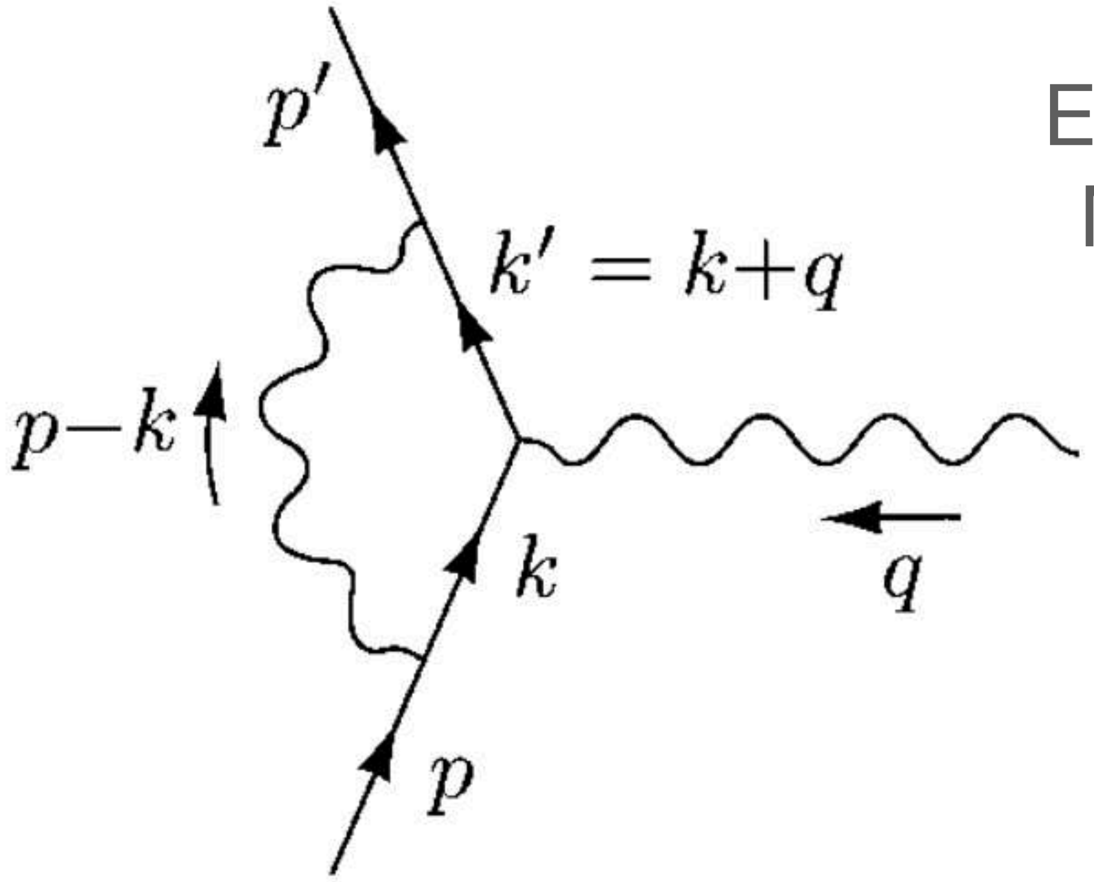
微扰QCD和精确计算研究进展

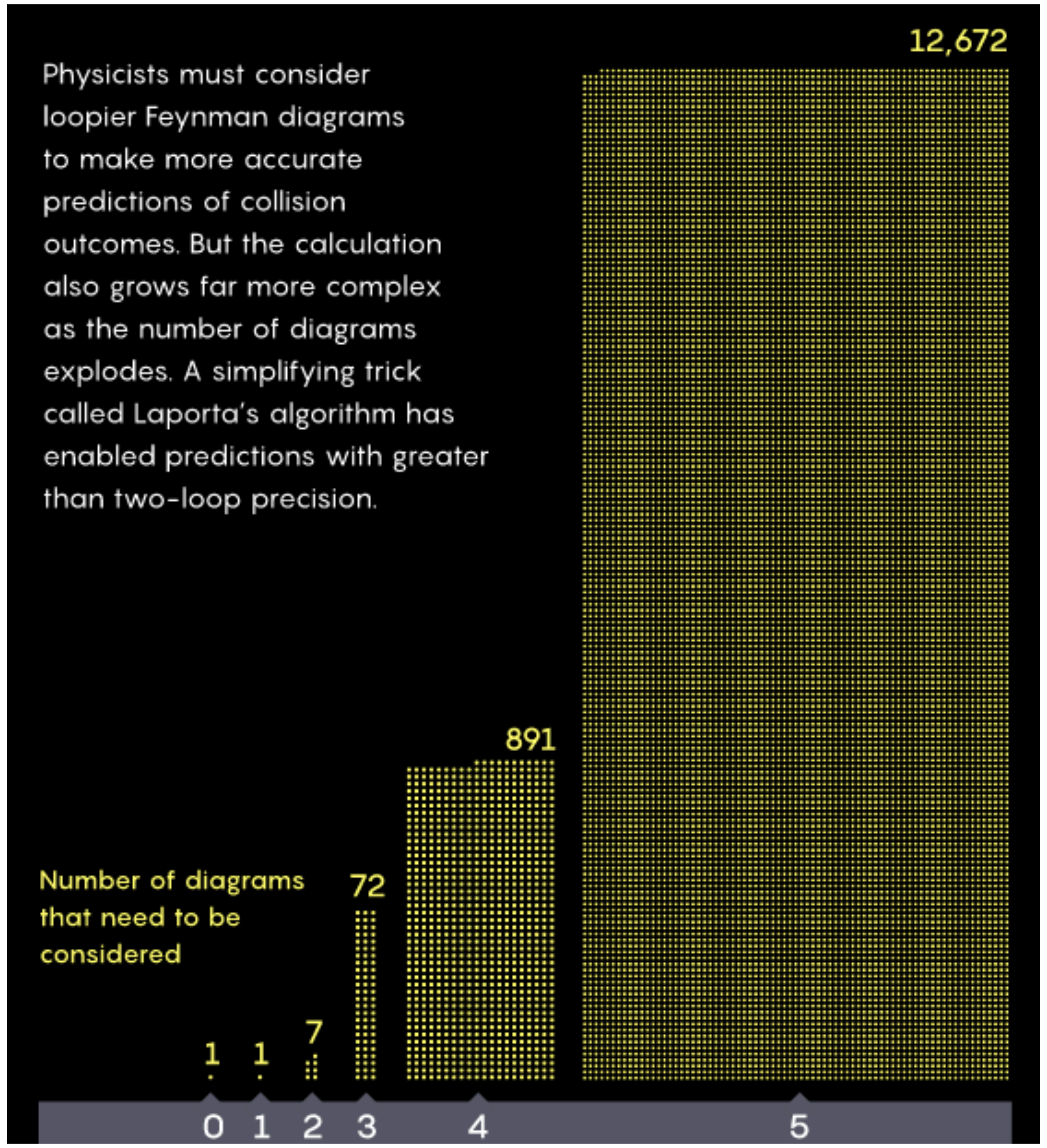
朱华星（ Hua Xing Zhu)
浙江大学

中国物理学会高能物理分会第十一届全国会员代表大会暨学术年会
辽宁师范大学 2022年8月8日

Never forget where we started



Electron Anomalous Magnetic Moment



A calculation which established the foundation of Quantum Electrodynamics

Schwinger, Phys. Rev. 73, 416

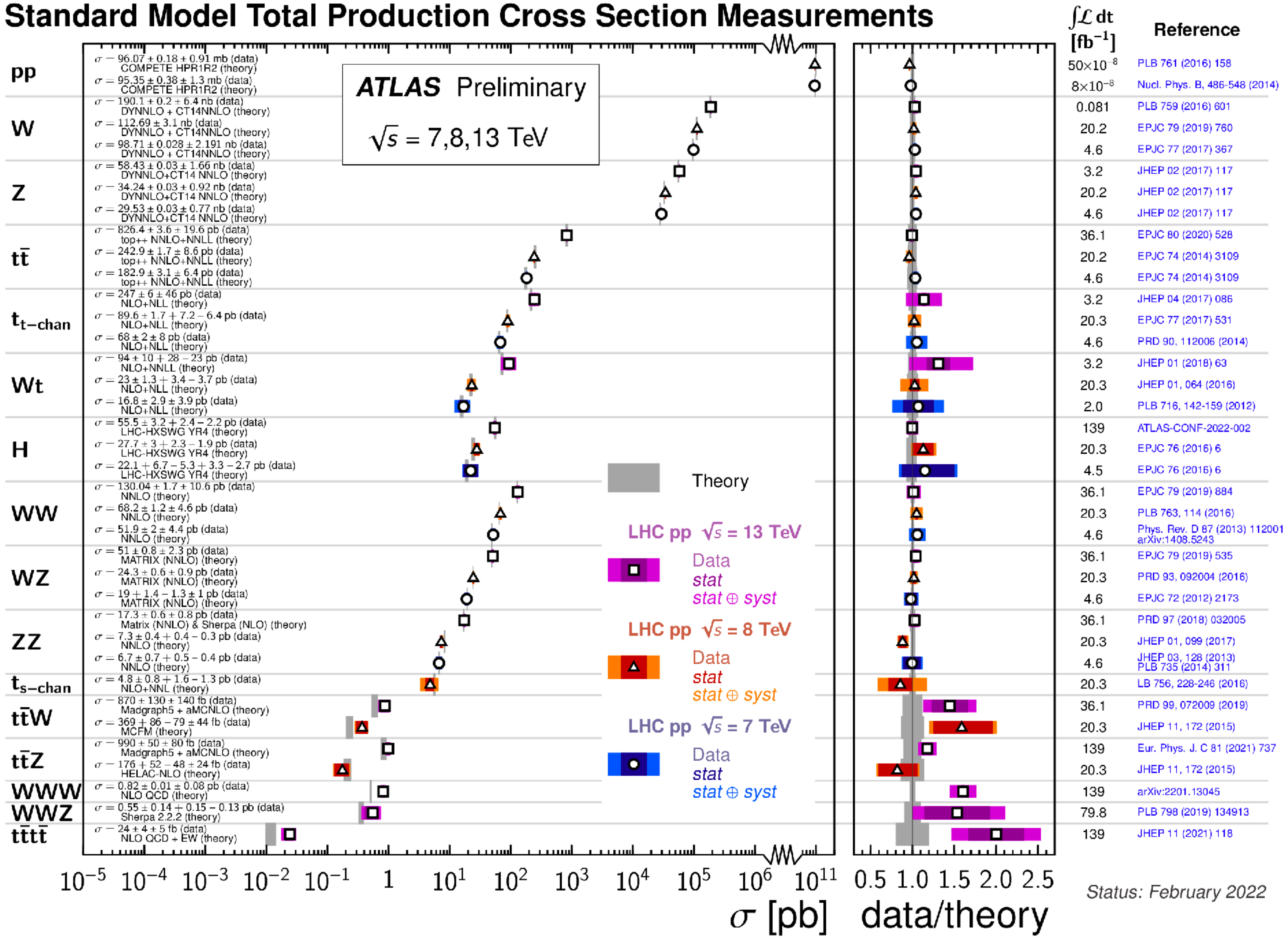
$$a_e = 0.001\,159\,652\,181\,643(764)$$

