Theory overview: QCD

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Asymptotic Freedom

50 years of QCD

The Nobel Prize in Physics 2004

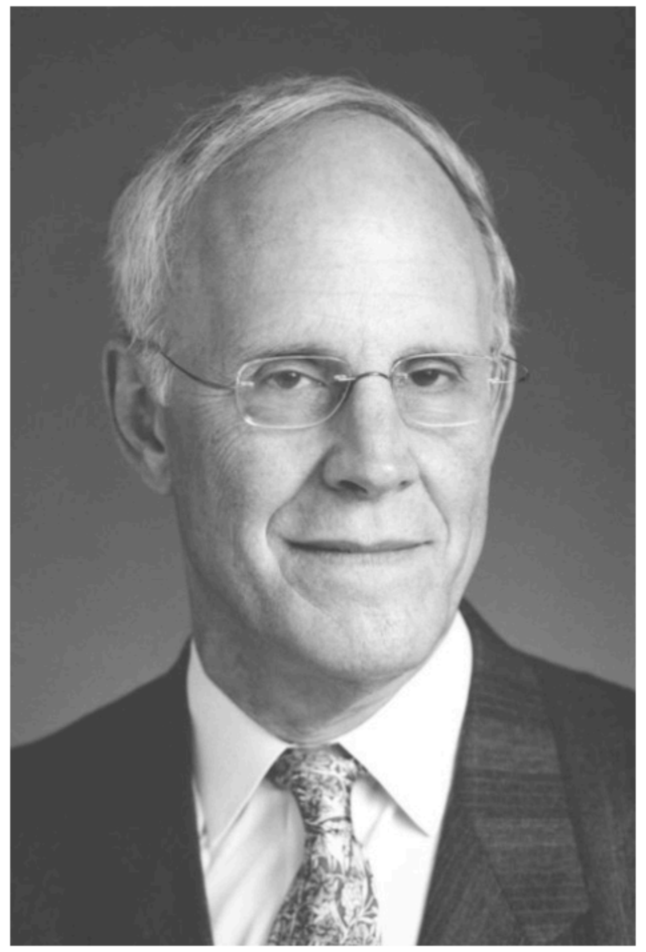


Photo from the Nobel Foundation archive.

David J. Gross

Prize share: 1/3

Photo from the Nobel Foundation archive.

H. David Politzer

Prize share: 1/3

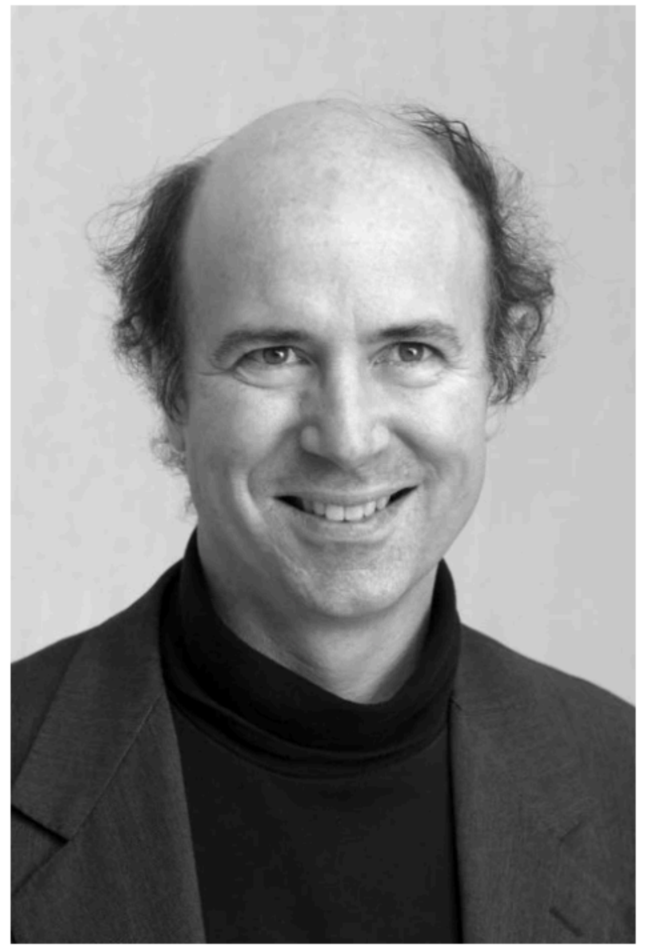


Photo from the Nobel Foundation archive.

Frank Wilczek

Prize share: 1/3

The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek "for the discovery of asymptotic freedom in the theory of the strong interaction"

Asymptotic Freedom

QCD beta function

'73 '74 '80 '97 2016

$$\frac{d\alpha_s}{d\ln\mu^2} = \beta(a_s) = -\alpha_s\left(\frac{\alpha_s}{\pi}\beta_0 + \left(\frac{\alpha_s}{\pi}\right)^2\beta_1 + \left(\frac{\alpha_s}{\pi}\right)^3\beta_2 + \left(\frac{\alpha_s}{\pi}\right)^3\beta_3 + \left(\frac{\alpha_s}{\pi}\right)^4\beta_4 + \cdots\right)$$

$$\beta_0 = \frac{1}{4}\left\{11 - \frac{2}{3}n_f,\right\}, \quad \beta_1 = \frac{1}{4^2}\left\{102 - \frac{38}{3}n_f\right\},$$

$$\beta_2 = \frac{1}{4^3}\left\{\frac{2857}{2} - \frac{5033}{18}n_f + \frac{325}{54}n_f^2\right\},$$

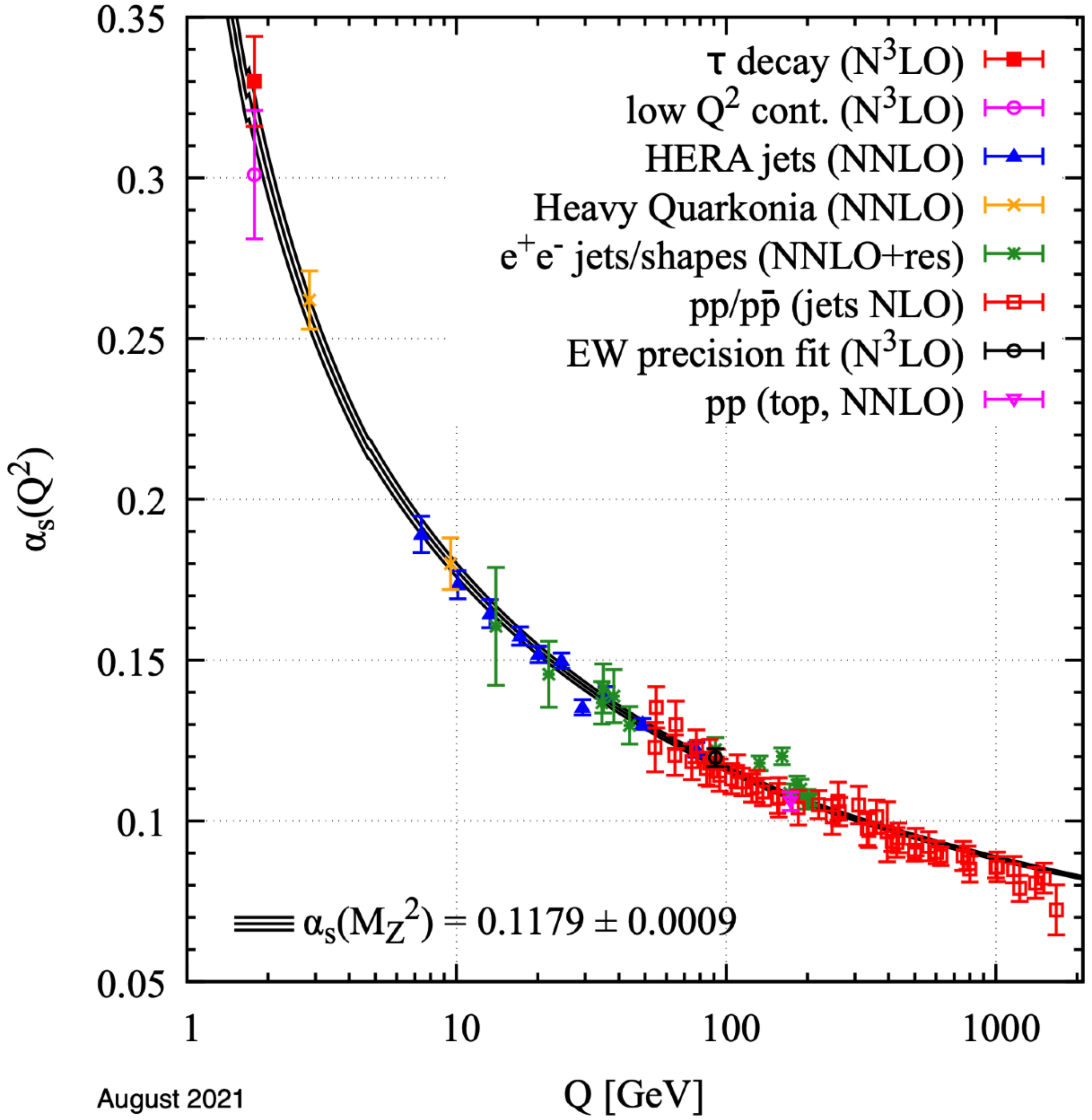
$$\beta_3 = \frac{1}{4^4}\left\{\frac{149753}{6} + 3564\zeta_3 - \left[\frac{1078361}{162} + \frac{6508}{27}\zeta_3\right]n_f + \left[\frac{50065}{162} + \frac{6472}{81}\zeta_3\right]n_f^2 + \frac{1093}{729}n_f^3\right\},$$

$$\beta_4 = \frac{1}{4^5}\left\{\frac{8157455}{16} + \frac{621885}{2}\zeta_3 - \frac{88209}{2}\zeta_4 - 288090\zeta_5 + n_f\left[-\frac{336460813}{1944} - \frac{4811164}{81}\zeta_3 + \frac{33935}{6}\zeta_4 + \frac{1358995}{27}\zeta_5\right] + n_f^2\left[\frac{25960913}{1944} + \frac{698531}{81}\zeta_3 - \frac{10526}{9}\zeta_4 - \frac{381760}{81}\zeta_5\right] + n_f^3\left[-\frac{630559}{5832} - \frac{48722}{243}\zeta_3 + \frac{1618}{27}\zeta_4 + \frac{460}{9}\zeta_5\right] + n_f^4\left[\frac{1205}{2916} - \frac{152}{81}\zeta_3\right]\right\},$$

