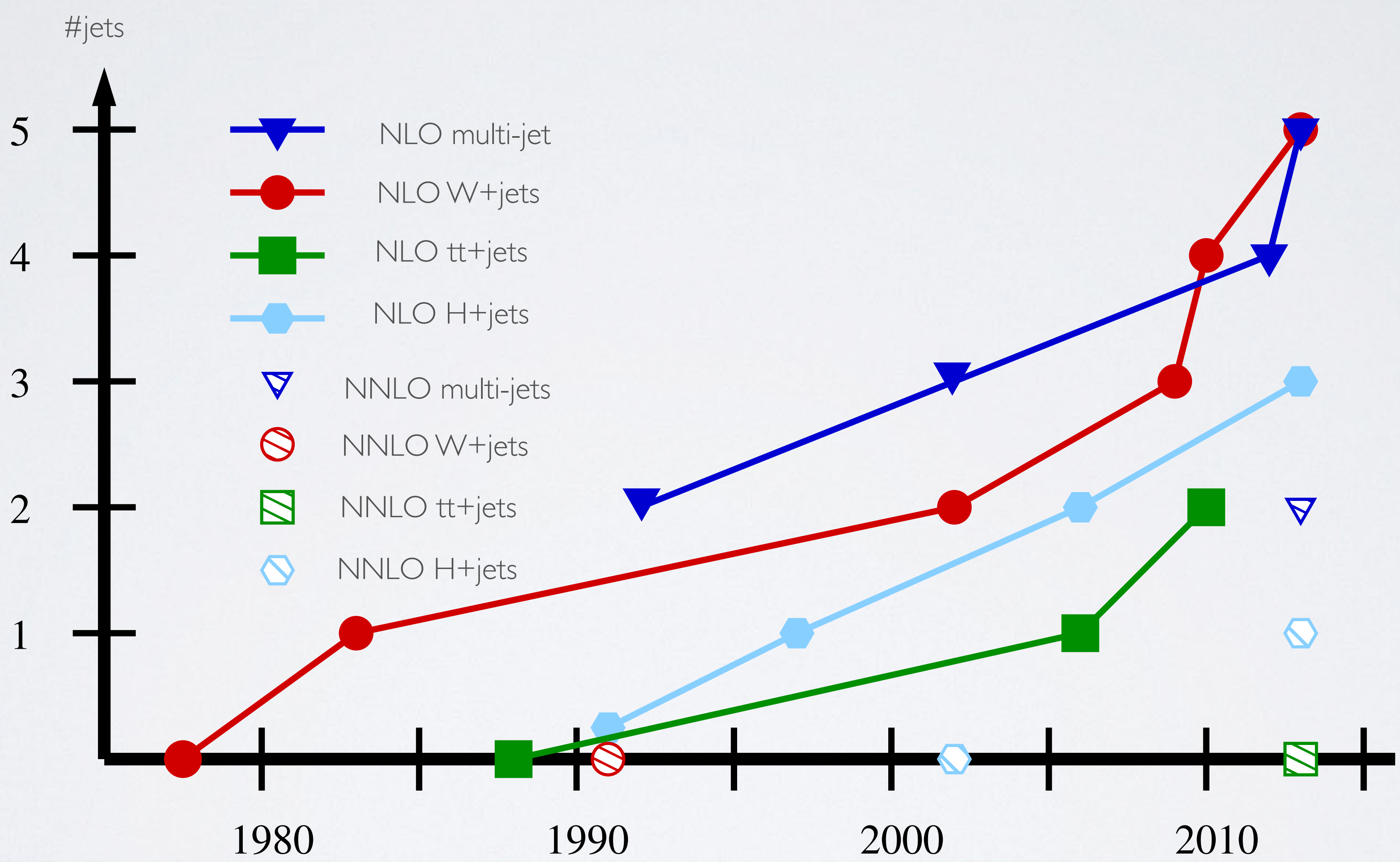
new algebraic algorithms - multi-scale bottleneck overcome!