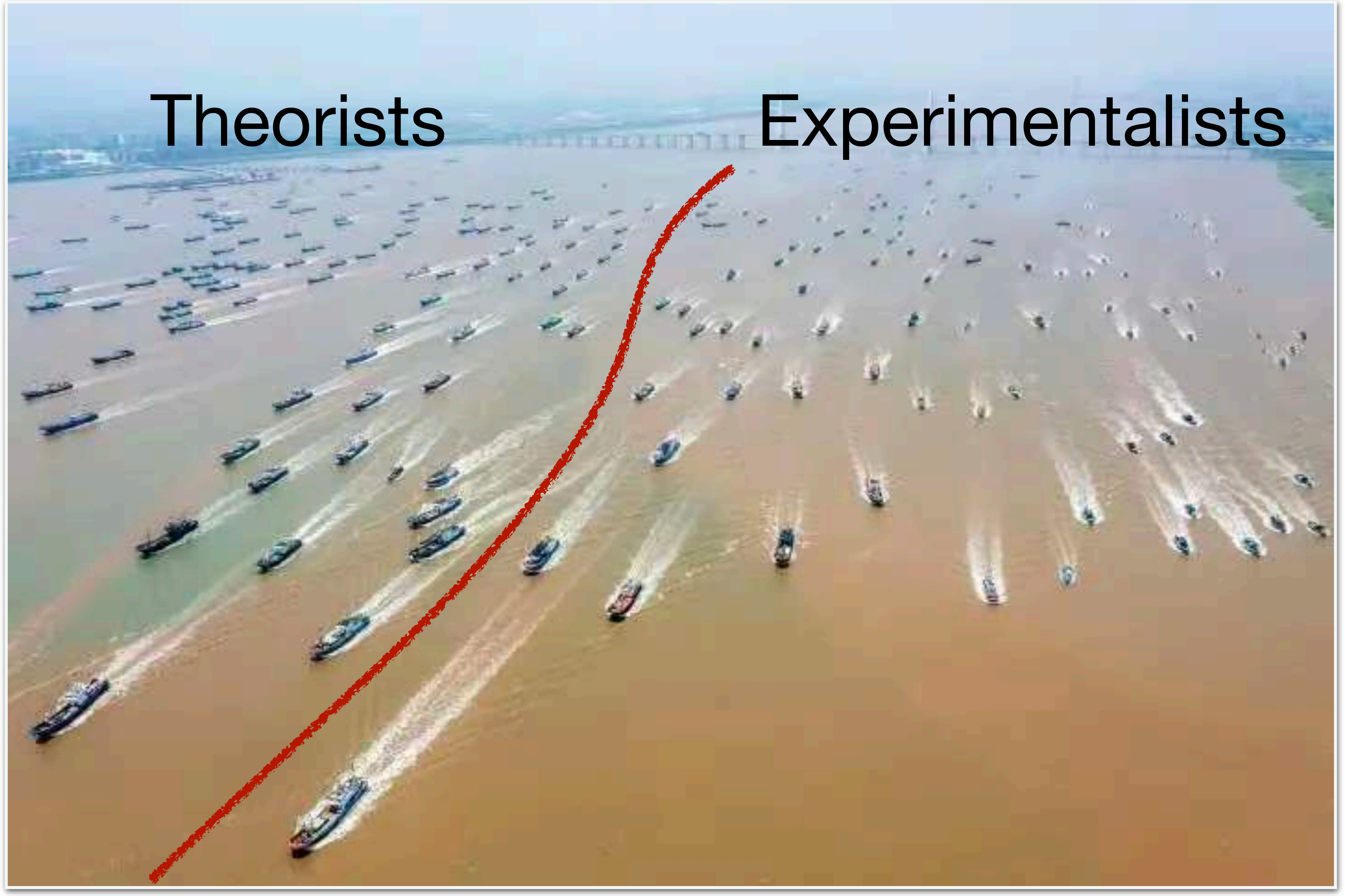
Aoyama, Hayakawa, Kinoshita, Nio, PRL109, 11807

$$a_e = 0.001\,159\,652\,180\,73(28)$$

Hannake, Hoogerheide, Gabrielse, PRA83, 052122

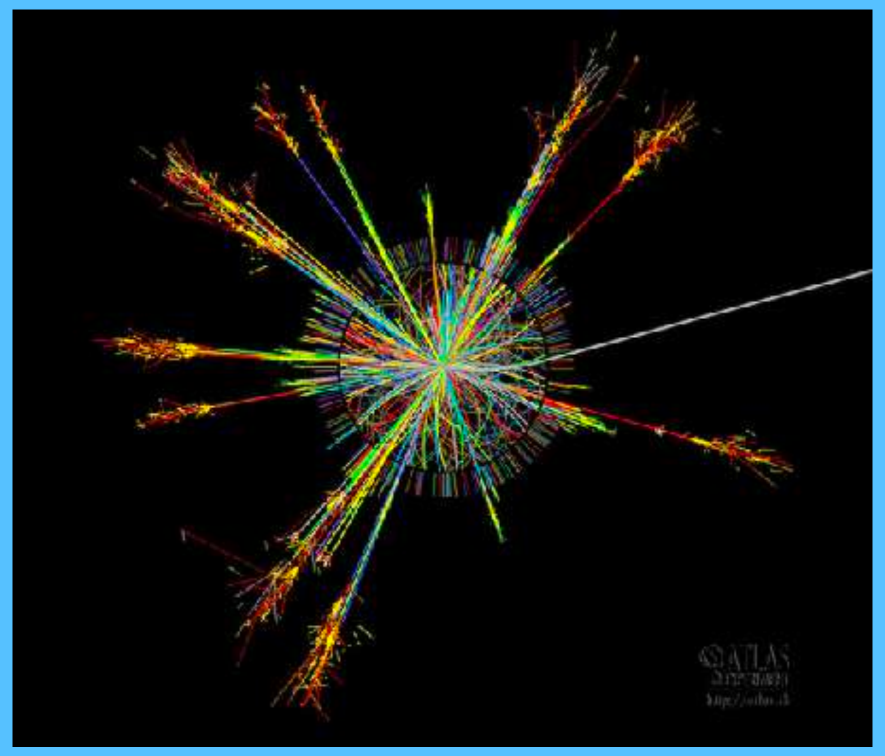
Collider physics as precision science

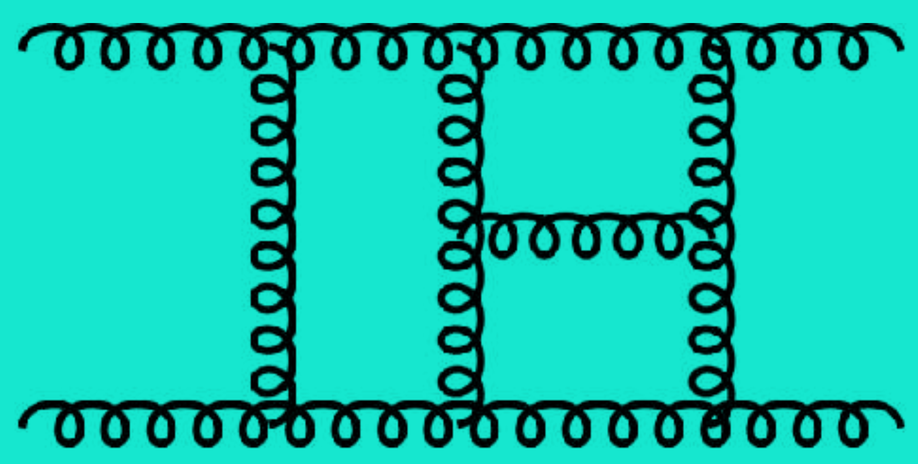


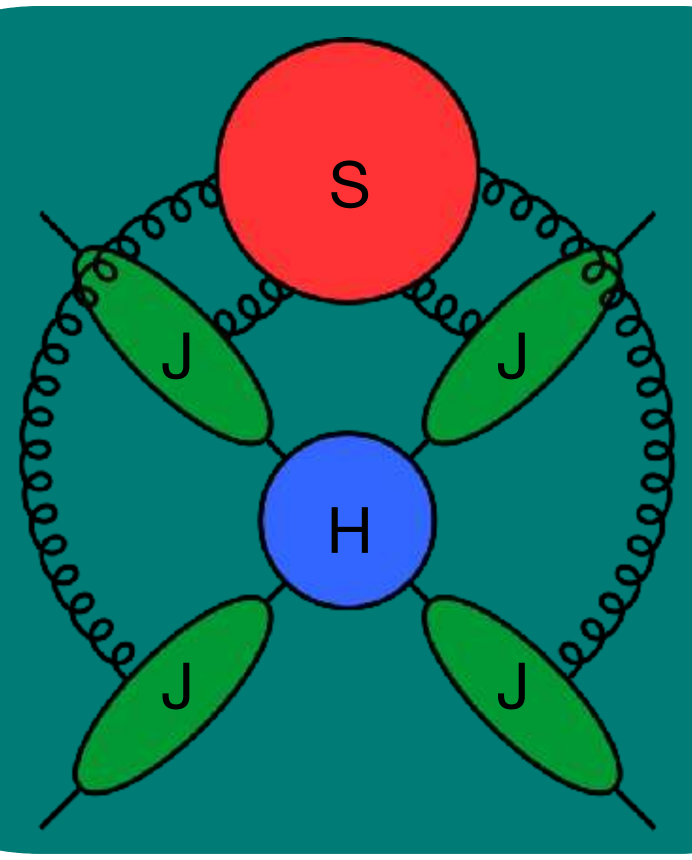


千帆竞发 百舸争流

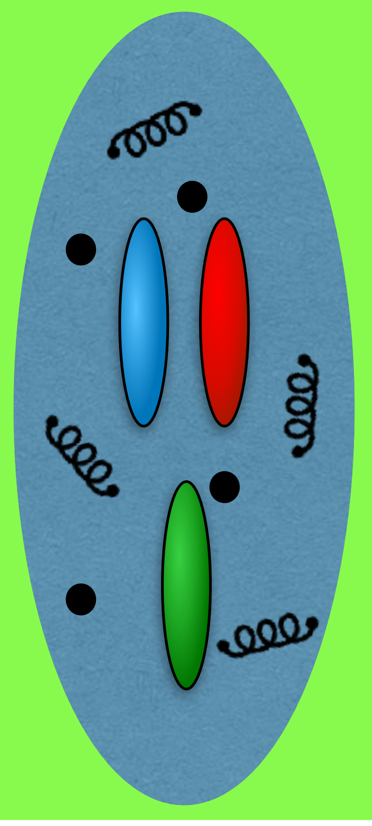
Master formula for collider physics

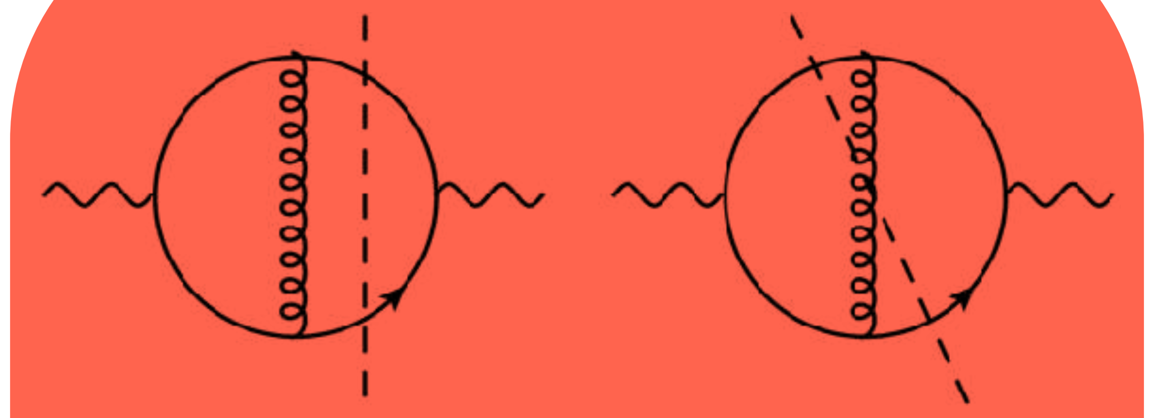




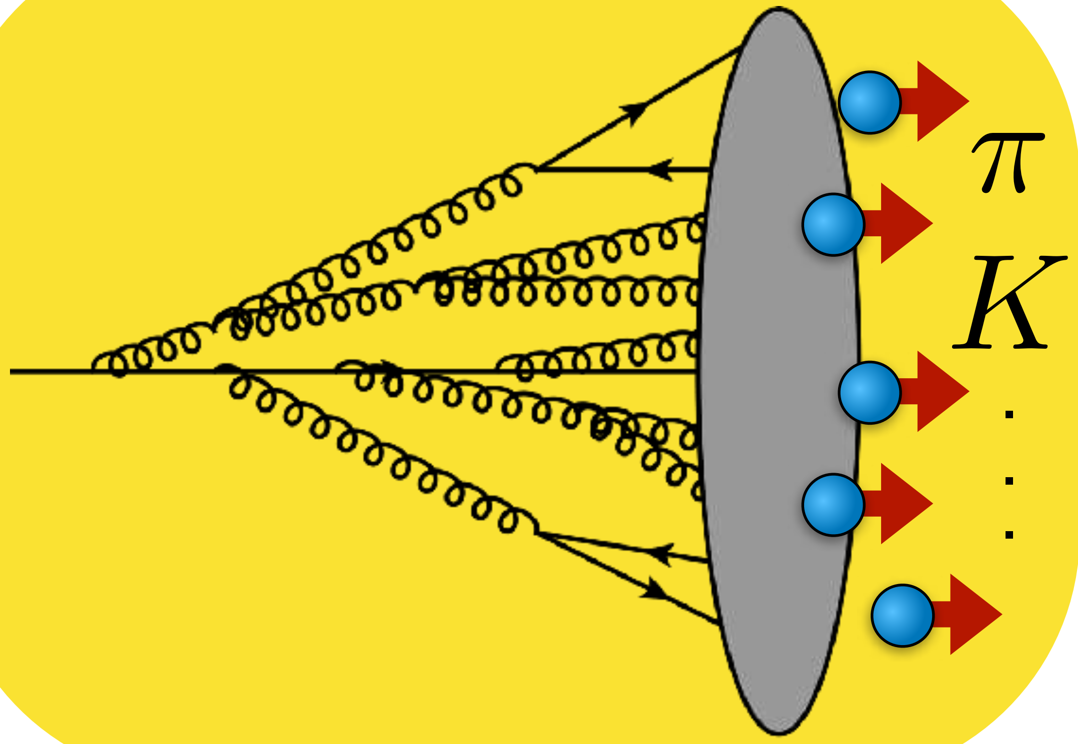


$$d\sigma(p_T, M^2, \ldots) = \mathrm{PDFs} \otimes \sum_j |\mathcal{M}_{i\to j}|^2 \otimes J \otimes \cdots$$