Baikov, Chetyrkin, Kuhn, 2016

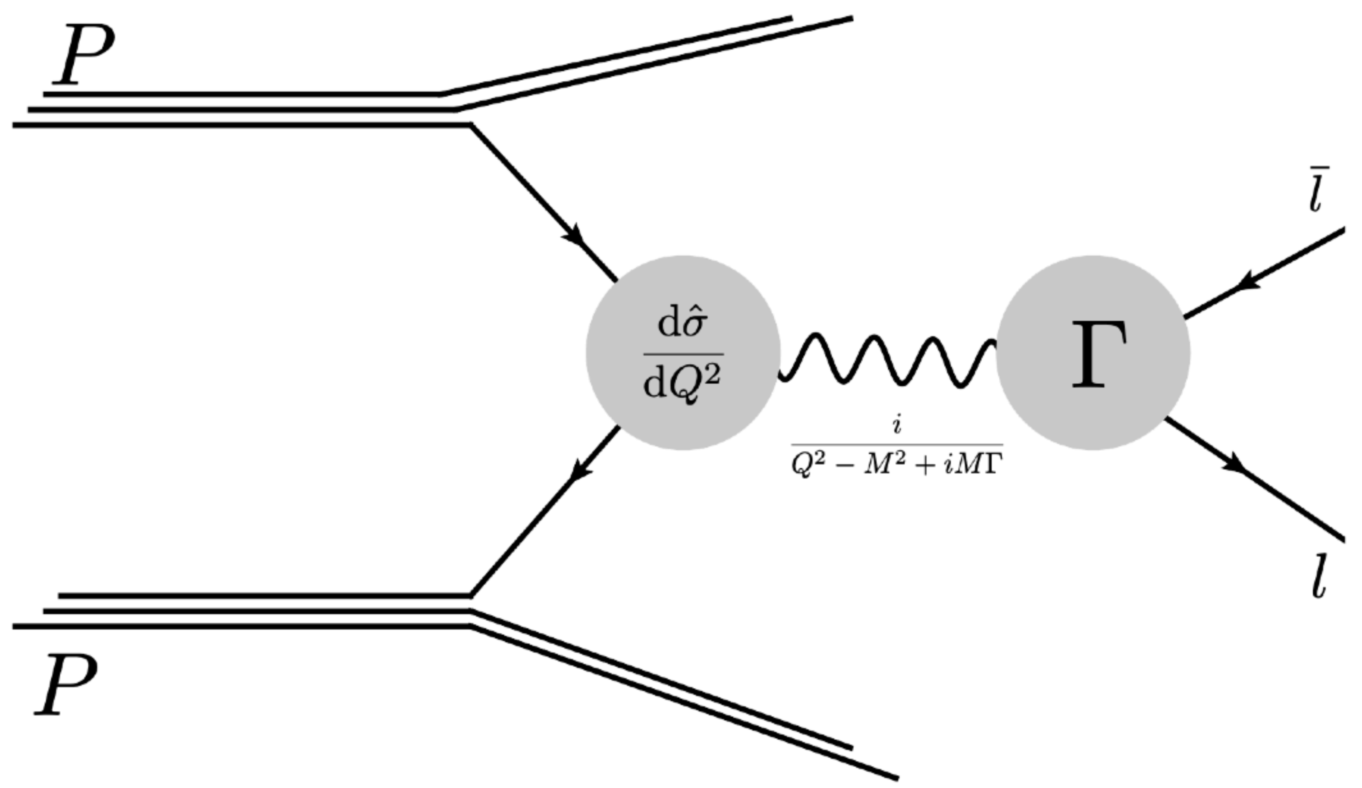
4-loop
5000 Diagrams

5-loop
1.5 Million Diagrams



QCD and LHCp

Factorize the physics associated with different scales



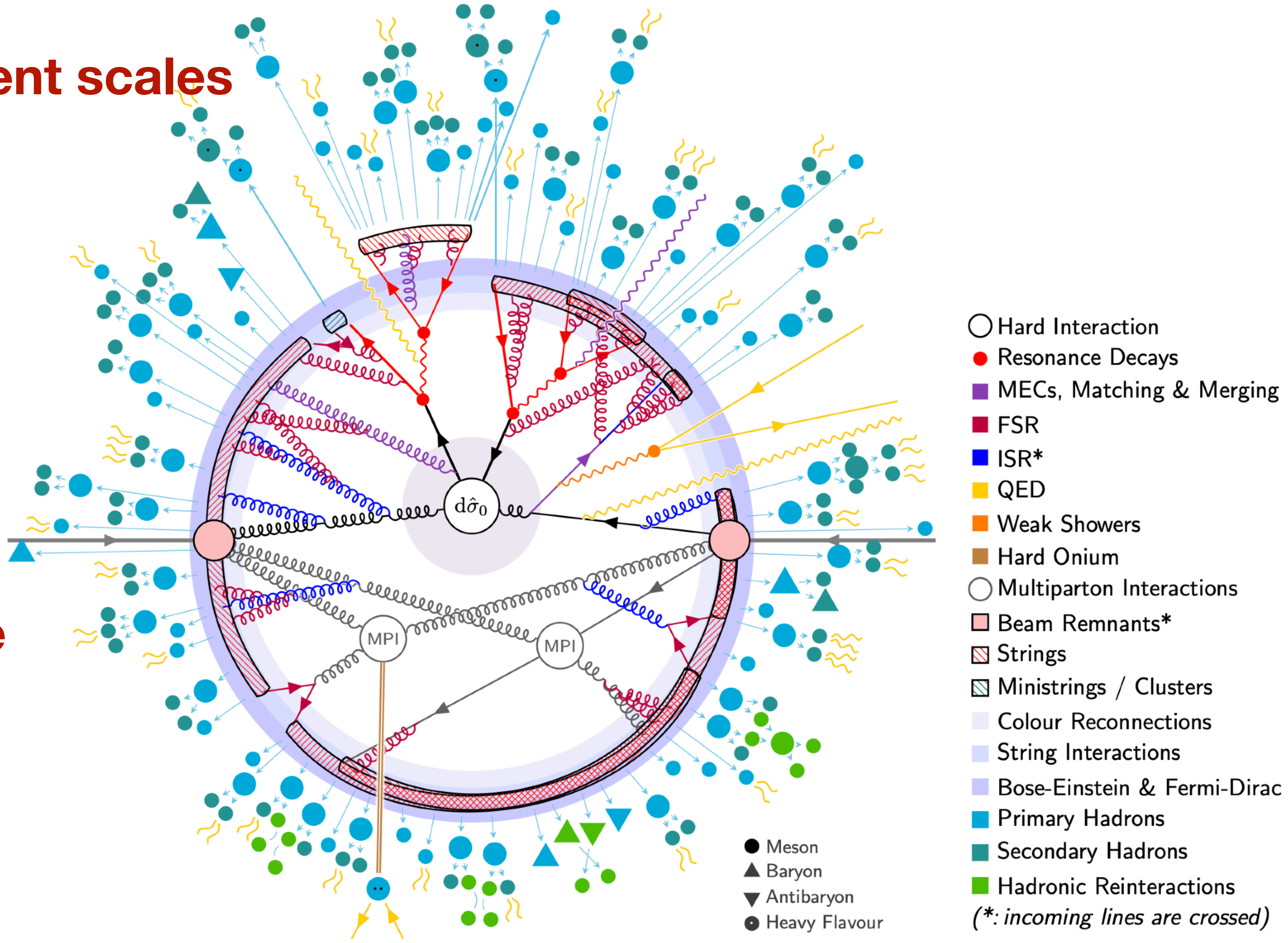


figure taken from PYTHIA 8.3 manual

Hard process: where energy scale is large and perturbative theory works well.

Evolution: Resummation. A bridge.

Hadronization: Non-perturbative

Fixed order

$$\frac{d\sigma}{d\mathcal{O}} = \frac{1}{2s}\sum_{a,b} \boxed{\int \frac{dx_1}{x_1} f_a(x_1) \int \frac{dx_2}{x_2} f_b(x_2)} \int \boxed{\Pi_i \frac{d^3\mathbf{p_i}}{(2\pi)^3 2E_i} (2\pi)^4 \delta\big(p_a + p_b - \sum_i p_i\big) \left|\mathcal{M}(a+b\to\{i\})\right|^2 \delta(\mathcal{O} - O(\{p_i\}))}$$

Theoretical Predictions rely on PDFs and Partonic Cross Section

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Theoretical Predictions rely on **PDFs and** **Partonic Cross Section**

PDFs

Non-Perturbative
Process Independent
CT, MSHT, NNPDF, PDF4LHC et al

reviews: Gao, Harland-Lang Rojo, Phys.Rep. 2018
Snowmass 2021 Whitepaper about PDF, arXiv:2203.13923

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- **NNLO PDFs require 3-loop splitting function**

  hep-ph/0403192, hep-ph/0404111

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To get N3LO PDFs four loop QCD splitting function required

available only for some specific color structures

arXiv:1610.07477, arXiv:1707.08315, arXiv:2307.04158, arXiv:2308.07958, arXiv:2310.01245, arXiv:2310.05744, arXiv:2310.12240

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- **Some Implementation about approximate N3LO PDFs**

  arXiv:2207.04739 (MSHT20aN^{3}LO), arXiv:2306.15294 (NNPDF)

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Theoretical Predictions rely on **PDFs and** **Partonic Cross Section**

Non-Perturbative

reviews: Gao, Harland-Lang Rojo, Phys.Rep. 2018

σ order	PDF order	$\sigma + \Delta\sigma_+ - \Delta\sigma_-$ (pb)	σ (pb) $+ \Delta\sigma_+ - \Delta\sigma_-$ (%)
	PDF uncertainties		
$\mathrm{N^3LO}$	$\mathrm{aN^3LO}$ (no theory unc.)	$4.1150 + 0.0638 - 0.0724$	$4.1150 + 1.55\% - 1.76\%$
	$\mathrm{aN^3LO}$ $(H_{ij} + K_{ij})$	$4.1150 + 0.0682 - 0.0755$	$4.1150 + 1.66\% - 1.83\%$
	$\mathrm{aN^3LO}$ (H'_{ij})	$4.1150 + 0.0678 - 0.0742$	$4.1150 + 1.65\% - 1.80\%$
	NNLO	$3.9941 + 0.0558 - 0.0631$	$3.9941 + 1.40\% - 1.58\%$
NNLO	NNLO	$3.9974 + 0.0557 - 0.0633$	$3.9974 + 1.39\% - 1.58\%$

P

7.04158,
0.05744,

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Theoretical Predictions rely on **PDFs and** **Partonic Cross Section**

Universal

Perturbative but Process Dependent

The hadronic cross section

$$\sigma = \sigma_0 \times \left(1 + \frac{\alpha_s}{4\pi}\kappa_1 + \left(\frac{\alpha_s}{4\pi}\right)^2 \kappa_2 + \left(\frac{\alpha_s}{4\pi}\right)^3 \kappa_3 + \cdots\right)$$

LO **NLO** **NNLO** **N3LO**

NLO QCD corrections: **well studied method with automatic tools**

arXiv:1405.0301

However,

1. **QCD corrections to loop induced process (virtual correction corresponds to 2loop)**
2. **NLO EW corrections**
3. **NLO QCD corrections for BSM**

…

see talks by Dan Zhao and Xiao Zhang

Fixed order

$$\sigma = \sigma_0 \times \left(1 + \frac{\alpha_s}{4\pi}\kappa_1 + \left(\frac{\alpha_s}{4\pi}\right)^2 \kappa_2 + \left(\frac{\alpha_s}{4\pi}\right)^3 \kappa_3 + \cdots\right)$$

LO NLO NNLO N3LO

amplitude → scalar integral → master integral → integral evaluation

Tensor Reduction
PV,
generation function for
reduction coefficients

IBP Reduction:
FIRE, Reduze2, Kira,

differential equation method
AMFLOW
FIESTA
pySecDec
et al

NNLO QCD corrections: { 2-loop virtual

Fixed order

$$\sigma = \sigma_0 \times \left(1 + \frac{\alpha_s}{4\pi}\kappa_1 + \left(\frac{\alpha_s}{4\pi}\right)^2 \kappa_2 + \left(\frac{\alpha_s}{4\pi}\right)^3 \kappa_3 + \cdots\right)$$

LO NLO NNLO N3LO

amplitude → scalar integral → master integral → integral evaluation

NNLO QCD corrections:

- **2-loop virtual**
  - amplitude → scalar integral: Tensor Reduction, PV, generation function for reduction coefficients
  - scalar integral → master integral: IBP Reduction: FIRE, Reduze2, Kira,
  - integral evaluation: differential equation method, AMFLOW, FIESTA, pySecDec, et al
- **virtual real**
  - standard one-loop tools

Fixed order

$$\sigma = \sigma_0 \times \left(1 + \frac{\alpha_s}{4\pi}\kappa_1 + \left(\frac{\alpha_s}{4\pi}\right)^2 \kappa_2 + \left(\frac{\alpha_s}{4\pi}\right)^3 \kappa_3 + \cdots\right)$$

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- **virtual real**
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- **double-real**
  - Antenna, Qt subtraction, N-jettiness, sector decomposition, sector-improved residue subtraction, ColorFul, nested soft-collinear subtraction, Project to Born,

