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LHC RUN III AND THE PRECISION FRONTIER

European Research Council
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NEW PHENO CHALLENGES AT THE LHC PRECISION FRONTIER

- **Lecture I:**
  “LHC Run III and the precision frontier”
- **Lecture II:**
  “New frontiers in the determination of the proton structure”
- **Lecture III:**
  “Hints for new physics from precision physics”

AIM: GIVE A PERSONAL PERSPECTIVE ABOUT WHAT I IDENTIFY AS MOST EXCITING CHALLENGES THAT MODERN COLLIDER PHENOMENOLOGY FACES.

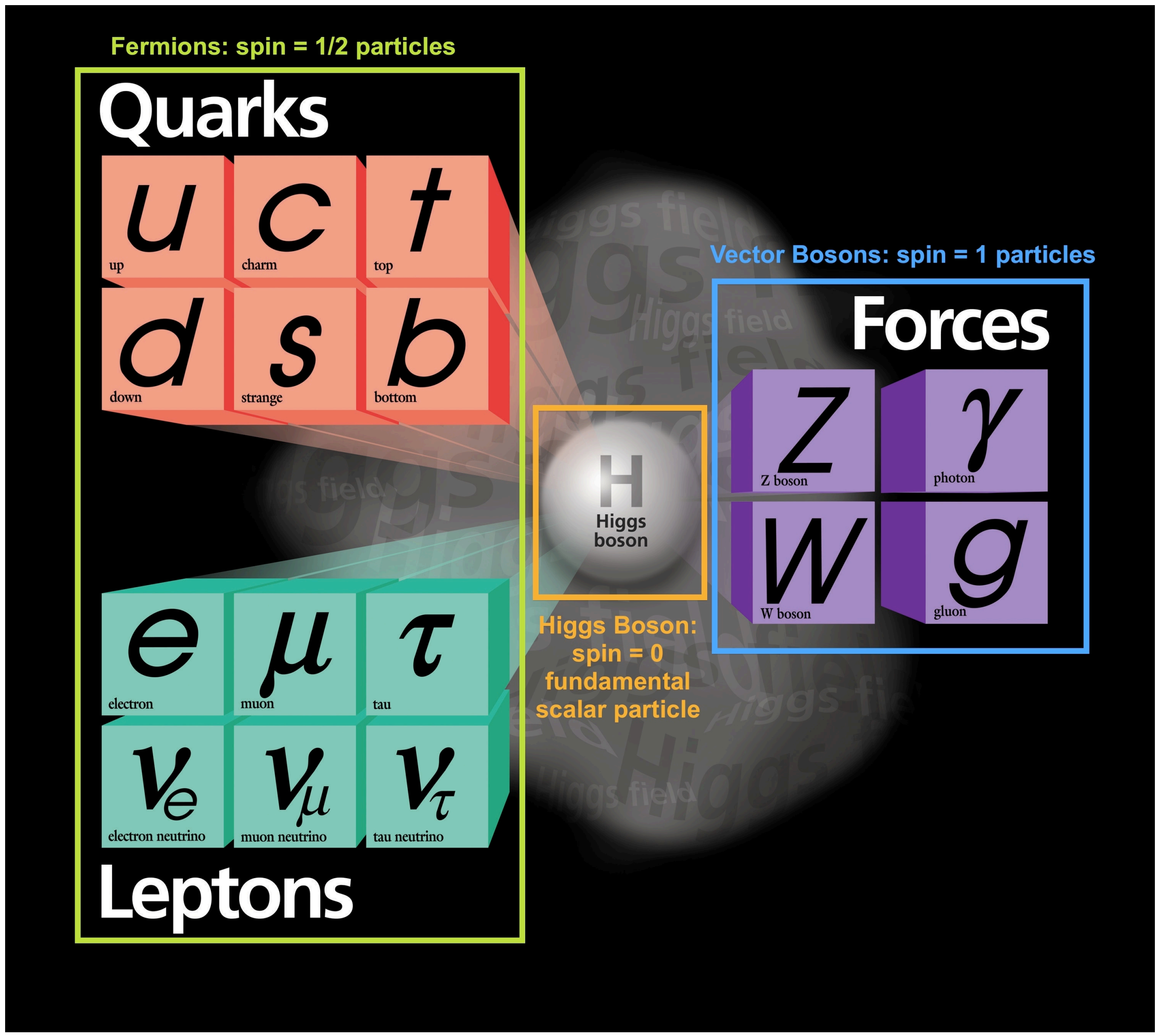
DISCLAIMER: IMPOSSIBLE TO GO INTO ALL DETAILS THAT TOPICS DESERVE NOR TO COVER ALL RELEVANT TOPICS.

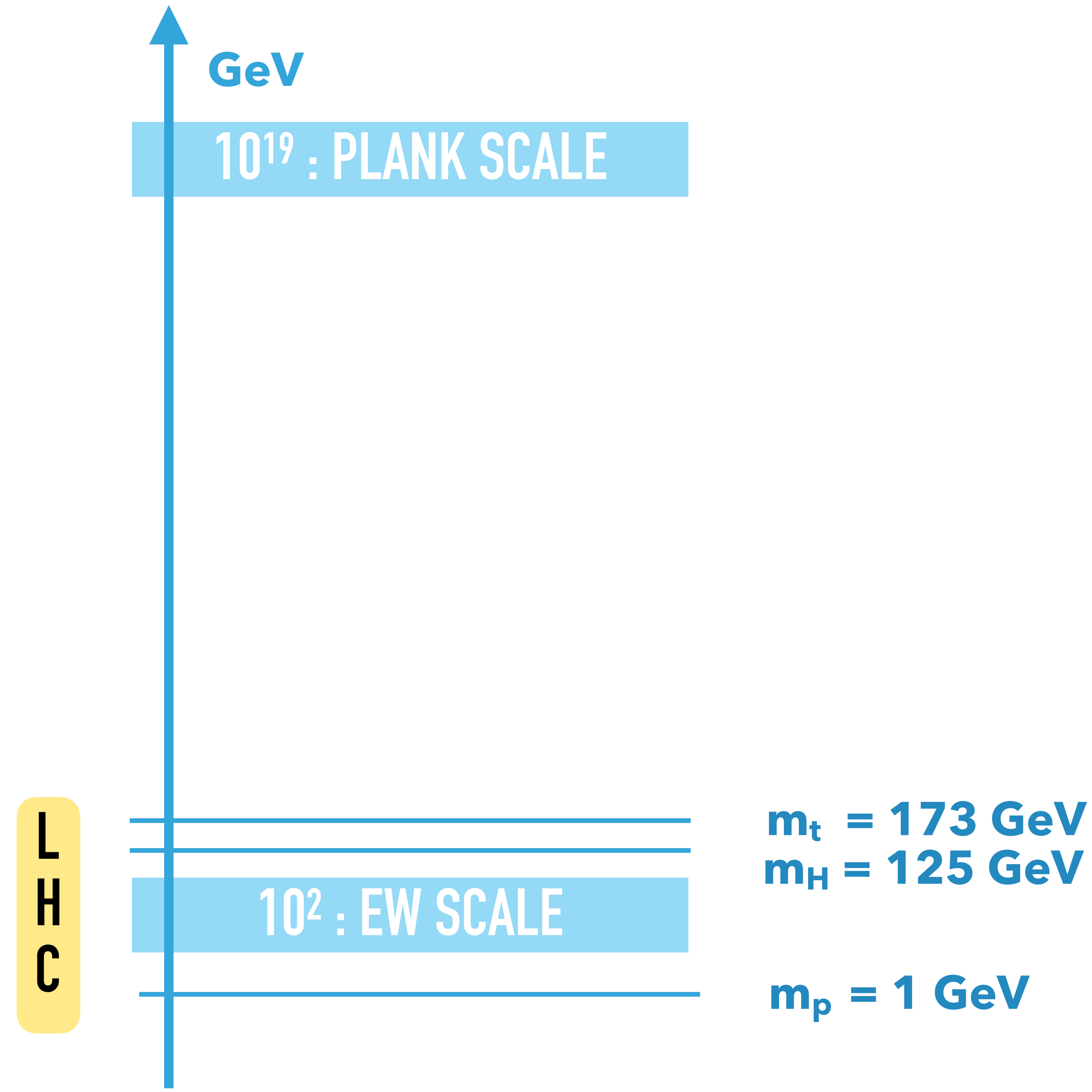
LHC RUN III AND THE PRECISION FRONTIER

I. Introduction
    I. Basics of collider phenomenology
    II. Basics of QCD
II. The precision ingredients at the LHC
    I. The strong coupling constant
    II. QCD fixed order computations
    III. Beyond fixed order QCD

1. INTRODUCTION

EXPLORING THE HIGH ENERGY FRONTIER AT THE LHC…





- Huge gap between EW scale and Planck scale and many outstanding unanswered questions (neutrino masses, dark matter…)
- The discovery of the Higgs at the LHC opens a new era of exploration of the high energy frontier at particle colliders

….VIA PRECISION PHYSICS

“***Precision*** is the keystone to ***consolidate our description of nature***, increase the sensitivity to SM deviations, give credibility to discovery claims[…].

The LHC has also proven to be a ***discovery machine***, and in a context broader than just Higgs and BSM phenomena. Altogether, it delivered results that could not have been obtained otherwise, immensely enriching our understanding of nature. ”

M. Mangano, “The LHC at 10: the physics legacy”, CERN courier

1.1 BASICS OF COLLIDER PHENOMENOLOGY

COLLIDER PHYSICS

The purpose of collider phenomenology is to test theoretical predictions experimentally in a controllable environment

Theory

- QFT
- Lagrangian
- Models:
  - SM
  - SUSY
  - ...
- Cross Sections

Collider (Accelerator)

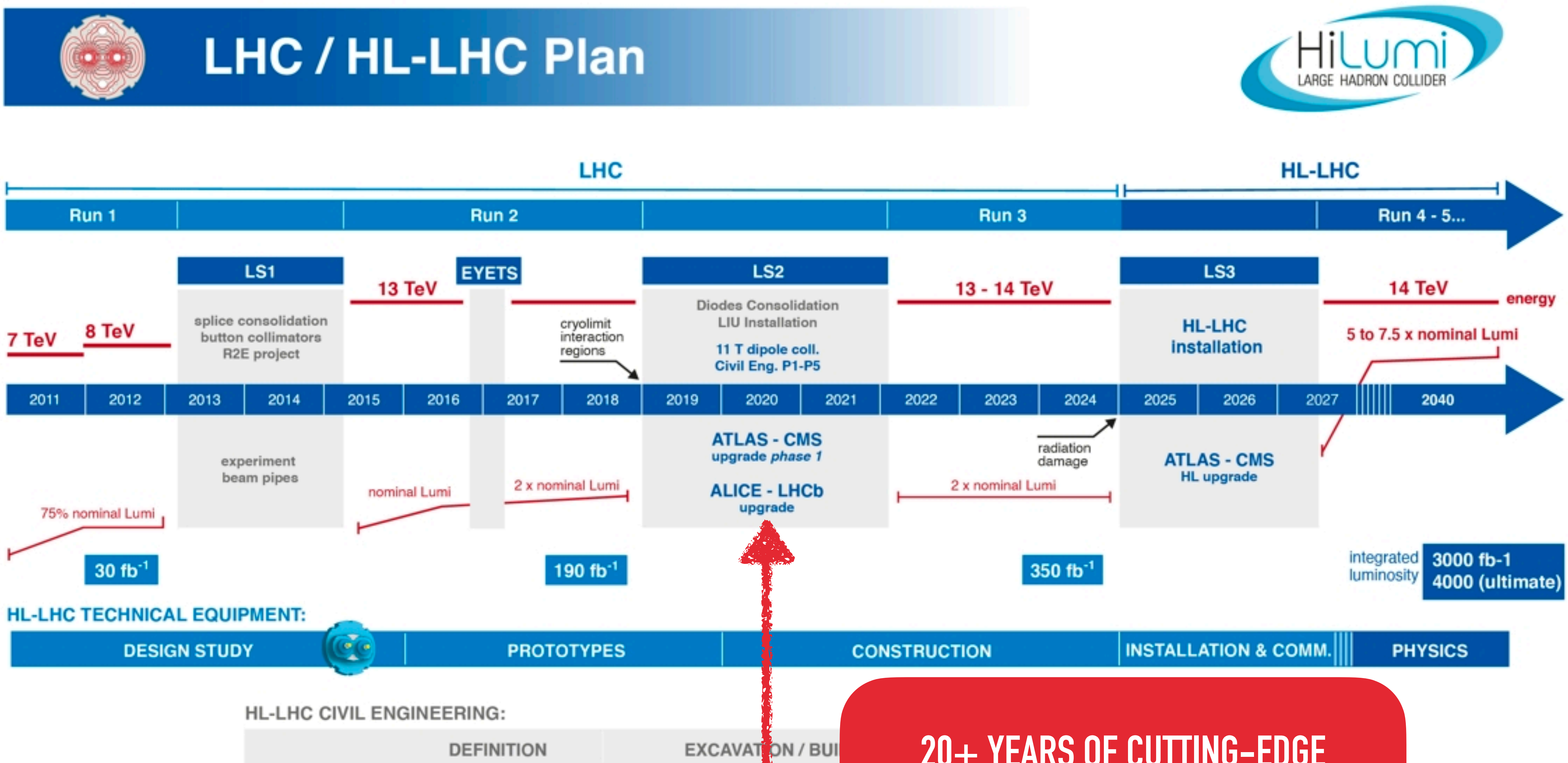
Experiment

- Measurement of properties physical objects
  - momentum
  - energy
  - angles
  - ...
- Assess systematic uncertainties

Interpretation

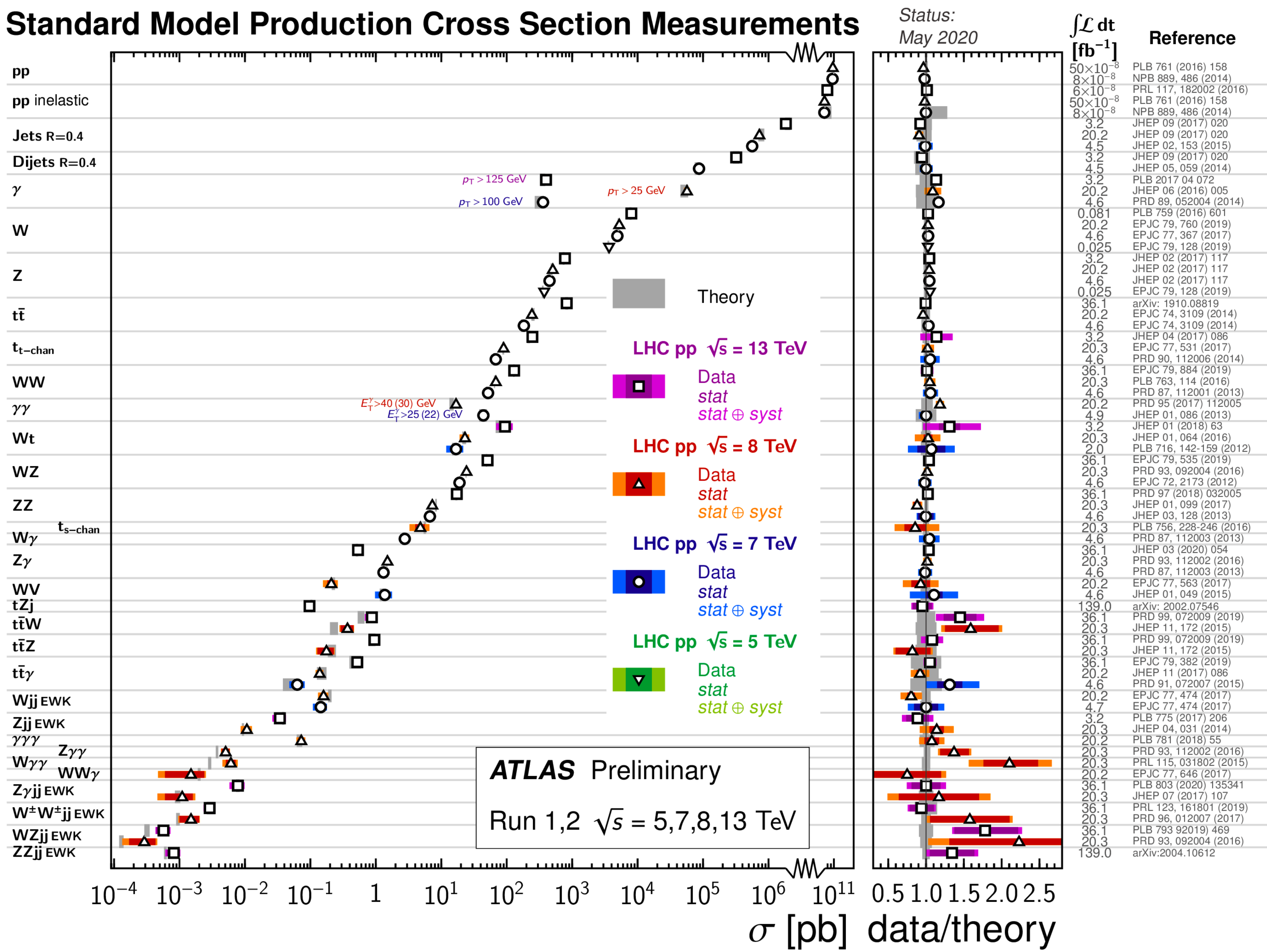
- Signal/Background
- Statistics

THE LHC SCHEDULE



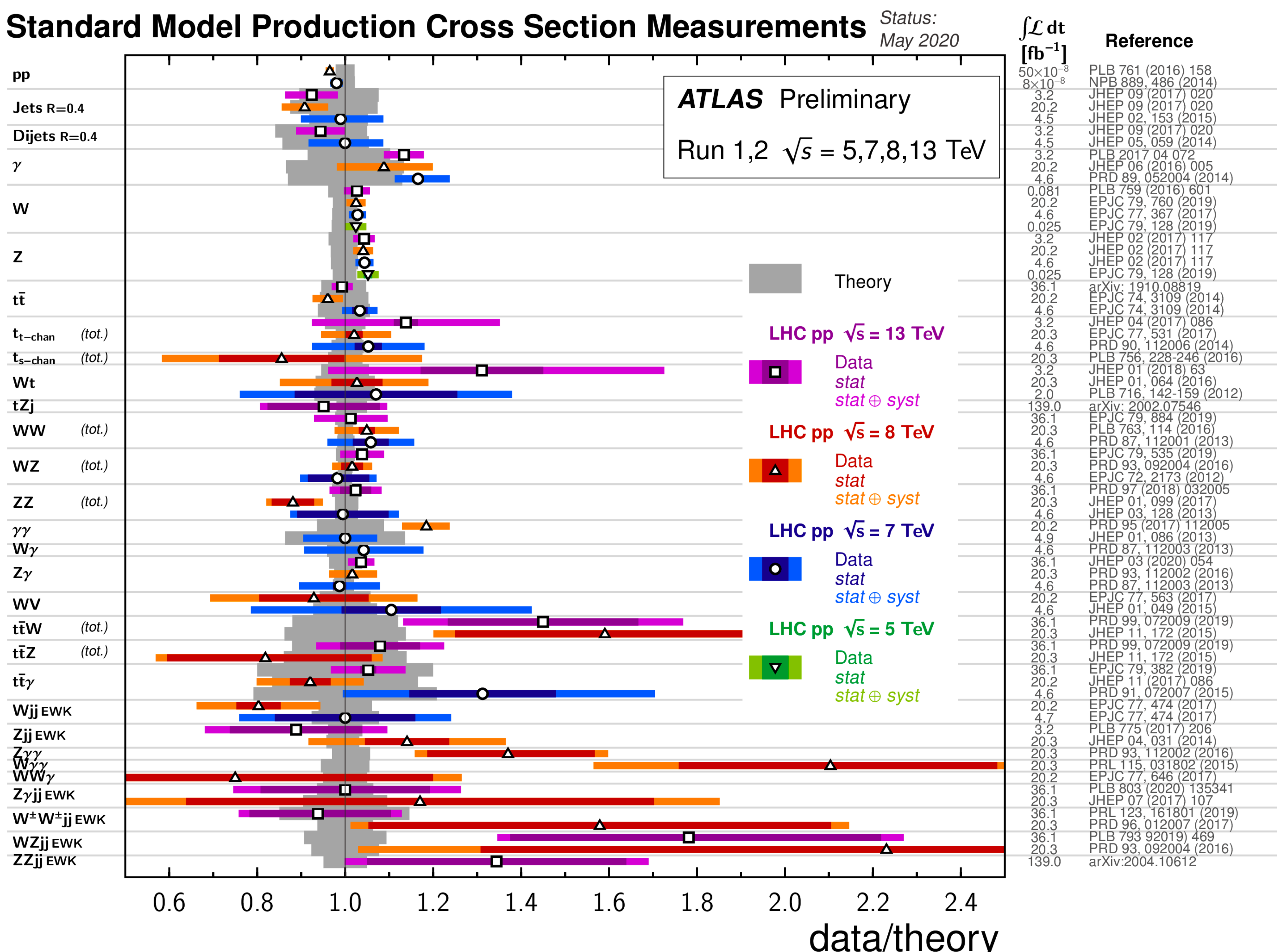
20+ YEARS OF CUTTING-EDGE PHENOMENOLOGY AHEAD

THE PRECISION FRONTIER



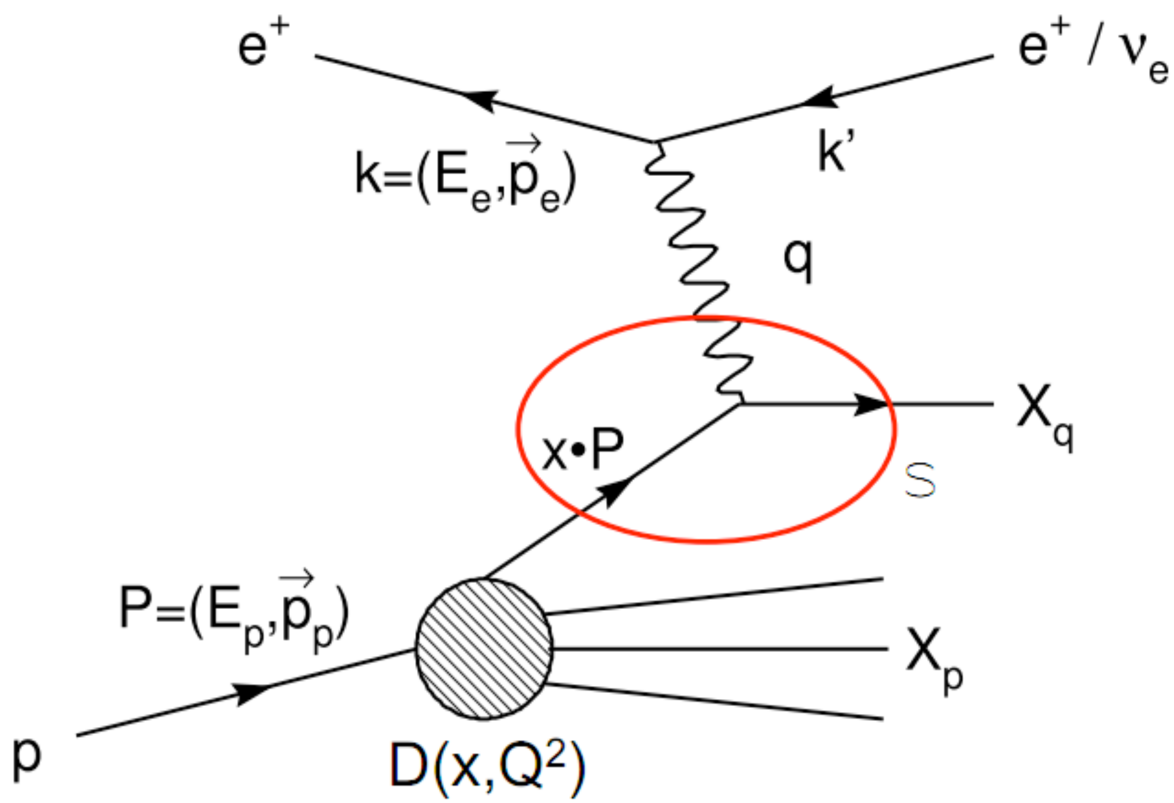
THE PRECISION FRONTIER

LHC = QCD + ε



1.11 BASICS OF QCD

DEEP INELASTIC SCATTERING



$$s = (P+k)^2$$ c.o.m. energy²

$$Q^2 = -(k-k')^2$$ momentum transfer²

$$x = Q^2/2(P\cdot q)$$ scaling variable

$$\frac{d\sigma_{\rm elastic}}{dq^2} = \left(\frac{d\sigma}{dq^2}\right)_{\rm point} \cdot F^2_{\rm elastic}(q^2)\,\delta(1-x)\,dx$$

$$\frac{d\sigma_{\rm inelastic}}{dq^2} = \left(\frac{d\sigma}{dq^2}\right)_{\rm point} \cdot F^2_{\rm inelastic}(q^2,x)\,dx$$

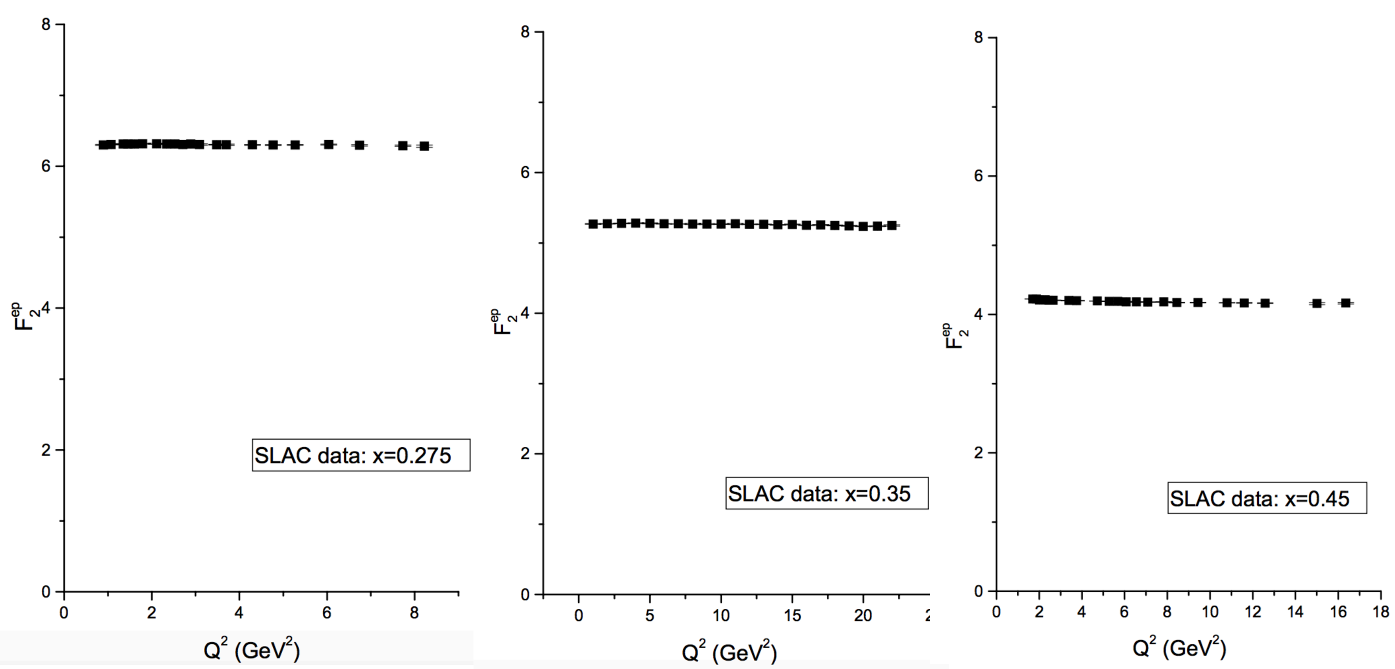
What should one expect for $F_{\rm inelastic}(q^2,x)$?