Ossola, Papadopoulos, Pittau, Bern, Dixon, Kosower, Berger, Forde, Ita, Maitre, Ellis, Giele, Kunszt, Melnikov, SB, Biedermann, Uwer, Yundin, Mastrolia, Cullen, Greiner, Heinrich, Luisoni, Ossola, Peraro, Reiter, Tramontano, Pozzorini, Cascoli, Maierhöfer,…

performing algebra numerically led to **automated** codes capable of 2⟶5/6 processes at NLO.

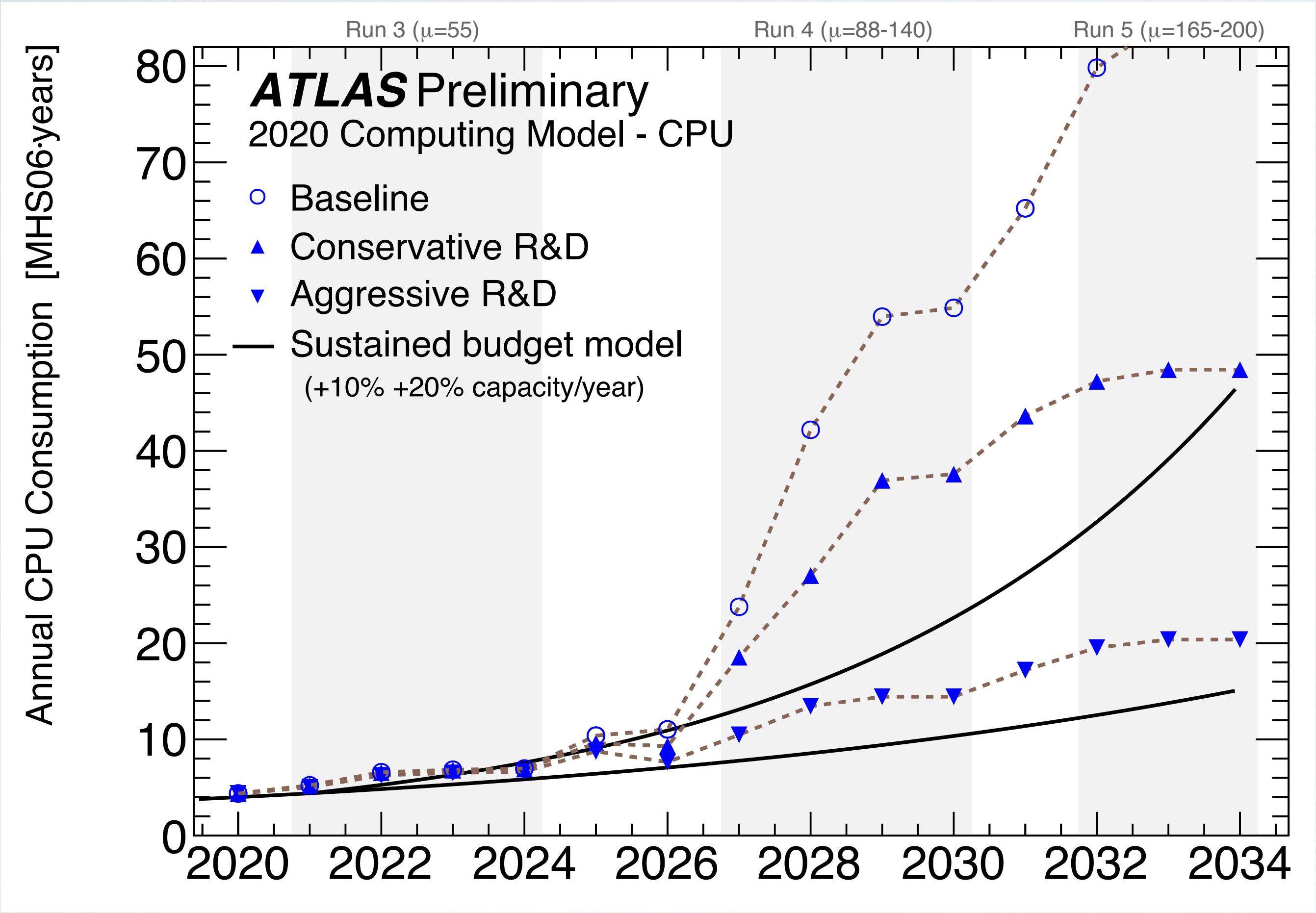
HELAC-NLO, BLACKHAT, GOSAM, NJET, RECOLA, MADLOOP, OPENLOOPS

NLO QCD corrections in 2013



what’s the computational cost?