Fixed order

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LO NLO NNLO N3LO

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almost all 2 to 2 processes are done
frontier is 2 to 3, bottleneck 2-loop pentagon diagram

ttbar+H arXiv:2210.07846
three jet arXiv:2301.01086
dijet+photon arXiv2304.06682
ttbar+W arXiv:2306.16311

a fresh look at $q\bar{q} \to Ng$,
arXiv: 2310.17598

Fixed order

Hard interactions

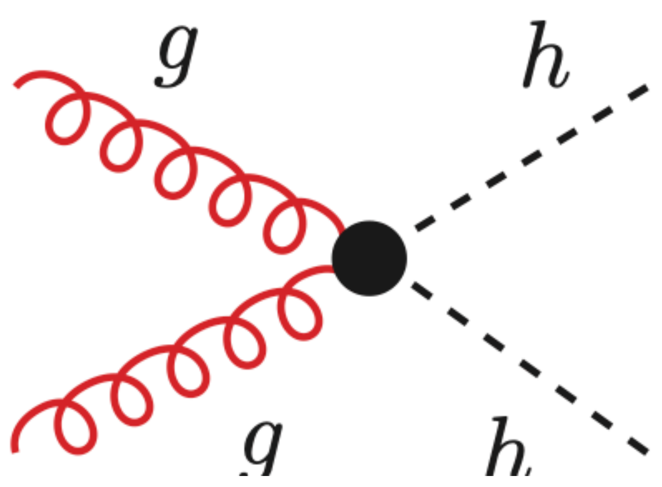
$$\sigma = \sigma_0 \times \left(1 + \frac{\alpha_s}{4\pi}\kappa_1 + \left(\frac{\alpha_s}{4\pi}\right)^2 \kappa_2 + \left(\frac{\alpha_s}{4\pi}\right)^3 \kappa_3 + \cdots\right)$$

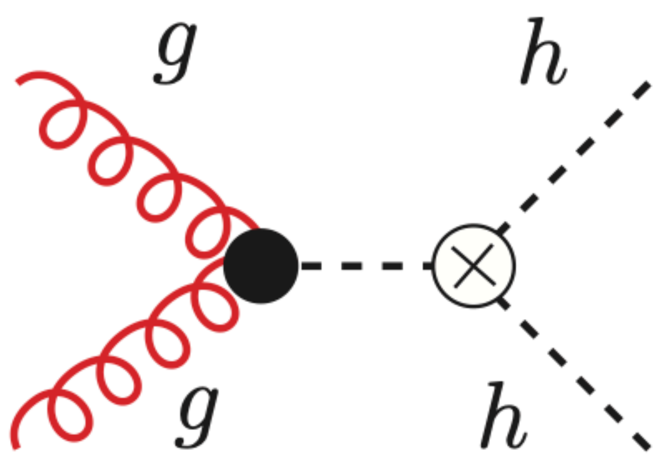
LO NLO NNNLO N3LO

NNNLO QCD corrections:

gg2H	inclusive ’15, differential ’21
ff2H	inclusive ’19, differential ’23
DY	inclusive ’20, differential 22
WH	Baglio, Duhr, Mistlberger, Szafron, 2022
HH	Chen, HTL, et al, 2019
Hjj (VBF)	Dreyer, Karlberg, 2016
HHjj(VBF)	Dreyer, Karlberg, 2018
$e^+e^- \to t\bar{t}$	Chen, Guan, He, Liu, Ma
…	…

Fixed order





Chen, HTL, Shao, Wang, PLB and JHEP, 2020

Developments in Effective theory

- **LO**
- **NLO** arXiv: hep-ph/9805244
- **NNLO** arXiv:1305.5206., arXiv:1309.6594, arXiv: 1408.2422, arXiv:1606.09519
- **NNNLO**

Our works: arXiv:1909.06808, arXiv:1912.13001

- **NNLL+(N)NLO**

D.Y.Shao, C.S.Li, HTL, J.Wang, arXiv:1301.1245 arXiv:1505.07122, arXiv: 1807.03704

Developments in Full theory

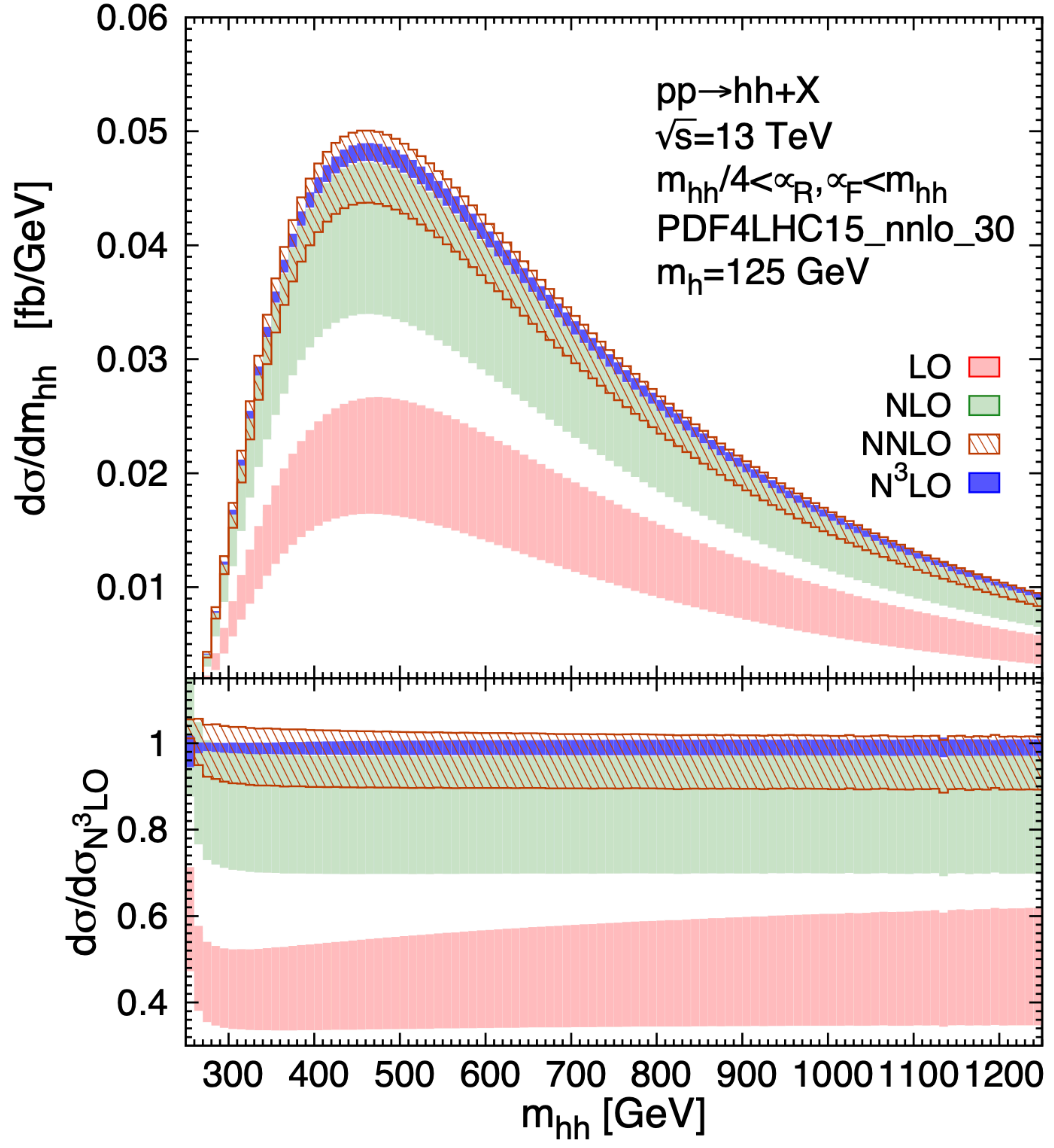
- **LO** PLB 197 (1987) 269, NPB 309 (1988) 282, arXiv:hep-ph/9603205
- **NLO** arXiv: 1604.06447, arXiv:1608.04798, arXiv:1811.05692, arXiv:1907.06408
- **PS+NLO** arXiv:1703.09252, arXiv:1711.03319, arXiv:1903.08137
- **NLL+NLO q_T** arXiv:1609.01691
- ....

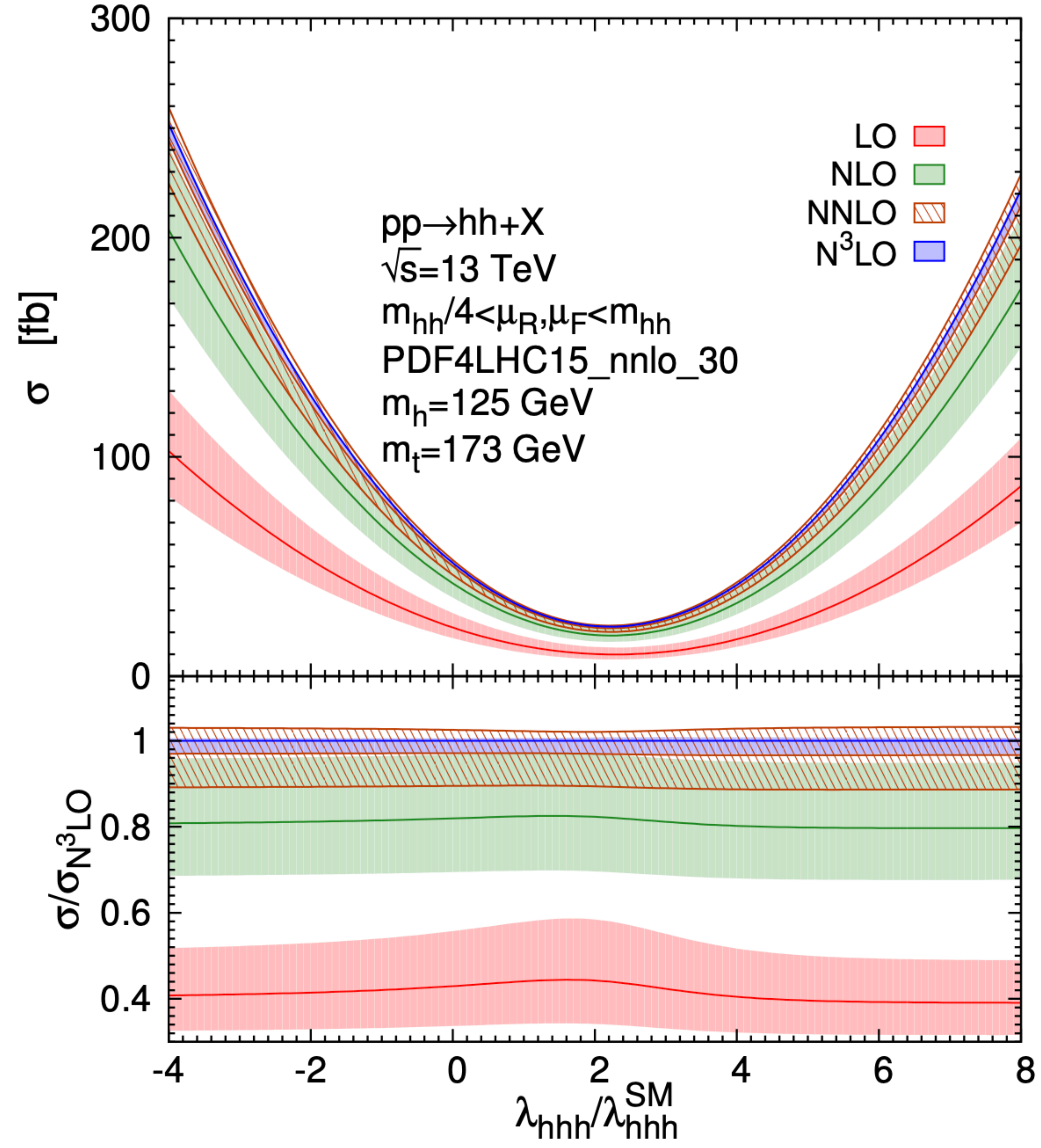
$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
LO	$13.80^{+31\%}_{-22\%}$	$17.06^{+31\%}_{-22\%}$	$98.22^{+26\%}_{-19\%}$	$2015^{+19\%}_{-15\%}$
NLO	$25.81^{+18\%}_{-15\%}$	$31.89^{+18\%}_{-15\%}$	$183.0^{+16\%}_{-14\%}$	$3724^{+13\%}_{-11\%}$
NNLO	$30.41^{+5.3\%}_{-7.8\%}$	$37.55^{+5.2\%}_{-7.6\%}$	$214.2^{+4.8\%}_{-6.7\%}$	$4322^{+4.2\%}_{-5.3\%}$
N^{3}LO	$31.31^{+0.66\%}_{-2.8\%}$	$38.65^{+0.65\%}_{-2.7\%}$	$220.2^{+0.53\%}_{-2.4\%}$	$4439^{+0.51\%}_{-1.8\%}$