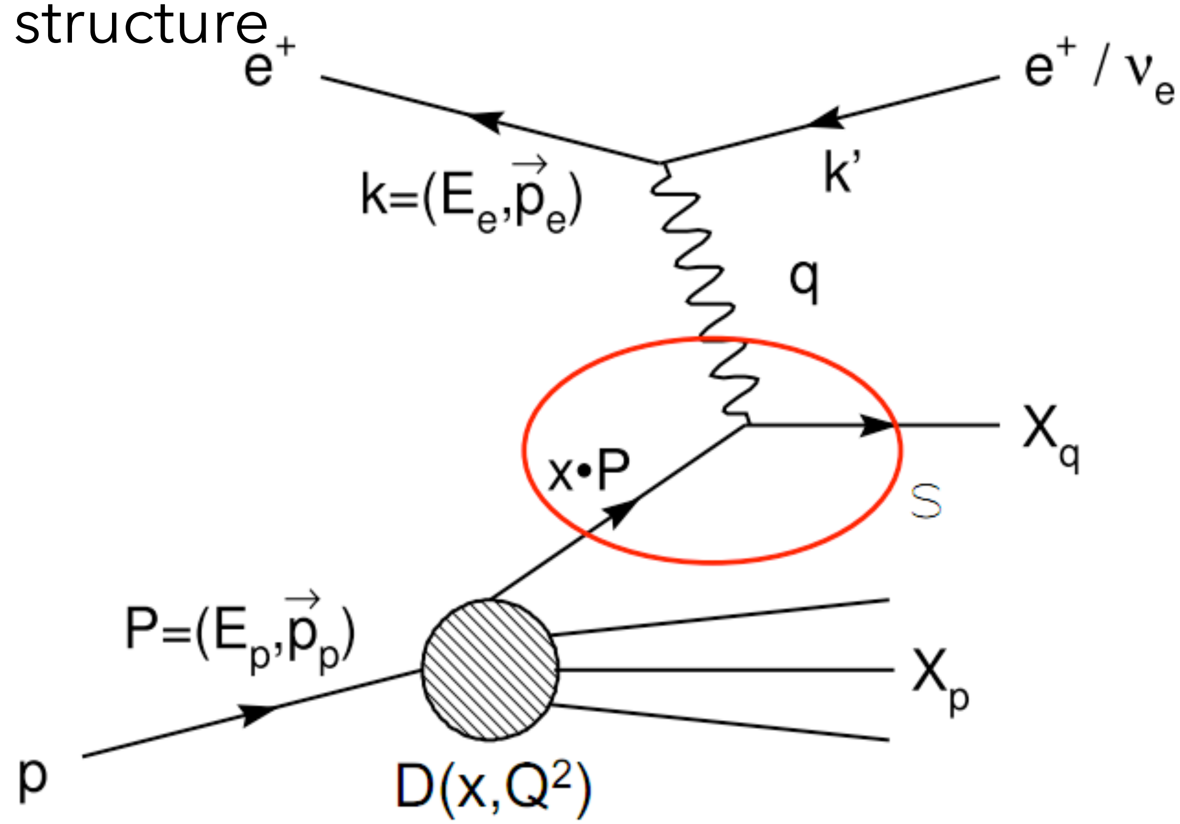
THE PARTON MODEL

Feynman, 1969

- Virtual photon scatters incoherently off massless, free, point like, spin 1/2 partons
- The functions q(x) are the Parton Distribution Functions encode probability that a parson carries a fraction x of parent proton's
- They encode information about proton deep structure

$$F_2^{\gamma,Z}(x) \;=\; x\sum_{i=1}^{n_f} c_i\,[q_i(x)+\bar{q}_i(x)]$$





THIS MOTIVATED THE SEARCH FOR A WEAKLY-COUPLED THEORY AT HIGH ENERGY!

QCD CRUCIAL FEATURES

$$\mathcal{L}_{\text{QCD}} = \sum_f \overline{\psi}_i^{(f)} \left(i\gamma_\mu D^\mu_{ij} - m_f \delta_{ij} \right) \psi_j^{(f)} - \frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu}$$

$$D^\mu_{ij} = \partial_\mu \delta_{ij} + i g_s t^a_{ij} A^\mu_a \qquad F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_s f_{abc} A^b_\mu A^c_\nu$$

Asymptotic freedom (UV property)

- Perturbative calculation
- Parton model
- …

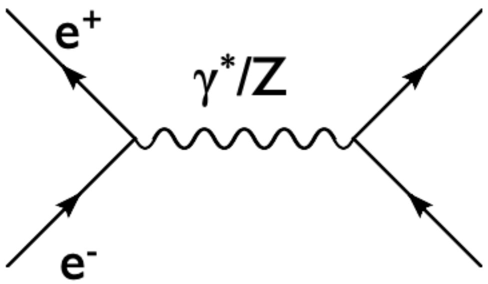
Universality (IR property)

- Collinear Factorisation (PDFs & FFs)
- Parton Showers
- Resummation
- …

QCD CRUCIAL FEATURE #1: ASYMPTOTIC FREEDOM

- One of the first tests of QCD was the measurement of the R-ratio, defined as

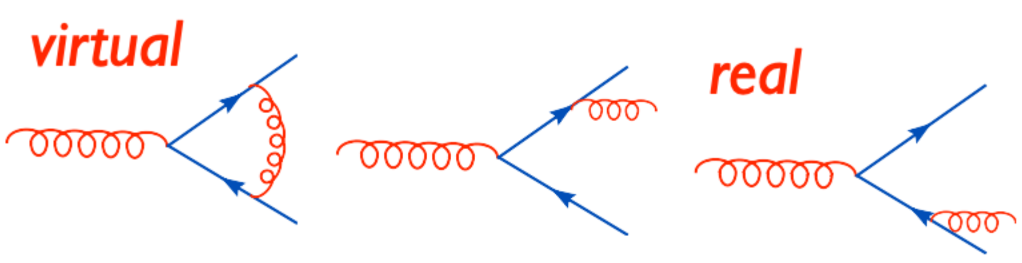
$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



- At leading order in QCD

$$R^{(0)} = N_c \sum_i e_i^2$$

- First order QCD corrections (Next-to-Leading Order)



$$R^{(1)} = R^{(0)}\left(1 + \frac{\alpha_S}{\pi}\right) \qquad \alpha_S \equiv \frac{g_S^2}{4\pi}$$

QCD CRUCIAL FEATURE #1: ASYMPTOTIC FREEDOM

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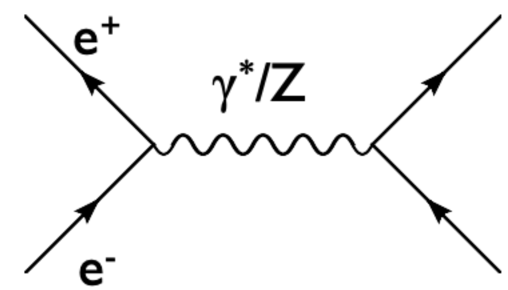
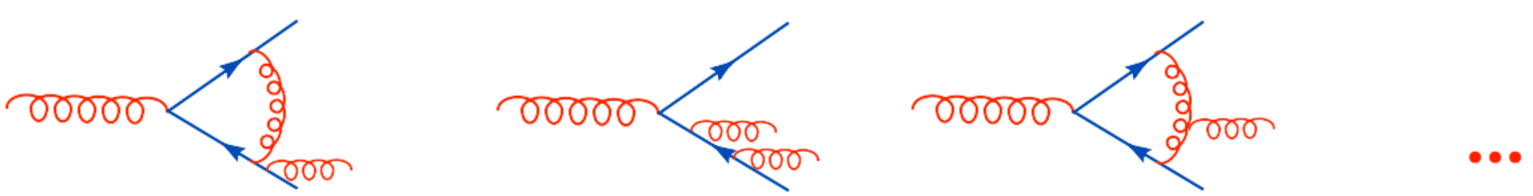


- Second order QCD correction (NNLO = next-to-next-to-leading order)



$$R^{(2)} = R^{(0)} \left(1 + \frac{\alpha_S}{\pi} + \left(\frac{\alpha_S}{\pi}\right)^2 \left(c + \pi b_0 \log\left(\frac{M_{\rm UV}^2}{Q^2}\right)\right)\right) \qquad b_0 = \frac{11N_c - 4n_f T_R}{12\pi}$$

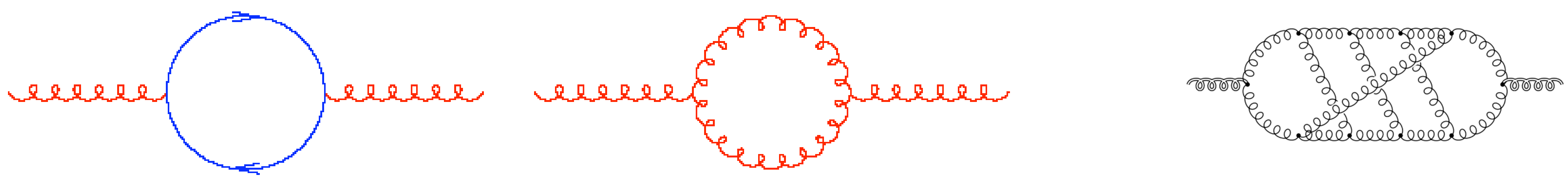
- UV divergences do not cancel => Renormalisation procedure: the UV divergence is dealt with renormalisation of bare coupling

$$\alpha_S(\mu) = \alpha_S^{\rm bare} + b_0 \log\left(\frac{M_{\rm UV}^2}{\mu^2}\right)(\alpha_S^{\rm bare})^2 \quad \Rightarrow \quad \mu^2 \frac{d\alpha_S(\mu)}{\mu^2} = -b_0 \alpha_S^2(\mu) + \ldots$$

QCD CRUCIAL FEATURE #1: ASYMPTOTIC FREEDOM

$$\mu^2 \frac{d\alpha}{d\mu^2} = \beta(\alpha) = -(b_0\alpha^2 + b_1\alpha^3 + b_2\alpha^4 + \cdots)$$

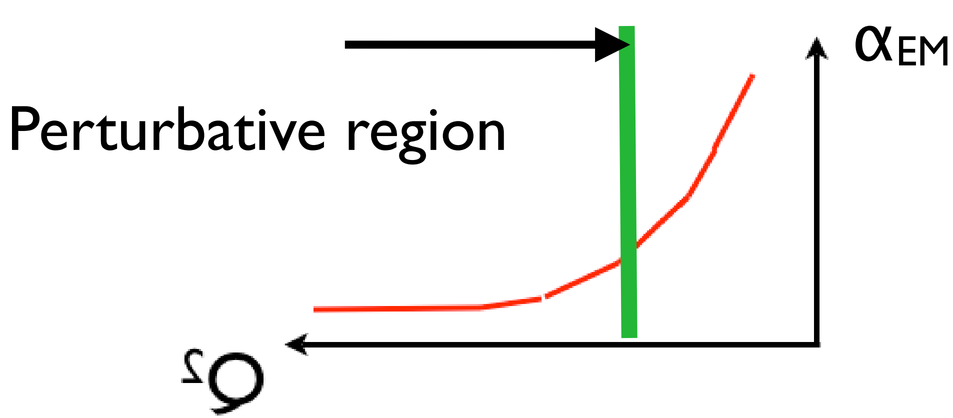
Known up to b_4 (5 loops): arXiv: 1606.08659, … , arXiv: 1709.08541

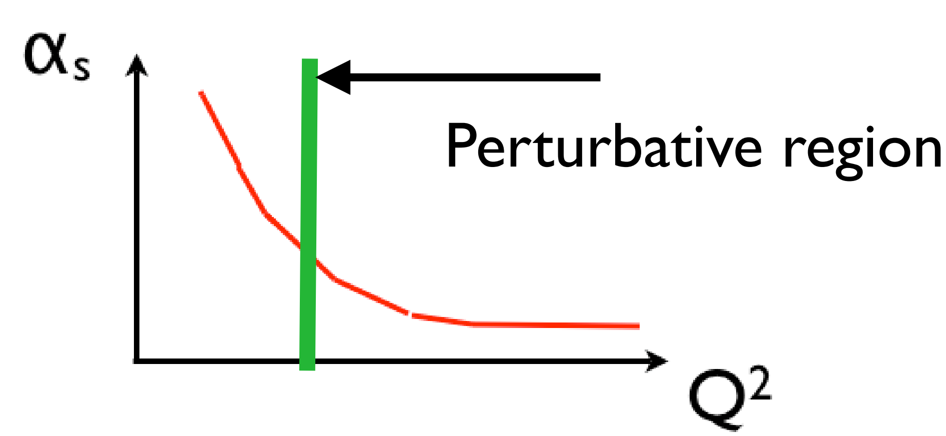


Roughly speaking, quark loop diagrams contribute with Nf negative terms in b_0, while the gluon loop, diagram gives a positive contribution proportional to N_c, which is dominant and make the overall beta function negative.

$$b_0 = \frac{11N_c - 2n_f}{12\pi} > 0 \quad \Rightarrow \quad \beta(\alpha_S) < 0 \quad \text{in QCD}$$

$$b_0 = -\frac{n_f}{3\pi} > 0 \quad \Rightarrow \quad \beta(\alpha_{\rm EM}) > 0 \quad \text{in QED}$$

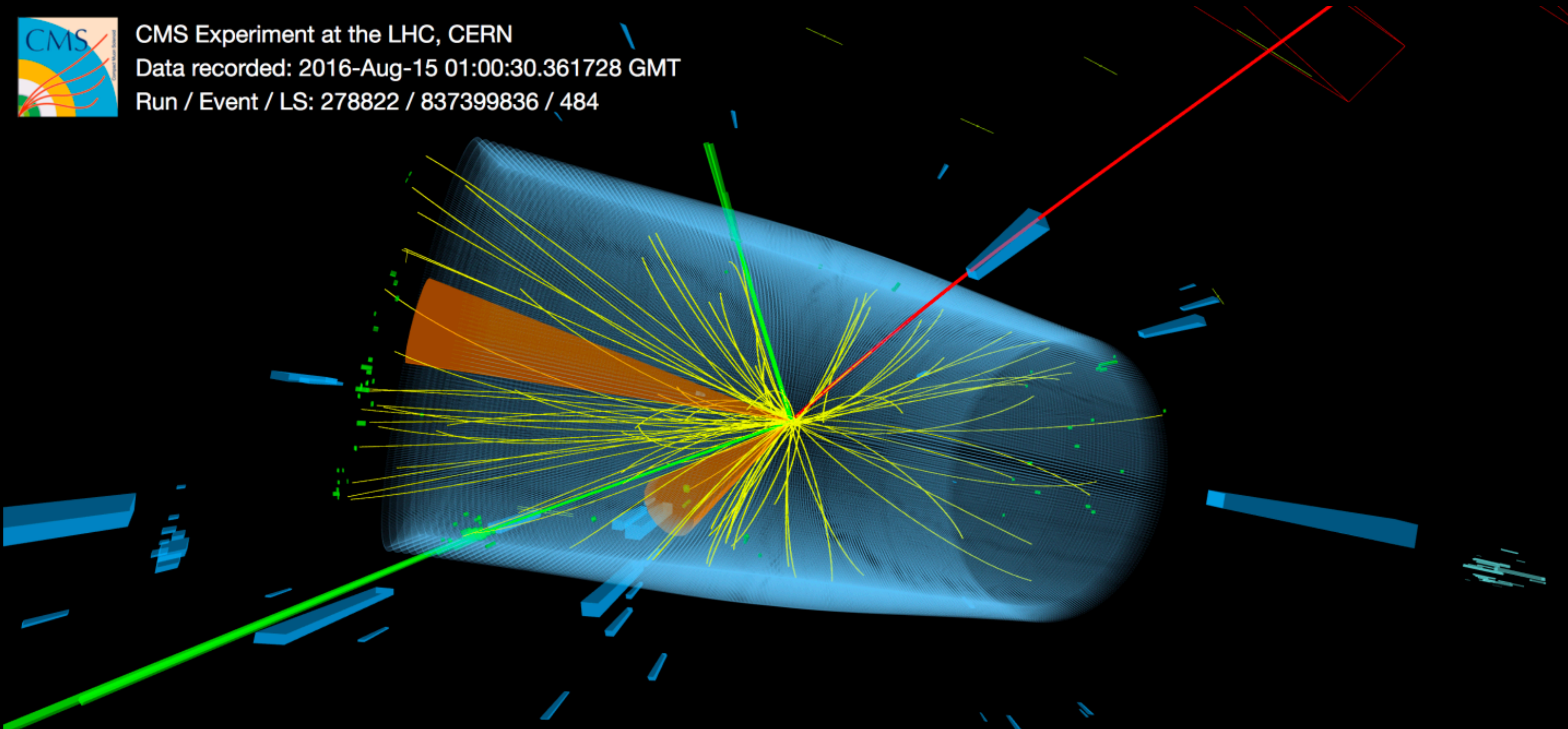




THE PRECISION INGREDIENTS AT THE LHC

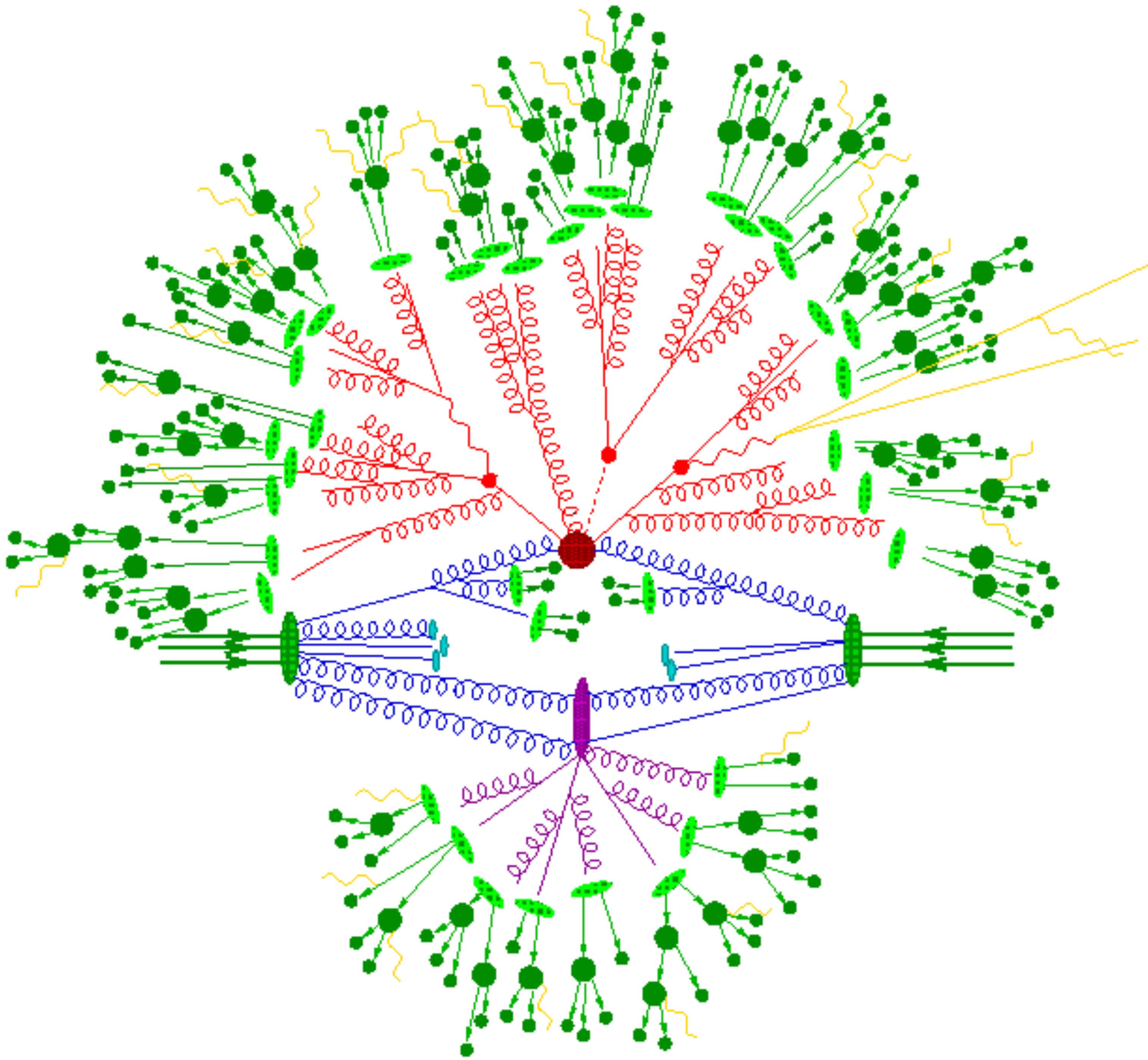
EVENTS AT HADRON COLLIDERS

pp -> t (b W ($\mu\nu$)) Z(ee) q

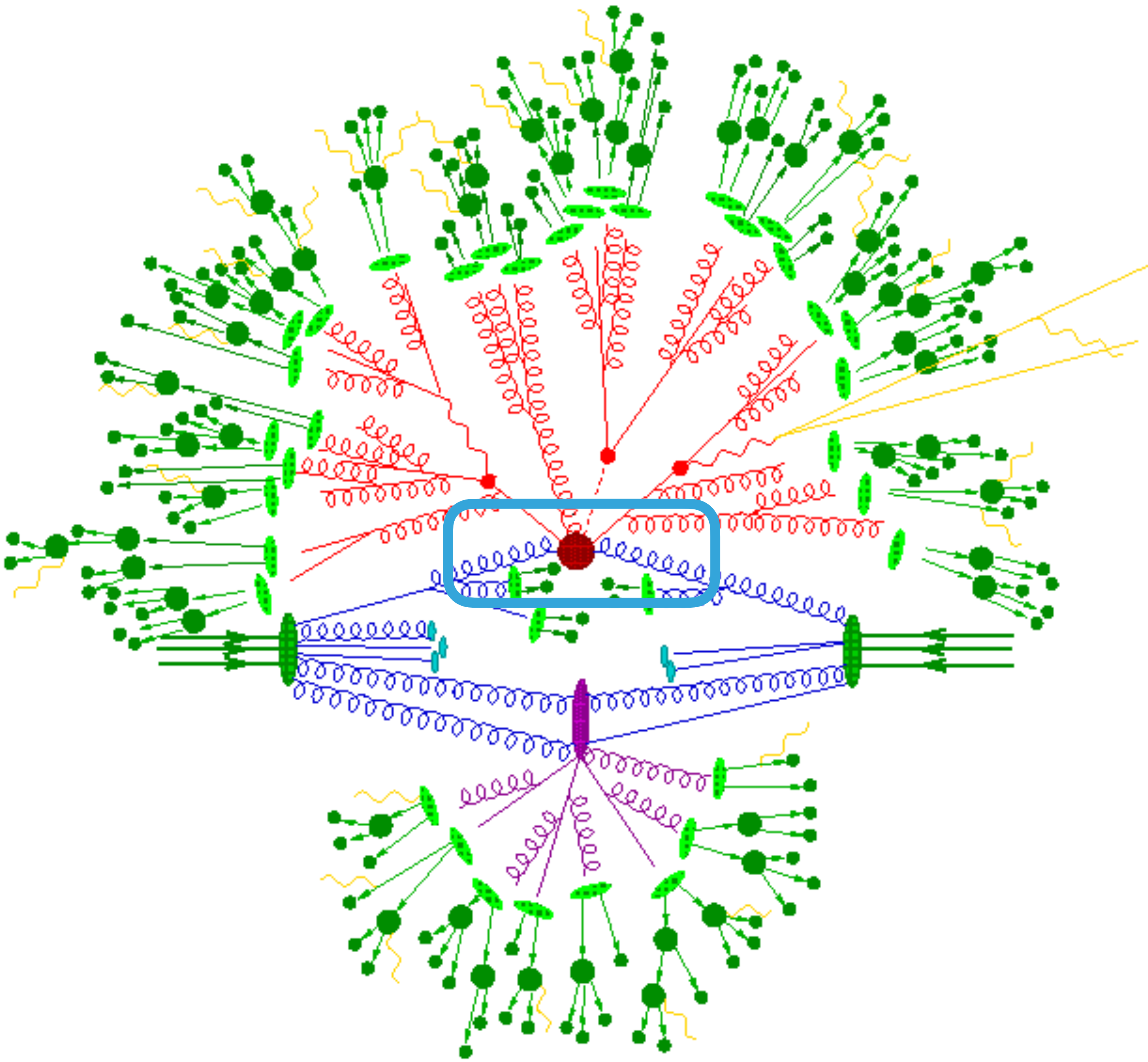


A top + Z candidate collision recorded by CMS. The tZq state is characterised by three leptons (in this case two electrons and one muon), a jet produced from decay of a bottom quark, and a forward jet that is close to the LHC beam direction (Image: CMS/CERN)