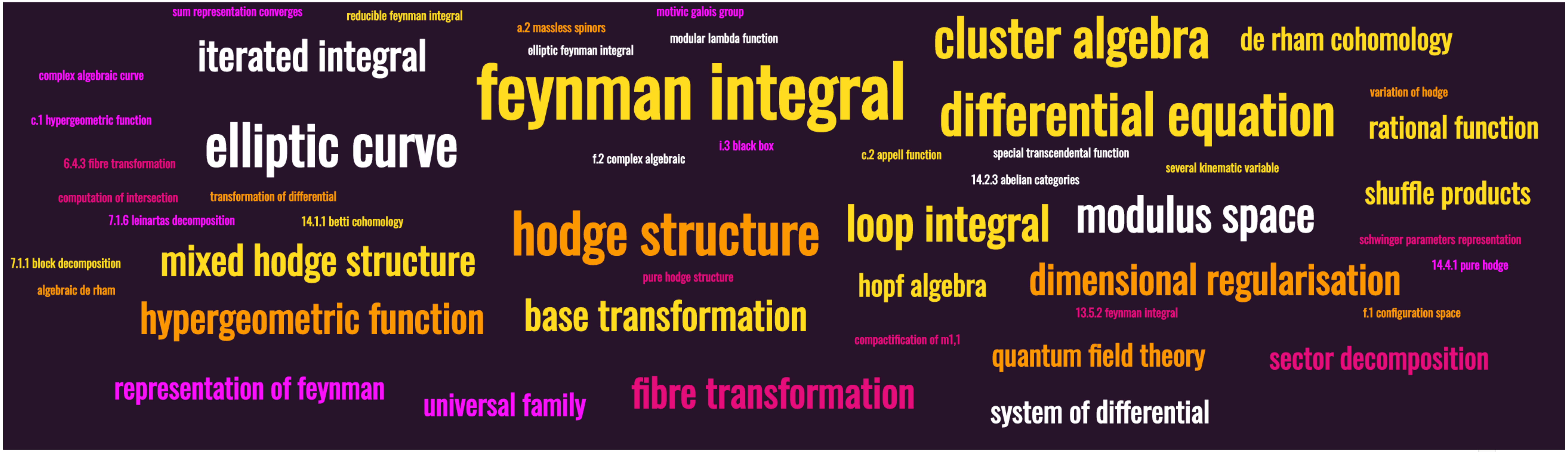
$$\infty_{\mathrm{IR}} - \infty_{\mathrm{IR}} = \text{finite}$$



Theorist’s tools

Feynman Integrals as a branch of experimental mathematics

Experimental mathematics is an approach to mathematics in which **computation** is used to investigate mathematical objects and identify properties and patterns.



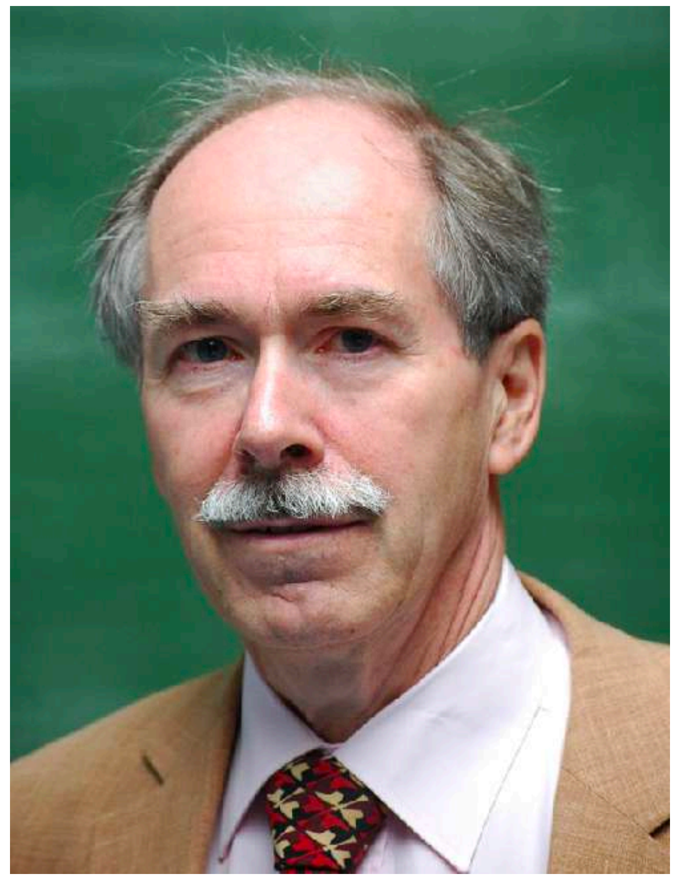
Word cloud extracted from Weinzierl, 2201.03593

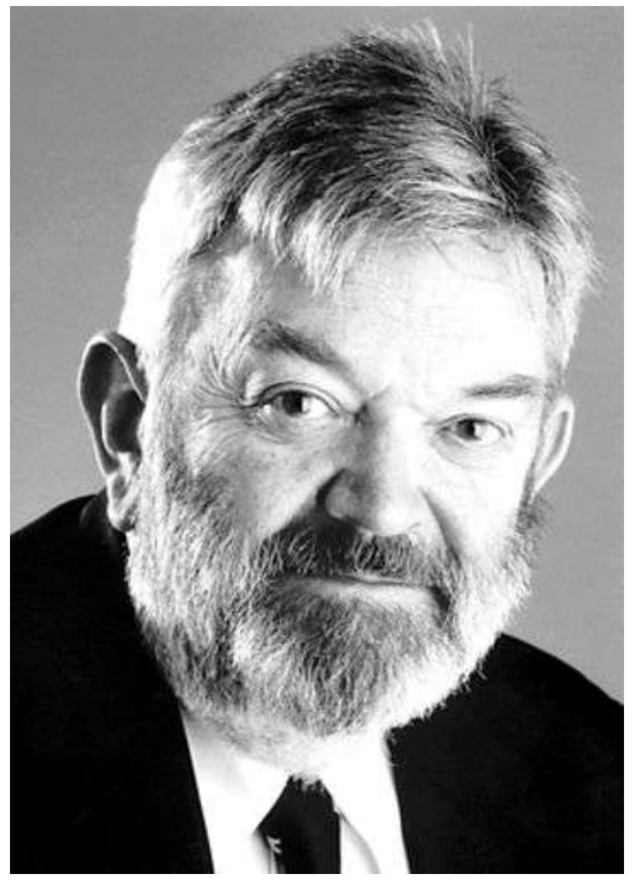
SCALAR ONE-LOOP INTEGRALS

G. 't HOOFT and M. VELTMAN
Institute for Theoretical Physics, University of Utrecht, Netherlands*

Received 16 January 1979

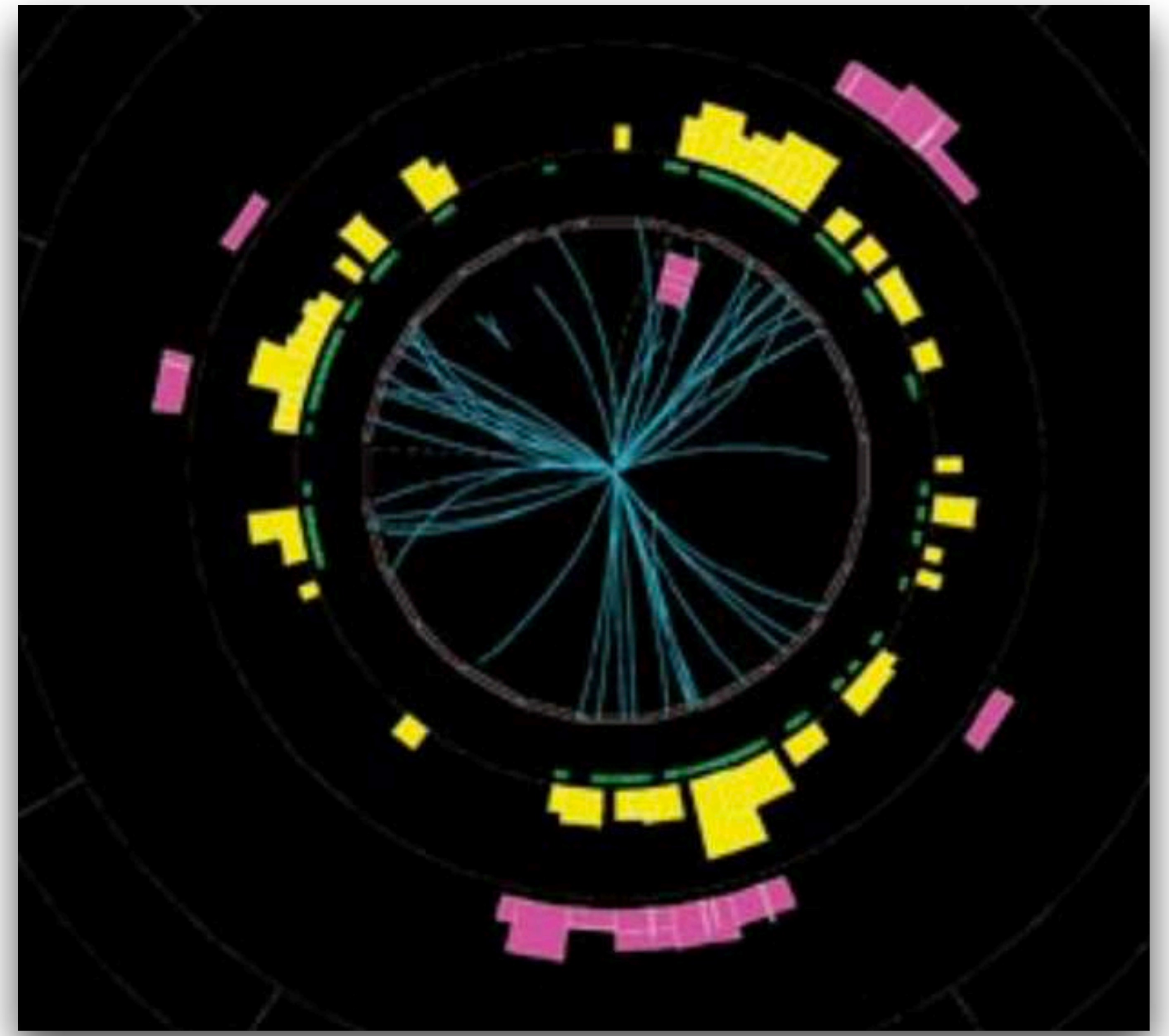
NPB153 (1979) 365-401

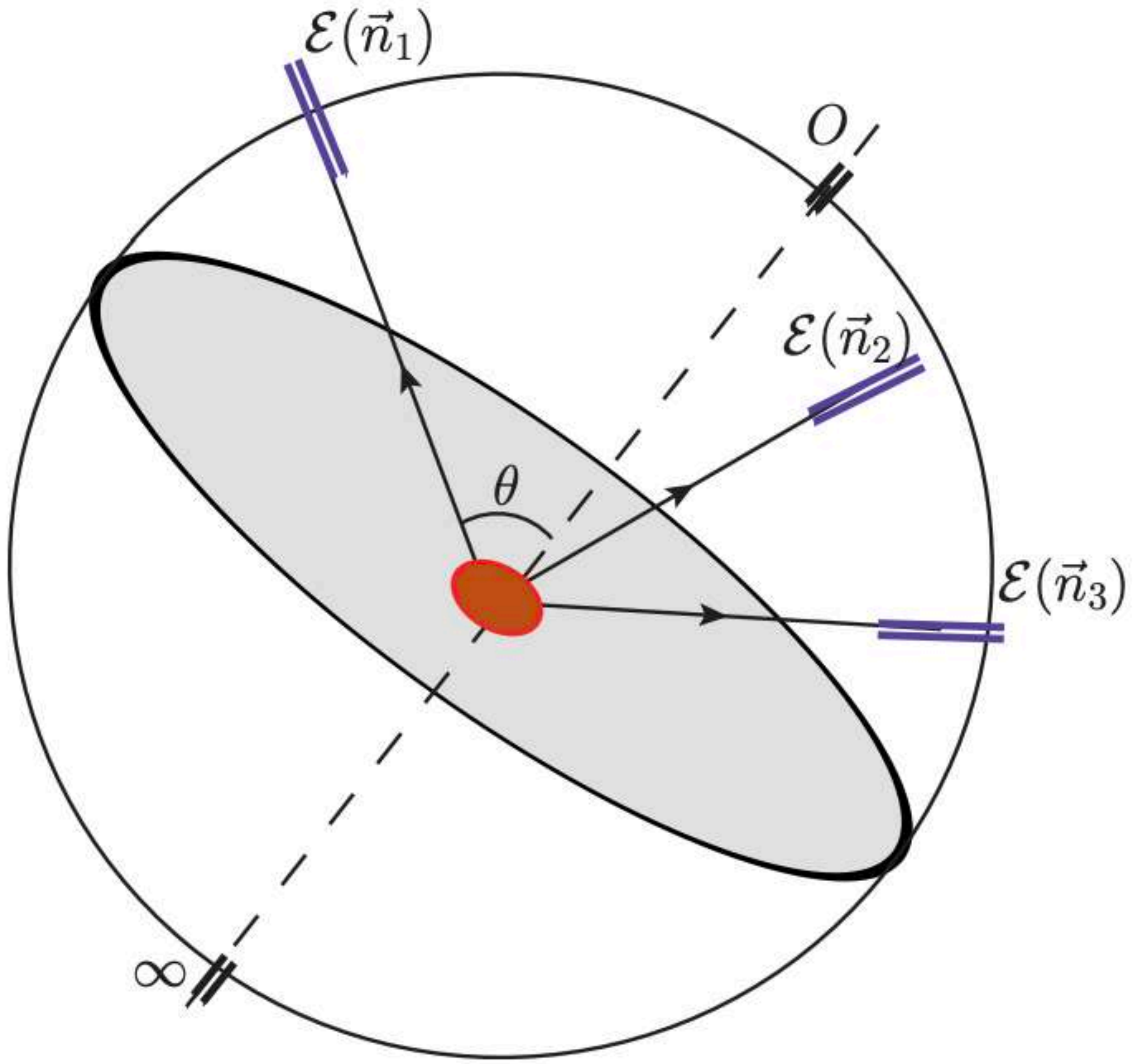




- A classic reference for all one-loop integrals
- Precision calculation becomes an industry from here
- Many of the concepts from the previous slides can't be found
- Demonstrate a continuous revolution in this field