- ❑ the QCD corrections are very prominent
- ❑ NLO QCD corrections are around 87%
- ❑ NNLO QCD corrections are around 18%
- ❑ N3LO QCD corrections are around 3%
- ❑ N3LO scale uncertainties are less than 3%

Fixed order

$\sqrt{s}$
LO
NLO
NNLO
N^3LO





Full theory

269,
282,
03205

Xiv:1608.04798,
iv:1907.06408

arXiv:1711.03319,

Xiv:1609.01691

ominent

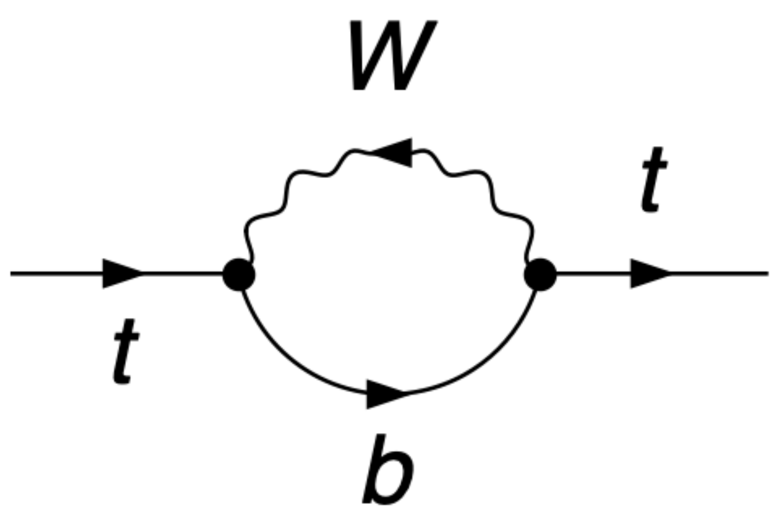
d 87%

nd 18%

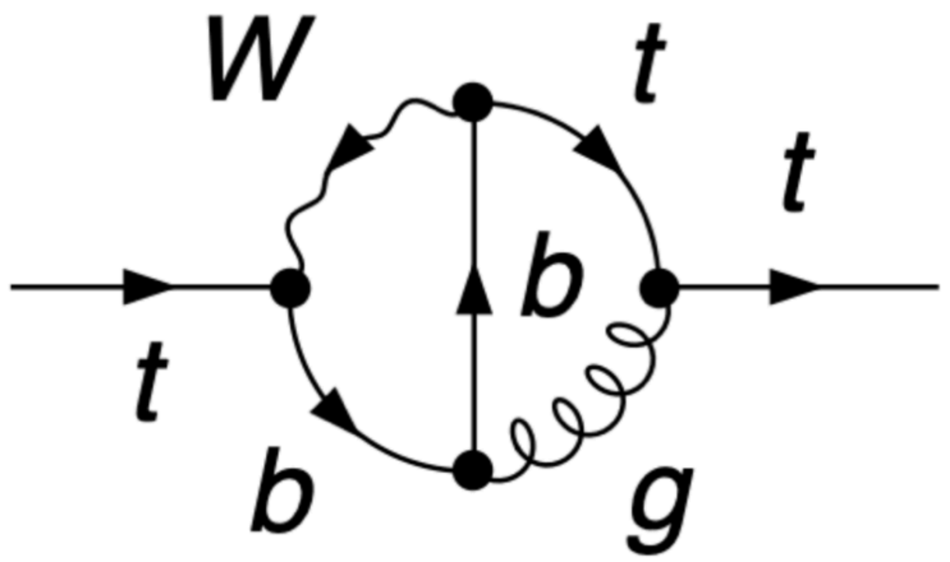
nd 3%

ss than 3%

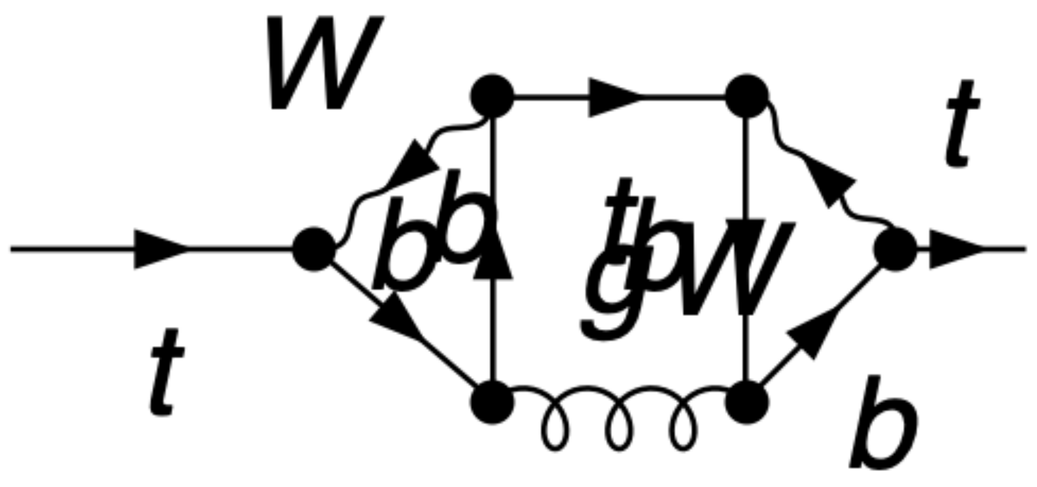
Fixed order



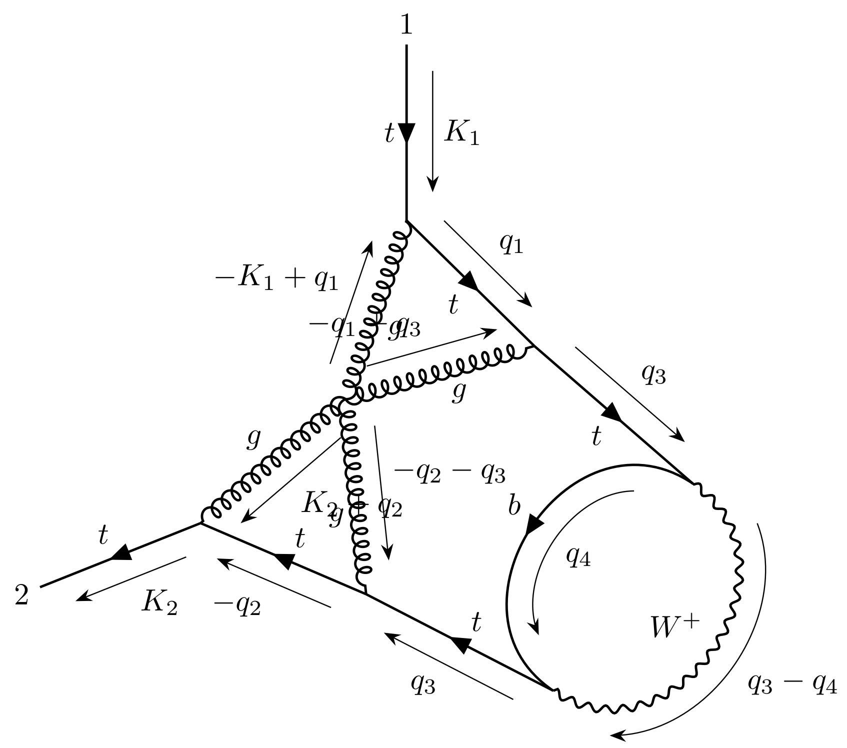
1-loop, LO



2-loop, NLO

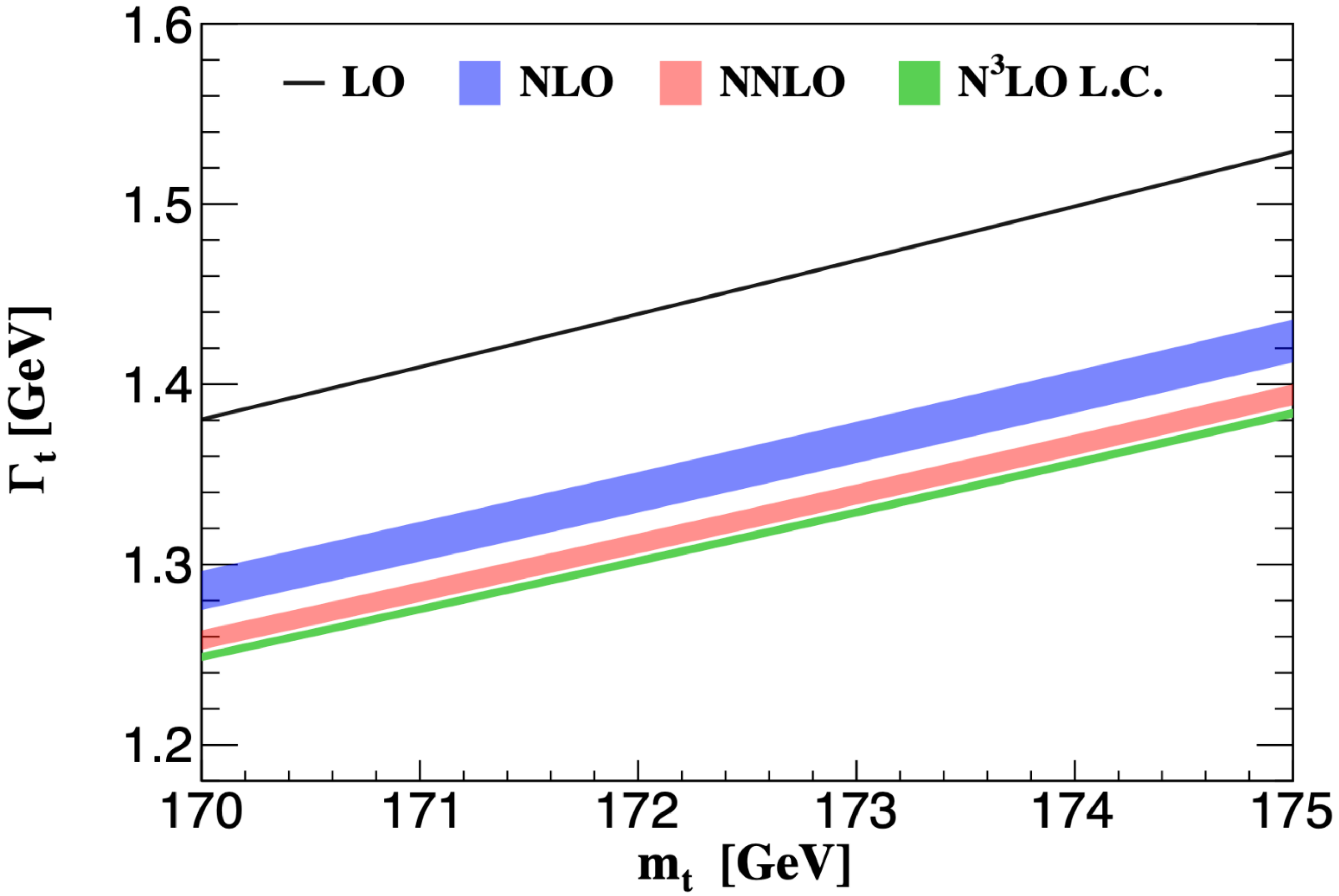


3-loop, NNLO



4-loop, NNNLO

$$\Gamma_t = \Gamma_0 \left[X_0 + \frac{\alpha_s}{\pi} X_1 + \left(\frac{\alpha_s}{\pi}\right)^2 X_2 + \left(\frac{\alpha_s}{\pi}\right)^3 X_3 \right]$$



NLO: Bigi, Dokshitzer, Khoze, Kuhn,Zerwas, 1986, Jezabek, Kuhn 1989, Czarnecki 1990, Li, Oakes, Yuan 1991