EVENTS AT HADRON COLLIDERS

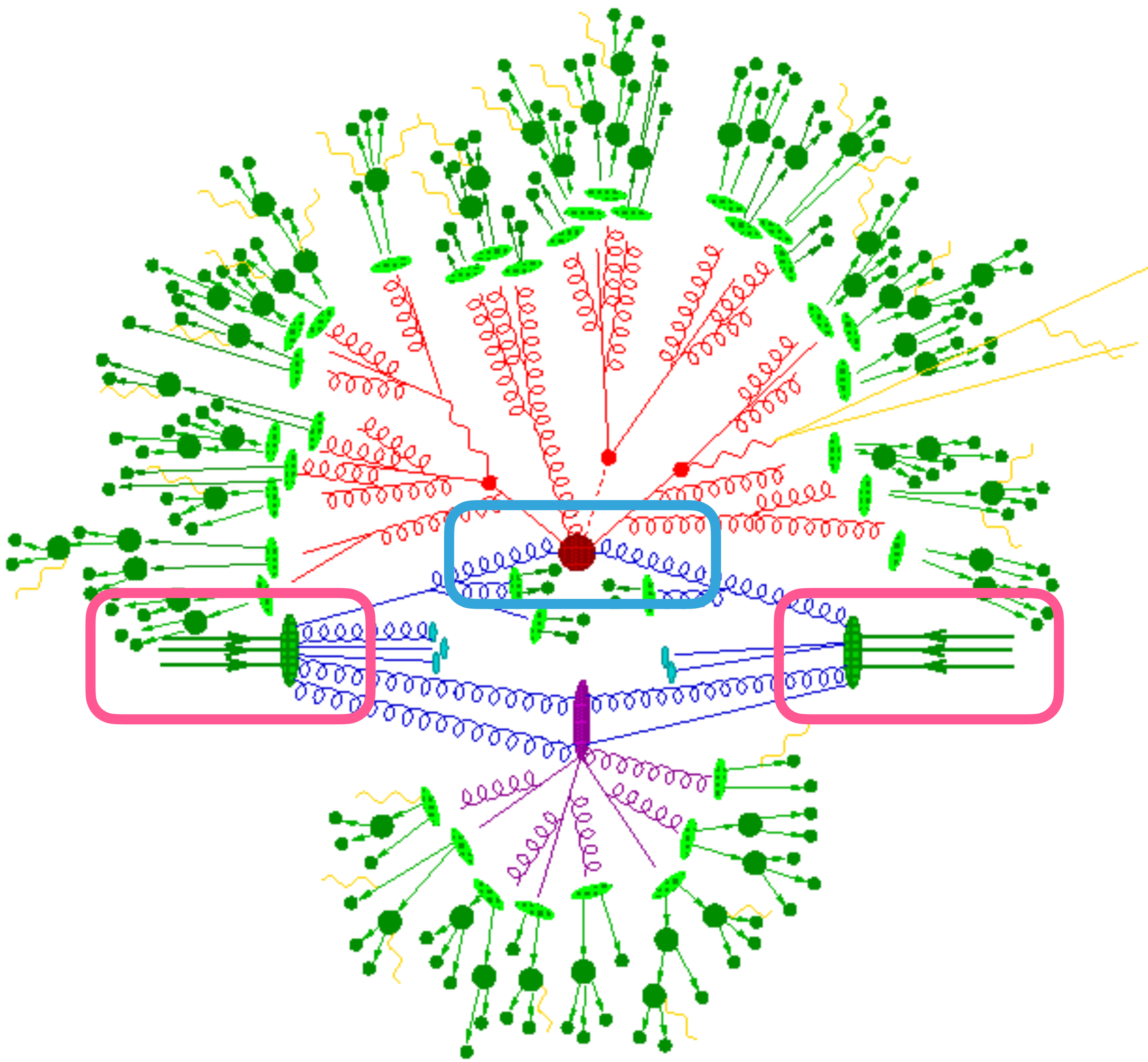


EVENTS AT HADRON COLLIDERS



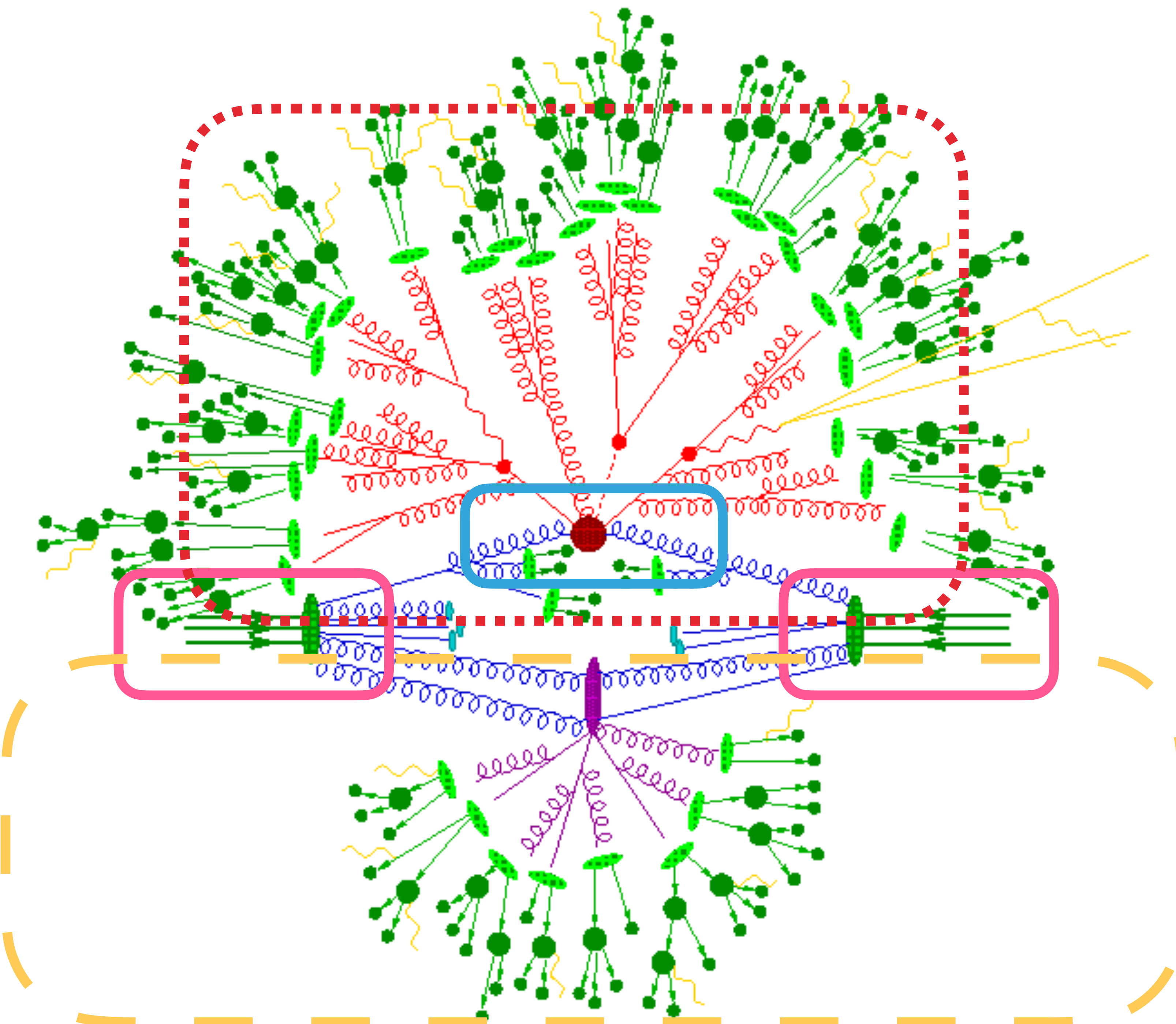
- Hard scattering of partons (Perturbative QCD+EW)

EVENTS AT HADRON COLLIDERS



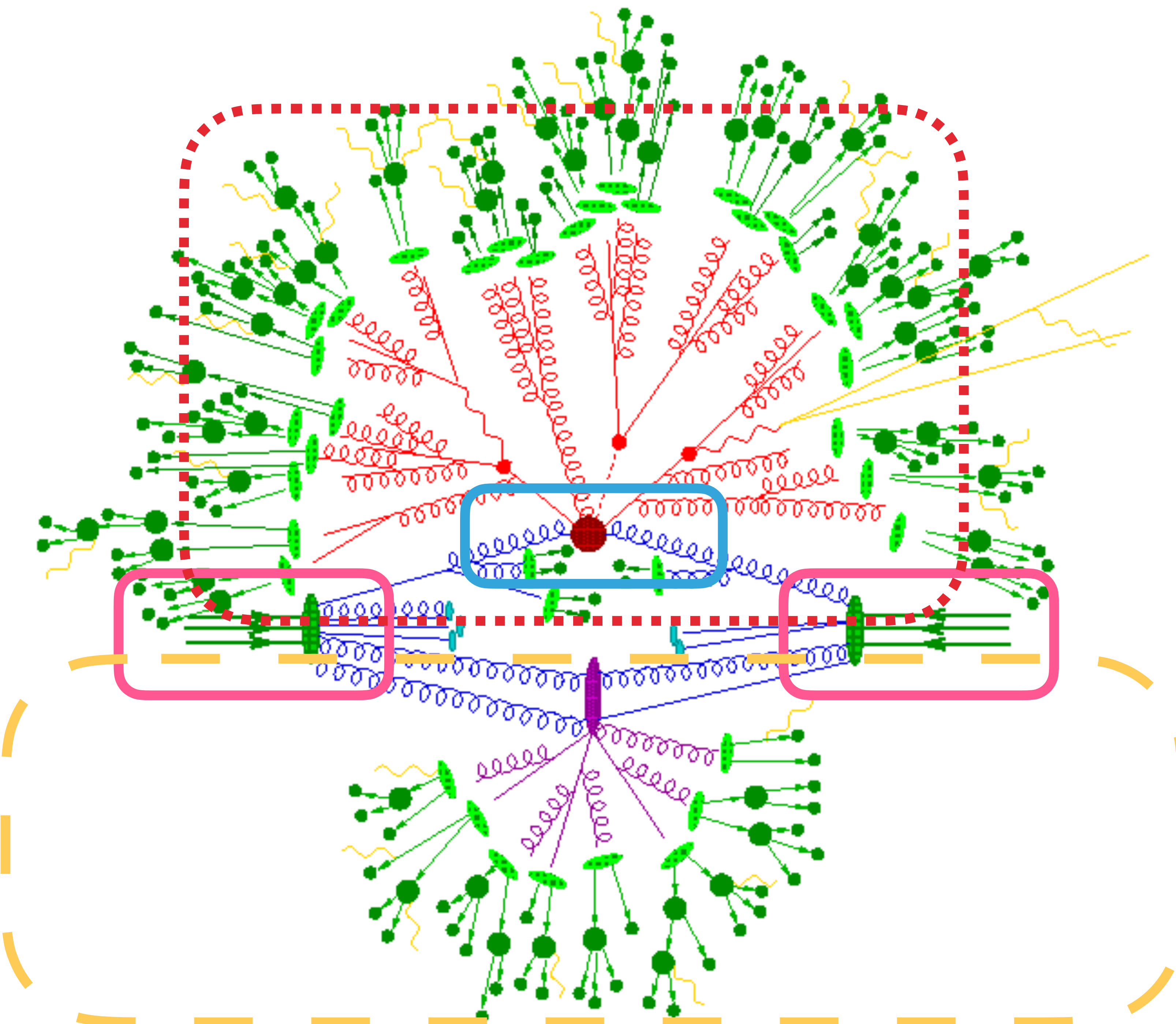
- Hard scattering of partons (Perturbative QCD+EW)
- The structure of the proton: parton distribution functions

EVENTS AT HADRON COLLIDERS



- Hard scattering of partons (Perturbative QCD+EW)
- The structure of the proton: parton distribution functions
- Parton Showering and Hadronization
- Multiple Parton Interaction, Underlying Events

EVENTS AT HADRON COLLIDERS



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DIVIDE ET IMPERA!

FACTORIZATION: THE LHC MASTER FORMULA

$$\sigma^{pp\to ab} = \sum_{i,j=-n_f}^{n_f} \int dz_1\, dz_2\, f_i(z_1,\mu_F)\, f_j(z_2,\mu_F)\, \hat{\sigma}^{ij\to ab}(z_1 z_2 S, \alpha_s(\mu_R), \mu_F) + \mathcal{O}\left(\frac{\Lambda^n}{S^n}\right)$$

PDFs: universal functions that parametrise the proton structure

Partonic cross section computed in perturbative QCD + EW corrections

Parton showers, hadronisation

Soft stuff: higher twists, multiple parton interaction, underlying event

THE STRONG COUPLING CONSTANT

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$\alpha_s(\mu_F)$ $\alpha_s(\mu_F)$ $\alpha_s(\mu_R)$

- In pQCD all theoretical predictions are expressed in terms of the renormalised coupling $\boldsymbol{\alpha}_S(\mu^2)$, a function of unphysical renormalization and factorization scales μ_R and μ_F
- When one takes μ_R close to the scale of the momentum transfer Q in a given process, then $\boldsymbol{\alpha}_S(Q^2)$ is indicative of the effective strength of the strong interaction in that process
- Beside the quark masses, the only free parameter in the QCD Lagrangian is $\boldsymbol{\alpha}_S$

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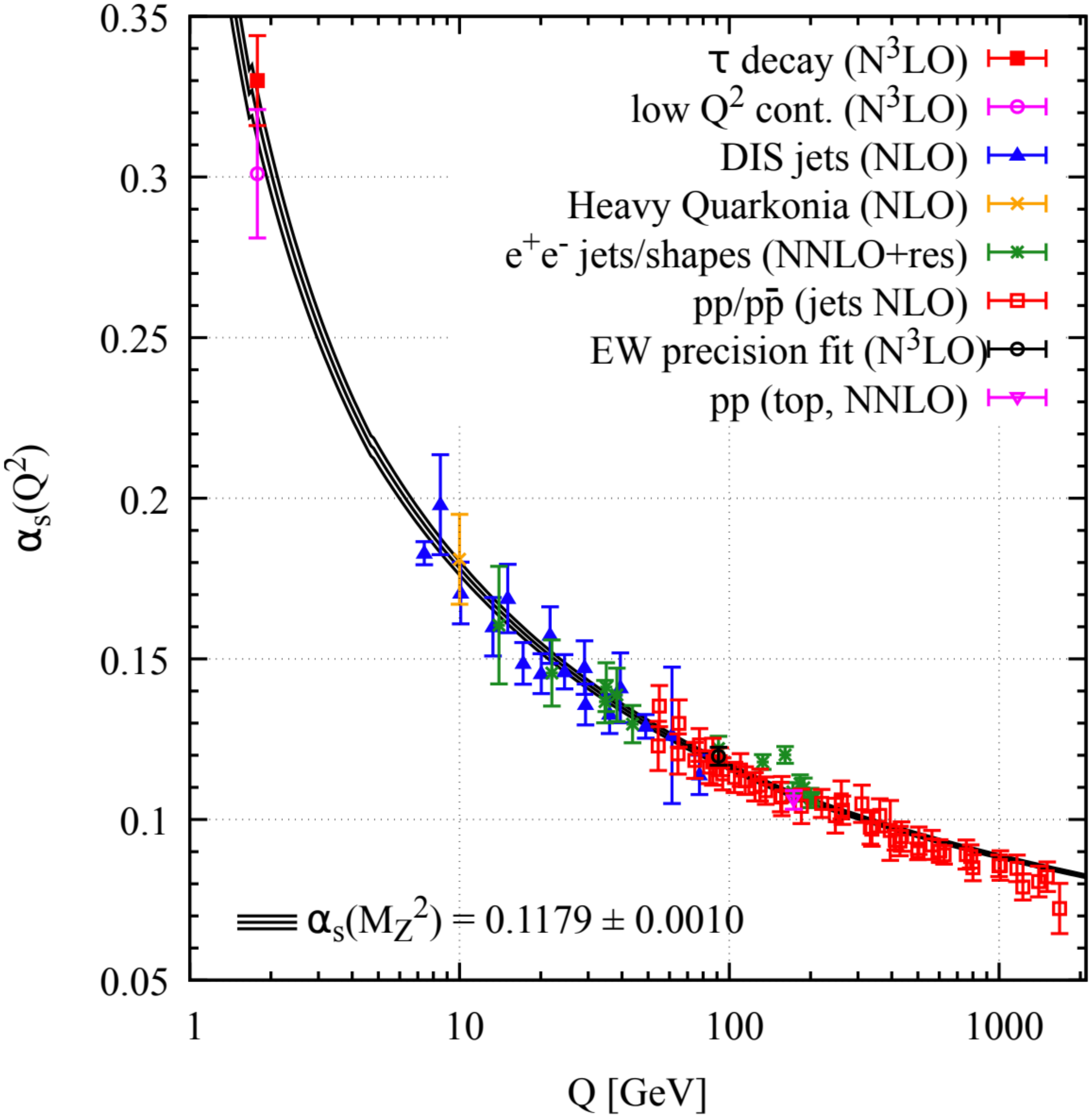
- When one takes μ_R close to the scale of the momentum transfer Q in a given process, then $\alpha_S(Q^2)$ is indicative of the effective strength of the strong interaction in that process
- Beside the quark masses, the only free parameter in the QCD Lagrangian is α_S
- The coupling constant not a physical observable, rather quantity defined in the context of perturbation theory, which enters predictions for measurable observables.

THE STRONG COUPLING CONSTANT

PDG 2020 average from fit of specific experimental observables



THE STRONG COUPLING CONSTANT

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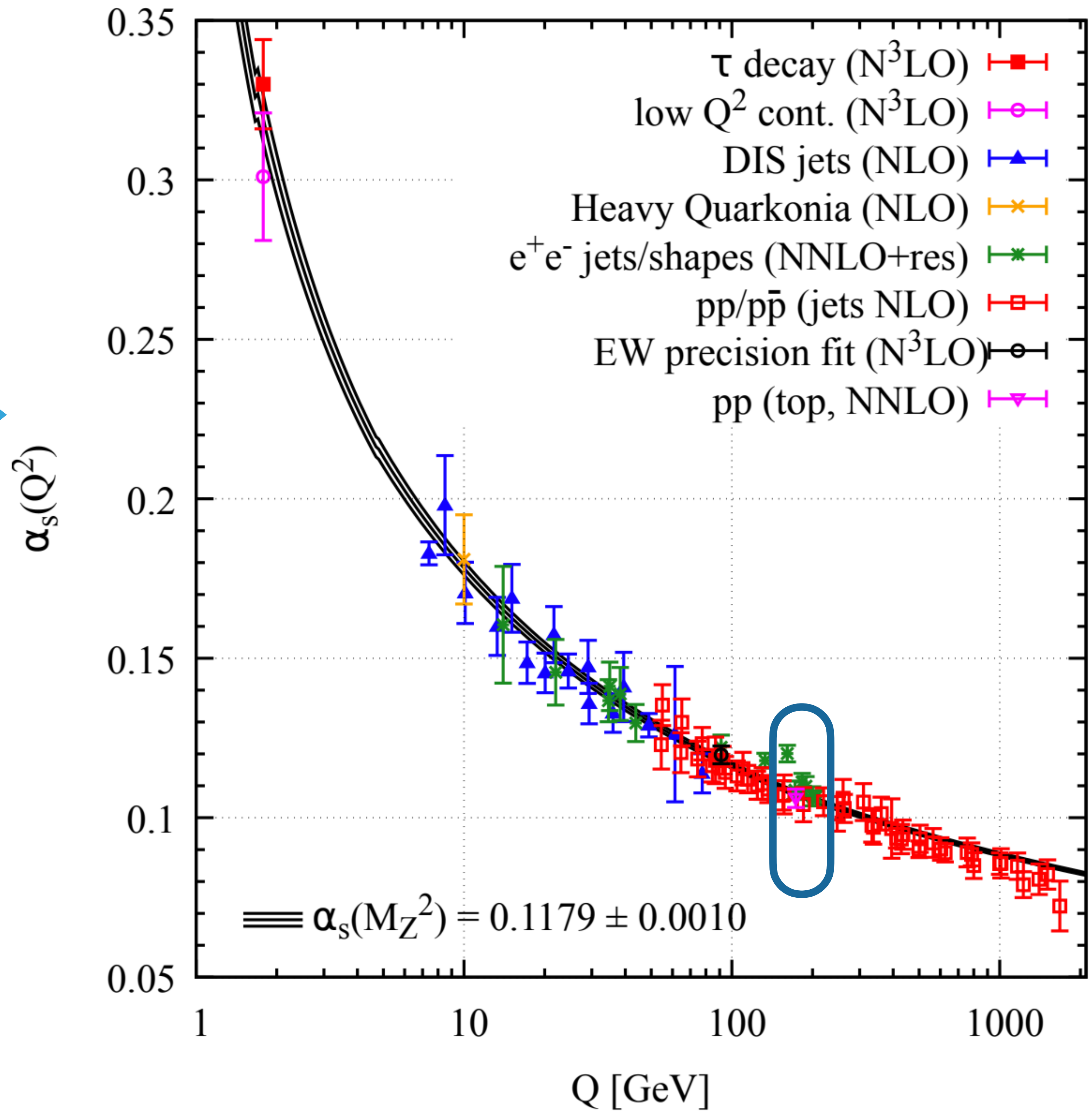
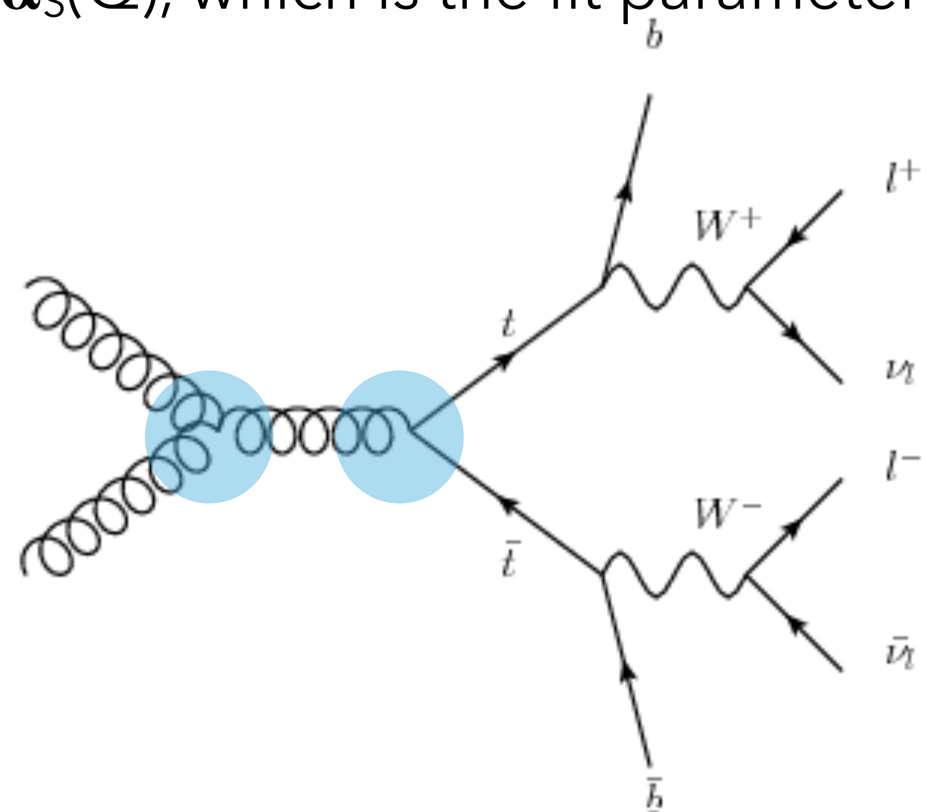


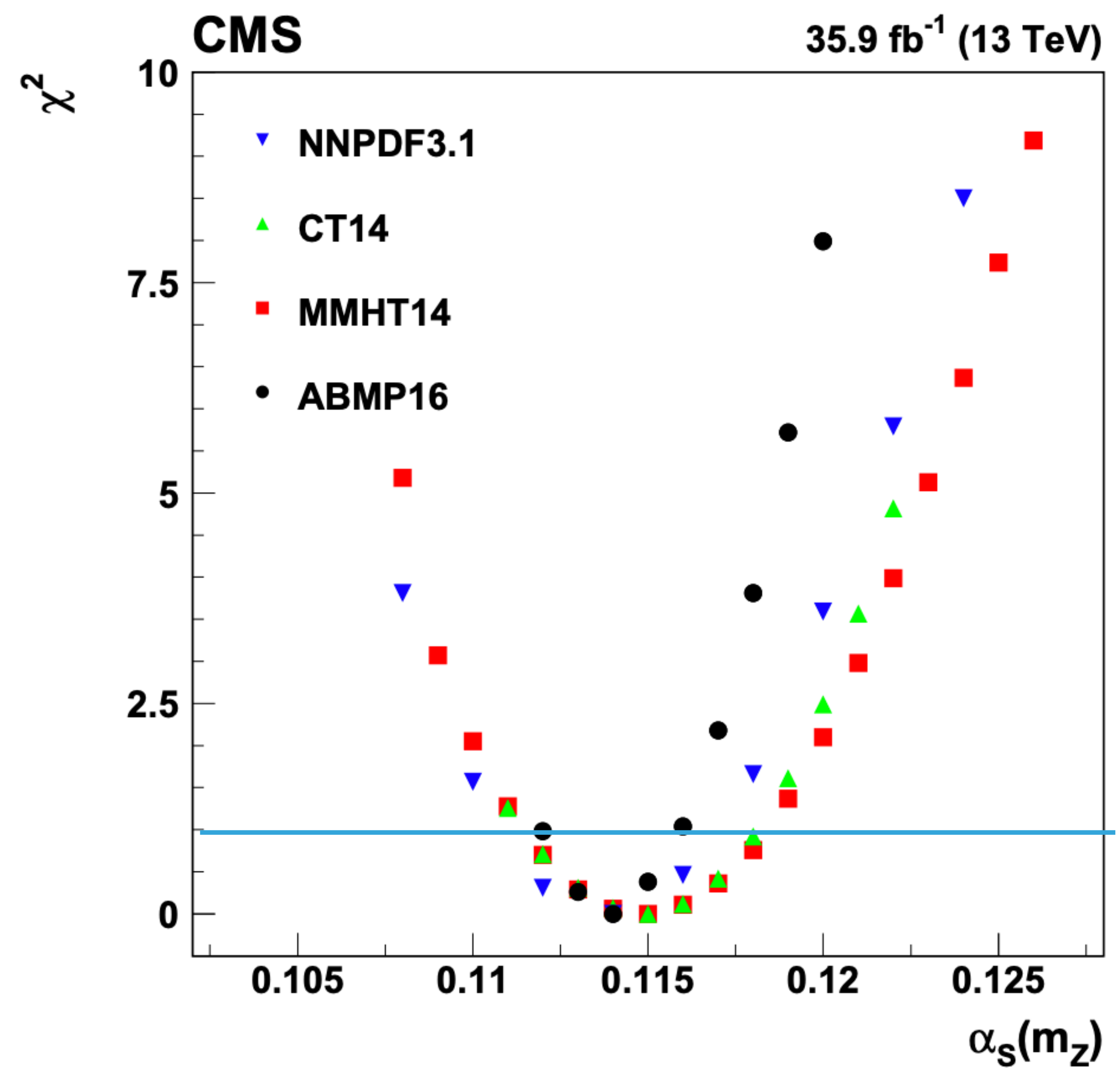
THE STRONG COUPLING CONSTANT: AN EXAMPLE

CMS collaboration
arXiv:1812.10505

- Example: CMS determination of m_t and $\alpha_S(M_Z)$ from tt~ production cross section in leptonic channel

- Results depend on experimental systematics (in D_i and cov_{ij}) and theoretical prediction T_i, which, for a given perturbative order depends on $\alpha_S(Q)$, which is the fit parameter





$$\chi^2 = \sum_{i,j=1}^{N_{\rm dat}} (D_i - T_i)(\mathrm{cov})^{-1}_{ij}(D_j - T_j)$$

II.II FIXED-ORDER QCD COMPUTATIONS

$$\sigma^{pp\to ab} = \sum_{i,j=-n_f}^{n_f} \int dz_1\, dz_2\, f_i(z_1,\mu_F)\, f_j(z_2,\mu_F)\, \hat{\sigma}^{ij\to ab}(z_1 z_2 S, \alpha_s(\mu_R), \mu_F) + \mathcal{O}\left(\frac{\Lambda^n}{S^n}\right)$$

PARTONIC CROSS SECTIONS

The partonic cross section is calculated by

$$\hat{\sigma}^{ij\to ab} = \frac{1}{2s}\int\left[\prod_{k=1}^{n}\frac{d^3\vec{q}_k}{(2\pi)^3 2E_k}\right]\left[(2\pi)^2\delta^{(4)}\left(\sum_k q_k^\mu - (p_1+p_2)^\mu\right)\right]|\mathcal{M}_{ij\to ab}(\mu_F,\mu_R)|^2$$

[flux factor] × [phase space] × [squared matrix element]

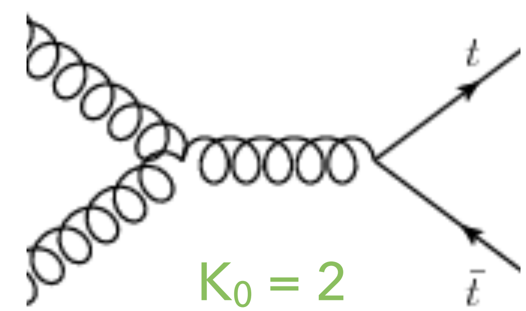
Short distance coefficients as an expansion in α_S (from theory)

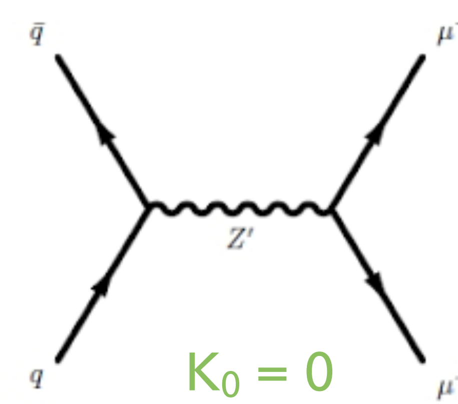
$$\hat{\sigma}^{ij\to ab} = (\alpha_s)^{k_0}\sigma_0 + (\alpha_s)^{k_0+1}\sigma_1 + (\alpha_s)^{k_0+2}\sigma_2 + \ldots$$