Cluster algebra structure in physical observable?





$$
\begin{aligned}
g_1 &= \mathrm{Li}_2(-v_2)\\
g_2 &= \mathrm{Li}_2(1+w_3) + \mathrm{Li}_2(1+\bar{w}_3) + 2\,\mathrm{Li}_2(-v_3)\\
&\quad - \mathrm{Li}_2(1+w_1) - \mathrm{Li}_2(1+\bar{w}_1) - 2\,\mathrm{Li}_2(-v_1)\\
g_3 &= \mathrm{Li}_2(-z_2) - \mathrm{Li}_2(-\bar{z}_2) + \frac{1}{2}\ln|z_2|^2 \ln\frac{1+z_2}{1+\bar{z}_2}\\
g_4 &= \mathrm{Li}_2(1+w_1) - \mathrm{Li}_2(1+\bar{w}_1) + \mathrm{Li}_2(1+w_2)\\
&\quad - \mathrm{Li}_2(1+\bar{w}_2) + \mathrm{Li}_2(1+w_3) - \mathrm{Li}_2(1+\bar{w}_3)\\
g_5 &= \pi^2\\
g_6 &= \ln^2\frac{\bar{w}_1}{w_1}\\
g_7 &= \ln\frac{\bar{w}_1}{w_1}\,\ln|z_2|^2\\
g_8 &= \ln(1+v_3)\ln|z_1|^2 - \ln(1+v_1)\ln|z_3|^2
\end{aligned}
$$

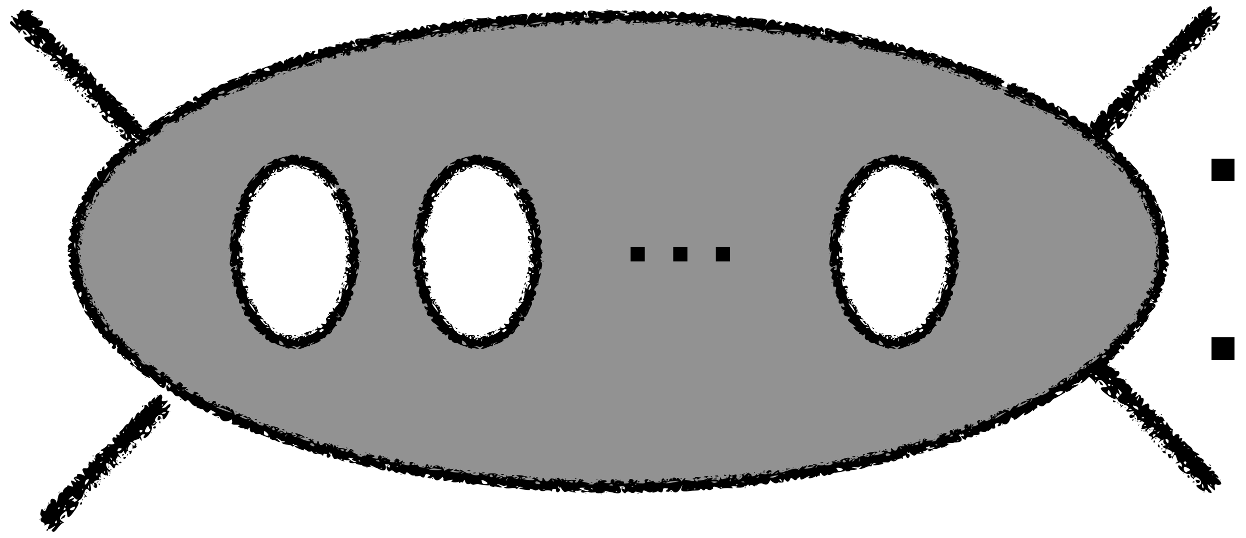
K. Yan, X.Y. Zhang, 2203.04349;
T.Z. Yang, X.Y. Zhang, 2208.01051

$$
x_1,\ x_2,\ x_3 = \frac{1+x_2}{x_1},\ x_4 = \frac{1+x_3}{x_2} = \frac{1+x_1+x_2}{x_1 x_2},
$$
$$
x_5 = \frac{1+x_4}{x_3} = \frac{1+x_1}{x_2},\ x_6 = \frac{1+x_5}{x_4} = x_1,\ x_7 = \frac{1+x_6}{x_5} = x_2,\ \ldots
$$

Appearance of a A_3 cluster algebra in an e+e- observable!

Vector space of Feynman integrals

Tkachov; Chetyrkin, Tkachov, 1981

$\mathcal{A}^{(L)}(p_i) =$  $= \underbrace{\begin{pmatrix} c_1 & c_2 & c_3 & \cdots & c_n \end{pmatrix}}_{\text{Rational coefficients}} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ \cdots \\ I_n \end{pmatrix}$

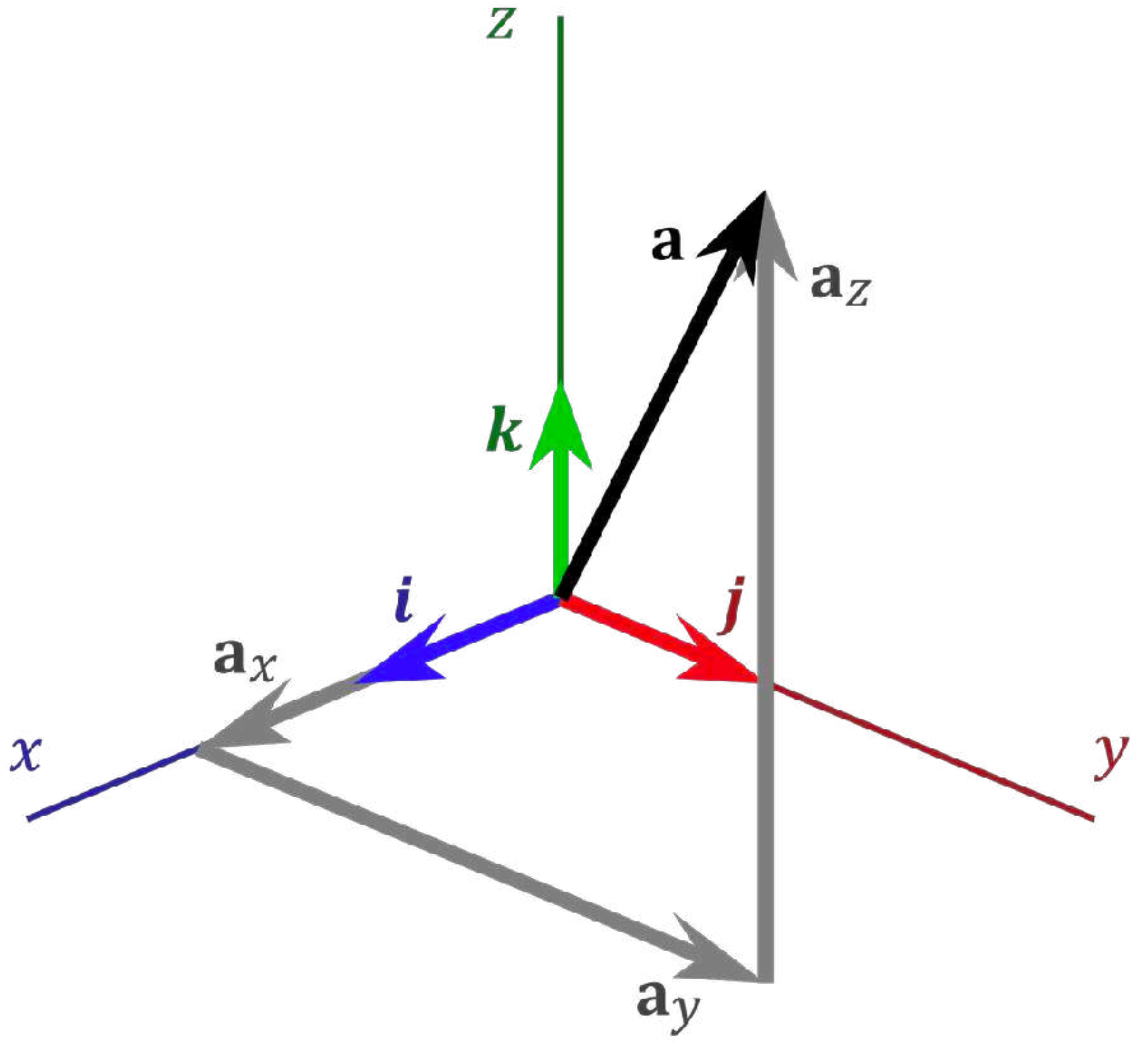
Rational coefficients

Master Integrals

Process independent
Finite dimensional

Question: how to find the coefficients?

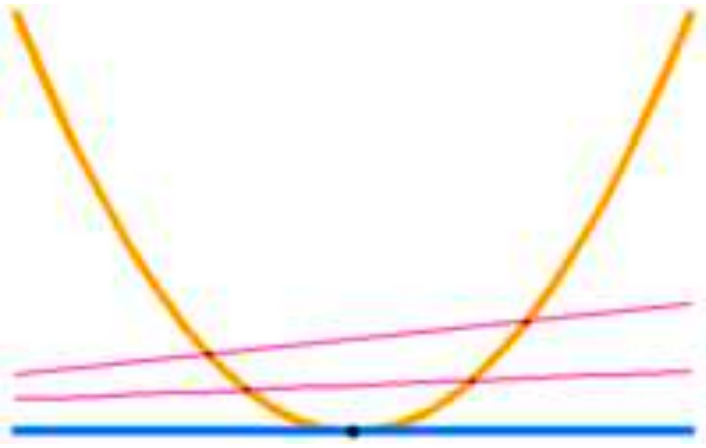
Solved at one-loop [Britto, Cachazo, B. Feng, 2004]; in principle also at higher loops (∞ computing power)



- Dual vector
- Inner product

$a_x = \vec{i} \cdot \vec{a}$

What is the dual of Feynman integrals?
What is the proper inner product?



Intersection Theory

Mastrolia, Mizera, 2018

Intersection theory and canonical Feynman integrals

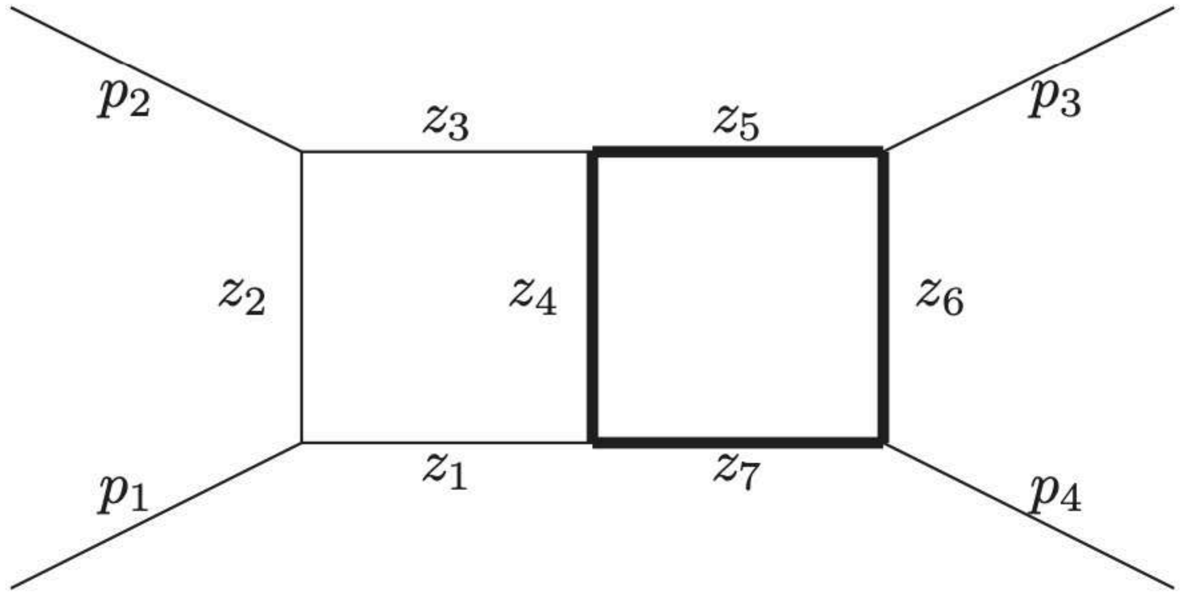
- In actual calculation, we want not just the reduction to Feynman integrals, but to "simple" Feynman integrals: canonical FI [Henn, 2013]