LHC MC computing requirement projections



- Moore's Law no longer applies
- HL-LHC could have limitiations from MC statistics without new developments

from

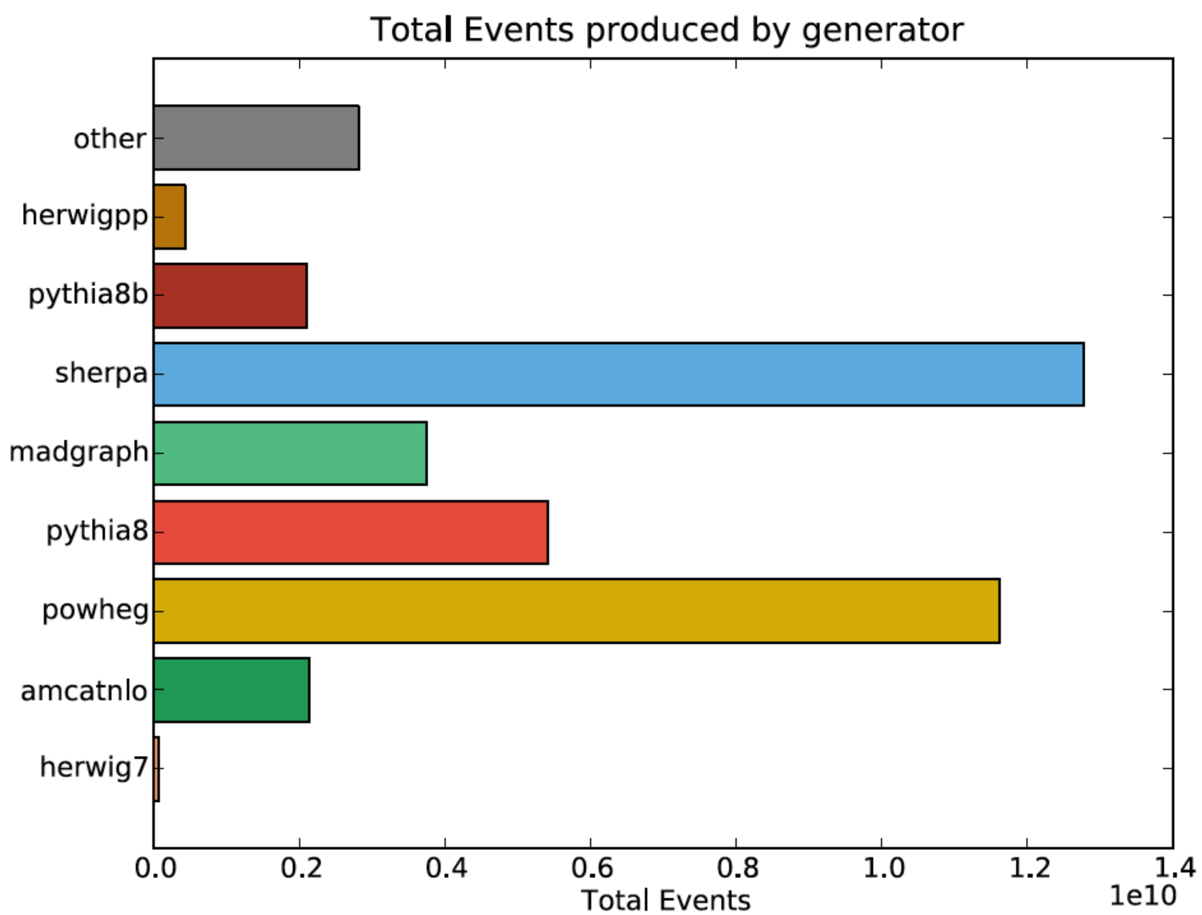