Leading Order

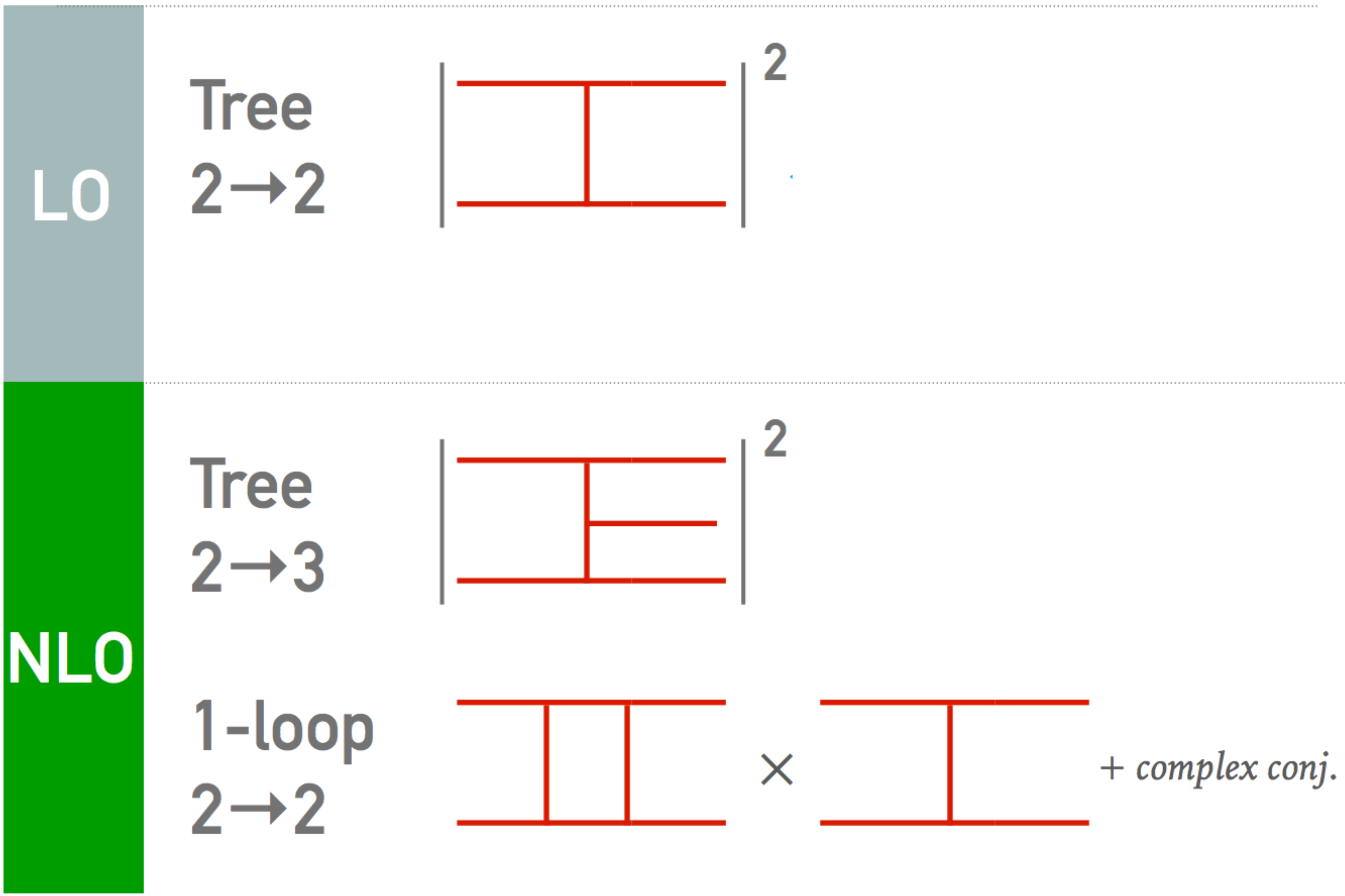
Next-to-Leading Order

Next-to-Next-to-Leading Order





THE PARTONIC CROSS SECTION



From Gavin Salam’s lectures
Quy Nhon Vietnam 2018

THE PARTONIC CROSS SECTION

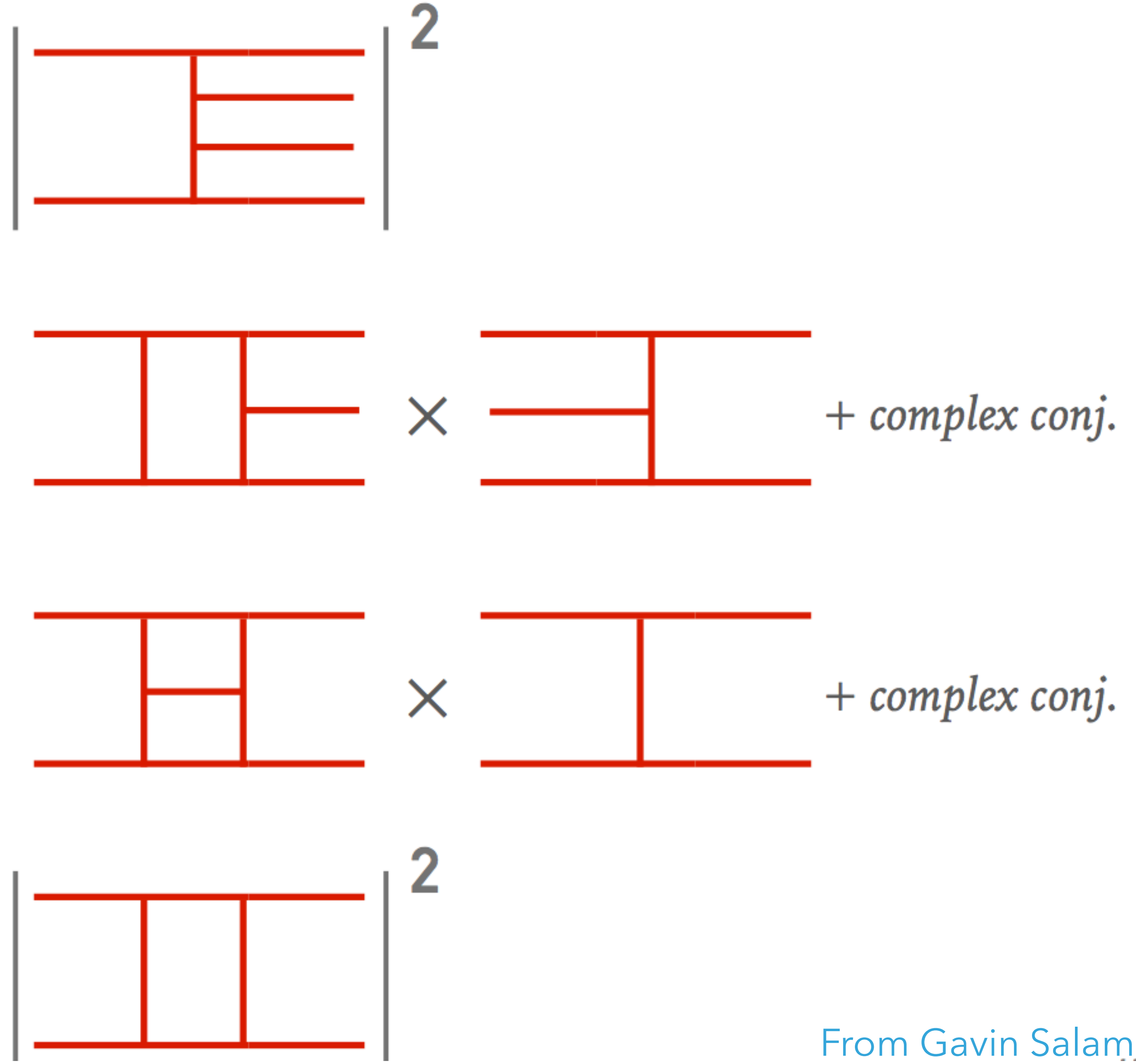
NNLO

Tree
2→4

1-loop
2→3

2-loop
2→2

1-loop
2→2



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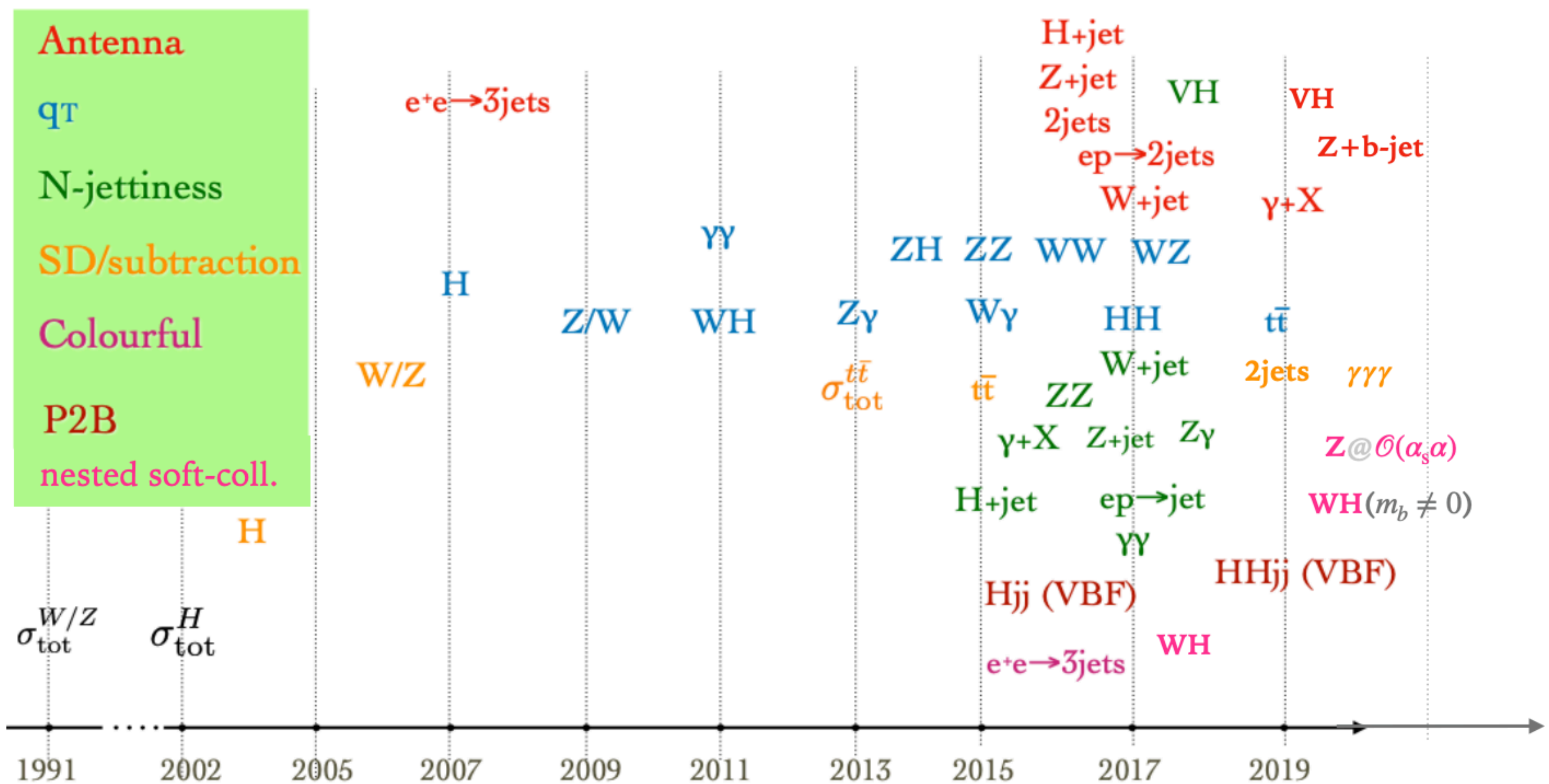
PARTONIC CROSS SECTION COMPUTATION: STATE OF THE ART

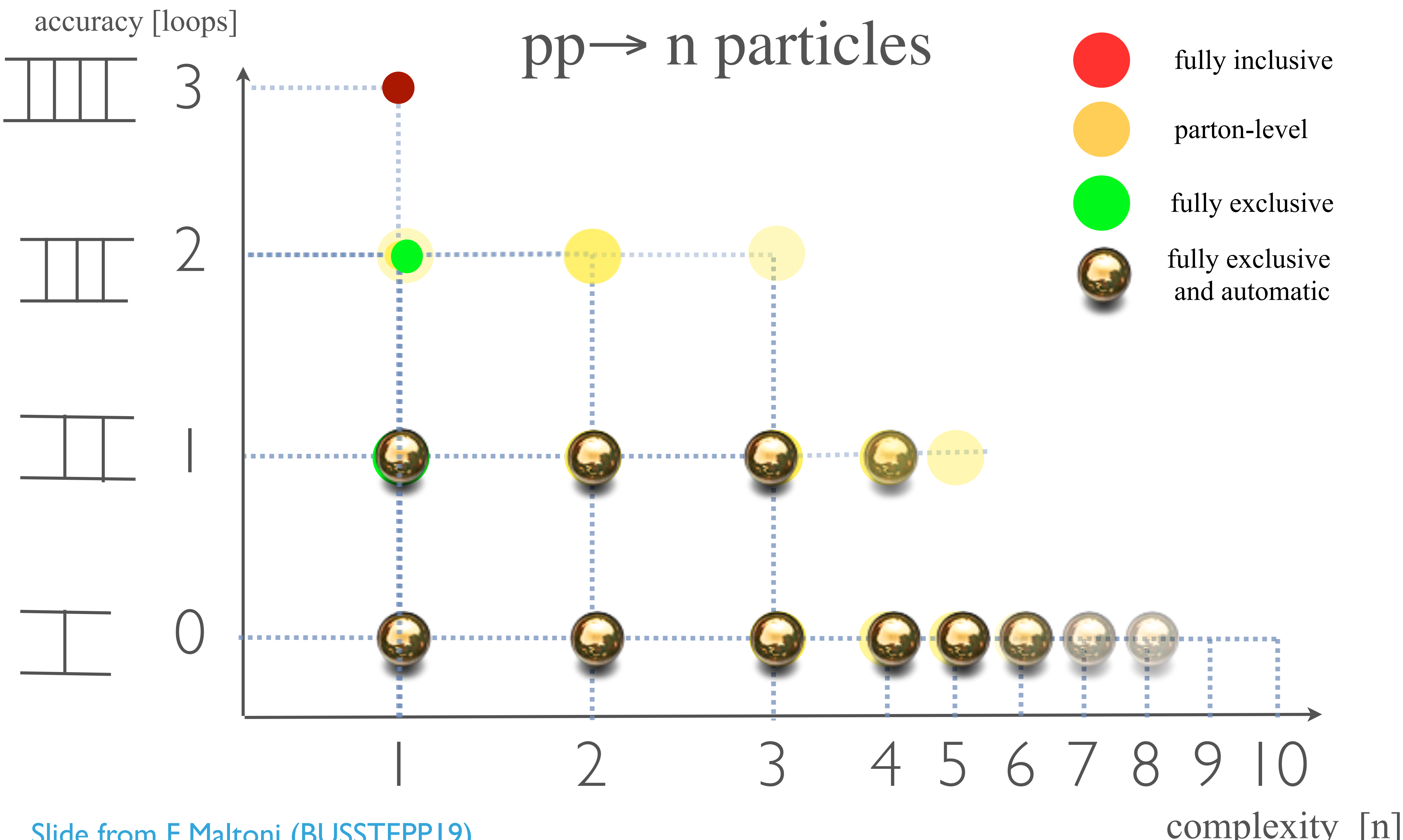
TIMELINE FOR NNLO



A. Huss, QCD@LHC-X 2020

- LO: almost all processes
- NLO: most processes (automated calculations)
- NNLO: all 2 → 1 and 2→2 (explosion of calculations in the past few years)
- N3LO: five processes so far: strong indication about perturbative series convergence!

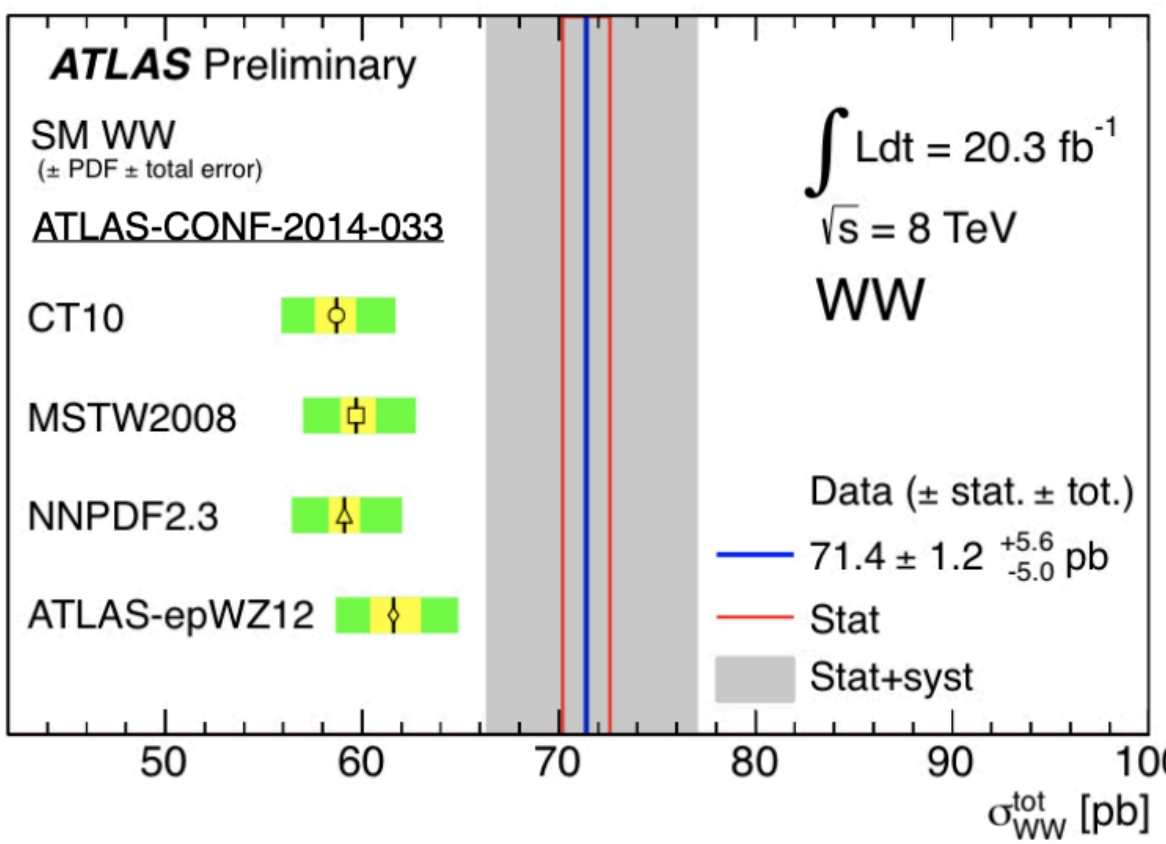
PARTONIC CROSS SECTION COMPUTATION: STATE OF THE ART

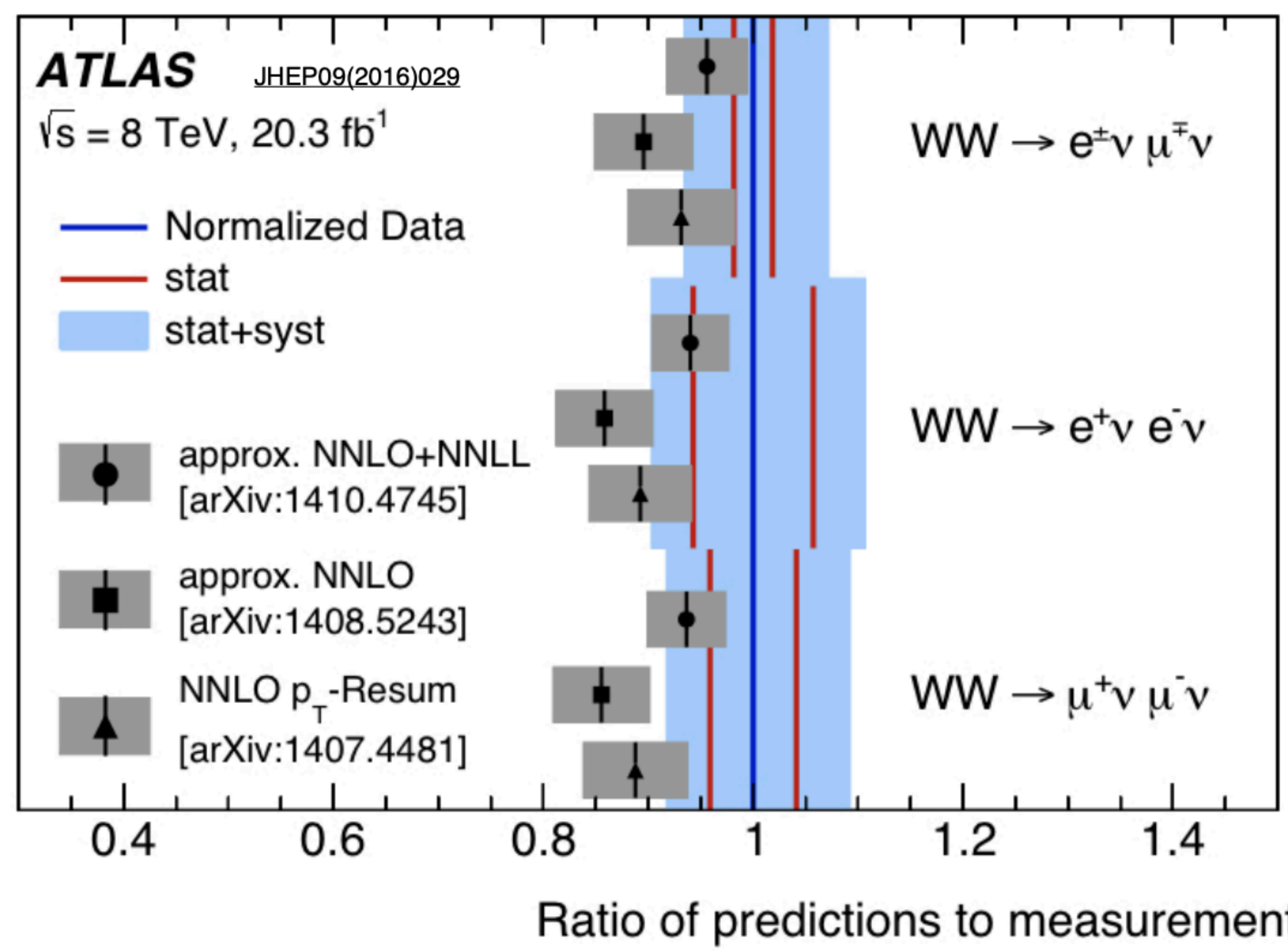


Slide from F. Maltoni (BUSSTEPP19)

EXAMPLE OF IMPACT OF NNLO CORRECTIONS

- Early ATLAS and CMS measurement (2013) of WW production off (NLO) theoretical predictions by about 3σ ➜ SUSY chargino production?
- Once NNLO (Gerhmann et al 2014) and resummation effects on jet-veto efficiency (Maede et al, Monni et al 2014) discrepancy is strongly reduced



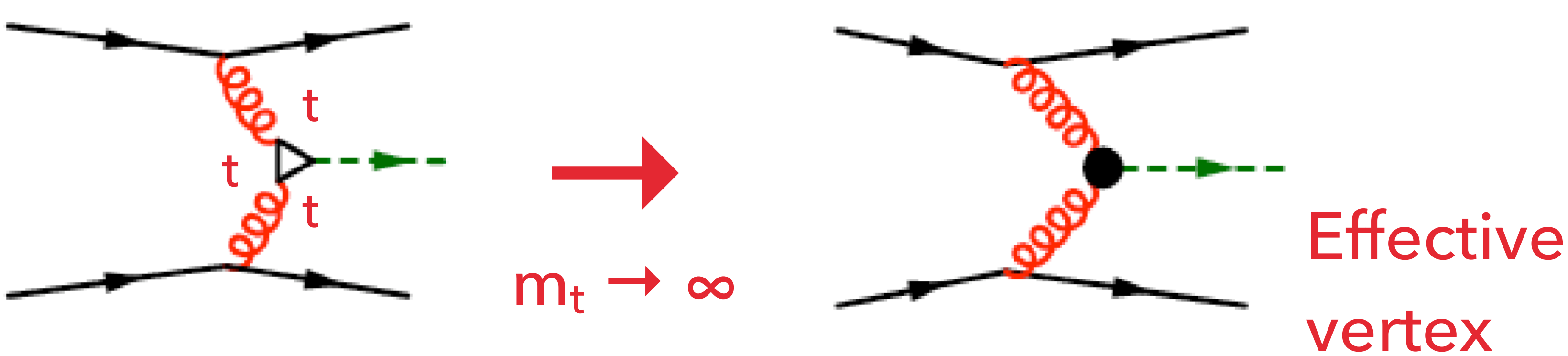


N3LO: GLUON FUSION INTO HIGGS

pp → H (via gluon fusion) is the main Higgs production channel at the LHC and is one of only four hadron collider processes known at N3LO (Anastasiou et al, arXiv:1602.00695) along with

- ★ Higgs production via vector boson fusion Dreyer et al, arXiv:1811.07906
- ★ Bottom pair fusion into Higgs Duhr et al, arXiv:1904.09990
- ★ Photon-mediated NC + CC Drell-Yan Duhr et al, arXiv:2001.07717, 2007.13313

$$\sigma(pp \to H) = (961\,\mathrm{pb}) \times (\alpha_s^2 + 10.4\alpha_s^3 + 38\alpha_s^4 + 48\alpha_s^5 + \cdots)$$



$$\alpha_s \equiv \alpha_s(M_H/2)$$
$$\sqrt{s_{pp}} = 13\,\mathrm{TeV}$$

Here the perturbative series does not converge very well!