NNLO: Gao, Li, Zhu 2013, Brucherseifer, Caola, Melnikov 2013

Chen, HTL, Wang, Wang, PRD, arXiv:2212.06341

Chen, HTL, Li, Wang, Wang, Wu, arXiv 2309.00762

Chen, Chen, Guan, Ma, arXiv:2309.0193

see the talks by Long Chen and YeFan Wang

Resummation

At leading power, generally the cross section can be factorized into

$$d\sigma = \boxed{H} \otimes \boxed{B_1 \otimes B_2} \otimes \boxed{J_1 \otimes J_2} \otimes \boxed{S}$$

hard function

happens at high scale

beam function

initial state collinear radiation

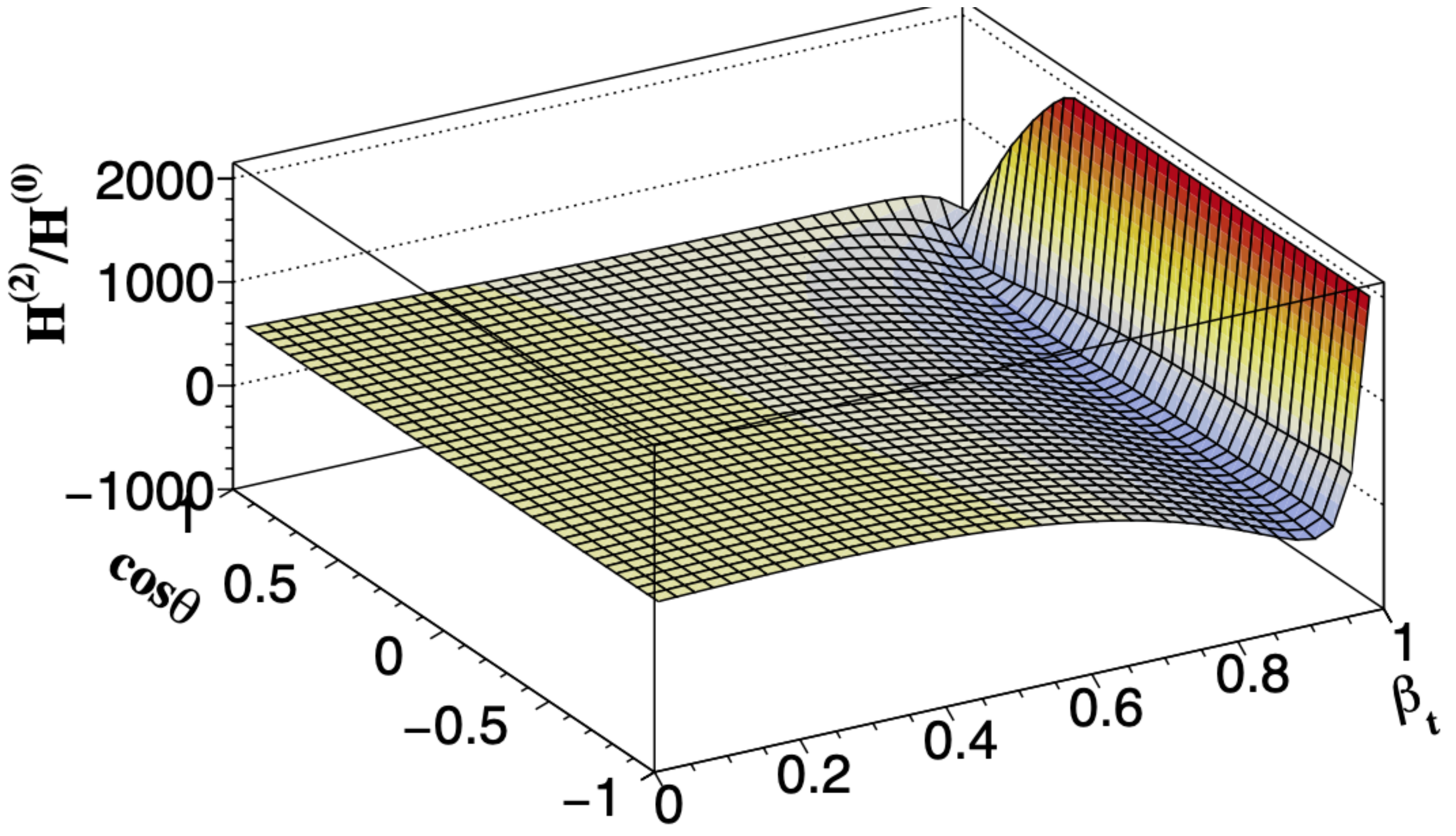
Jet function

final state collinear radiation

soft radiation

Hard function

2-loop hard function for tW,
Chen, Dong, HTL, Li, Wang, Wang, JHEP 2022



3-loop and 4-loop calculation about the form factors

3-loop anomalous dimensions

$$\begin{aligned}
\boldsymbol{\Gamma}(\{\underline{p}\},\{\underline{m}\},\mu) = & \sum_{(i,j)} \frac{\boldsymbol{T}_i \cdot \boldsymbol{T}_j}{2} \gamma_{\text{cusp}}(\alpha_s) \ln \frac{\mu^2}{-s_{ij}} + \sum_{I,j} \boldsymbol{T}_I \cdot \boldsymbol{T}_j \gamma_{\text{cusp}}(\alpha_s) \ln \frac{m_I \mu}{-s_{Ij}} - \sum_{(I,J)} \frac{\boldsymbol{T}_I \cdot \boldsymbol{T}_J}{2} \gamma_{\text{cusp}}(\beta_{IJ}, \alpha_s) \\
& + \sum_i \gamma^i(\alpha_s) \mathbf{1} + \sum_I \gamma^I(\alpha_s) \mathbf{1} + f(\alpha_s) \sum_{(i,j,k)} \mathcal{T}_{iijk} + \sum_{(i,j,k,l)} \mathcal{T}_{ijkl} F_4(\beta_{ijkl}, \beta_{ijkl} - 2\beta_{ilkj}, \alpha_s) \\
& + \sum_I \sum_{(i,j)} \mathcal{T}_{ijII} F_{\text{h2}}(r_{ijI}, \alpha_s) + \sum_I \sum_{(i,j,k)} \mathcal{T}_{ijkI} F_{\text{h3}}(r_{ijI}, r_{ikI}, r_{jkI}, \alpha_s) \\
& + [\text{ non-dipole contributions involving two or more massive partons}] + \mathcal{O}(\alpha_s^4)
\end{aligned}$$

One Massive Parton, Liu, Schalch, PRL, 2022

Resummation

At leading power, generally the cross section can be factorized into

$$d\sigma = H \otimes B_1 \otimes B_2 \otimes J_1 \otimes J_2 \otimes S$$

hard function	beam function	Jet function	soft radiation
happens at high scale	initial state collinear radiation	final state collinear radiation	

Beam, soft and jet functions are process independent

3-loop TMD beam function (TMDPDFs) Luo, Yang et al PRL, 2020
Elbert, Mistlberger, Vita, JHEP, 2019

3-loop n-jettiness beam function
Elbert, Mistlberger, Vita, JHEP, 2020
Baranowski et al, JHEP, 2023

4-loop Rapidity Anomalous Dimension, Moult, Zhu, Zhu, JHEP, 2020, Duhr, Mistlberger, Vita, JHEP, 2020

2-loop soft function for Jet veto, Abreu, Gaunt, Monni, Szafron, JHEP, 2022
2-loop beam for Jet veto, Bell, Brune, Das, Wald, JHEP, 2023, Abreu, Gaunt, Monni, Szafron, JHEP 2023

Resummation

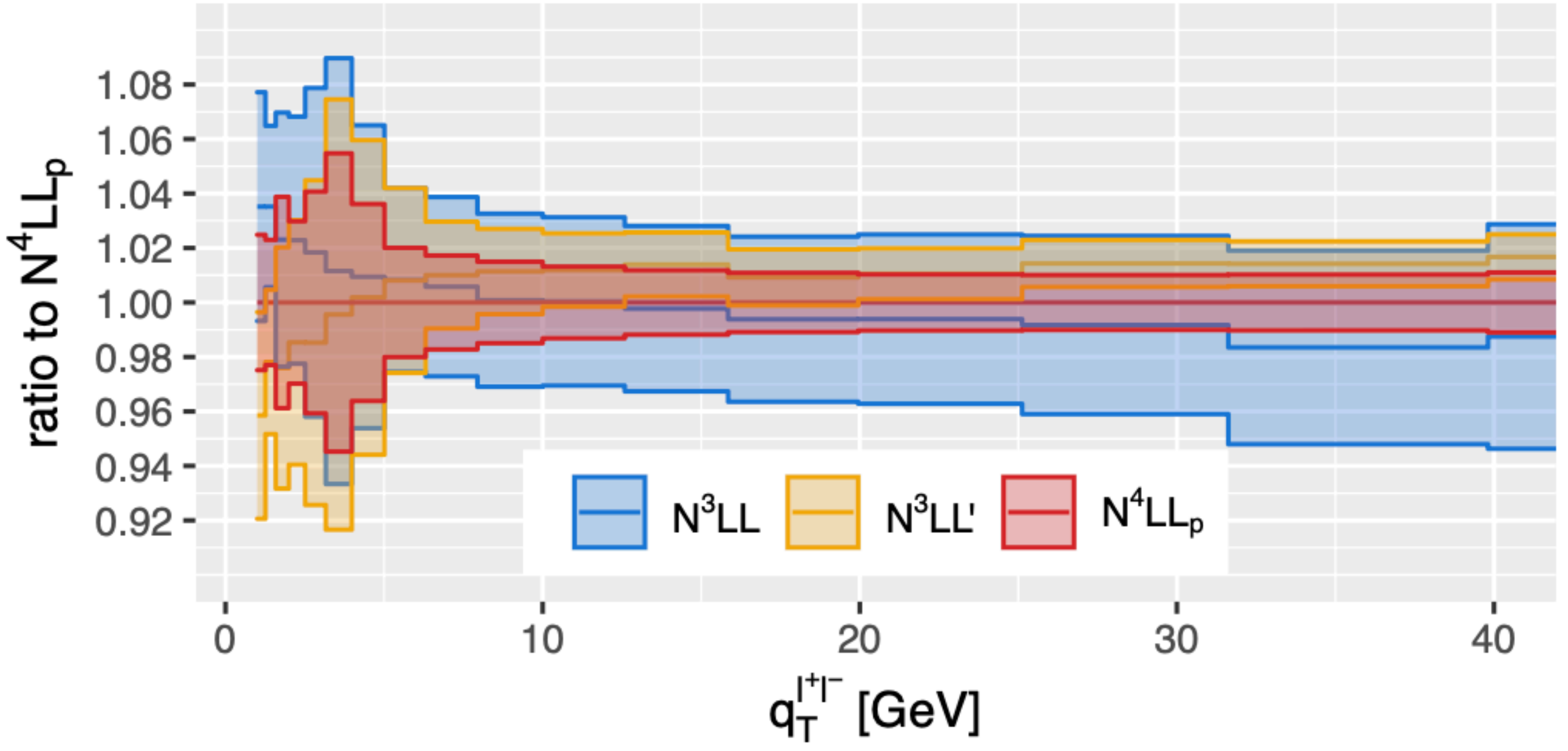
$$d\sigma = H \quad \otimes \quad B_1 \otimes B_2 \quad \otimes \quad J_1 \otimes J_2 \quad \otimes \quad S$$

Large logs can be resummed by solving the RG equations of different functions

Drell-Yan q_T resummation at N4LL or N3LL

Camarda, Cieri, Ferrera, 2023
Neumann, Campbell, PRD 2023,

Order	Boundary conditions	Anomalous dimensions γ_i (noncusp)	Anomalous dimensions $\Gamma_{\text{cusp}}, \beta$	FO matching (nonsingular)
LL	1	-	1-loop	-
NLL	1	1-loop	2-loop	-
NLL$'$ (+NLO)	α_s	1-loop	2-loop	α_s
NNLL (+NLO)	α_s	2-loop	3-loop	α_s
NNLL$'$ (+NNLO)	α_s^2	2-loop	3-loop	α_s^2
N^{3}LL (+NNLO)	α_s^2	3-loop	4-loop	α_s^2
N^{3}LL$'$ (+N^{3}LO)	α_s^3	3-loop	4-loop	α_s^3
N^{4}LL (+N^{3}LO)	α_s^3	4-loop	5-loop	α_s^3