Christian Gütschow

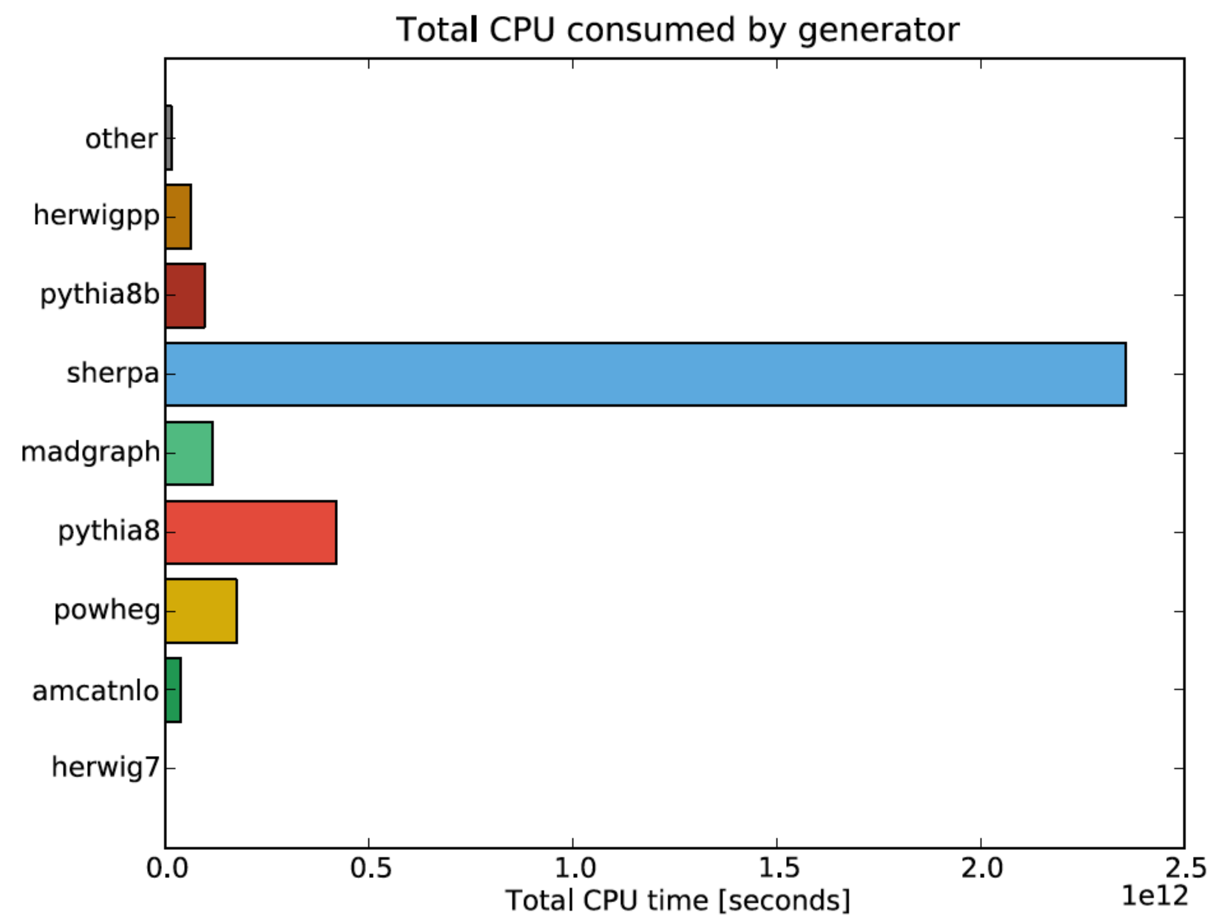
at

Taming the accuracy of event generators workshop CERN, June 2020

Breakdown by generator (bit outdated, but not too bad)