N3LO: GLUON FUSION INTO HIGGS

- The perturbative series is written in terms of powers of $\alpha_S(\boldsymbol{\mu}_R)$, with renormalisation scale $\boldsymbol{\mu}_R = \boldsymbol{\mu}_0 = M_H/2$ and for a factorization scale $\boldsymbol{\mu}_F = \boldsymbol{\mu}_0 = M_H/2$
- But $\boldsymbol{\mu}_R$ and $\boldsymbol{\mu}_F$ are arbitrarily chosen ~ M_H at any given perturbative order. Their variation introduces terms of higher perturbative order.

$$\alpha_S(\tilde{\mu}^2) = \alpha_S(\mu^2) - b_0 \log\left(\frac{\tilde{\mu}^2}{\mu^2}\right) \alpha_S^2(\mu^2)$$

N3LO: GLUON FUSION INTO HIGGS

- The perturbative series is written in terms of powers of $\alpha_S(\mu_R)$, with renormalisation scale $\mu_R = \mu_0 = M_H/2$ and for a factorization scale $\mu_F = \mu_0 = M_H/2$
- But μ_R and μ_F are arbitrarily chosen ~ M_H at any given perturbative order. Their variation introduces terms of higher perturbative order.
- Free to rewrite cross section in terms of α_S for any choice of μ_R (here keep μ_F fixed for simplicity)

NLO

$$\sigma(pp \to H) = \sigma_0 \times \left(\alpha_s^2(\mu) + (10.4 + 2b_0 \ln\frac{\mu^2}{\mu_0^2})\alpha_s^3(\mu)\right)$$

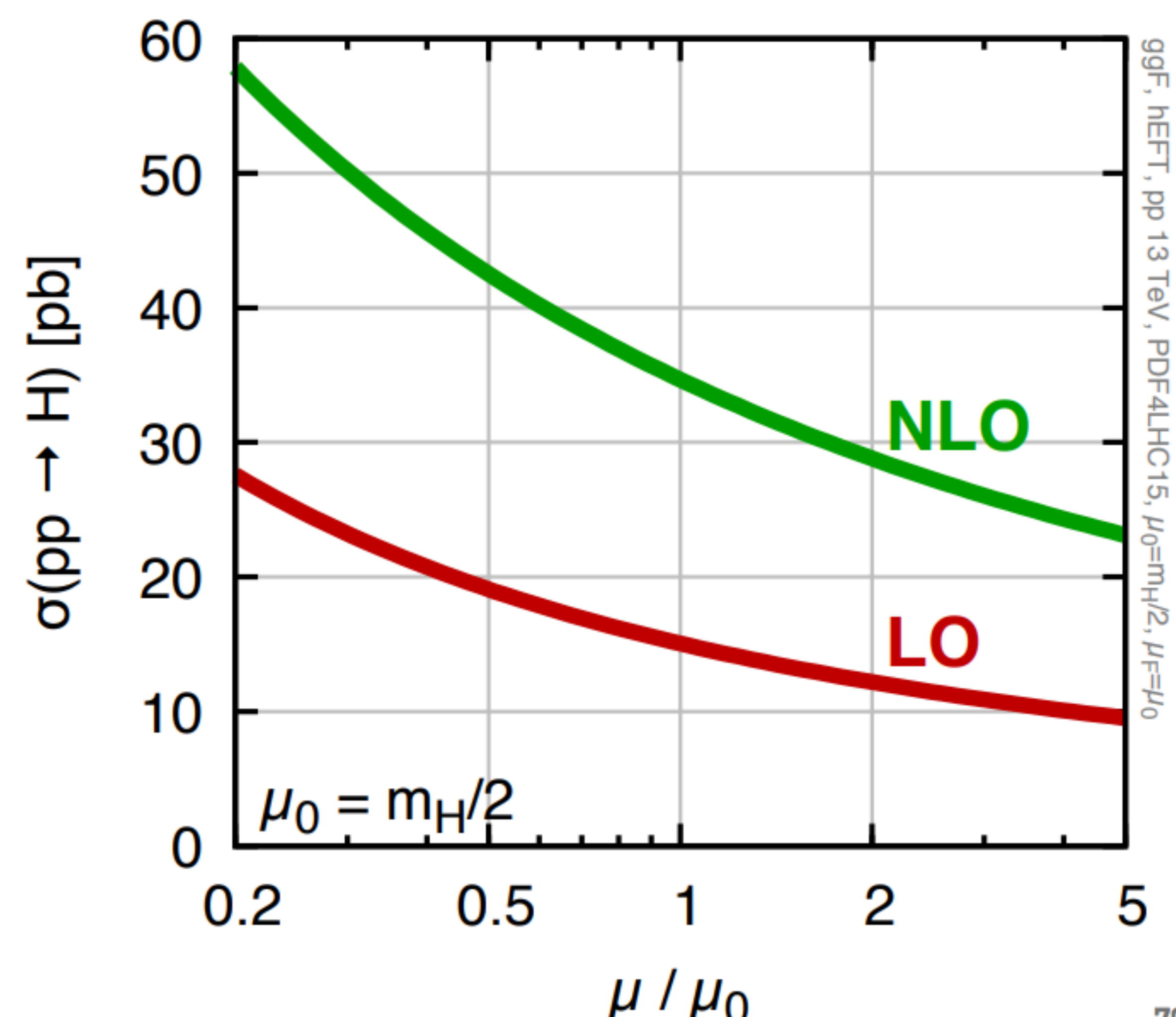


Illustration from Gavin Salam's lectures Quy Nhon Vietnam 2018

N3LO: GLUON FUSION INTO HIGGS

- The perturbative series is written in terms of powers of $\alpha_S(\mu_R)$, with renormalisation scale $\mu_R = \mu_0 = M_H/2$ and for a factorization scale $\mu_F = \mu_0 = M_H/2$
- But μ_R and μ_F are arbitrarily chosen ~ M_H at any given perturbative order. Their variation introduces terms of higher perturbative order.
- Free to rewrite cross section in terms of α_S for any choice of μ_R (here keep μ_F fixed for simplicity)

NNLO

$$\sigma(pp \to H) = \sigma_0 \times \Big(\alpha_s^2(\mu) + (10.4 + 2b_0 \ln \frac{\mu^2}{\mu_0^2})\alpha_s^3(\mu) + c_4(\mu)\alpha_s^4(\mu)\Big)$$

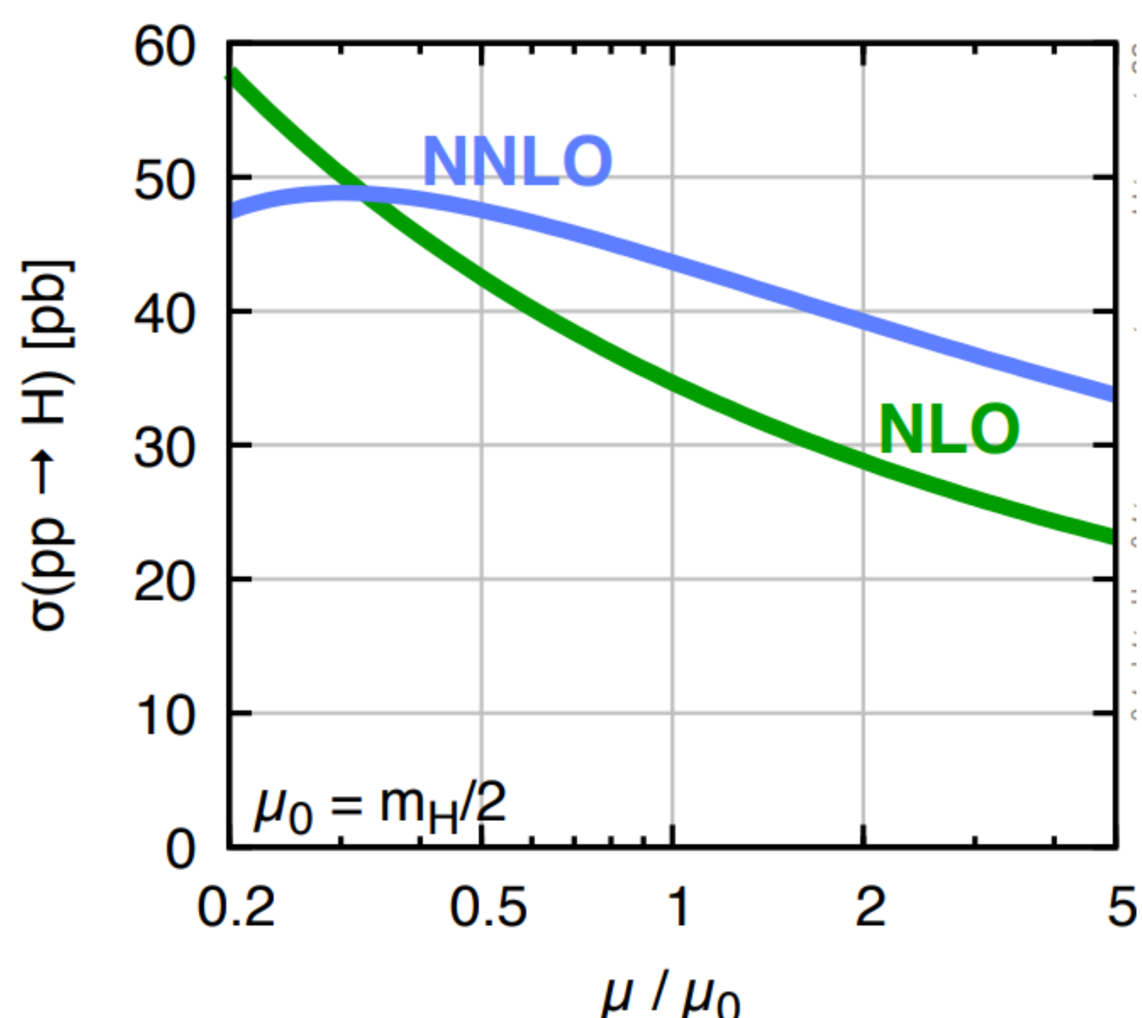


Illustration from Gavin Salam's lectures Quy Nhon Vietnam 2018

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- But μ_R and μ_F are arbitrarily chosen ~ M_H at any given perturbative order. Their variation introduces terms of higher perturbative order.
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N3LO

$$\sigma(pp \to H) = \sigma_0 \times \left(\alpha_s^2(\mu) + (10.4 + 2b_0 \ln \frac{\mu^2}{\mu_0^2})\alpha_s^3(\mu) + c_4(\mu)\alpha_s^4(\mu) + c_5(\mu)\alpha_s^5(\mu)\right)$$

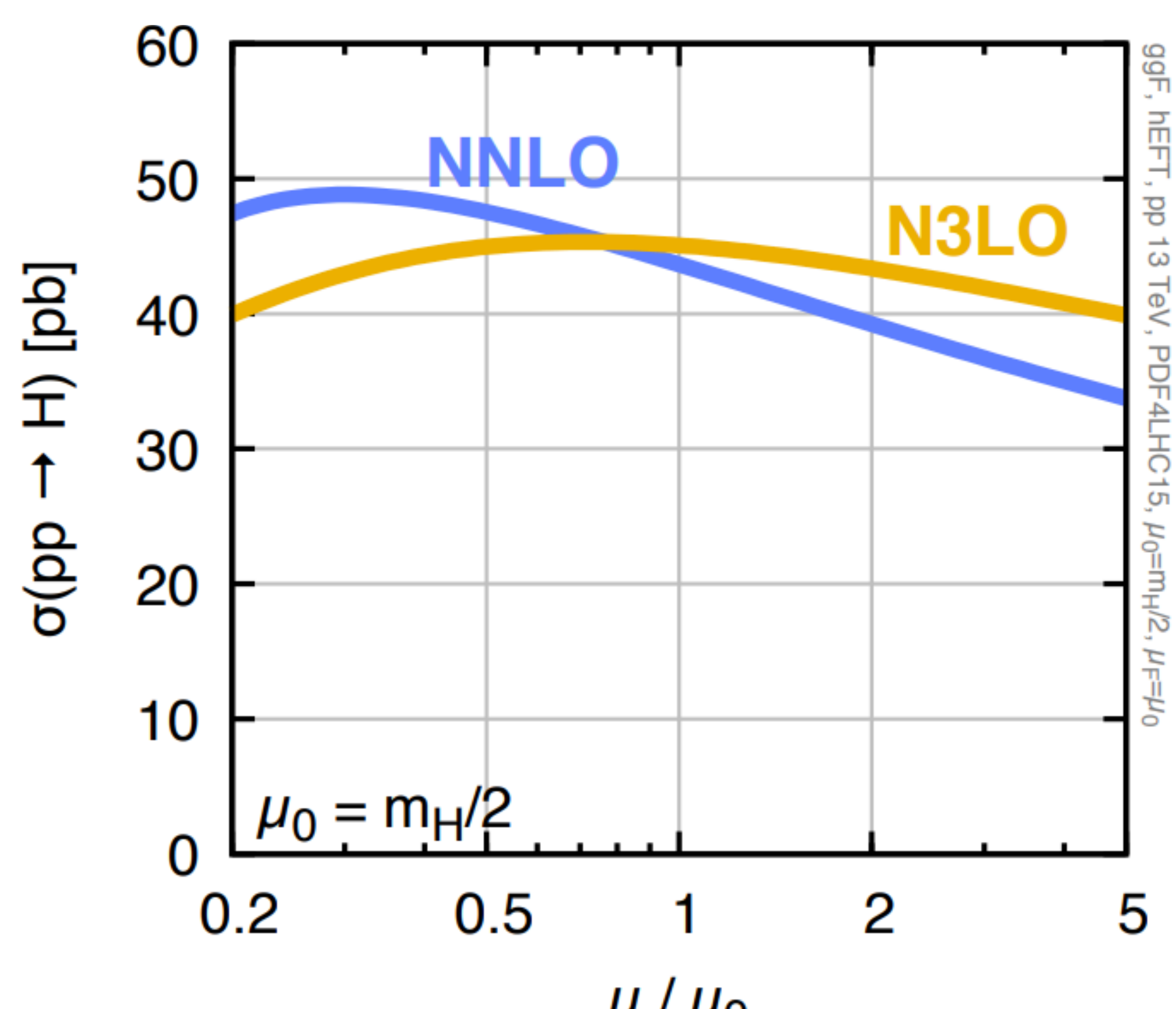
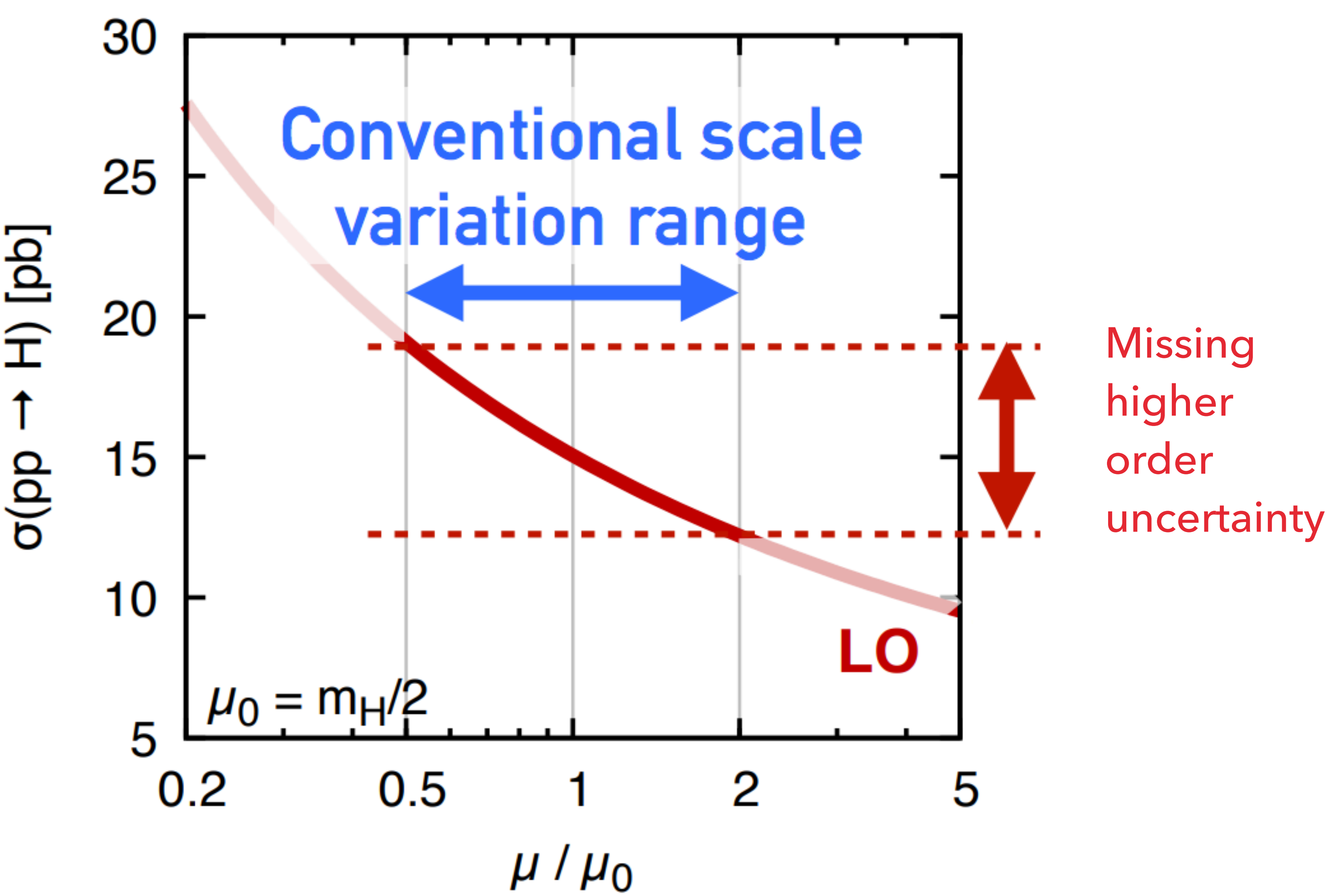
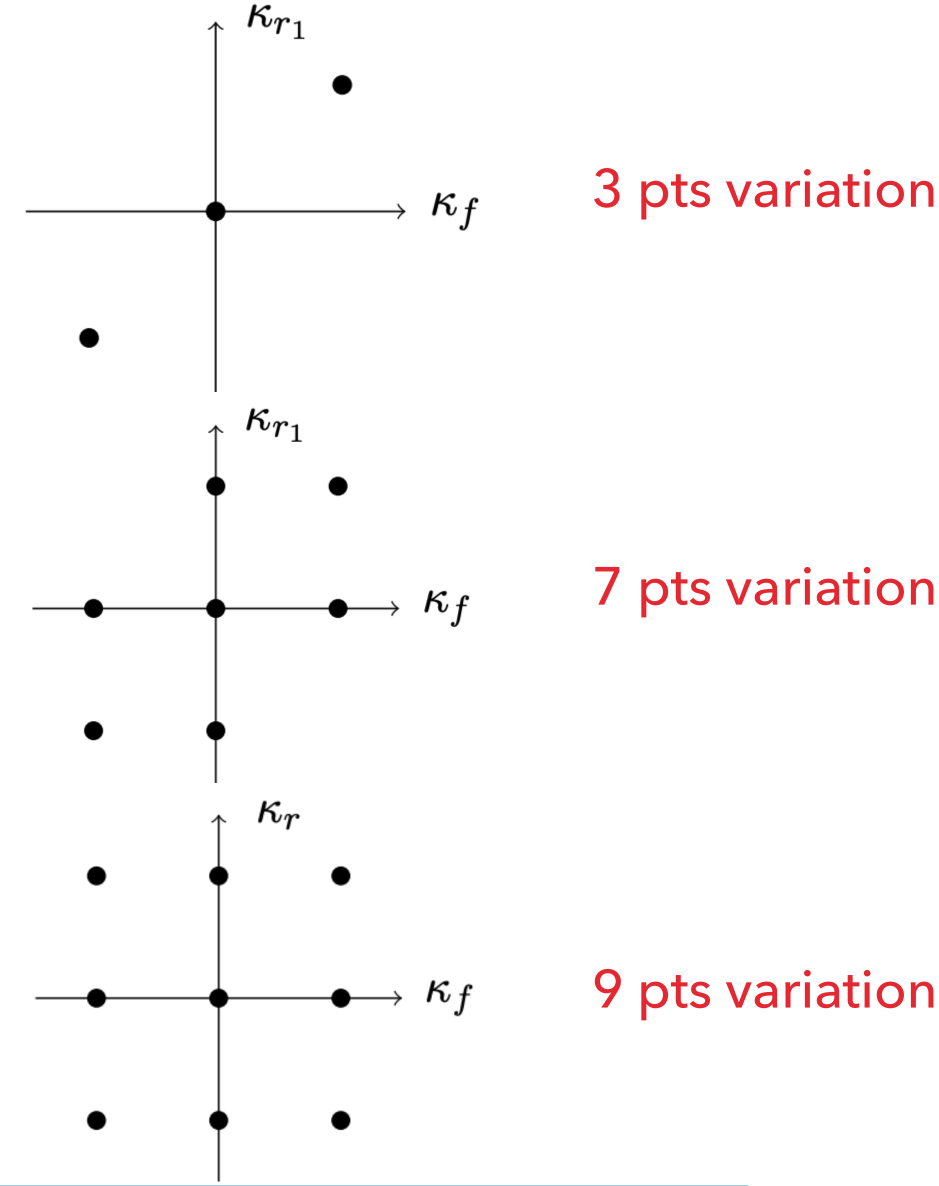


Illustration from Gavin Salam’s lectures Quy Nhon Vietnam 2018

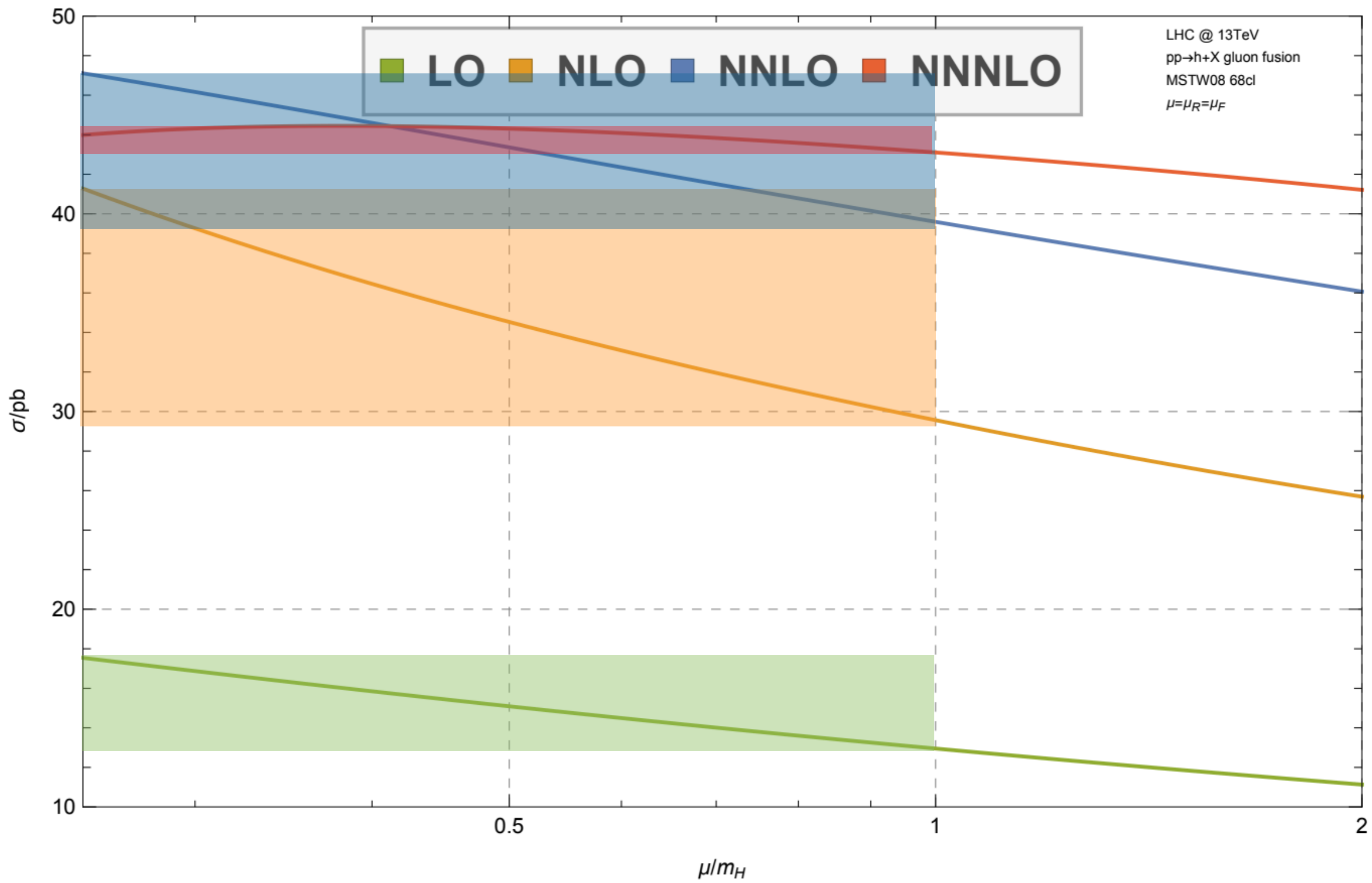
N3LO: GLUON FUSION INTO HIGGS





Convention: missing higher order uncertainties (or scale uncertainty or theory uncertainty) is estimated by change of cross section when varying μ_R and μ_F scales up and down by a factor of 2.