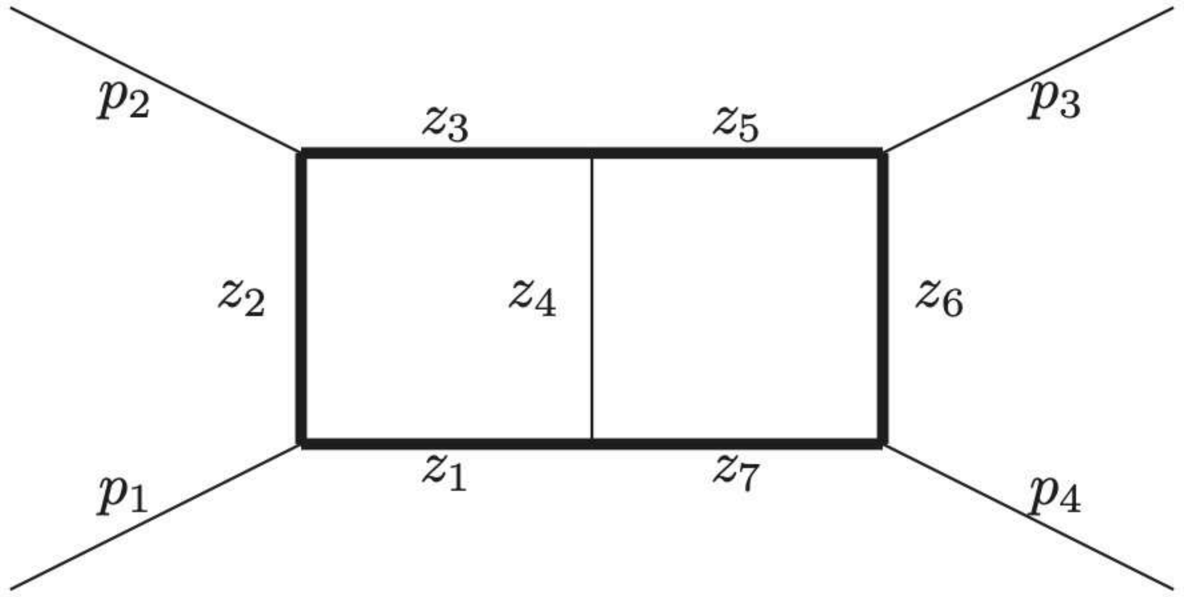
- A novel method for directly constructing canonical FI from intersection theory using generalized Baikov representation

J.Q. Chen, X.H. Jiang, C.C. Ma, X.F. Xu, L.L. Yang, 2202.08127

$$\langle\varphi_1| = s\sqrt{st(st-4m^2(s+t))}\,\langle F_{111111100}|\,,$$
$$\langle\varphi_2| = s^2\,\langle F_{1111111-10}|\,,$$
$$\langle\varphi_3| = -2s^2t\,\langle F_{111111100}| - 2s^2\,\langle F_{1111111-10}| + 2s^2\,\langle F_{11111110-1}| - 4s\,\langle F_{1111111-1-1}| - 2s^2\,\langle F_{101111100}| - 4st\,\langle F_{110111100}| - 4s\,\langle F_{101110100}| + 4s\,\langle F_{101111000}| - \frac{4t(1-2\epsilon)}{\epsilon}\,\langle F_{101011100}| + 8t\,\langle F_{110111000}|\,,$$
$$\langle\varphi_4| = \sqrt{s(s-4m^2)}\left(-2st\,\langle F_{111111100}| + 2s\,\langle F_{11111110-1}| + 4t\,\langle F_{110111100}|\right),$$
$$\langle\varphi_5| = st\,\langle F_{111111000}|\,,$$
$$\langle\varphi_6| = s\sqrt{s(s-4m^2)}\,\langle F_{101111100}|\,,$$
$$\langle\varphi_7| = \frac{s\sqrt{t(t-4m^2)}}{\epsilon}\,\langle F_{111102000}|\,,$$
$$\langle\varphi_8| = \frac{1-2\epsilon}{\epsilon^2}\,\langle F_{101200000}| - \frac{s(1-2\epsilon)}{\epsilon}\,\langle F_{111101000}| - \frac{s(t-4m^2)}{\epsilon}\,\langle F_{111102000}|\,,$$
$$\langle\varphi_9| = (s-t)\,\langle F_{110111100}|\,,$$
$$\langle\varphi_{10}| = \sqrt{st(st-4m^2(s+t))}\,\langle F_{110111100}|\,,$$
$$\langle\varphi_{11}| = s\,\langle F_{101111000}|\,,$$
$$\langle\varphi_{12}| = \frac{s(1-2\epsilon)}{\epsilon}\,\langle F_{101110100}|\,,$$
$$\langle\varphi_{13}| = \frac{s(1-2\epsilon)}{\epsilon}\,\langle F_{101011100}|\,,$$
$$\langle\varphi_{14}| = \frac{\sqrt{st(st-4m^2(s-t))}}{\epsilon}\,\langle F_{010211100}| + \frac{m^2\sqrt{st(st-4m^2(s+t))}}{\epsilon^2}\,\langle F_{010311100}|\,,$$
$$\langle\varphi_{15}| = \frac{\sqrt{s(s(t-m^2)^2-4t^2m^2)}}{\epsilon}\,\langle F_{010211100}|\,,$$
$$\langle\varphi_{16}| = -\frac{sm^2}{\epsilon^2}\,\langle F_{000311100}| - \frac{s(1-2\epsilon)}{\epsilon}\,\langle F_{010111100}| - \frac{sm^2}{\epsilon}\,\langle F_{010211100}|\,,$$
$$\langle\varphi_{17}| = \frac{s}{\epsilon}\,\langle F_{101102000}|\,,$$
$$\langle\varphi_{18}| = \frac{s\sqrt{s(s+4m^2)}}{\epsilon^2}\,\langle F_{102102000}| - \frac{\sqrt{s(s+4m^2)}}{2m^2\epsilon(1-2\epsilon)}\,\langle F_{000220000}|\,,$$
$$\langle\varphi_{19}| = -\frac{\sqrt{s(s-4m^2)}(1-2\epsilon)}{\epsilon^2}\,\langle F_{101010200}|\,,$$
$$\langle\varphi_{20}| = \frac{s}{2\epsilon}\,\langle F_{100210000}| - \frac{s}{4\epsilon^2}\,\langle F_{100220000}|\,,$$
$$\langle\varphi_{21}| = -\frac{t}{2\epsilon}\,\langle F_{010211000}| + \frac{t}{4\epsilon^2}\,\langle F_{010202000}|\,,$$
$$\langle\varphi_{22}| = -\frac{s}{\epsilon}\,\langle F_{110210100}| - \frac{sm^2}{\epsilon^2}\,\langle F_{010310100}|\,,$$

$$\langle\varphi_{23}| = -\frac{\sqrt{s(s-4m^2)}(1-2\epsilon)}{\epsilon^2}\,\langle F_{010110200}| - \frac{\sqrt{s(s-4m^2)}}{\epsilon}\,\langle F_{010210100}|\,,$$
$$\langle\varphi_{24}| = \frac{s}{\epsilon}\,\langle F_{010210100}| + \frac{2sm^2}{\epsilon^2}\,\langle F_{010310100}|\,,$$
$$\langle\varphi_{25}| = \frac{sm^2}{\epsilon^2}\,\langle F_{000311100}|\,,$$
$$\langle\varphi_{26}| = \frac{1-2\epsilon}{\epsilon}\,\langle F_{101200000}|\,,$$
$$\langle\varphi_{27}| = \frac{\sqrt{s(s-4m^2)}}{4\epsilon^2}\,\langle F_{100220000}| + \frac{\sqrt{s(s-4m^2)}}{2\epsilon^2}\,\langle F_{200120000}|\,,$$
$$\langle\varphi_{28}| = \frac{1}{4\epsilon^2}\,\langle F_{000220000}| - \frac{s}{2\epsilon^2}\,\langle F_{100220000}|\,,$$
$$\langle\varphi_{29}| = \frac{\sqrt{t(t-4m^2)}}{4\epsilon^2}\,\langle F_{010202000}| + \frac{\sqrt{t(t-4m^2)}}{2\epsilon^2}\,\langle F_{020102000}|\,,$$
$$\langle\varphi_{30}| = \frac{1}{4\epsilon^2}\,\langle F_{000220000}| - \frac{t}{2\epsilon^2}\,\langle F_{010202000}|\,,$$
$$\langle\varphi_{31}| = \frac{\sqrt{s(s-4m^2)}}{2\epsilon^2}\,\langle F_{000210200}|\,,$$
$$\langle\varphi_{32}| = \frac{1}{\epsilon^2}\,\langle F_{000220000}|\,.$$





Relevant for gg->γγ
gg->HH (small mass limit)

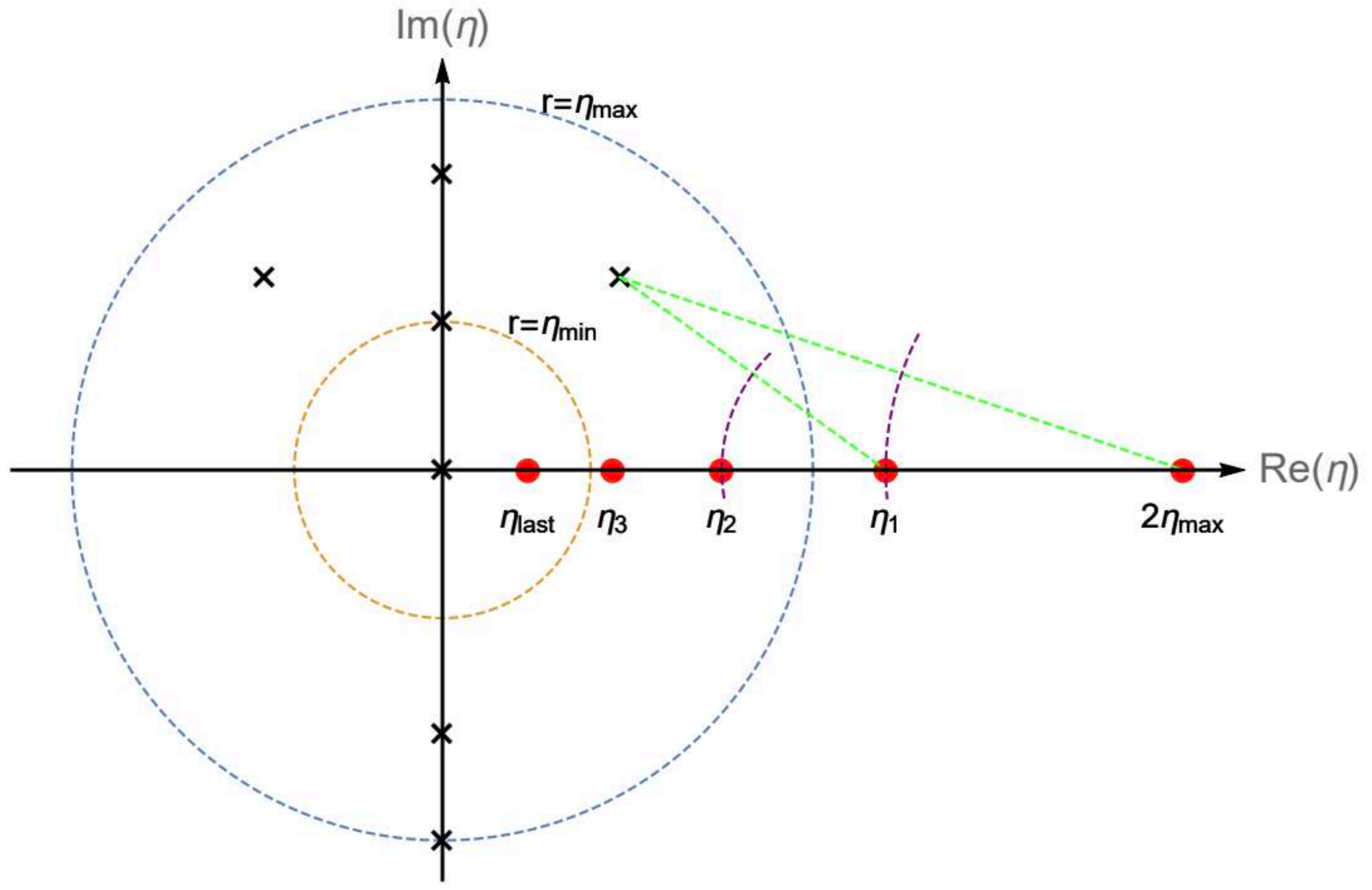
Seems promising, expected more interesting results to come!