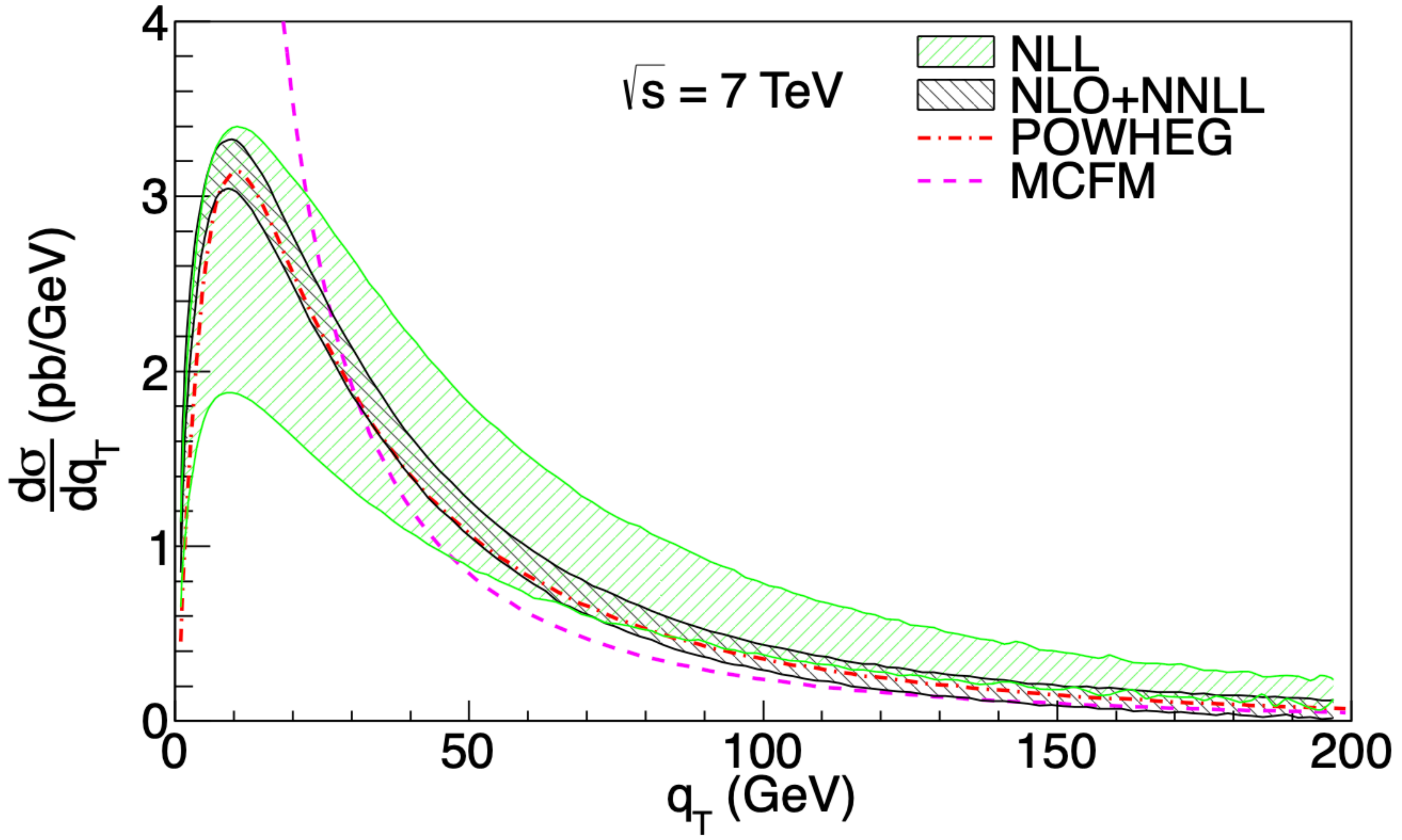


See Y. Fu's talk about this topic

Resummation

TMD resummation for top quark pair production

Zhu, Li, HTL, Shao, Yang, PRL and PRD, 2013



TEEC for dijet production at hadron collide.

$$\mathrm{TEEC} = \sum_{a,b} \int d\sigma_{pp\to a+b+X} \frac{2E_{T,a}E_{T,b}}{|\sum_i E_{T,i}|^2} \delta(\cos\phi_{ab} - \cos\phi)$$

Gao, HTL, Moult, Zhu, PRL, 2019

For TEEC/EEC observable to DIS process

HTL, Vitev, Zhu, JHEP, 2020

$$\mathrm{TEEC} = \sum_{a} \int d\sigma_{lp\to l+a+X} \frac{E_{T,l}E_{T,a}}{E_{T,l}\sum_i E_{T,i}} \delta(\cos\phi_{la} - \cos\phi)$$

HTL, Makris, Vitev, PRD, 2021

$$\mathrm{EEC} = \sum_{a} \int d\sigma_{lp\to l+a+X} \left(\frac{p\cdot p_a}{\sum_i p\cdot p_i}\right) \delta(\cos\chi - \cos\theta_{ap})$$

Resummation with Parton Shower

Parton shower accuracy is critical at the LHC

- the interpretation of data
- data analysis with machine-learning

Showers resum NLL resummation or beyond, and spin correlations

Many PanScales papers, arXiv:2305.08645, PanScales for DIS
Ravasio, Hamilton et al PRL, 2023, double soft emission can be included by veto algorithms

$$P_{\text{accept}} = \frac{|M_{\text{DS}}|^2}{\sum_h |M_{\text{shower},h}|^2}$$

Nagy, Soper, PRD, 2021, Dedector, how parton shower sums large logarithms
Herren, Hoche et al, JHEP, 2023, Alaric, new approach for parton shower
Assi, Hoche, 2023, Alaric for massive partons

Matching with fixed order calculations **combine resummation with hard emission**

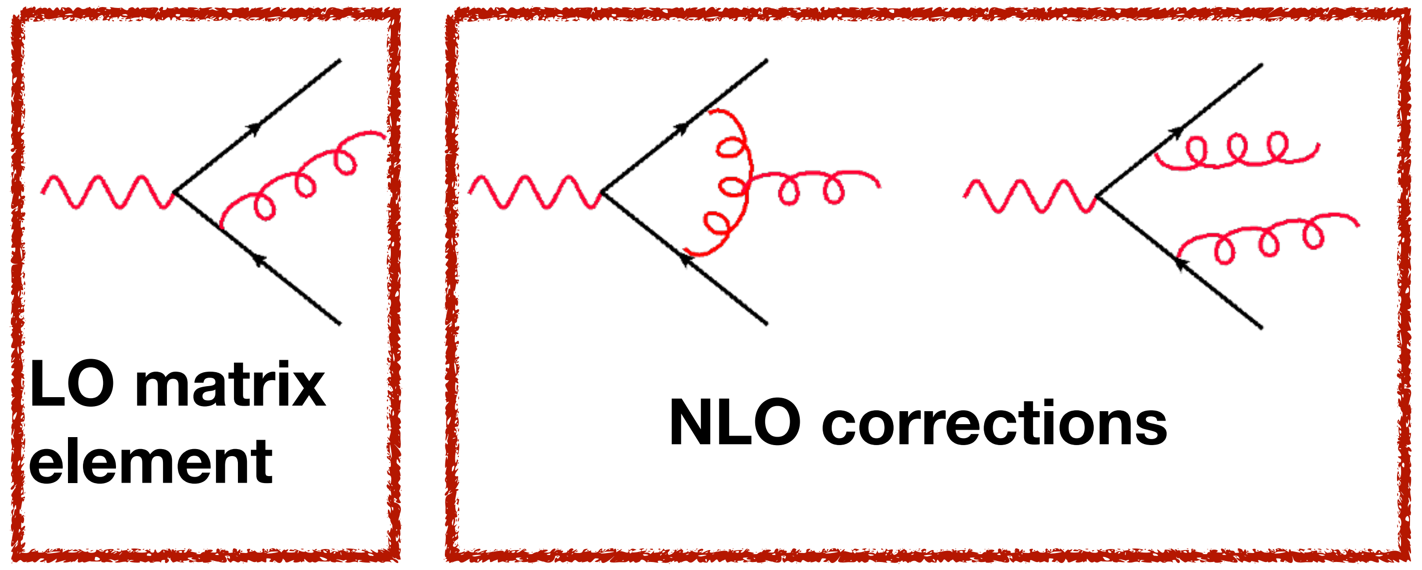
Mi

Method developed: UNLOPS, NNLOPS, Geneva, MiNNLOPS

NNLO+PS done for most of 2to2 process, but no light jet final state yet

Resummation with Parton Shower

In order to fully cover the phase space and reproduce the singularity at NNLO level, we need to have $2 \to 3$ and $2 \to 4$ showers