N3LO: GLUON FUSION INTO HIGGS

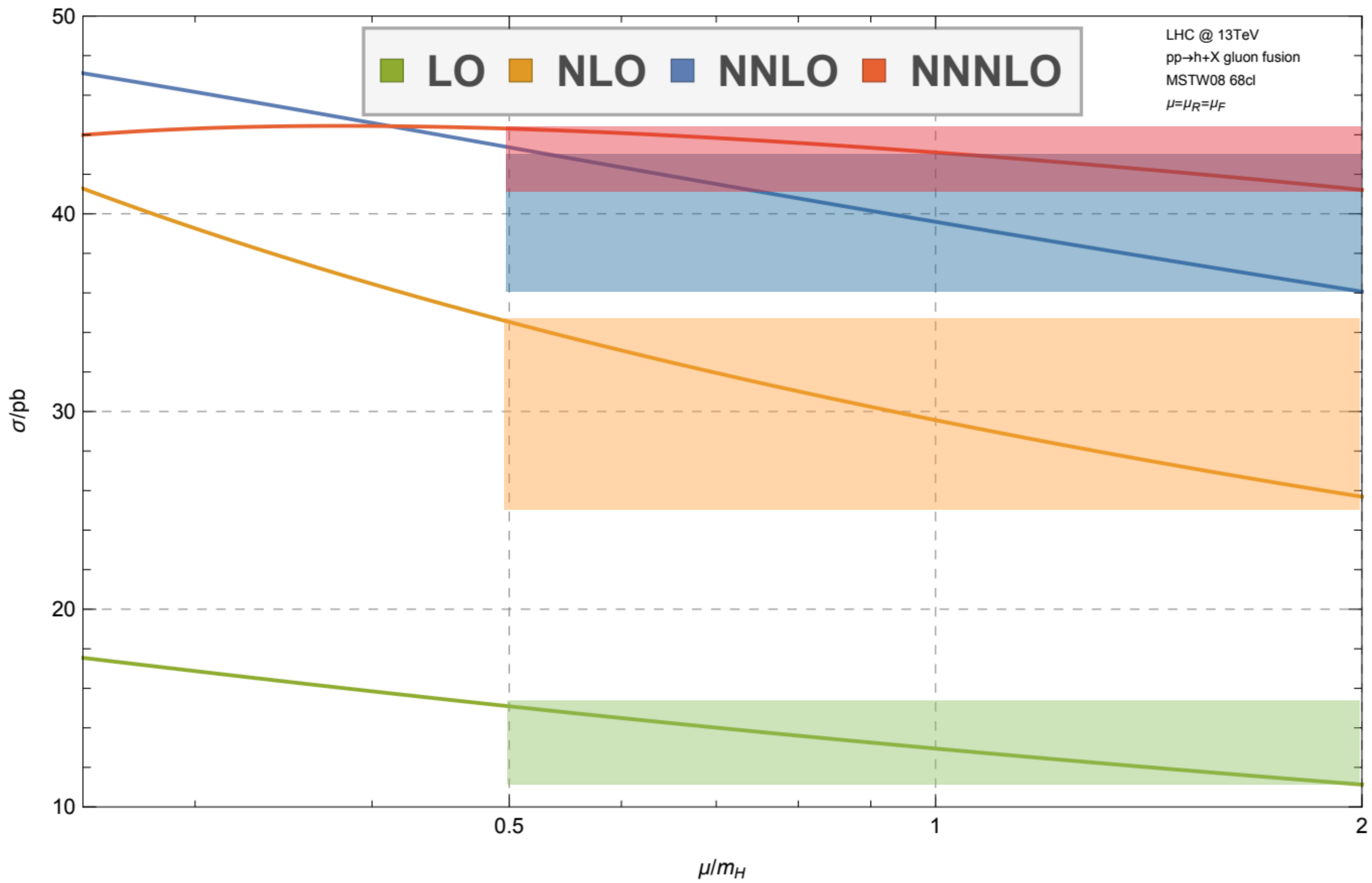


$$\mu_0 = \frac{M_H}{2}$$

The perturbative series displays convergence only at NNLO for $\boldsymbol{\mu}_0 = M_H/2$

Good news is that, at N3LO, the choice of $\boldsymbol{\mu}_R$ and $\boldsymbol{\mu}_F$ does not matter much

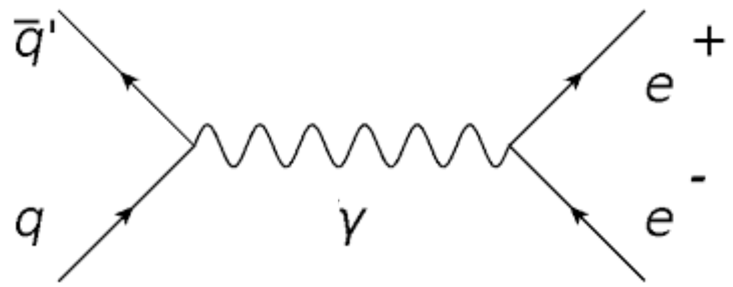
N3LO: GLUON FUSION INTO HIGGS



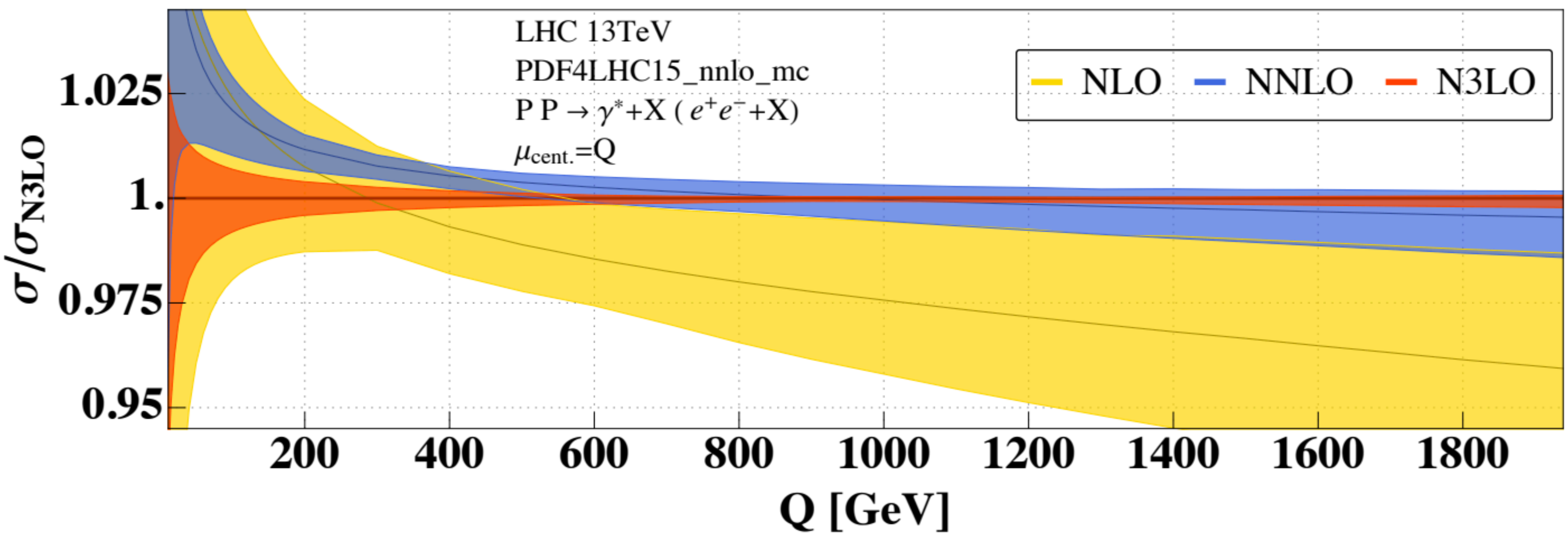
$$\mu_0 = M_H$$

N3LO: DRELL-YAN PRODUCTION

Durh et al 2001.07717

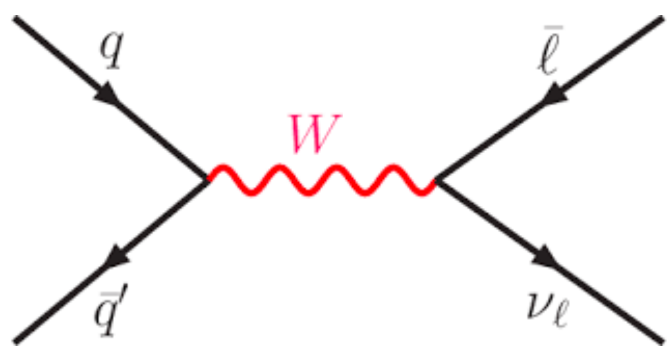


- Results at NLO and NNLO indicated a good convergence of the perturbative series. Size of the MHOU estimated at % level at NNLO.
- In contrast to the corrections to Higgs production, the shift of the predicted value of the DY cross section due to the inclusion of N3LO corrections is not contained in the naive scale variation bands of NNLO predictions for Q ≲ 400 GeV.

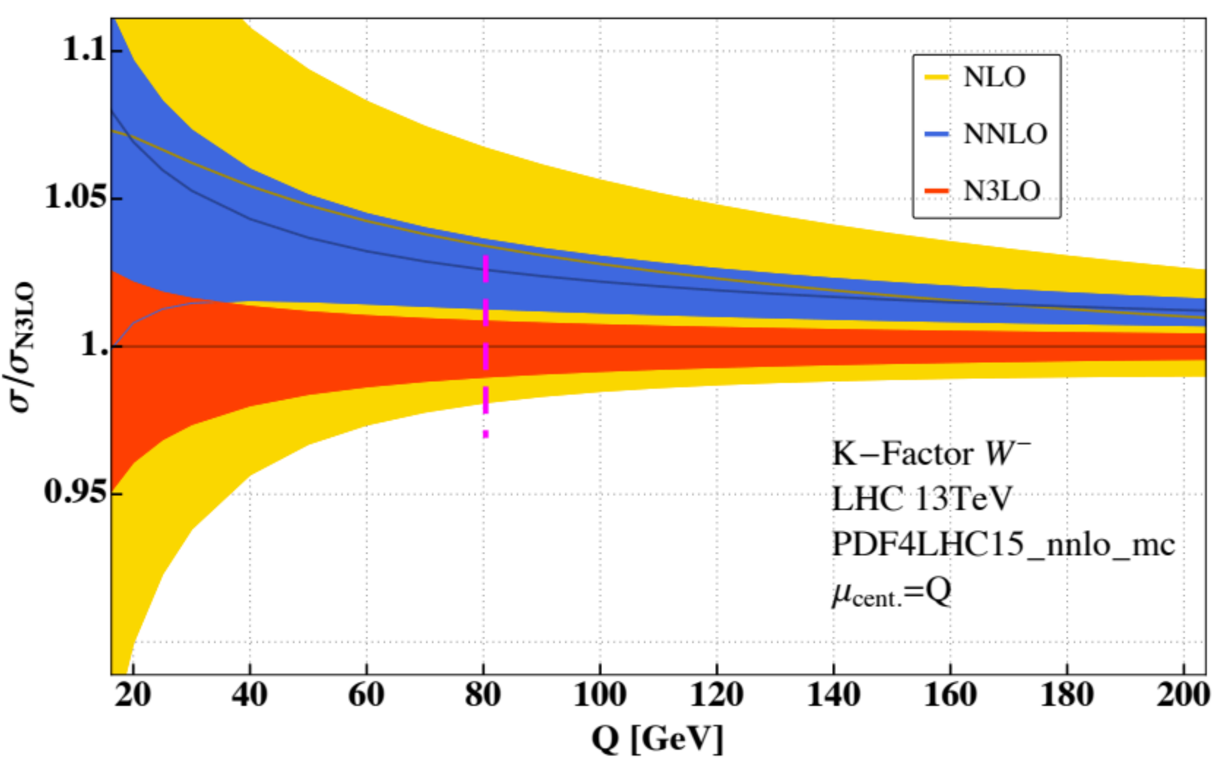


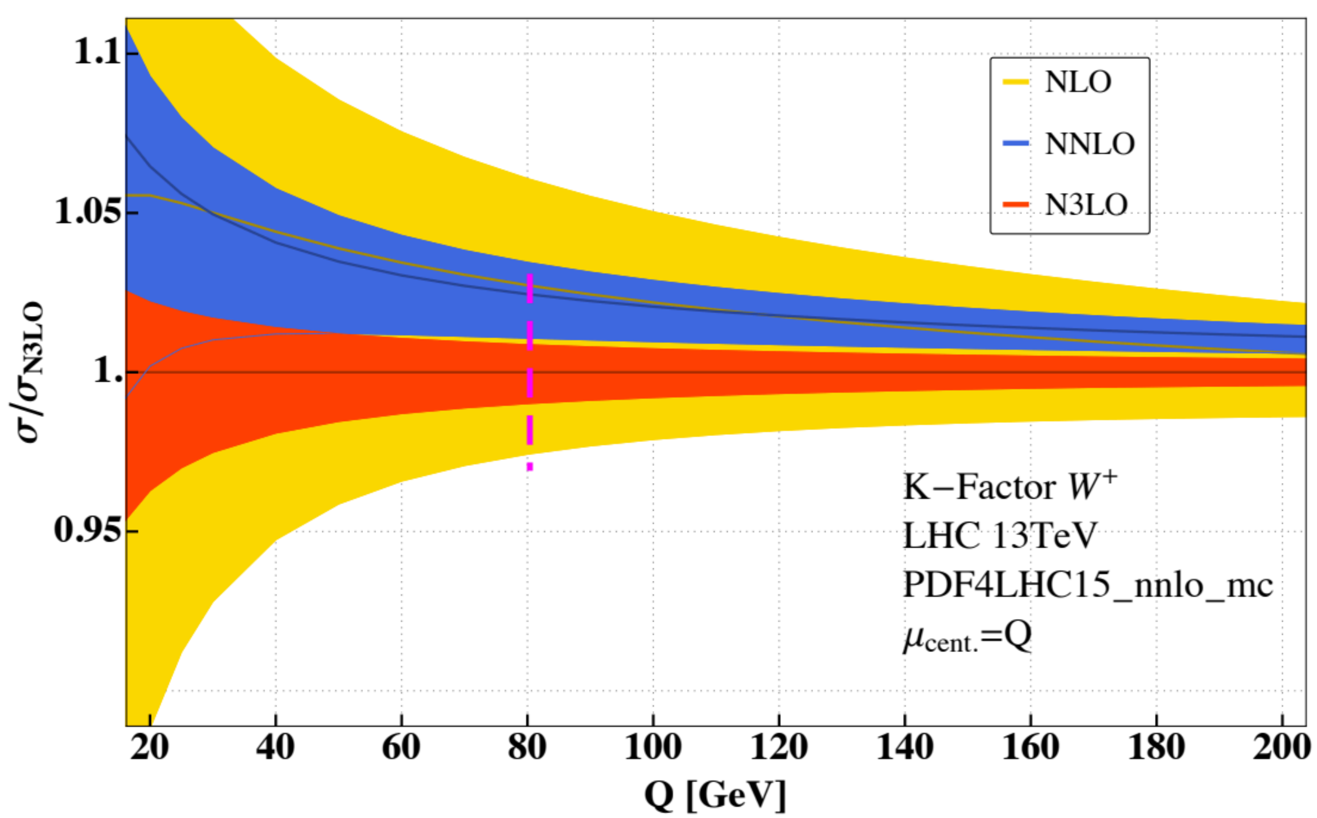
N3LO: DRELL-YAN PRODUCTION

Durh et al, 2007.13313



- Similar situation for W+ and W- production
- Rather than failure of perturbative series, results probably indicate underestimate of MHOU. Improved method to estimate it? See for example Bonvini 2006.16293
- Also mismatch between perturbative order in partonic cross section and PDFs (see tomorrow's lecture)



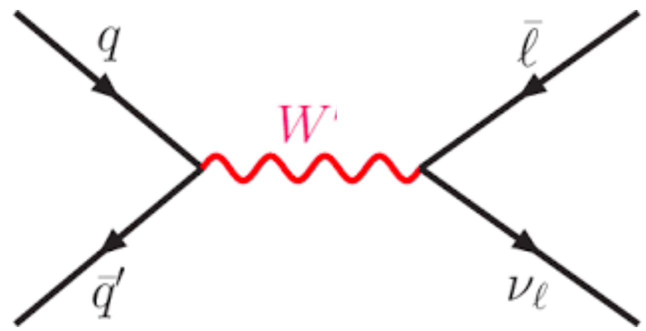


II.III BEYOND FIXED-ORDER QCD

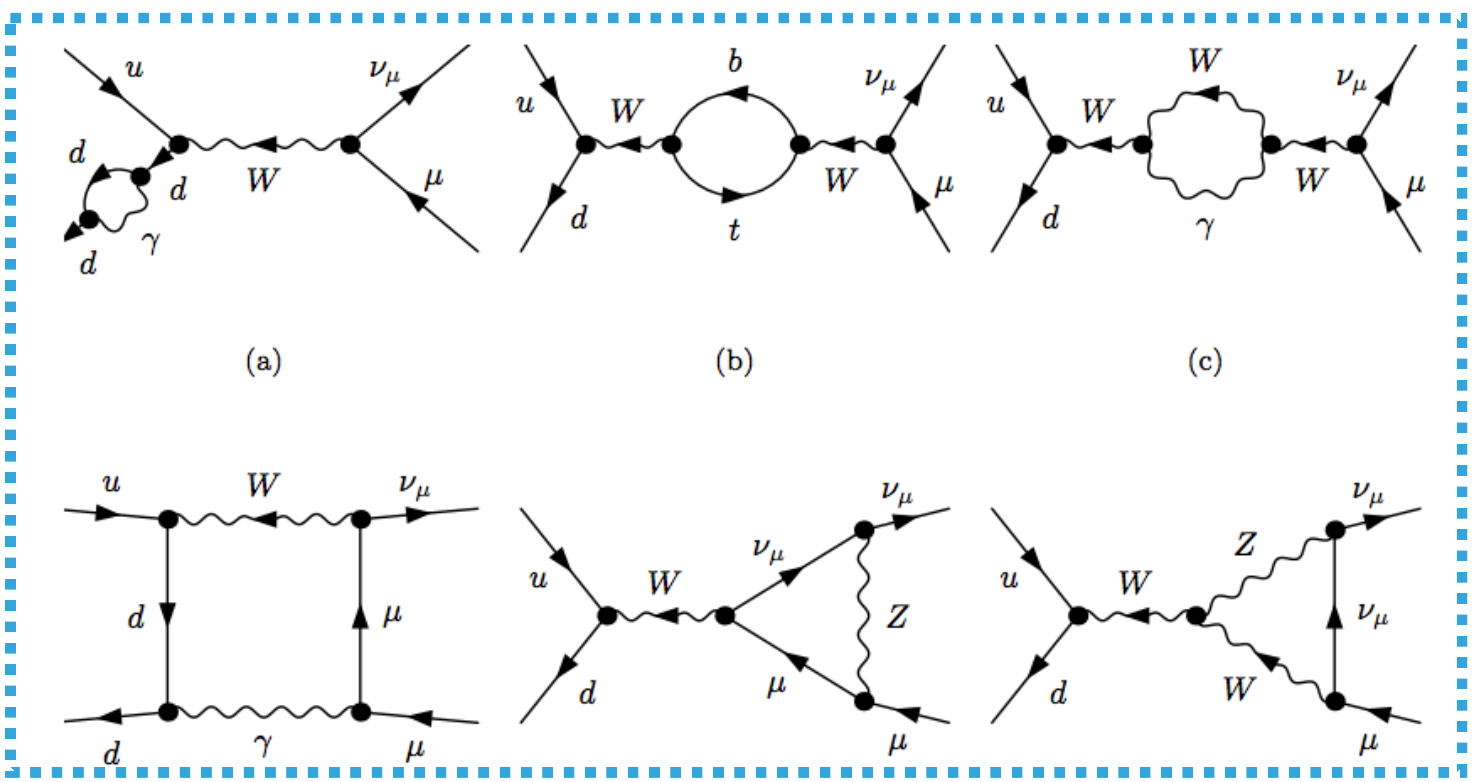
$$\sigma^{pp\to ab} = \sum_{i,j=-n_f}^{n_f} \int dz_1\, dz_2\, f_i(z_1,\mu_F)\, f_j(z_2,\mu_F)\, \hat{\sigma}^{ij\to ab}(z_1 z_2 S, \alpha_s(\mu_R), \mu_F) + \mathcal{O}\left(\frac{\Lambda^n}{S^n}\right)$$

#1: EW CORRECTIONS

- Because $\alpha_{EM}(Mz) \sim \alpha_S(Mz)/10 \Longrightarrow$ NLO EW corrections ~ NNLO QCD corrections



$$\mathcal{O}(\alpha_{\rm EM}^2) \times [1]$$



Virtual corrections

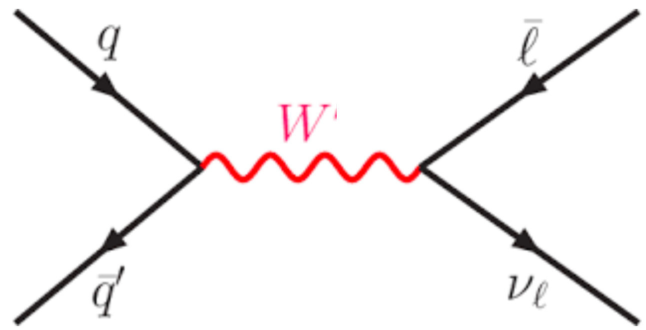
$$\mathcal{O}(\alpha_{\rm EM}^2) \times [1 + \alpha_{\rm EM}\, C_1]$$

$$+\frac{3\alpha_{\rm EM}}{\pi M_W^2}\log\left(\frac{s}{M_W^2}\right)$$

At large s these logs can become large

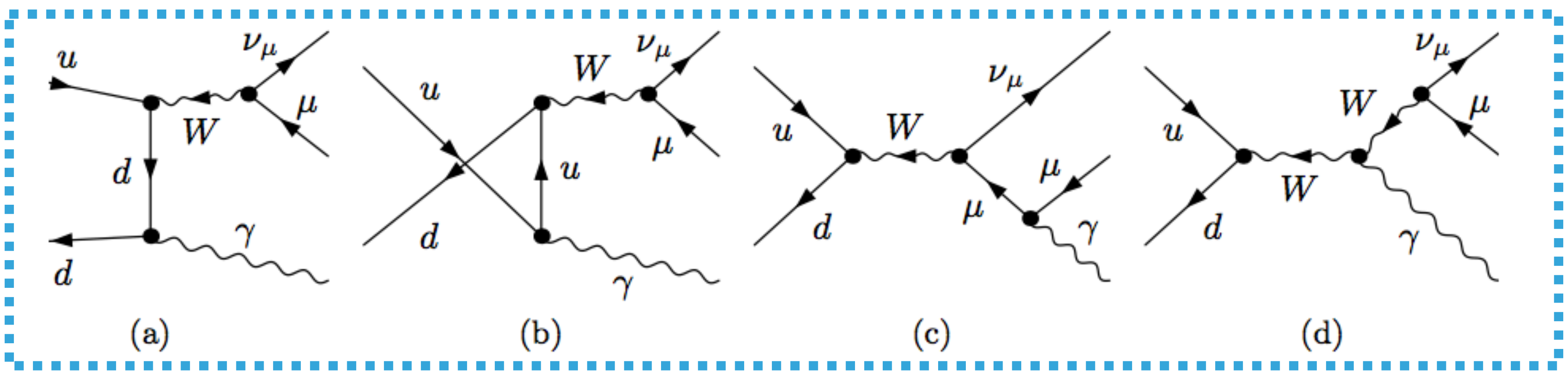
#1: EW CORRECTIONS

- Because $\alpha_{EM}(Mz) \sim \alpha_S(Mz)/10 \Longrightarrow$ NLO EW corrections ~ NNLO QCD corrections

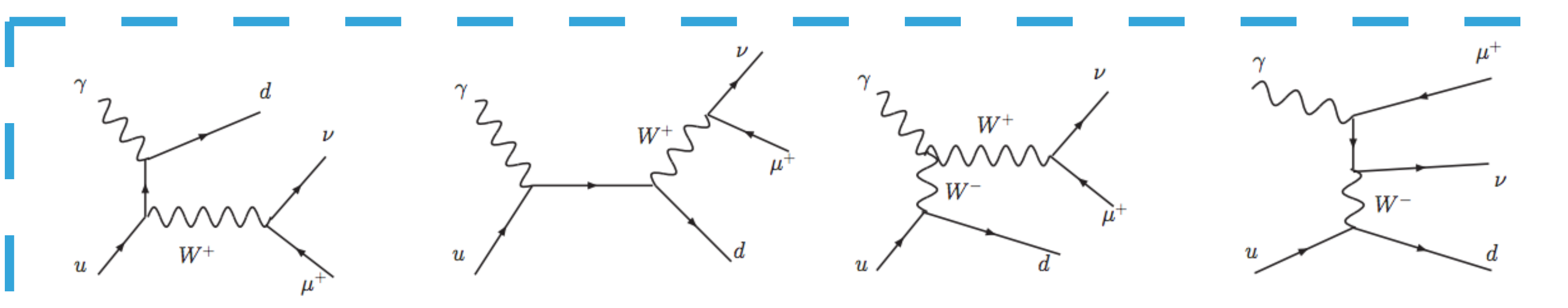


$$\mathcal{O}(\alpha_{\rm EM}^2) \times [1]$$

Real corrections - quark initiated

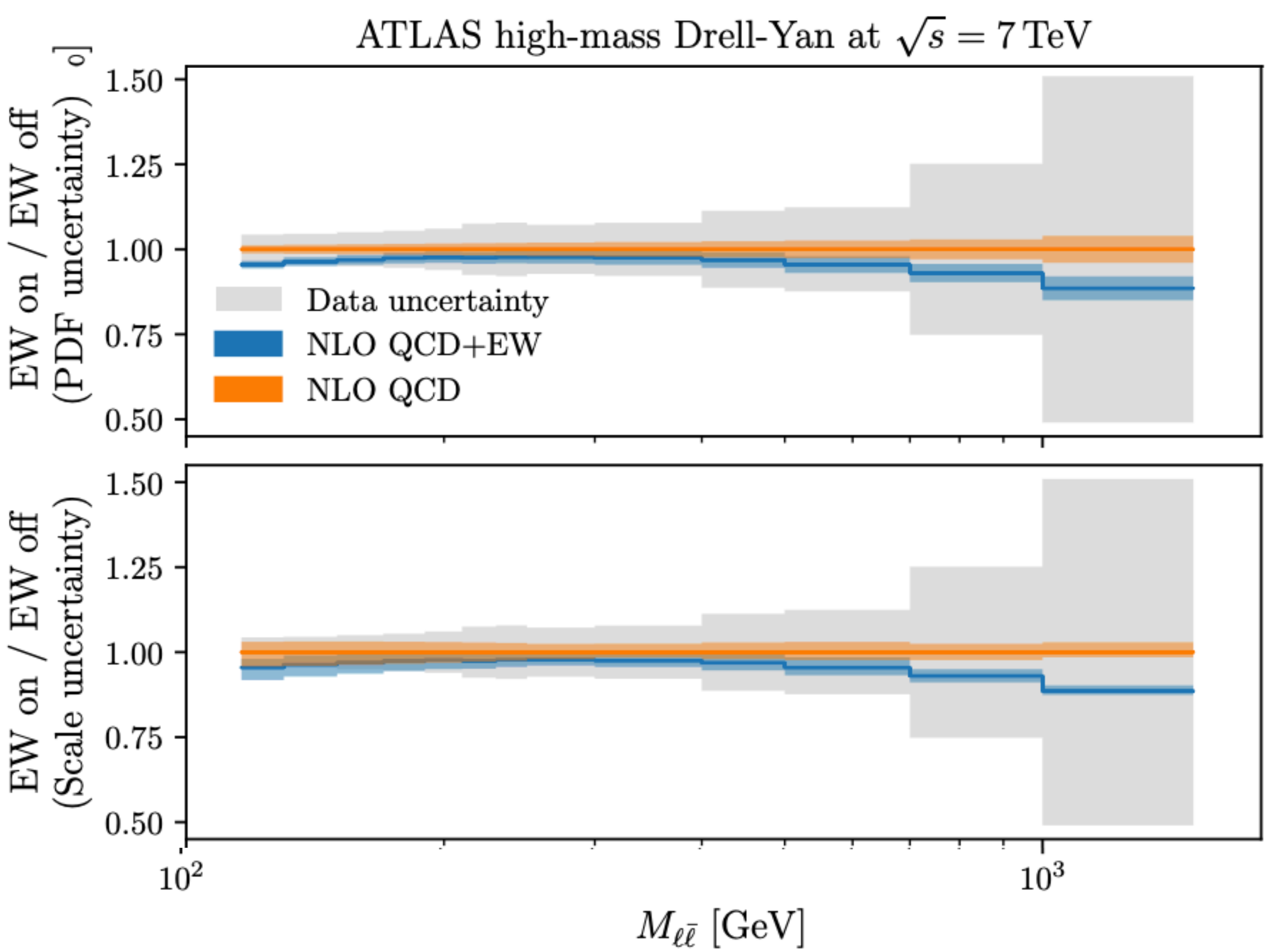


Real corrections - photon initiated

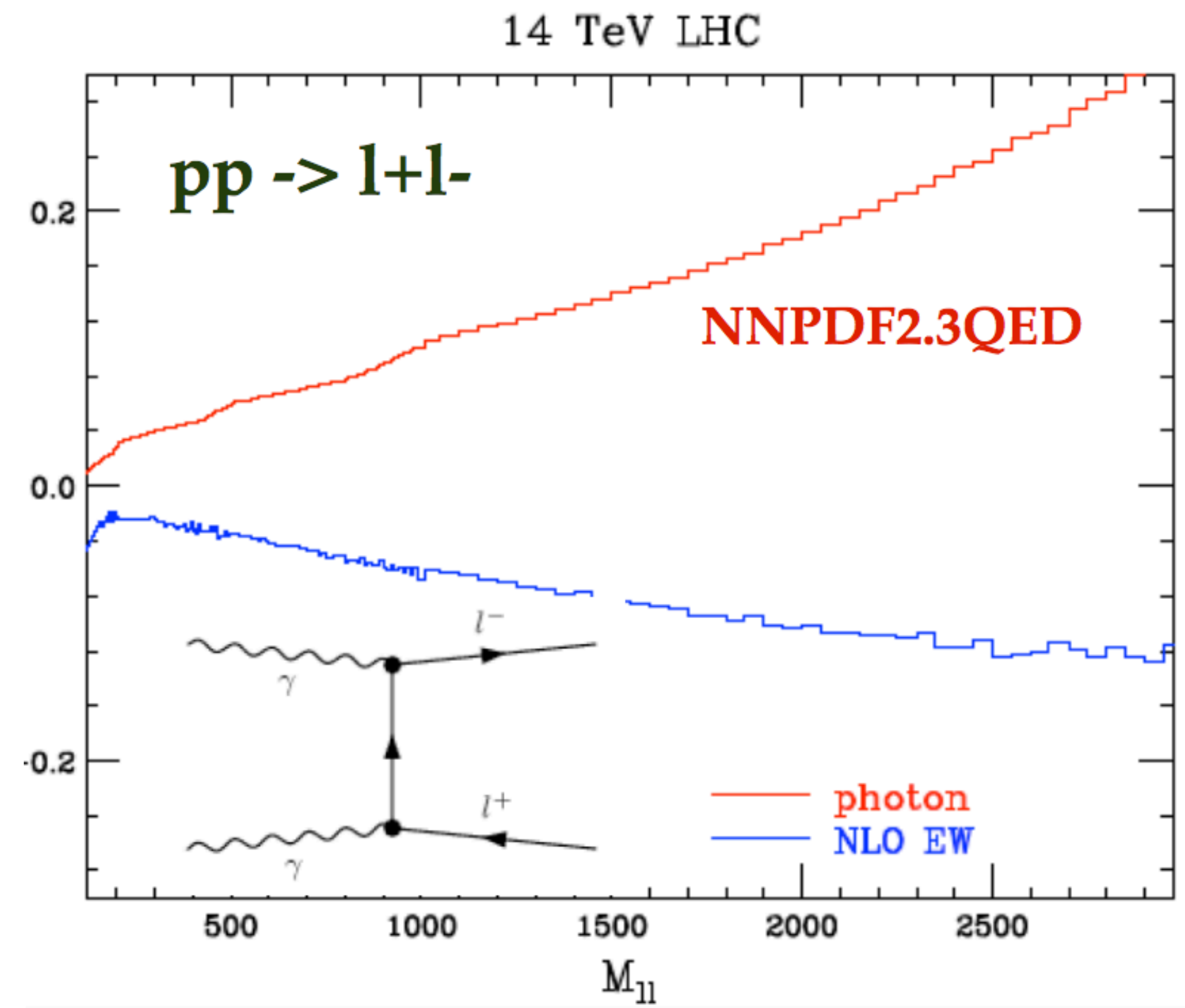


#1: EW CORRECTIONS

- NLO EW corrections become large in the large M and pT region of lepton but partially compensated by photon-initiated real corrections