Auxiliary Mass Flow Method

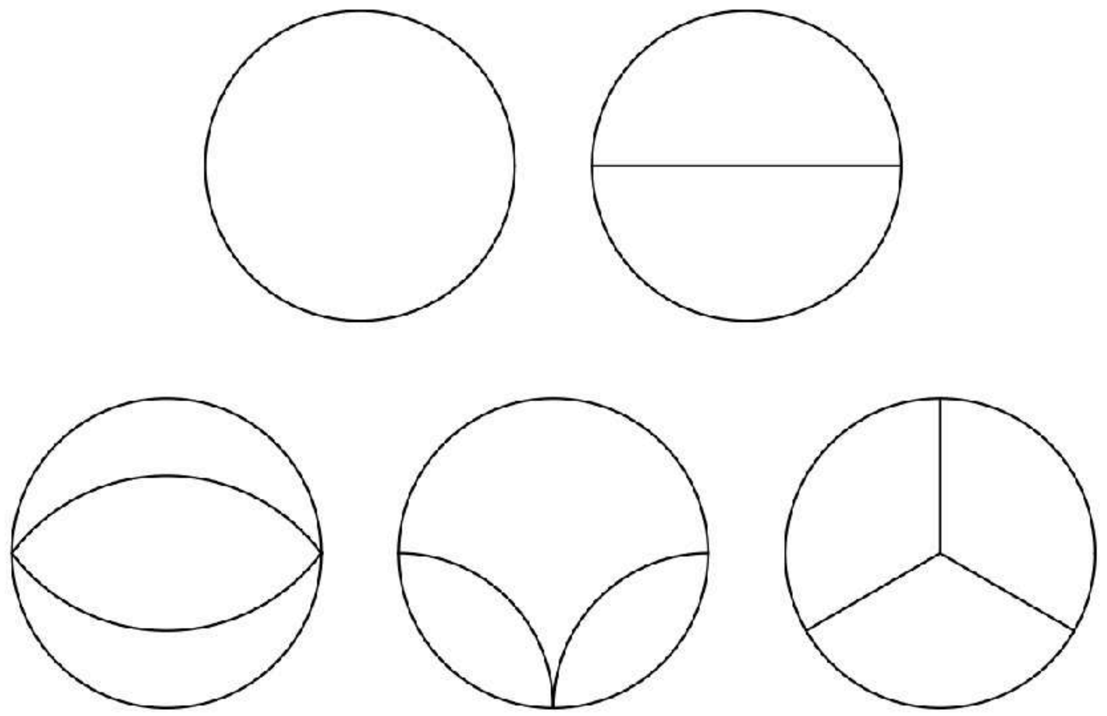
Developed from 2017 - 2022: X. Liu, Y.Q. Ma, C.Y. Wang, 1711.09572; X. Liu, Y.Q. Ma, 1801.10523; X. Guan, X. Liu, Y.Q. Ma, 1912.09294; X. Liu, Y.Q. Ma, 2201.11669, …

$$I_{\vec{\nu}}^{\text{mod}}(\epsilon,\eta) = \int \prod_{i=1}^{L} \frac{\mathrm{d}^D \ell_i}{\mathrm{i}\pi^{D/2}} \frac{\mathcal{D}_{K+1}^{-\nu_{K+1}} \cdots \mathcal{D}_N^{-\nu_N}}{(\mathcal{D}_1 + \lambda_1 \times \mathrm{i}\eta)^{\nu_1} \cdots (\mathcal{D}_K + \lambda_K \times \mathrm{i}\eta)^{\nu_K}}$$

$$I_{\vec{\nu}}(\epsilon) = \lim_{\eta \to 0^+} I_{\vec{\nu}}^{\text{mod}}(\epsilon,\eta)$$



Limit is taken by solving an ODE for η from ∞ to 0^+



AMFlow

Project ID: 32748265

Star 6

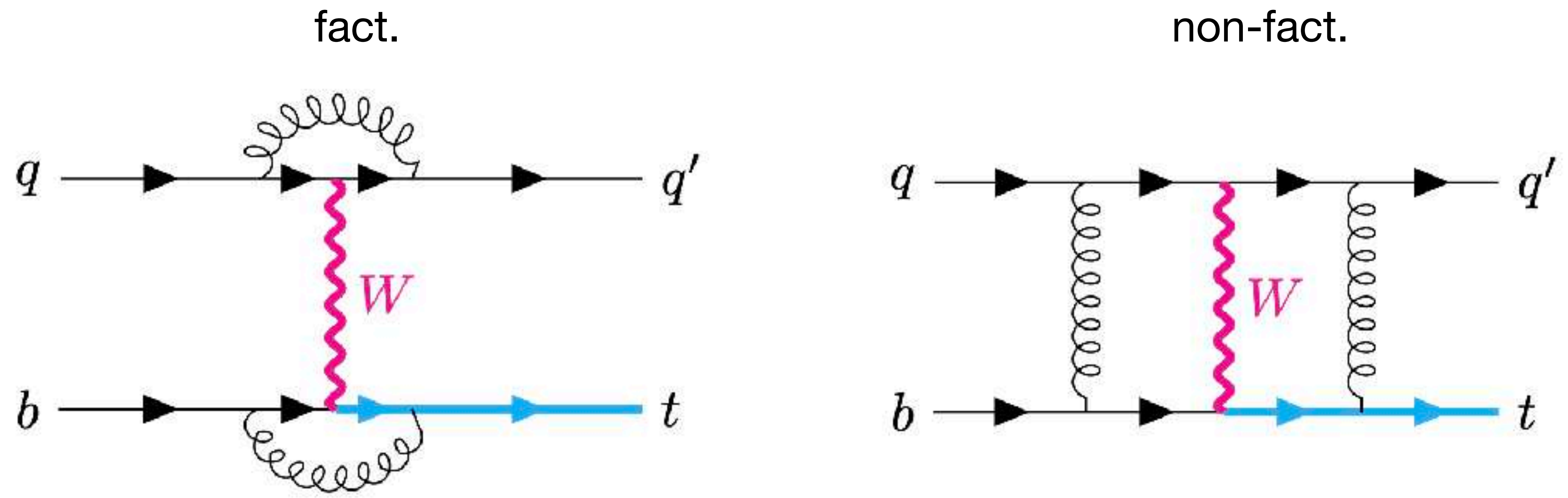
54 Commits 1 Branch 2 Tags 3.7 MB Project Storage 1 Release

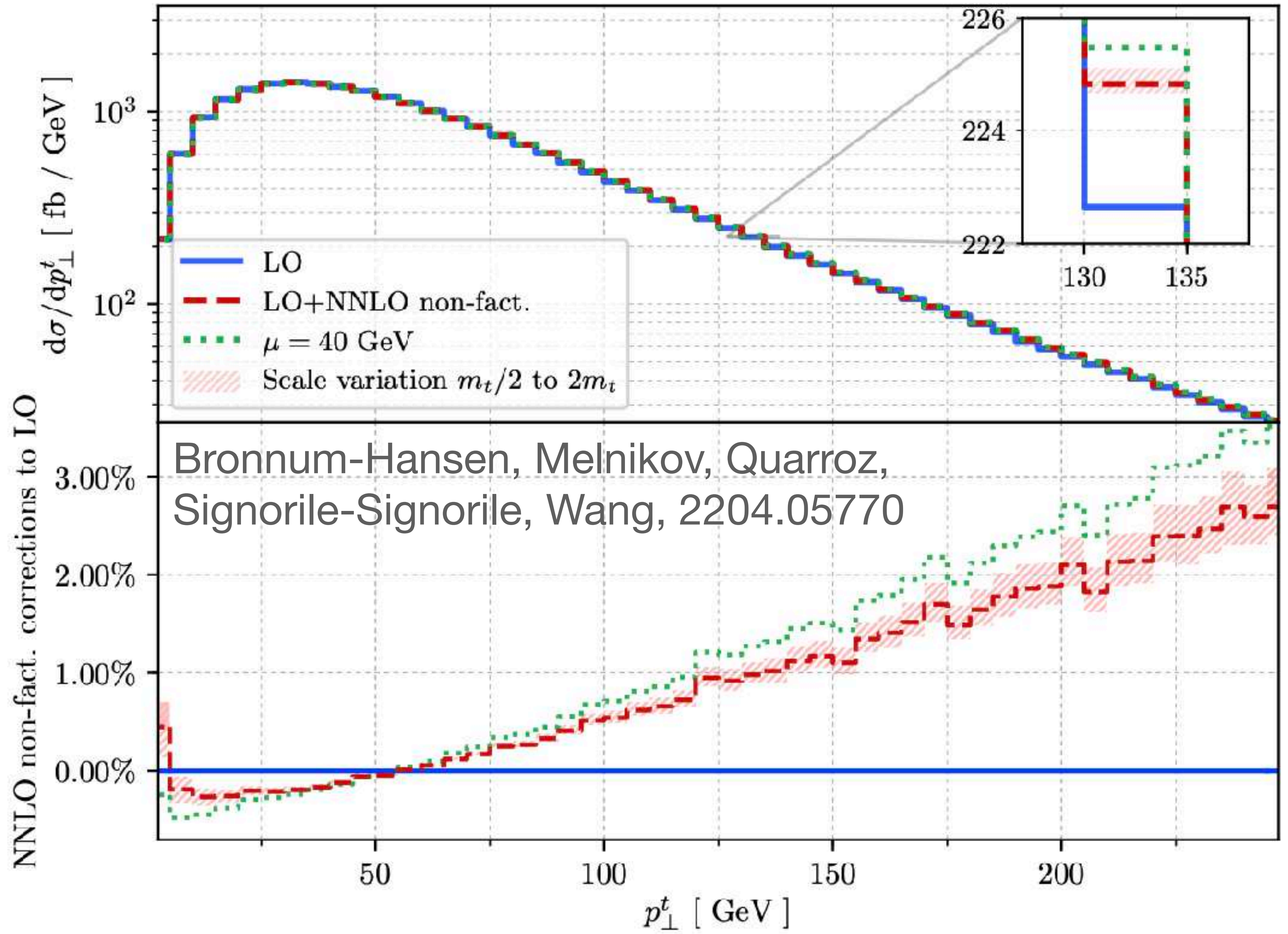
A proof-of-concept implementation of auxiliary mass flow method.

X. Liu, Y.Q. Ma, 2201.11669

Application of AMF method to single top production

- Large rate for single-top at the LHC can be used to measure properties of top quark and CKM.
- Previously NNLO corrections for factorisable only: [M. Brucherseifer, F. Caola, K. Melnikov; E. Berger, J. Gao, C.-P. Yuan, H.X. Zhu; J. Campbell, T. Neumann, Z. Sullvian].
- Main bottleneck was two-loop virtual non-factorizable diagrams, recently become available [C. Bronnum-Hansen, K. Melnikov, J. Quarroz, C.Y. Wang] using auxiliary mass flow method [X. Liu, Y.Q. Ma, C.Y. Wang].
- Only slightly smaller than factorisable corrections: 0.4% for inclusive Xsec, O(1-2)% for kinematical corrections. Need to be taken into account in future percent-level measurements.





Quarkonium decay at three loops

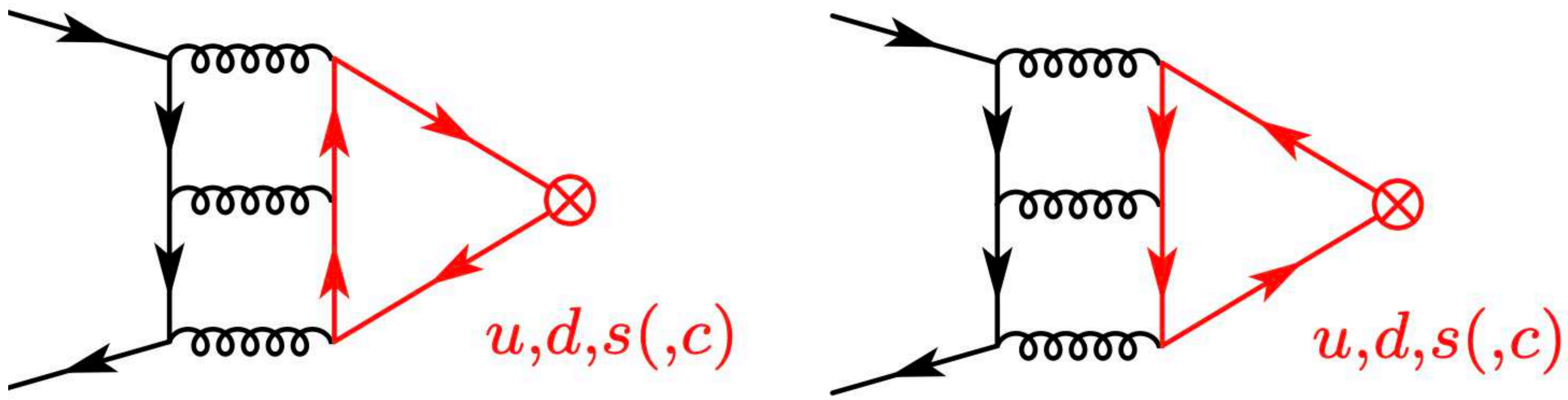
F. Feng, Y. Jia, Z.W. Mo, J.C. Pan, W.L. Sang, J.Y. Zhang, 2207.14259