- left plot: does not account for alternative multi-leg setups
- right plot: most CPU spent on high-precision multi-leg calculations
(e.g. for ATLAS: $V + 0, 1, 2j$@NLO$+3, 4j$@LO and $t\bar{t} + 0, 1j$@NLO$+2, 3, 4j$@LO)



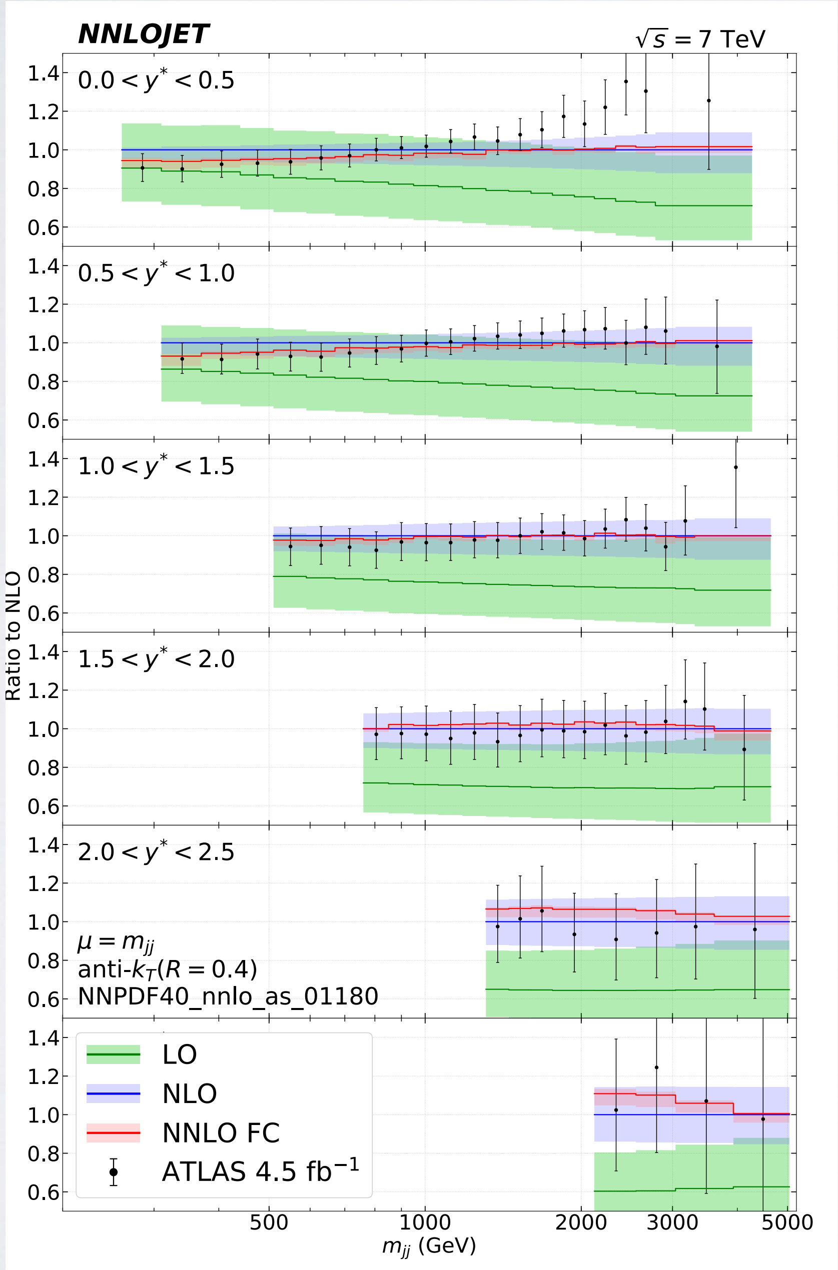


[courtesy of Josh McFayden]

- outlook: CPU spent on expensive setups expected to increase faster than for fast setups

and for NNLO precision?

many are still specialized (private) codes, NNLOjet, MATRIX, etc.



for some of the most expensive fixed order simulations

~ 200,000 CPU hours

example: full colour di-jets [Chen et al 2204.10173]