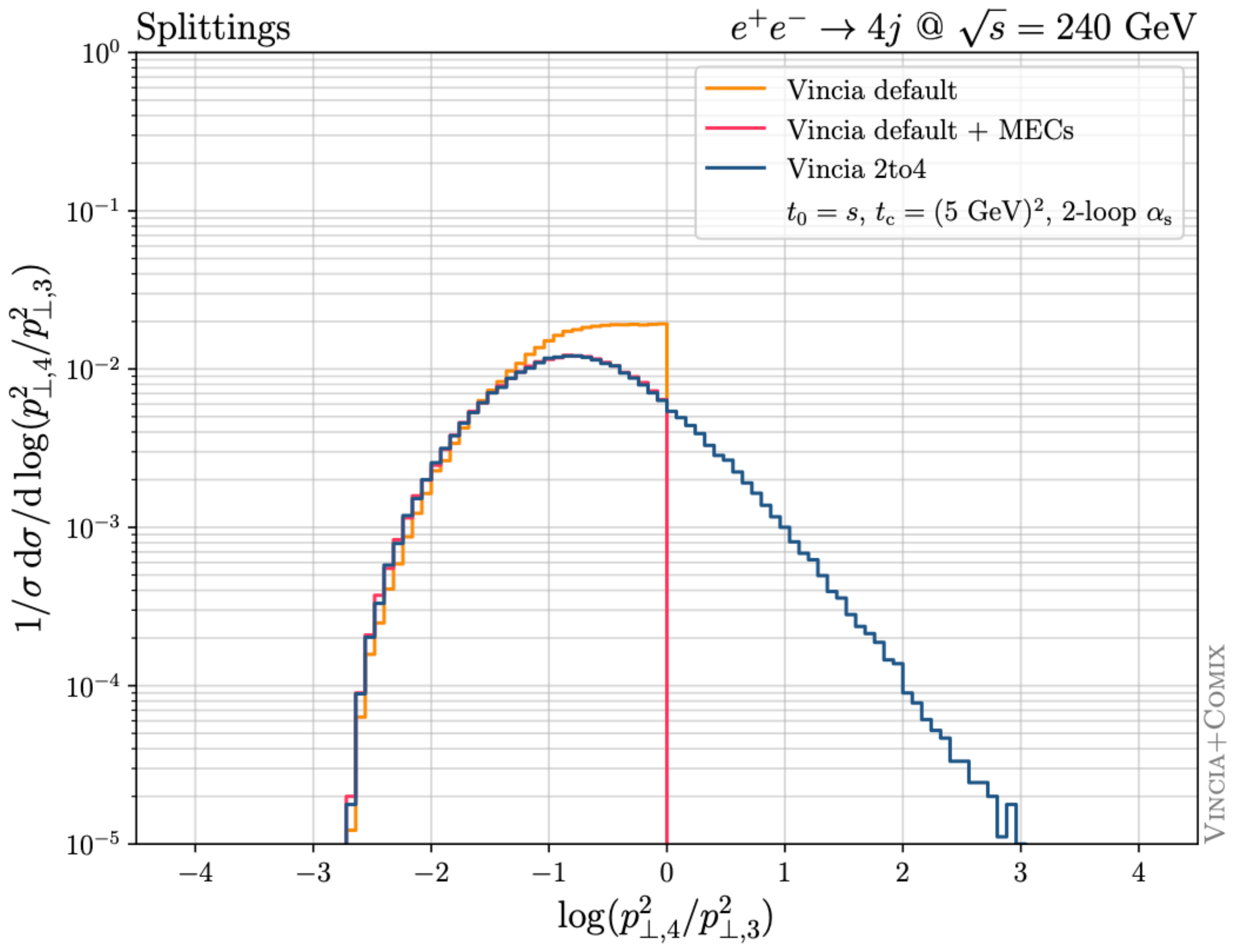


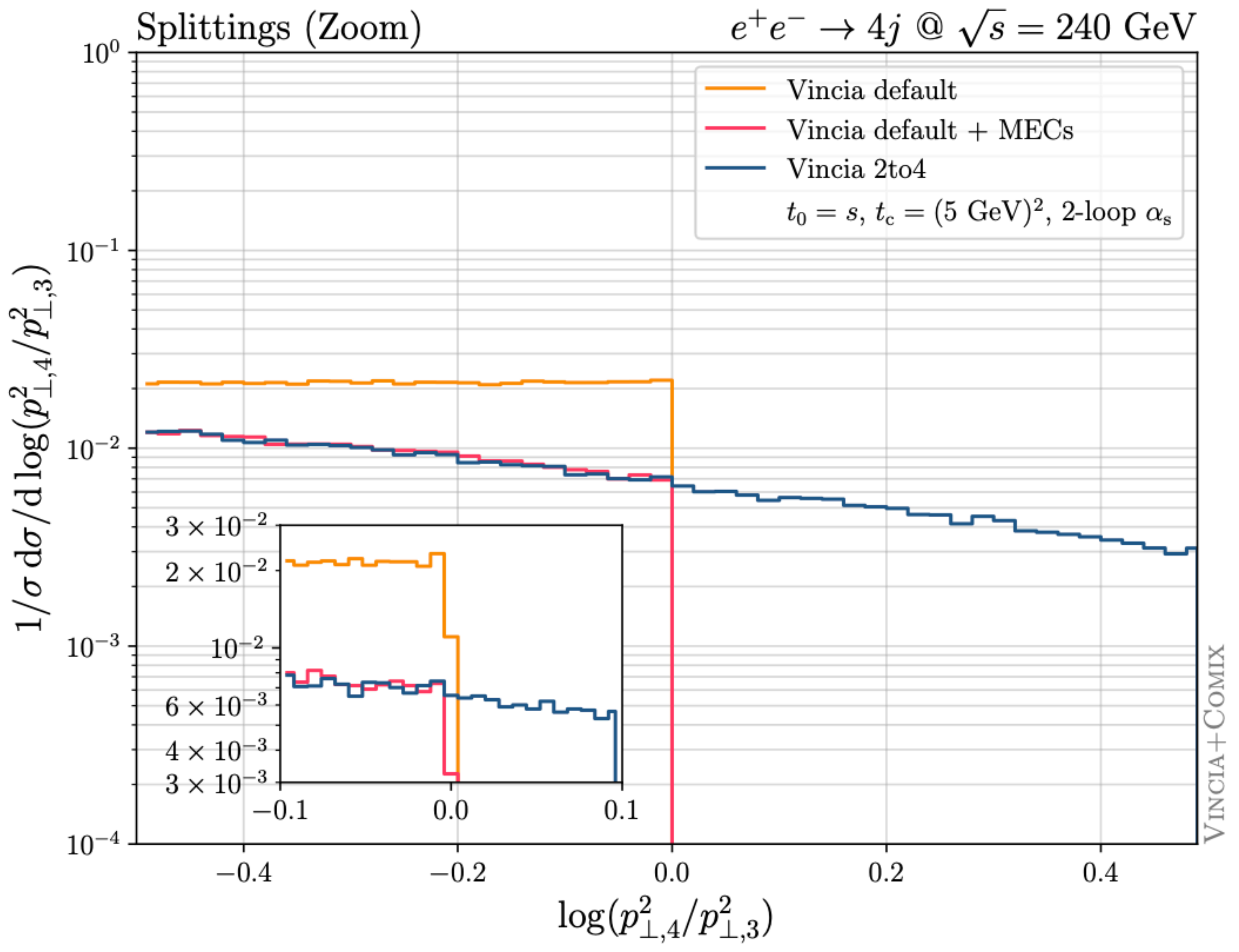
3 parton final state 3+4 parton final state

HTL, Skands, PLB, 2017

match final-state parton showers fully-differentially to NNLO calculations

Compbel, Hoech, HTL, Preuss, Skands, PLB, 2023





Jet

Jet Physics and it's applications

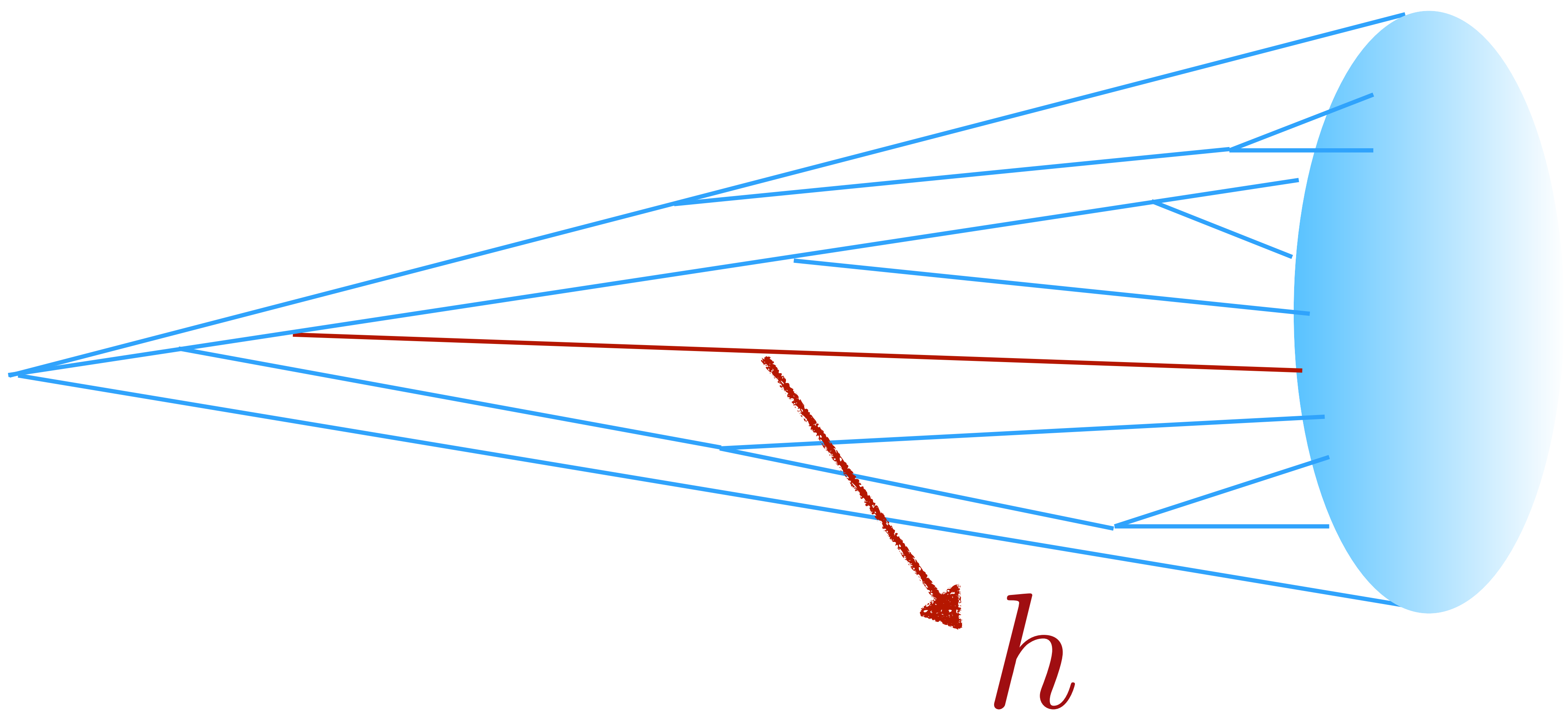
Object to study perturbative and nonperturbative QCD

Production of jets: automatical NLO generator, arXiv:2305.14620

talk by C.Y. Liu

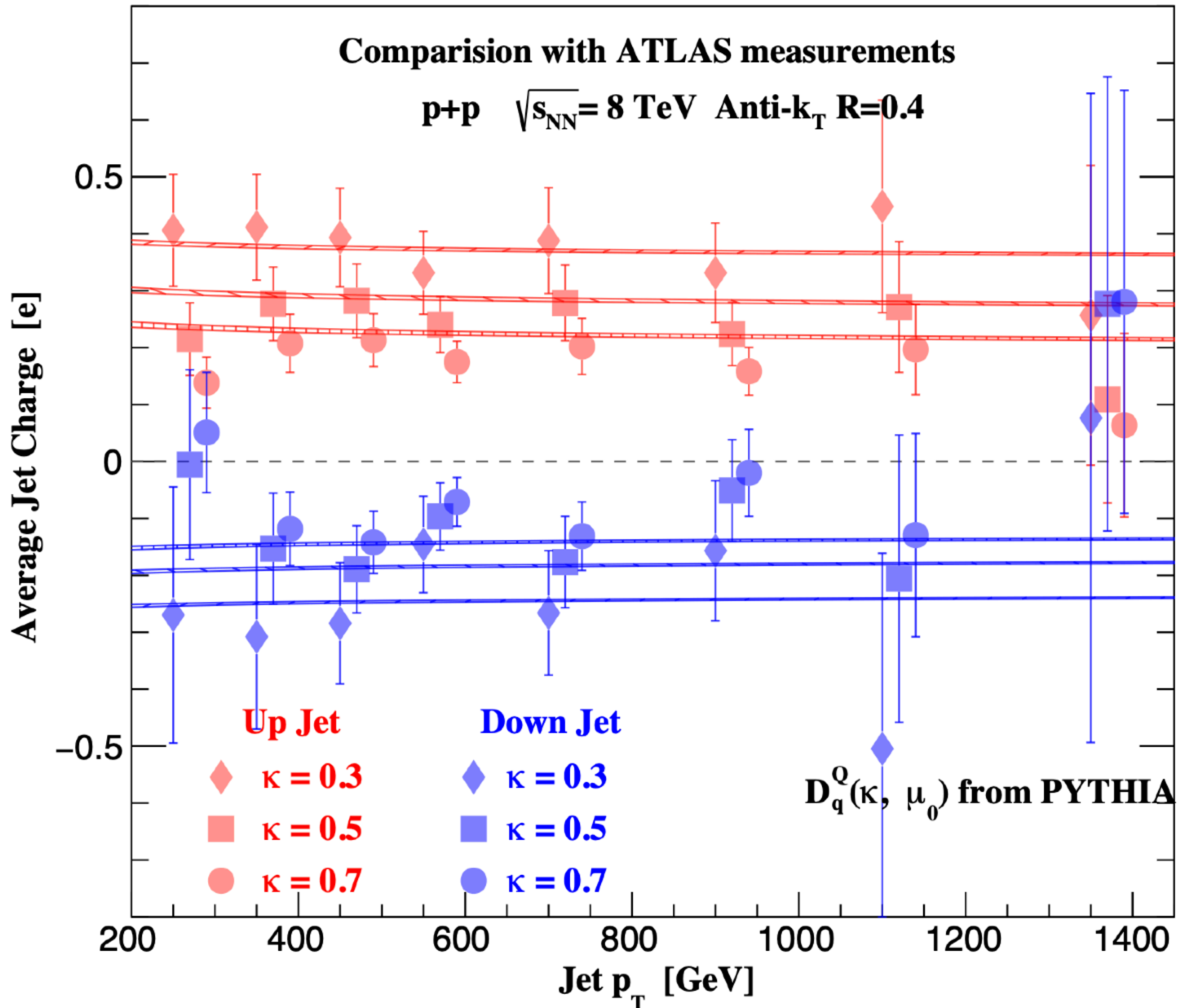
Resummation of Non-Global logs

talk by D.Y. Shao



Jet Property: groomed angle or momentum fraction, mass, angularity, jet fragmentation function, et al

about jet charge and its applications
HTL, Vitev, PRD, 2020
HTL, Vitev, PRL, 2021
HTL, Yan, Yuan, PLB, 2022
HTL, Yan, Yuan, PRL, 2023