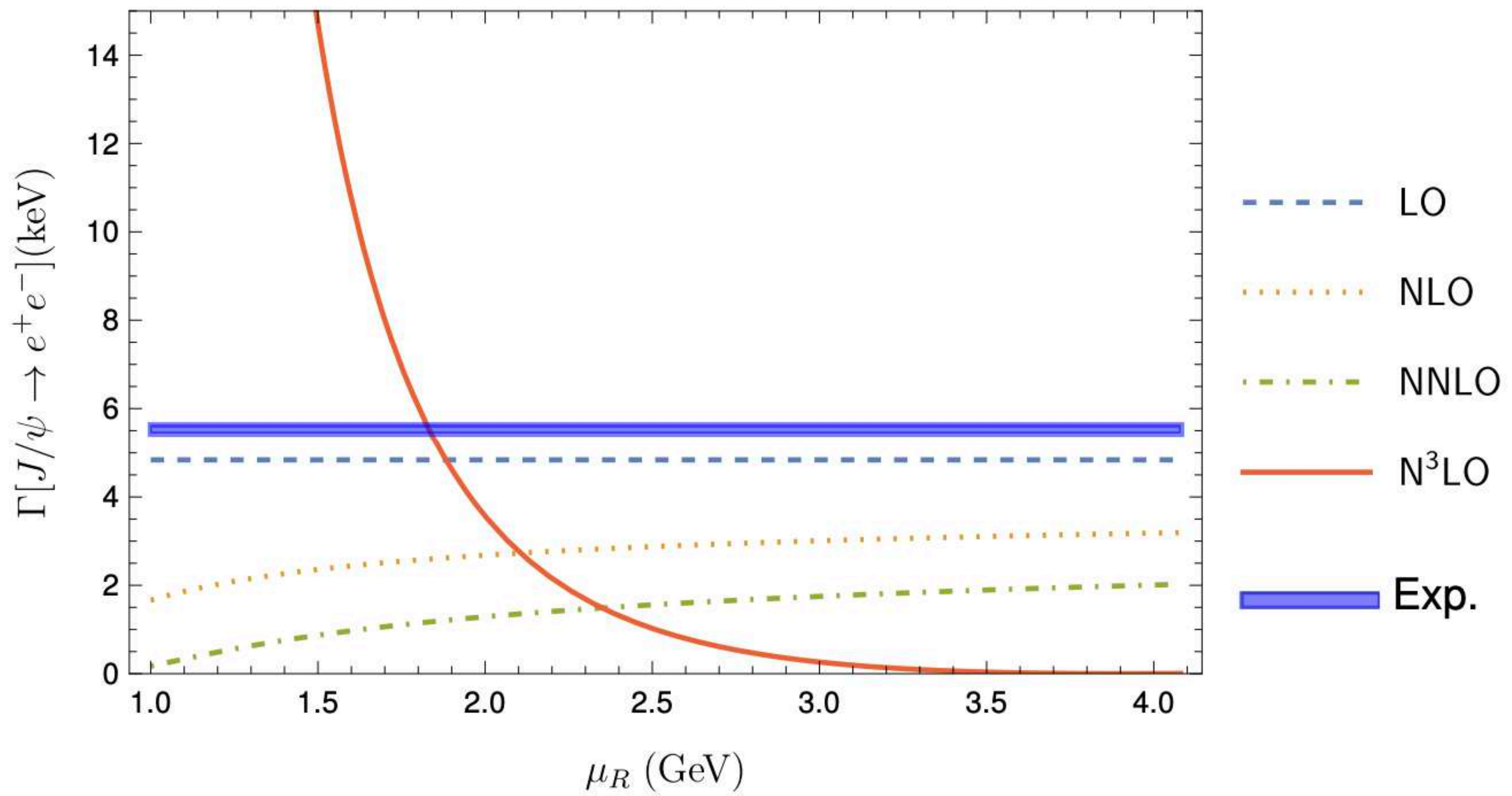
NRQCD:

$$\Gamma(V \to l^+ l^-) = \frac{8\pi\alpha^2 e_Q^2}{3M_V^2} \left| \mathcal{C}_{\rm dir} + \sum_{f \neq Q} \mathcal{C}_{{\rm ind},f} \frac{e_f}{e_Q} \right|^2 \left| \langle 0 | \chi^\dagger \boldsymbol{\sigma} \cdot \boldsymbol{\epsilon} \psi(\mu_\Lambda) | V(\boldsymbol{\epsilon}) \rangle \right|^2$$

$$\begin{aligned}
\mathcal{C}_{FFF} =& 36.49486245880592537633476189872792031664181, \\
\mathcal{C}_{FFA} =& -188.0778416598807139057999402327847645038910 5, \\
\mathcal{C}_{FAA} =& -97.73497326991838634234524500457409843988718 1, \\
\mathcal{C}_{FFL} =& 46.69169290551513246755826764126053601777912 6774, \\
\mathcal{C}_{FAL} =& 39.62371855452441907734204742205347751869812 04767, \\
\mathcal{C}_{FHL} =& -0.2702504391565021717321386913977786479239977 21, \\
\mathcal{C}_{FLL} =& -2.4683364544823741163705418765248618965896838 6, \\
\mathcal{C}_{FFH} =& -0.8435622911595001453055093736419593585798252, \\
\mathcal{C}_{FAH} =& -0.1024741614929317408574835971993802120163106, \\
\mathcal{C}_{FHH} =& 0.05123960751198372493493118588999641369844635617, \\
\mathcal{C}_{BFH} =& 2.115578267980906498436822221913944370044335 6 \\
& +{\rm i}\, 0.4942127107006720402412181080201603811552204 87), \\
\mathcal{C}^{(3)}_{{\rm ind},l} =& T_F B_F C_F(-0.945532642977386 + {\rm i}\, 1.28500237447426).
\end{aligned}$$

3-loop light-by-light diagram





CERN

10 years HIGGS boson discovery

The dawn of precision Higgs physics

ATLAS
Nature 607, 52-59(2022)

$$\mu = 1.05 \pm 0.04(\mathrm{th}) \pm 0.03(\mathrm{exp}) \pm 0.03(\mathrm{stat})$$

CMS
Nature 607, 60-68(2022)

$$\mu = 1.02 \pm 0.036(\mathrm{th}) \pm 0.033(\mathrm{exp}) \pm 0.029(\mathrm{stat})$$

Total exp: 14% Run 1 → 6% Run2 → ???

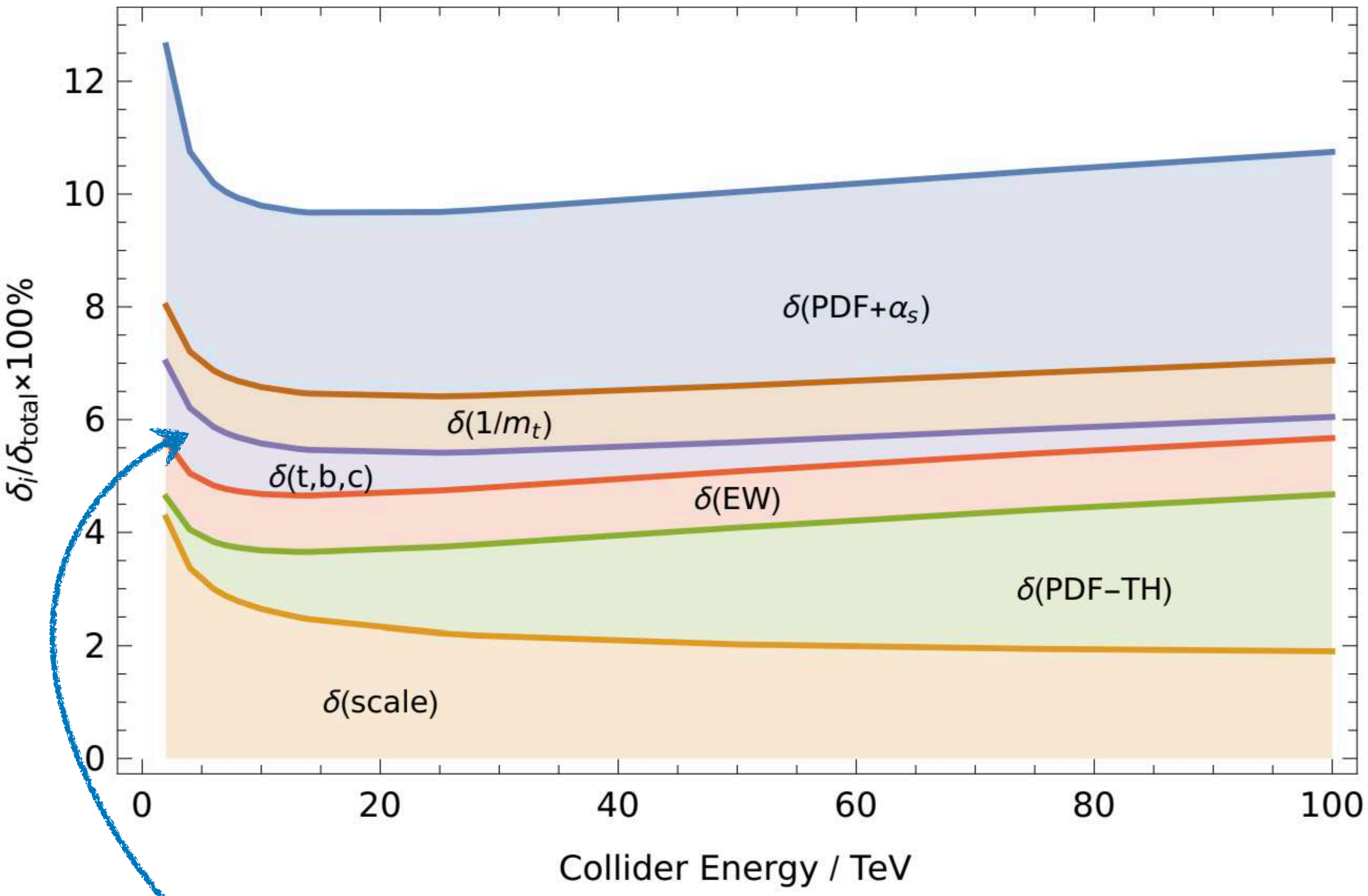
Pressure is on the theorists side to reduce theory uncertainties

Current status of theory uncertainties in ggF

$$
\begin{aligned}
\delta(\text{theory}) &= {}^{+0.13pb}_{-1.20pb} \quad \left({}^{+0.28\%}_{-2.50\%}\right) \quad \delta(\text{scale}) \\
&+ \pm 0.56pb \quad (\pm 1.16\%) \quad \delta(\text{PDF-TH}) \\
&+ \pm 0.49pb \quad (\pm 1.00\%) \quad \delta(\text{EWK}) \\
&+ \pm 0.41pb \quad (\pm 0.85\%) \quad \delta(\text{t,b,c}) \\
&+ \pm 0.49pb \quad (\pm 1.00\%) \quad \delta(1/m_t) \\
&= {}^{+2.08pb}_{-3.16pb} \quad \left({}^{+4.28\%}_{-6.5\%}\right), \\
\delta(\text{PDF}) &= \pm 0.89\text{pb} \quad (\pm 1.85\%), \\
\delta(\alpha_S) &= {}^{+1.25pb}_{-1.26pb} \quad \left({}^{+2.59\%}_{-2.62\%}\right).
\end{aligned}
$$

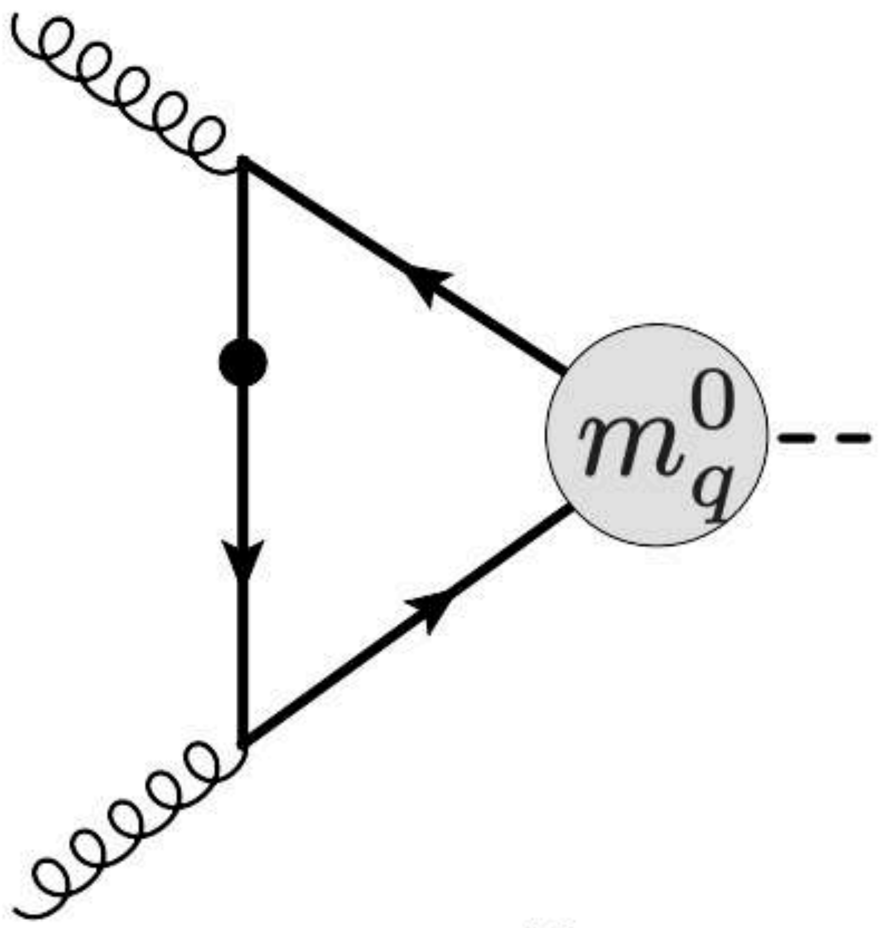
- Comparable uncertainties from different sources
- Largest uncertainties from strong coupling constant (come back later)
- Improving each of it is very challenging but very important!