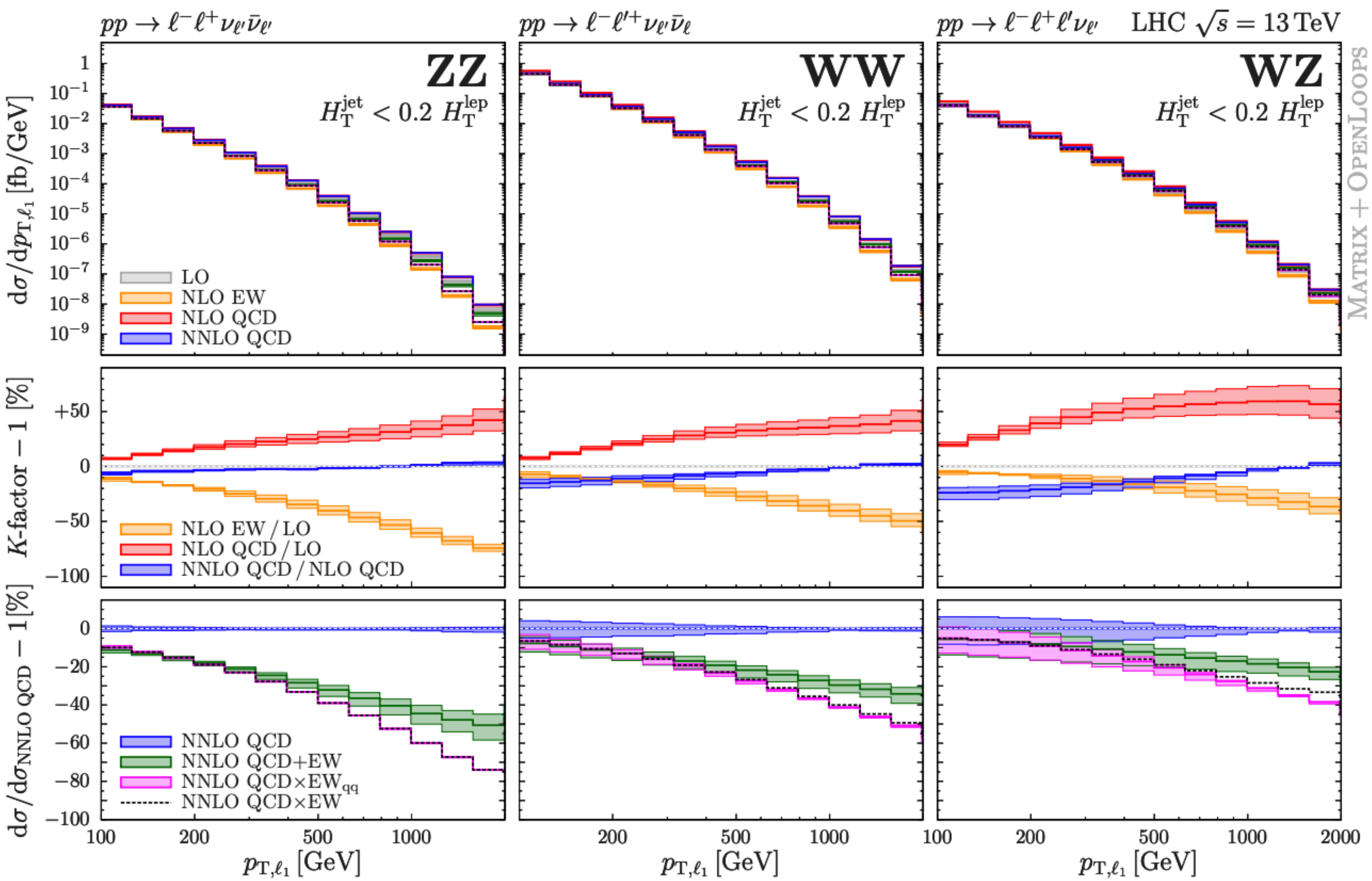


Carrazza et al, arXiv:2008.12789



Boughezal et al Phys.Rev. D89 (2014)3, 034030

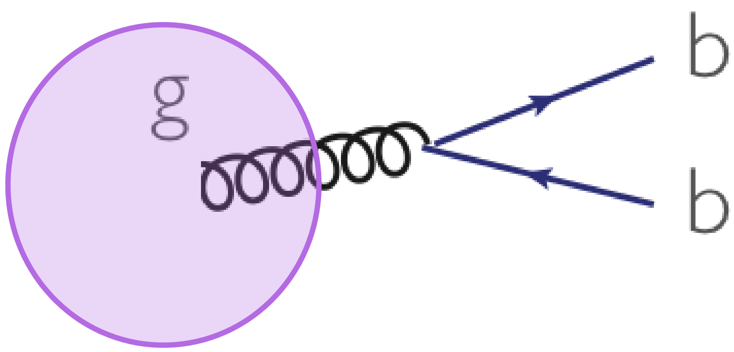
#1: FRONTIER: NNLO QCD + NLO EW

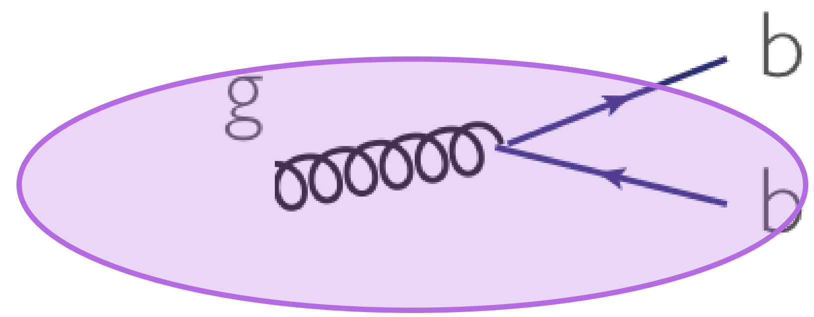


- Lots of activity in merging NNLO QCD and NLO EW calculations
  Grazzini et al 1912.0068, Bonciani et al 1911.06200, Bonciani et al 2007.06518,…

#2: 4FS VERSUS 5FS SCHEMES

- For all processes that feature bottom quarks at the hard-process level there are two ways of performing computations: **4F (four-flavour)** and **5F(five-flavour)** schemes



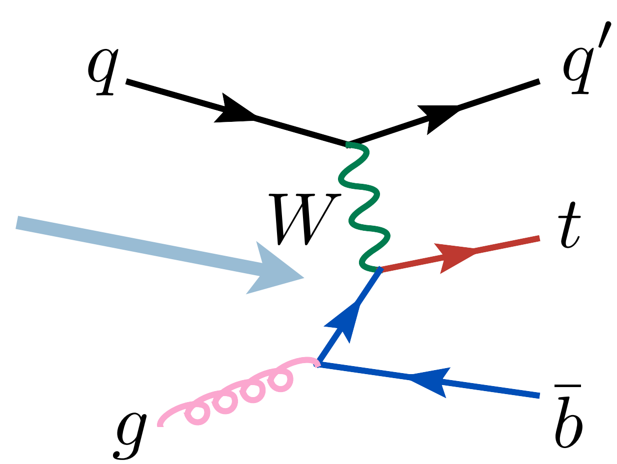


- Take a 4F scheme, in which bottom quark does not belong to the proton wavefunction

$$\frac{1}{t - m_b^2} \sim \frac{1}{p_T^2 + m_b^2}$$

$$t = (p_{\bar{b}} - p_g)^2,\; p_T^2 = p_{T,\bar{b}}^2$$

$$\int_0^{p_{T,max}^2} \frac{dp_T^2}{p_T^2 + m_b^2} = \log\left(\frac{p_{T,max}^2}{m_b^2}\right)$$



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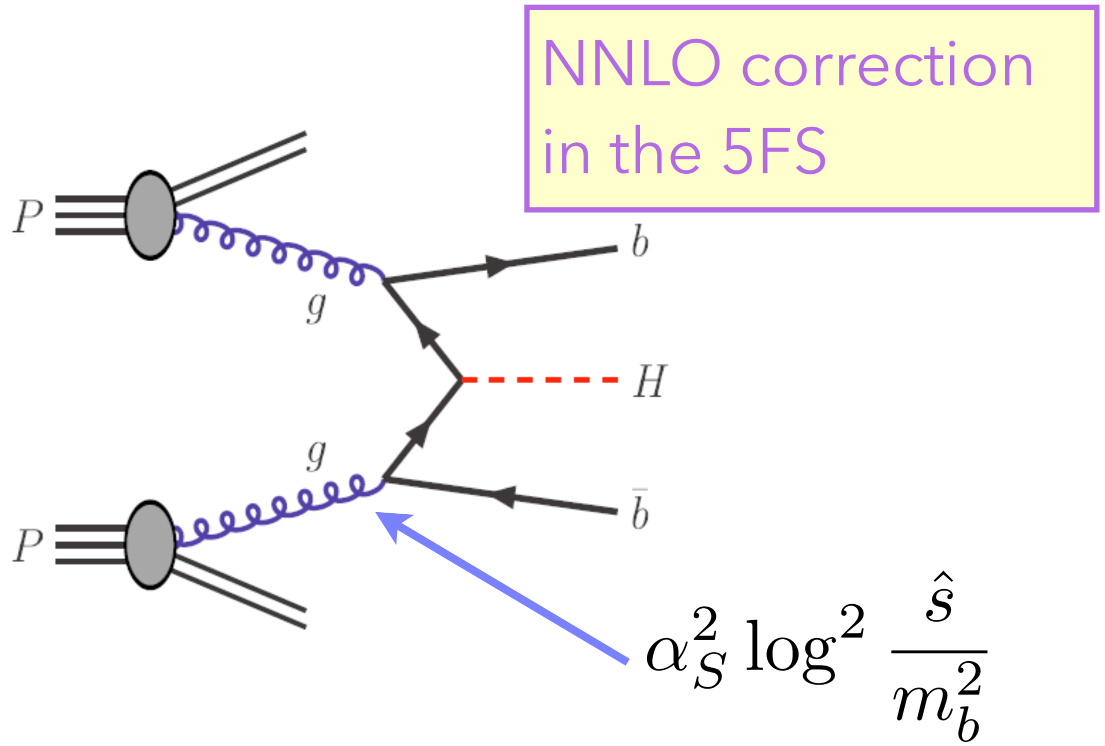
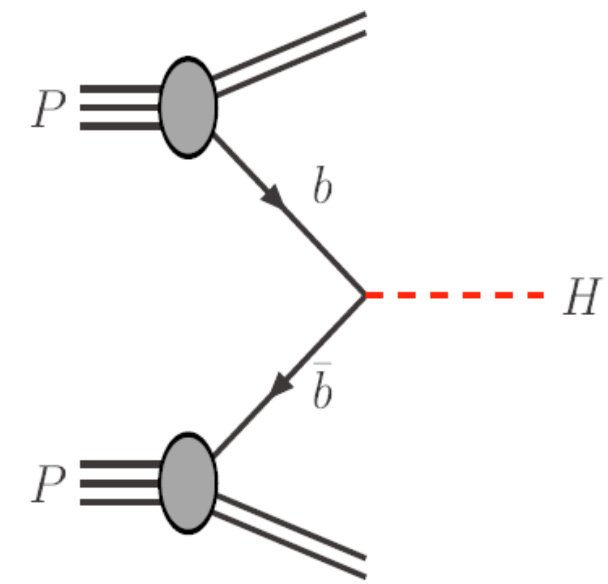




4F scheme

✘ It does not resum possibly large logs, yet it has them explicitly
✘ Computing higher orders is more difficult
✔ Mass effects are there at any order
✔ Straightforward implementation in MC event generators at LO and NLO

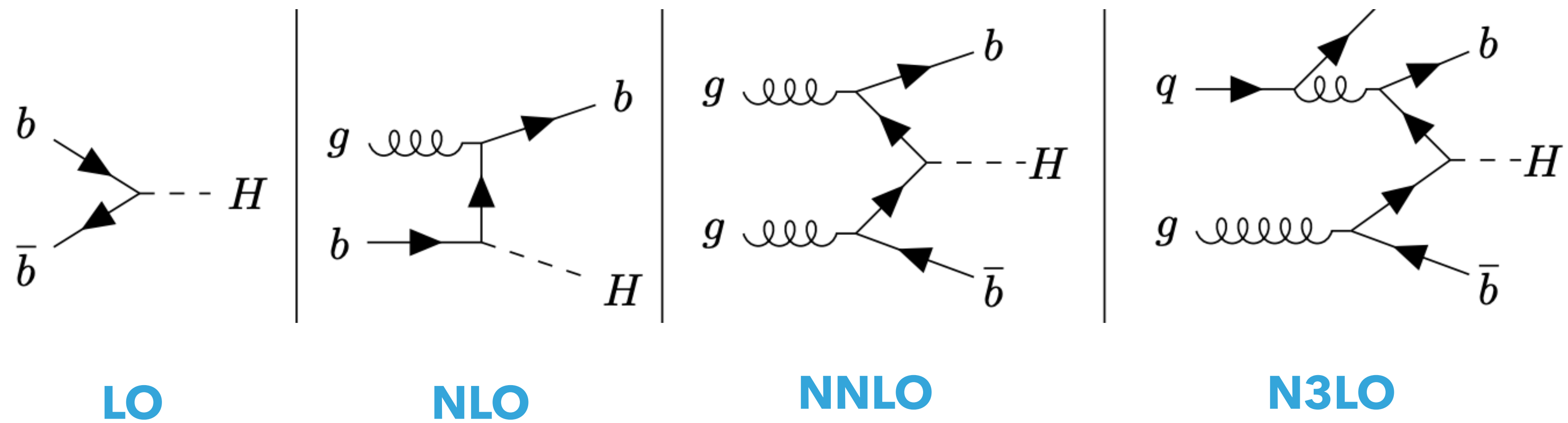
Decoupling or massive scheme

5F scheme

✔ It resums initial state large logs into b-PDFs leading to more stable predictions
✔ Computing higher orders is easier
✘ p_T of bottom enters at higher orders
✘ Implementation in MC depends on the gluon splitting model in the PS

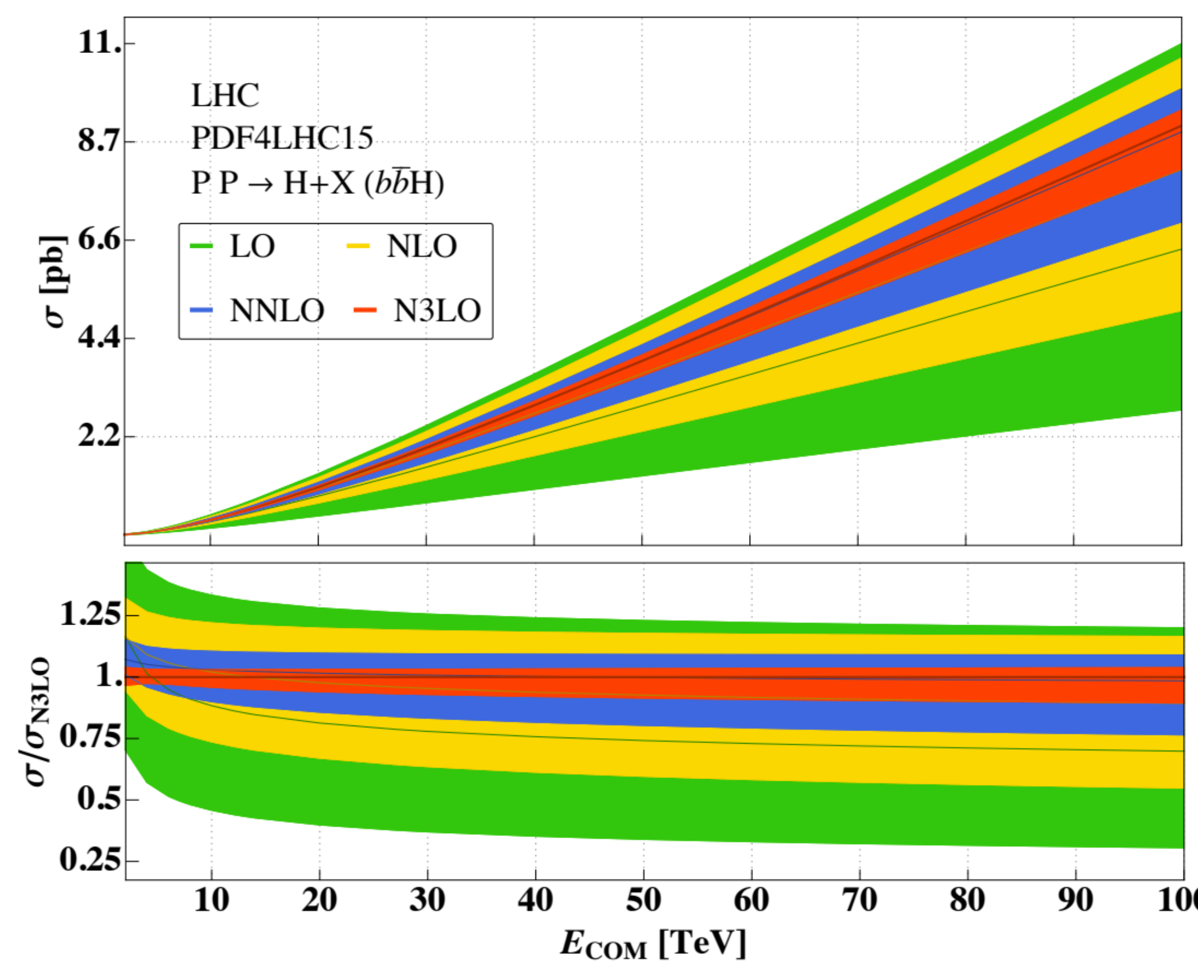
Massless scheme

#2: 4FS VERSUS 5FS - BOTTOM FUSION INTO HIGGS



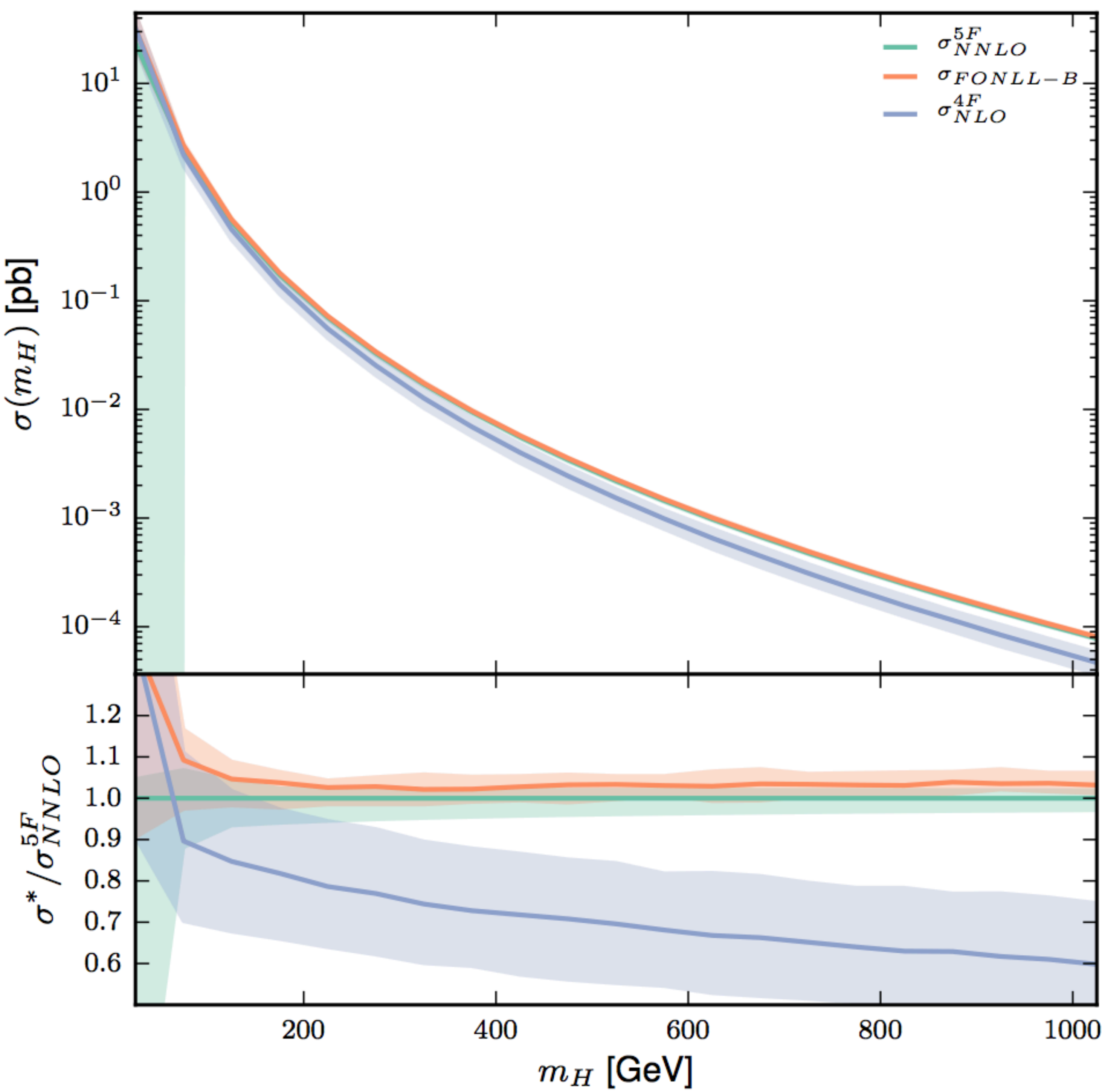
- Bottom quark fusion into Higgs is suppressed in the SM, but enhanced in new physics models in which there are two Higgs doublets (2HDM) or a triplet

- Here perturbative series converges well in the 5-Flavour-Scheme in which bottom quark (m_b ~ 4.5 GeV) is neglected and b treated as massless parton



Duhr et al, arXiv:1904.09990

#2: FRONTIER: 4FS VERSUS 5FS MATCHING



- Predictions in the 4F and 5F schemes consistently combined in consistent matching of bottom quark mass effects with resummation of collinear logarithms

- Lots of activity in matching processing in massive versus massless schemes in heavy quarks initiate processes, both at inclusive and <u>differential</u> level

Forte et al, arXiv:1508.01529
Forte et al, arXiv:1607.00389
Duhr, et al, arXiv:2004.04752

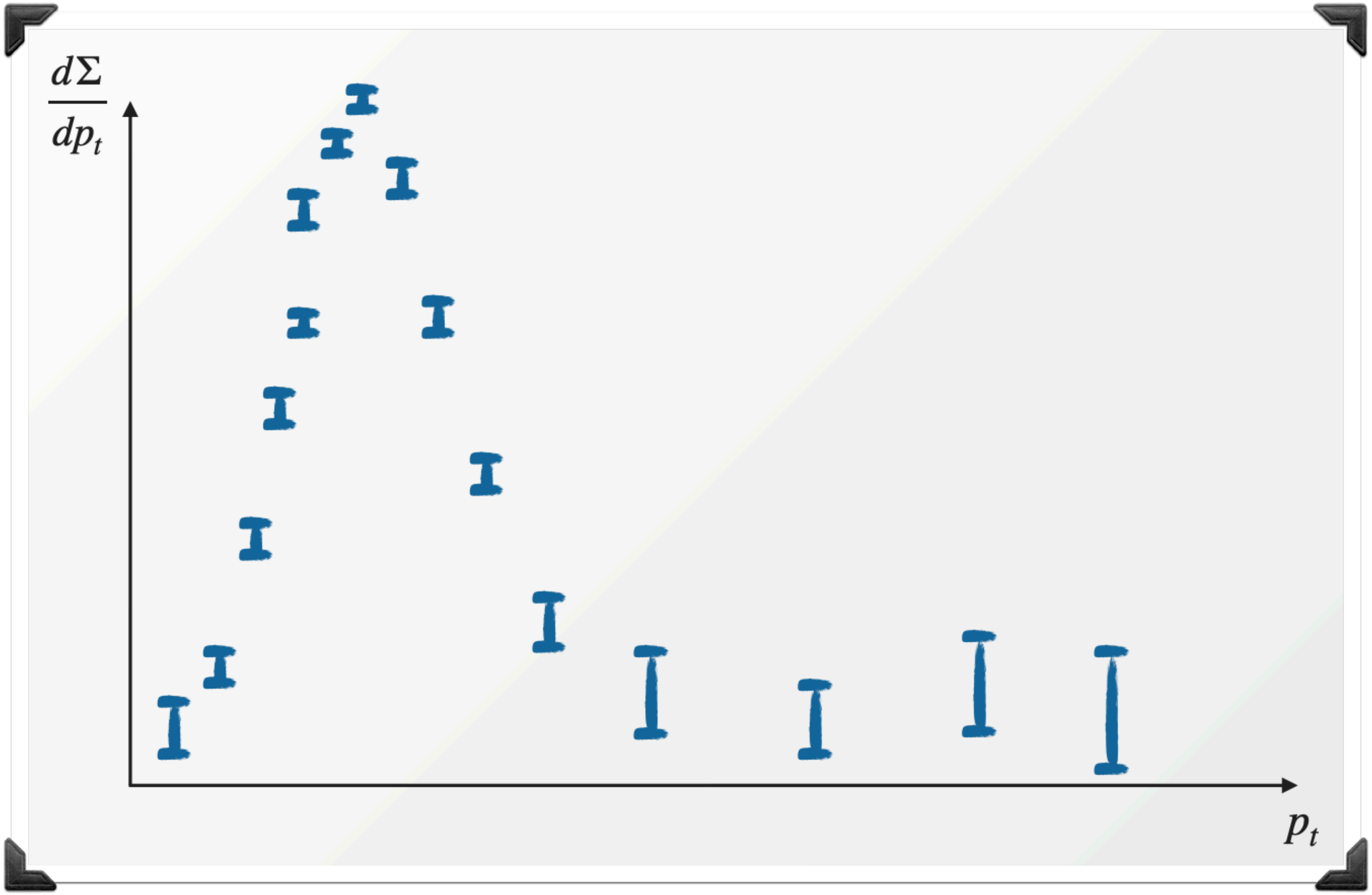
#3: RESUMMATIONS

- Many observables studied at the LHC depend on more than one scale; single or double logs of the ratio of those scales at all orders in perturbation theory.
- If the logarithms are large the convergence of the series is spoiled