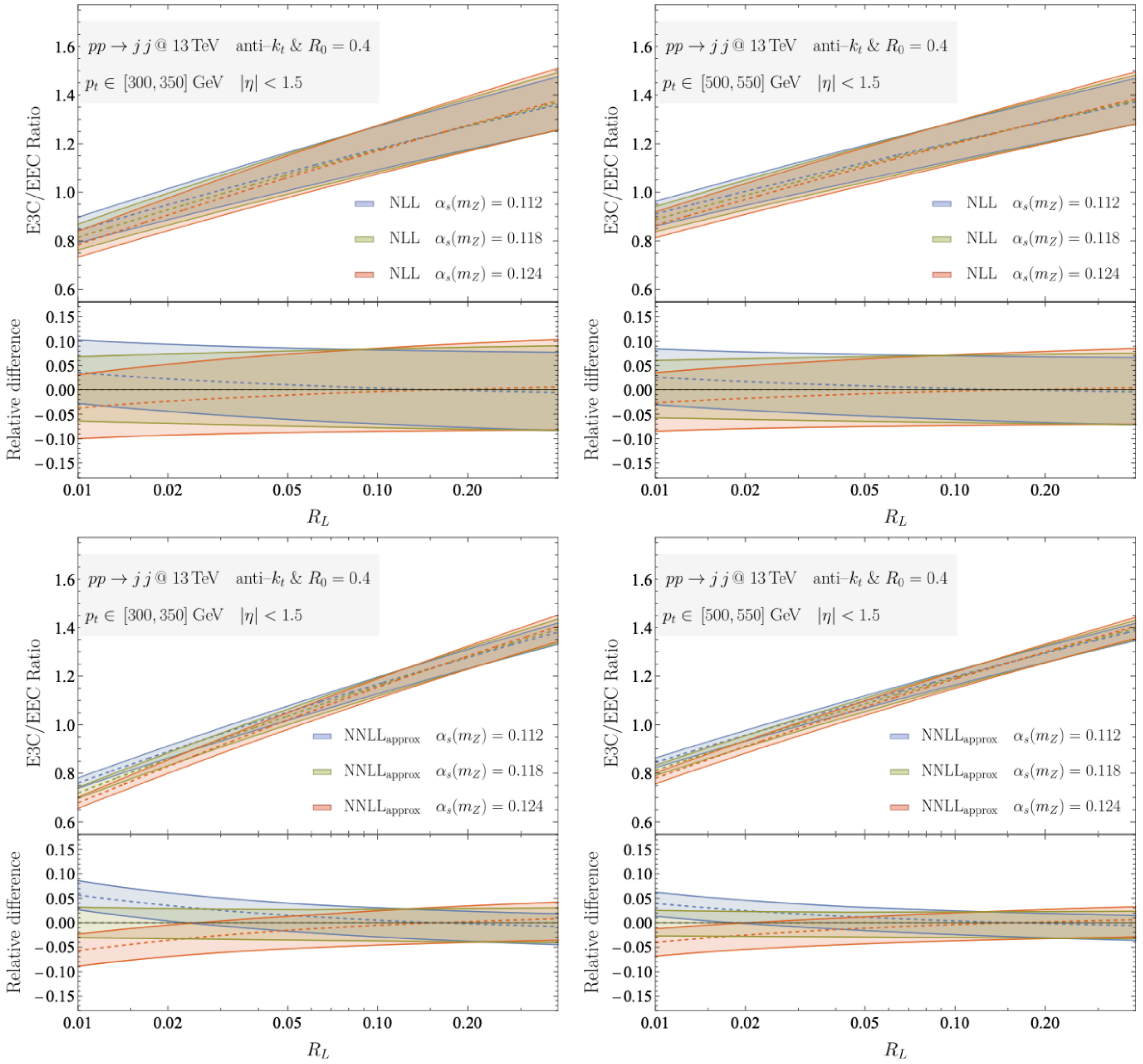


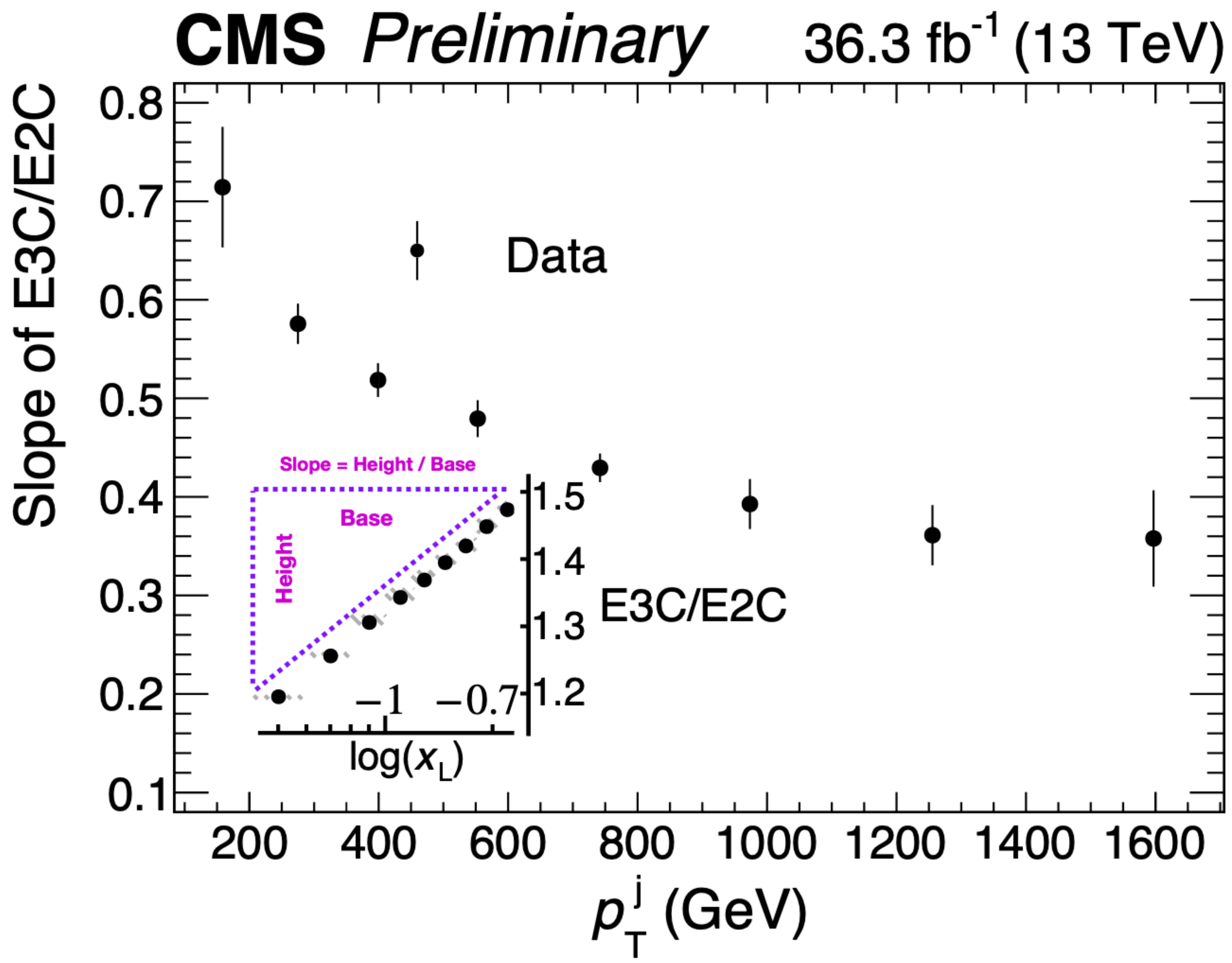
Jet

Jet Physics and it's applications   Energy Correlators

$$\frac{d\sigma^{[N]}}{dx_L} \equiv \sum_n \sum_{1\leq i_1,\cdots i_N \leq n} \int d\sigma \frac{\prod_{a=1}^{N} E_{i_a}}{Q^N} \delta\left(x_L - \max\left\{x_{i_1,i_2}, x_{i_1,i_3}, \cdots x_{i_{N-1},i_N}\right\}\right)$$

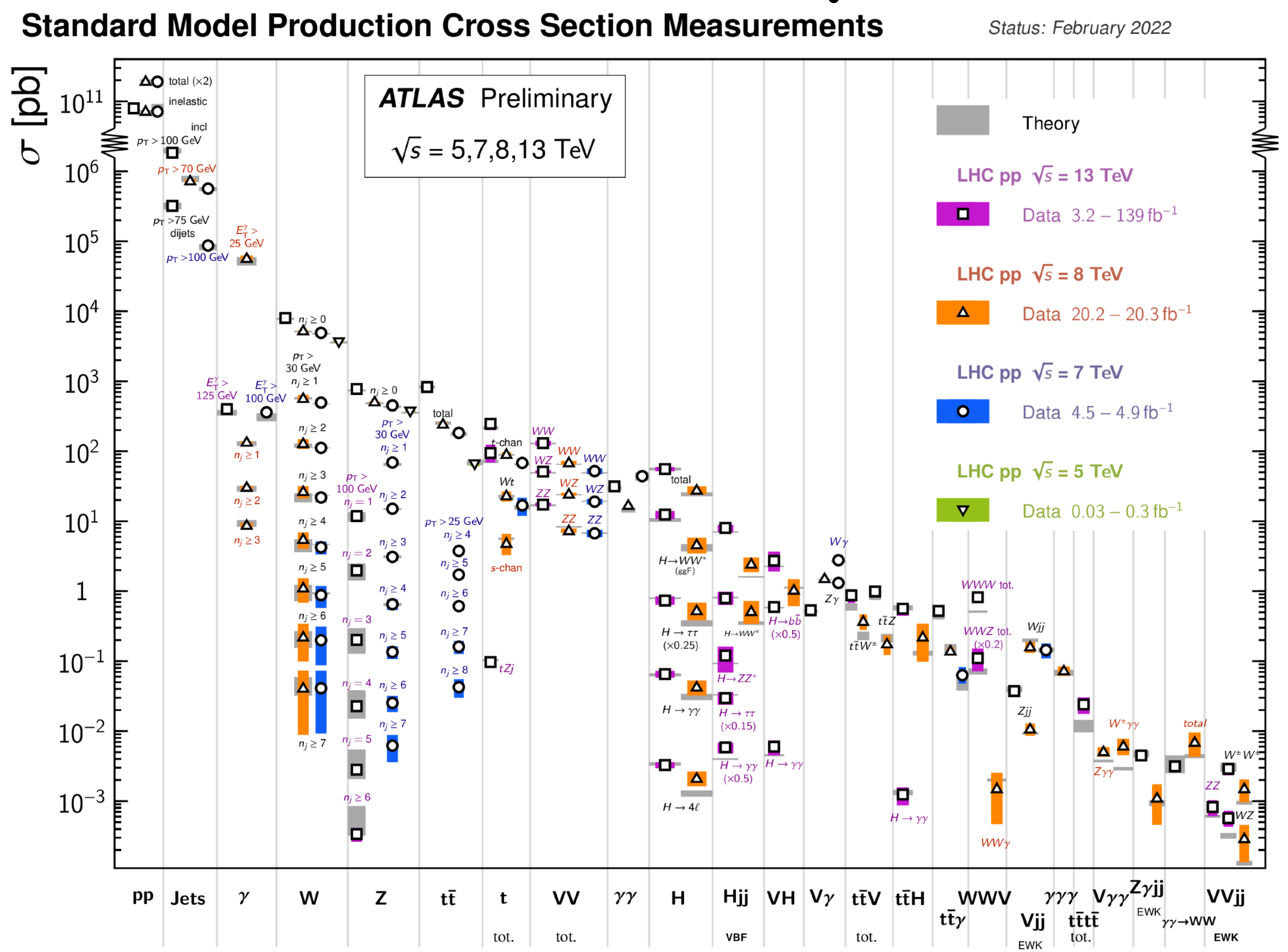
arXiv:2307.07510
arXiv:2307.15739
arXiv:2303.01530
arXiv:2301.01788
arXiv:2210.10061
arXiv:2209.02080
....





QCD and LHCp

Everything looks good



Summary

Compared to High Luminosity LHC (goal 4000 fb^{-1}), roughly 5% of data collected

Small deviations, if there are, will indicate possible signal for new physics

Precision predictions or tools are essential

Many other interesting results not covered by this talk.
Apology for it.

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Thank You !