Fixed order		All orders (L=some large log)	
$\frac{\sigma}{\sigma_0} = 1$	LO	$\ln\frac{\sigma}{\sigma_0} = \alpha^n L^{n+1}$	LL
$+ c_1\alpha$	NLO	$+ \alpha^n L^n$	NLL
$+ c_2\alpha^2$	NNLO	$+ \alpha^n L^{n-1}$	NNLL
$+ \dots$		$+ \dots$	

#3: RESUMMATIONS

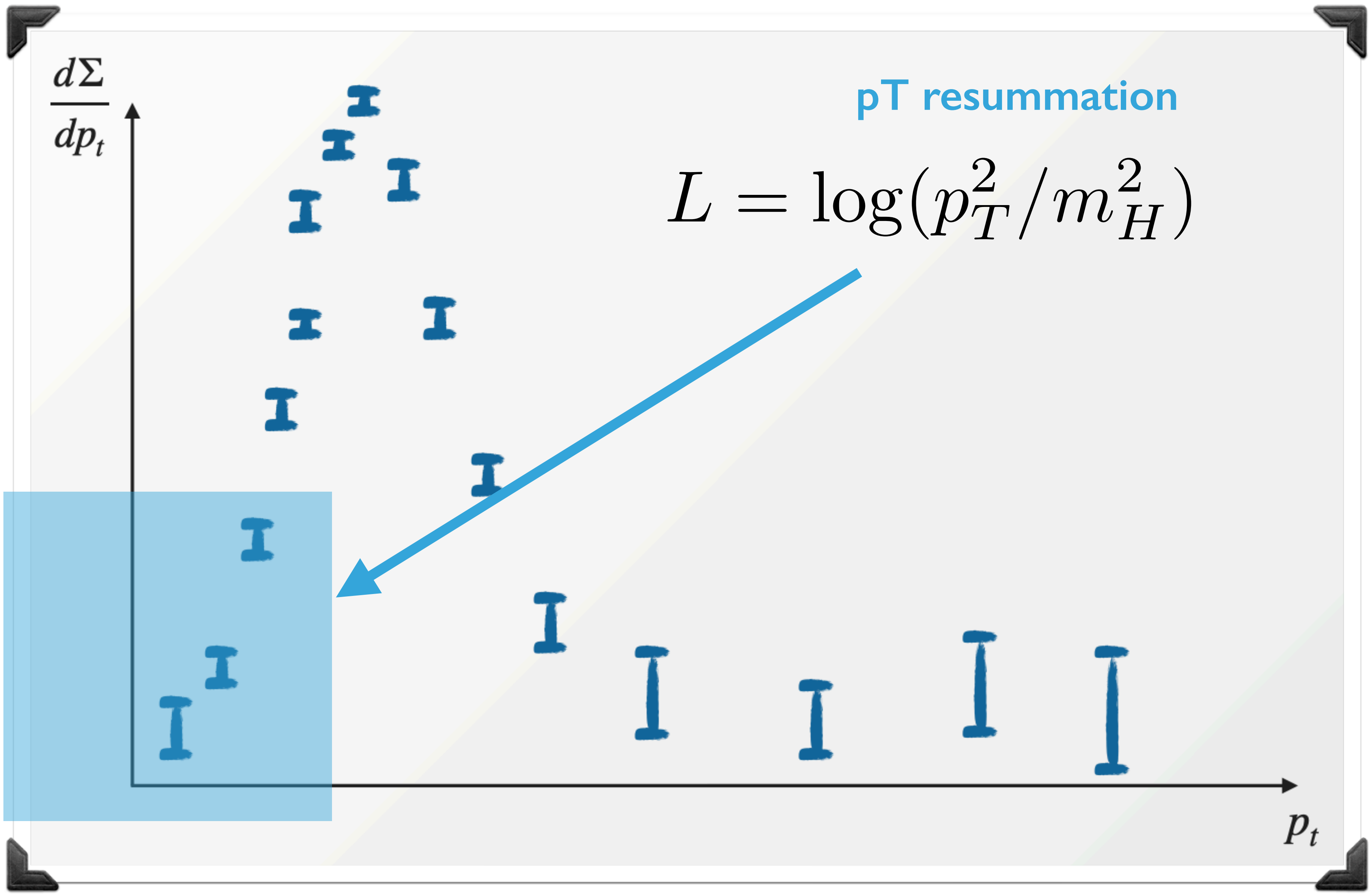
Take the Higgs transverse momentum spectrum



From Luca Rottoli’s talk QCD@LHC2018

#3: RESUMMATIONS

Take the Higgs transverse momentum spectrum



From Luca Rottoli’s talk QCD@LHC2018

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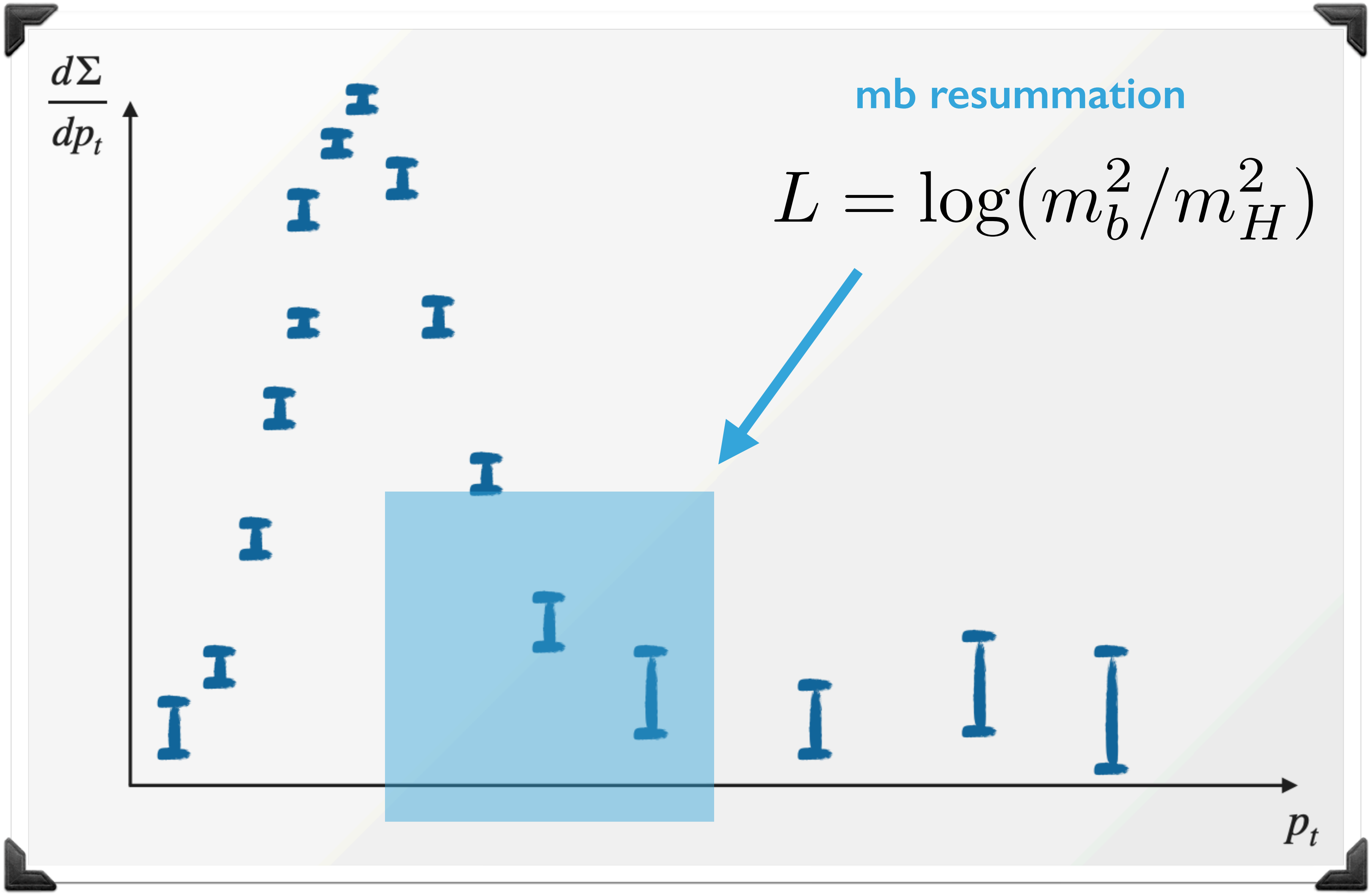
Take the Higgs transverse momentum spectrum



From Luca Rottoli's talk QCD@LHC2018

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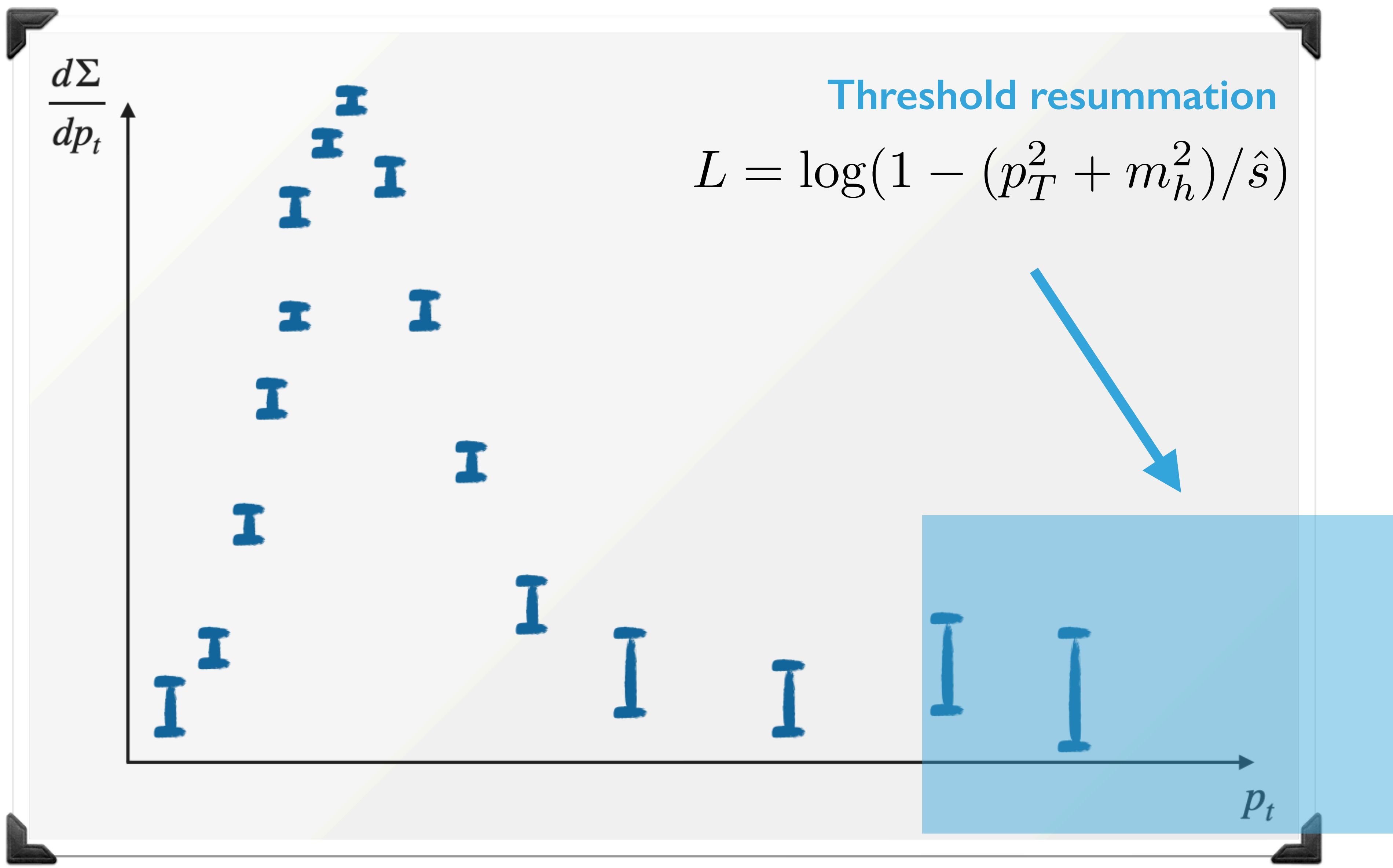
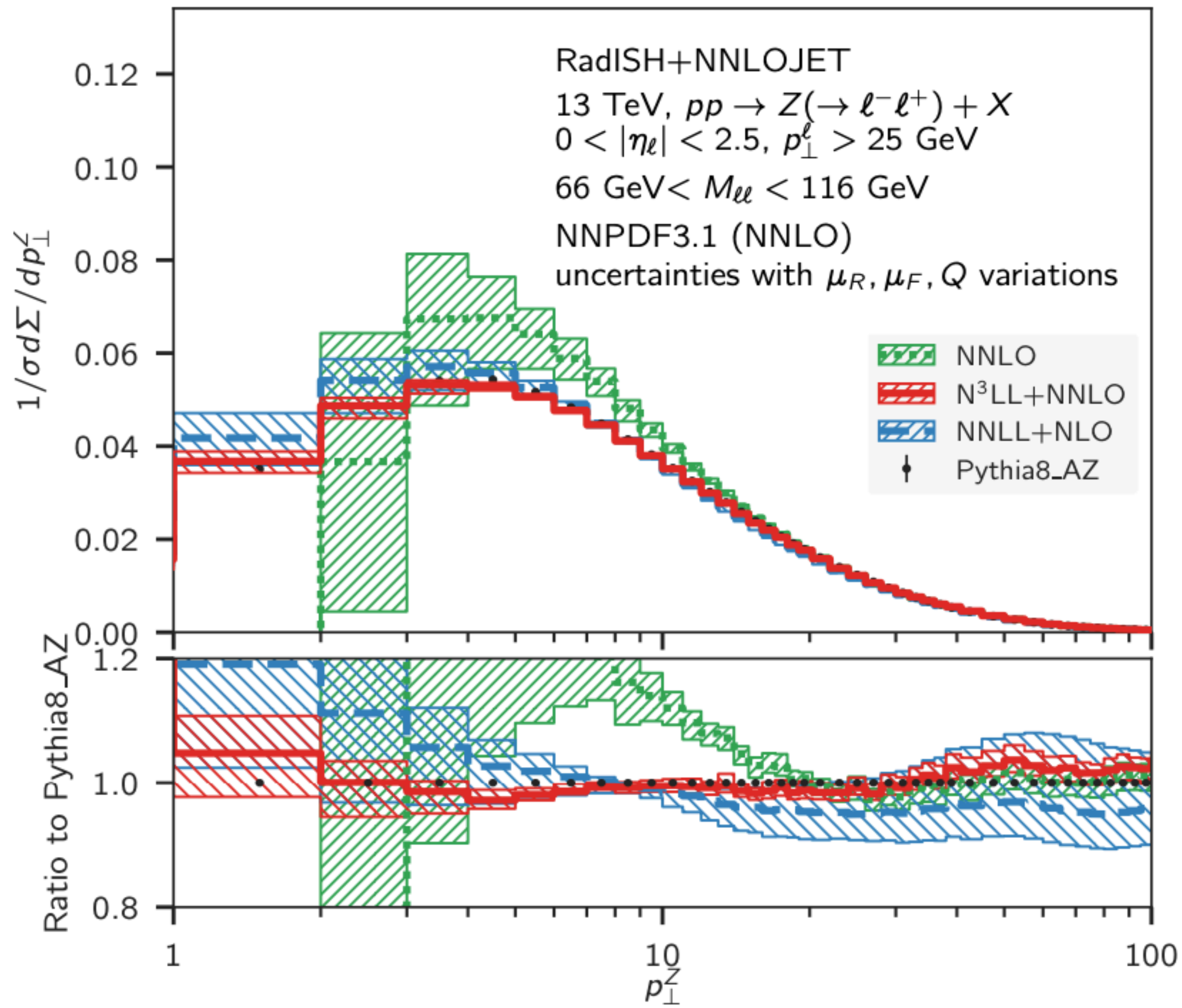
Take the Higgs transverse momentum spectrum



From Luca Rottoli's talk QCD@LHC2018

#3: FRONTIER: COMBINED RESUMMATIONS

Bizon et al, 1905.05171



- Huge recent progress in precision thanks to resummation, for example:
- Transverse Z pT resummation at NNNLL matched with NNLO [Bizon et al, 1905.05171]
- Combined QED and QCD pT resummation [Cieri et al, 1805.11948]
- Higgs pT at NNNLL+NNLO [Bizon et al, 1705.09127]

- Huge progress also in combined resummation: pT and small-x [Forte et al 1511.05561], pT and large-x [Marzani 1511.06039, Muselli et al 1701.01464], small-x and large-x [Bonvini et al 1802.07758], pT and jet radius [Banfi et al 1511.02886] …

REALISTIC EVENT SIMULATION

- Only time to talk about fixed order perturbative QCD+EW calculations (some matched with large log resummation), where the final state looks clean and well defined
- But real events look much more messy, and we need to connect fixed-order (resummed) QCD+EW calculations to realistic simulation of the hadronic final state.
- This is achieved by parton showers Monte Carlo event generators that bridge the gap from the hard interaction scale Q down to the hadronisation scale O(1 GeV)
- Need to be able to describe an arbitrarily number of parton branchings, i.e. need to 'dress' partons (and leptons) with radiation and turn partons into hadrons (hadronization).

HUGE PROGRESS IN MONTE CARLO TOOLS

- NLO+ (leading-log) PS well-established , automated and used in all advanced LHC analyses [MG5_aMCatNLO, POWHEG, SHERPA…]
- Frontiers: NNLO + PS and NLL parton showers

Lagrangian
Matrix elements (QCD and EW)
Resummation
Parton showers
Hadronisation
Jet algorithms
MPI …

Detector simulation
Pions, Kaons, ...
Reconstruction
B-tagging efficiency
Boosted decision tree
Neural network
...

Theory

Experiment

F. Maltoni BUSSTEPP 2019

(PARTIAL) CONCLUSIONS

- Precision physics opens up new fascinating challenges
- I hope I conveyed the feeling that, as the community has move forward at an incredible rate, still a lot of interesting and necessary developments to work on
- Only time to mention few of them: NNLO for higher multiplicities, N3LO, theory uncertainties, EW corrections and matching with QCD corrections, heavy flavour schemes, large log resummations and combined resummations, NNLO + PS, NLO parton showers.
- Did not have time to mention huge progress in jets physics and Monte Carlo simulations
- Tomorrow: PDFs
- On Wednesday: precision as a key to new physics

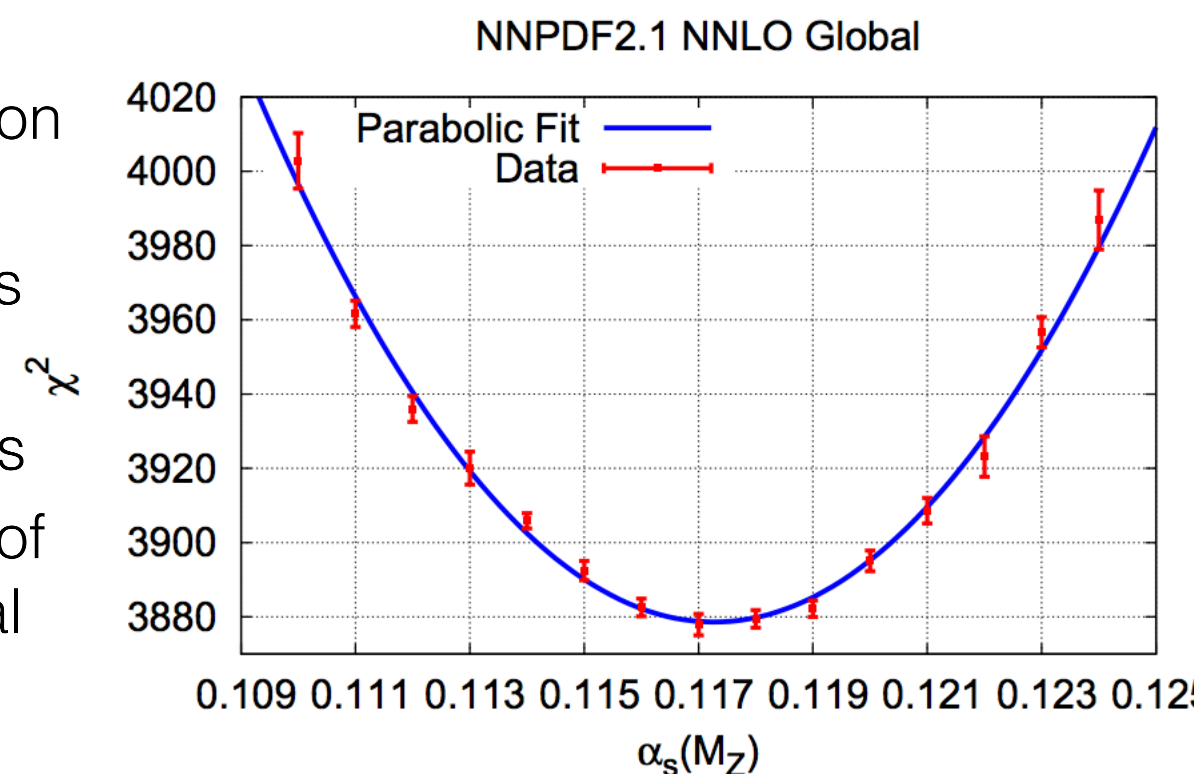
THANK YOU FOR YOUR ATTENTION!

EXTRA MATERIAL

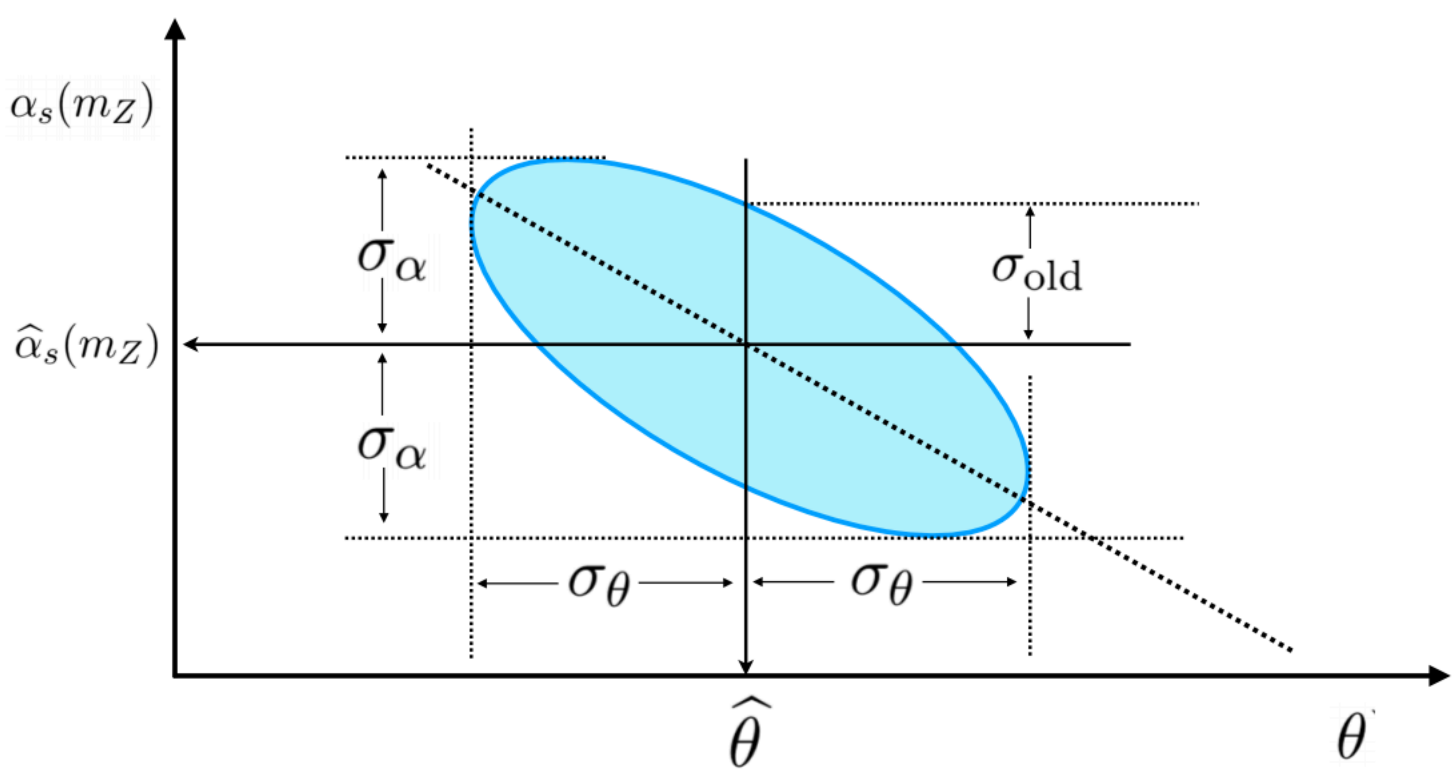
Collider	Site	Initial State	Energy	Discovery / Target
SPEAR (1972)	SLAC	e^+e^-	4 GeV	charm quark, tau lepton
PETRA (1978)	DESY	e^+e^-	38 GeV	gluon
SppS (1981)	CERN	$p\bar{p}$	600 GeV	W, Z bosons
LEP (1989)	CERN	e^+e^-	210 GeV	SM: elw and QCD
SLC (1989)	SLAC	e^+e^-	90 GeV	elw SM
HERA (1992)	DESY	$e\,p$	320 GeV	quark/gluon structure of proton
Tevatron (1987)	FNAL	$p\bar{p}$	2 TeV	top quark
BaBar / Belle (1999)	SLAC / KEK	e^+e^-	10 GeV	quark mix / CP violation
LHC (2010)	CERN	$p\,p$	7/8/14 TeV	Higgs boson, elw. sb, New Physics
RHIC	Brookhaven	pp, pA	200-510 GeV	Heavy ions, polarised beams
EIC	Fermilab	ep, eA	80 GeV	Nuclear, spin structure
ILC/CLIC			> 200 GeV / 3-5 TeV	hi. res of elw sb / Higgs couplings
FCC			100 TeV	disc. multi-TeV physics

THE STRONG COUPLING CONSTANT: A WARNING

- PDFs and α_S strongly correlated (PDF evolution with the scale and hard cross sections)
- Cleanest determinations of α_S from processes that do not require knowledge of the PDFs
- A determination of α_S jointly with the PDFs has advantage that it is driven by the combination of many experimental measurements from several different processes.



Ball et al, 1110.2483



Ball, Carrazza, Del Debbio, Forte, Kassabov, Rojo, Slade, MU 1802.03398

- Early determinations involve a scan over α_S and ignored PDF and α_S correlation in the fit
- Recent simultaneous determination of PDF and α_S using correlated replica method
- Many determination of α_S from analyses of specific LHC processes have been published recently (from tt~, Z and W production, jets)
- How reliable are such partial determination of α_S ?