Dulat, Lazopoulos, Mistlberger, 2018



Full mass dependence of heavy and light quark

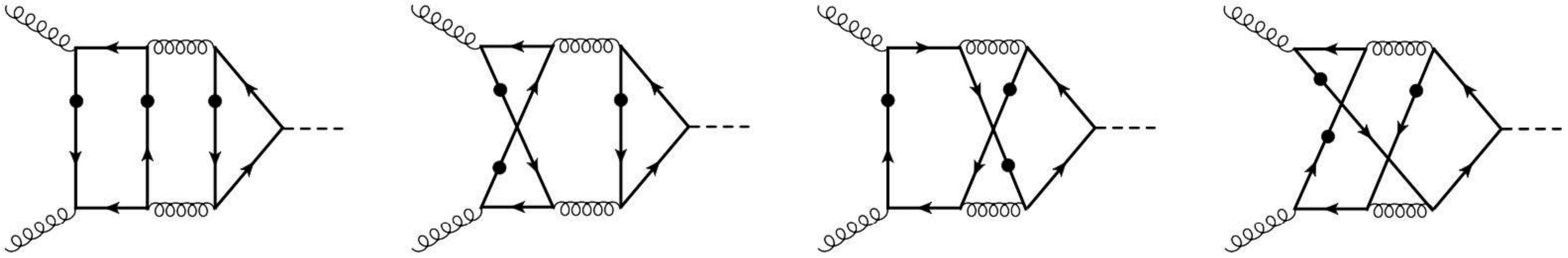
Light-quark loop corrections to ggF



T. Liu, Modi, Penin, 2111.01820

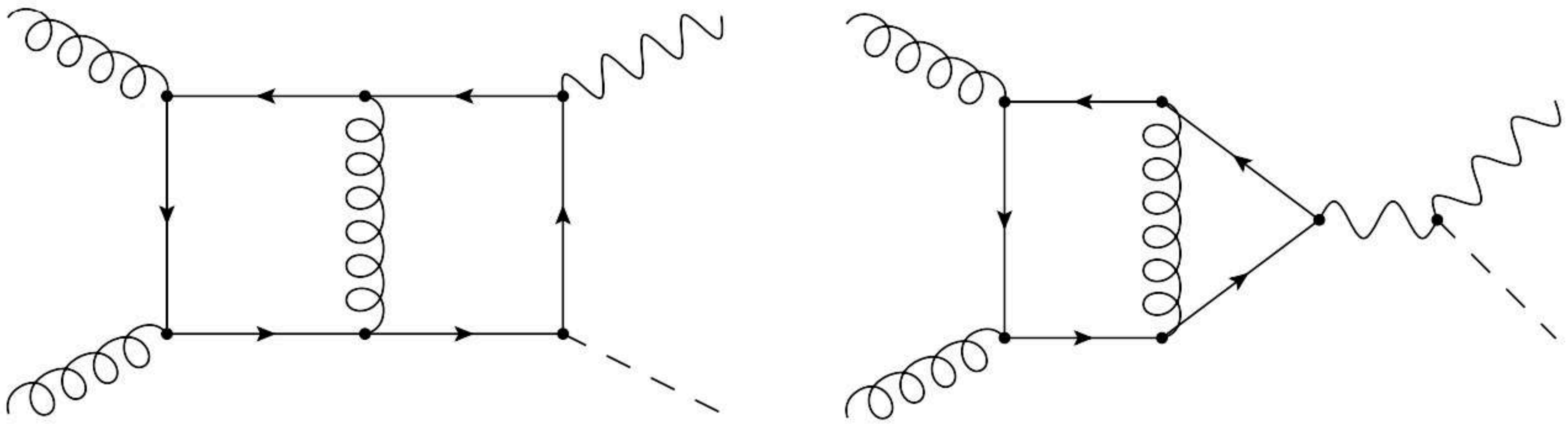
Next-to-Leading Power: $m_q\left[\alpha_s \log^2 \frac{m_q^2}{m_H^2} + \alpha_s^2 \log^4 \frac{m_q^2}{m_H^2} + \cdots\right]$

NNLP: $m_q^3\left[\alpha_s \log^2 \frac{m_q^2}{m_H^2} + \alpha_s^2 \log^4 \frac{m_q^2}{m_H^2} + \cdots\right]$

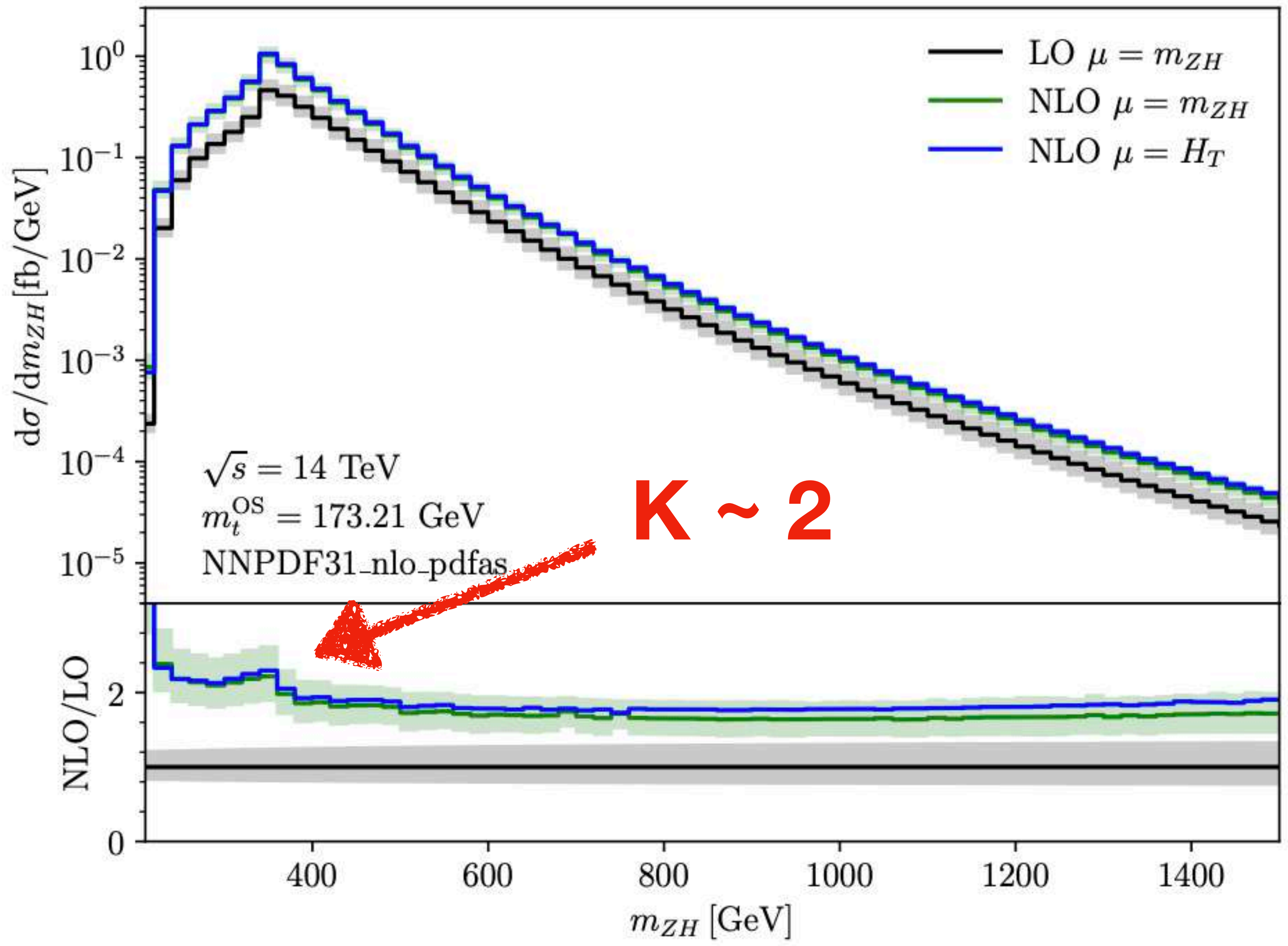


increasing accuracy of the QCD predictions [58]. On the basis of the double-logarithmic analysis we conclude that neglecting the terms suppressed by the mass ratio m_b^2/m_H^2 in such a calculation introduces a relative error at the scale of one percent in every order of the perturbative expansion. Our result can also be generalized to estimate the high-order

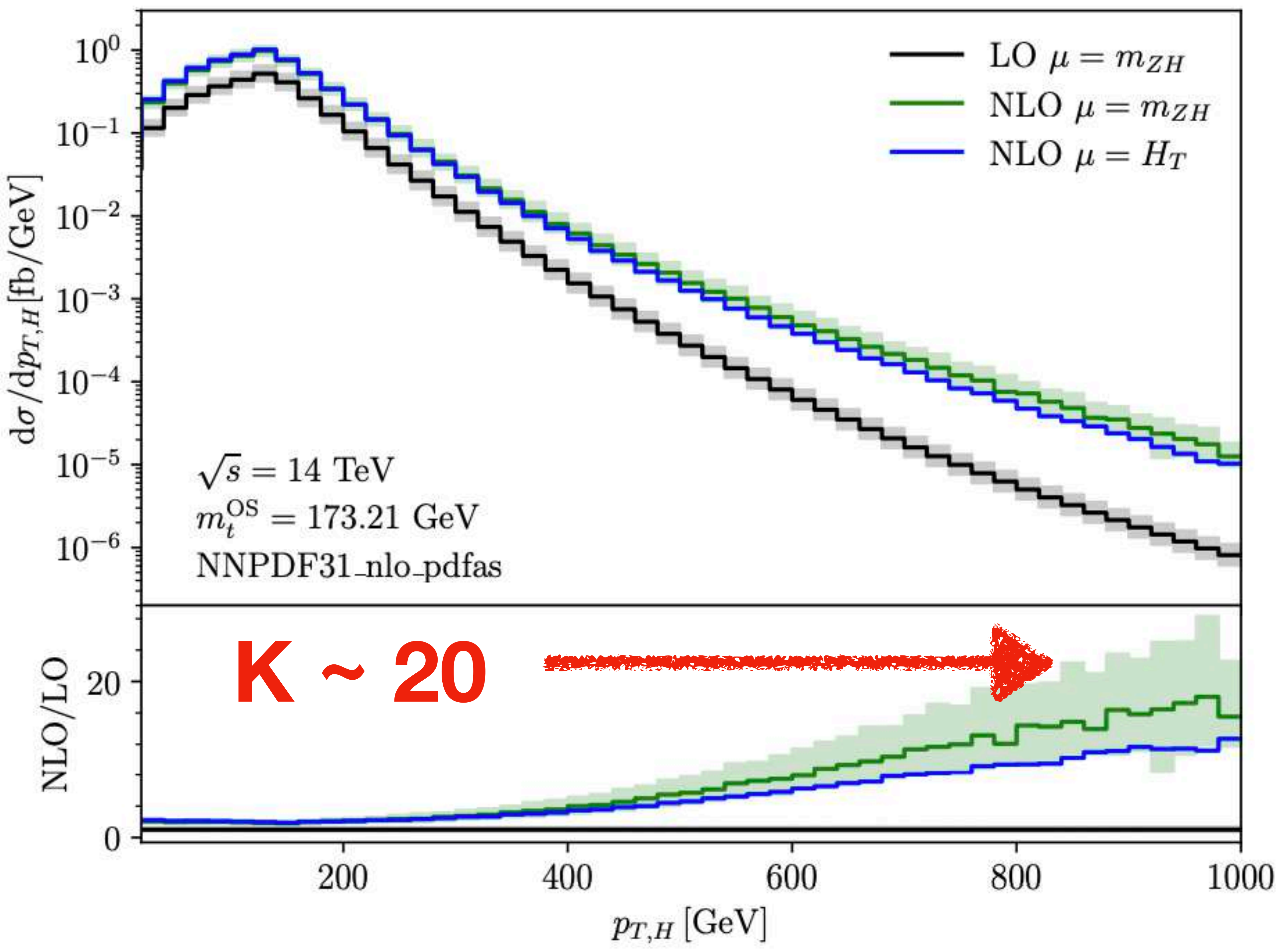
Top-quark loop corrections to ZH production

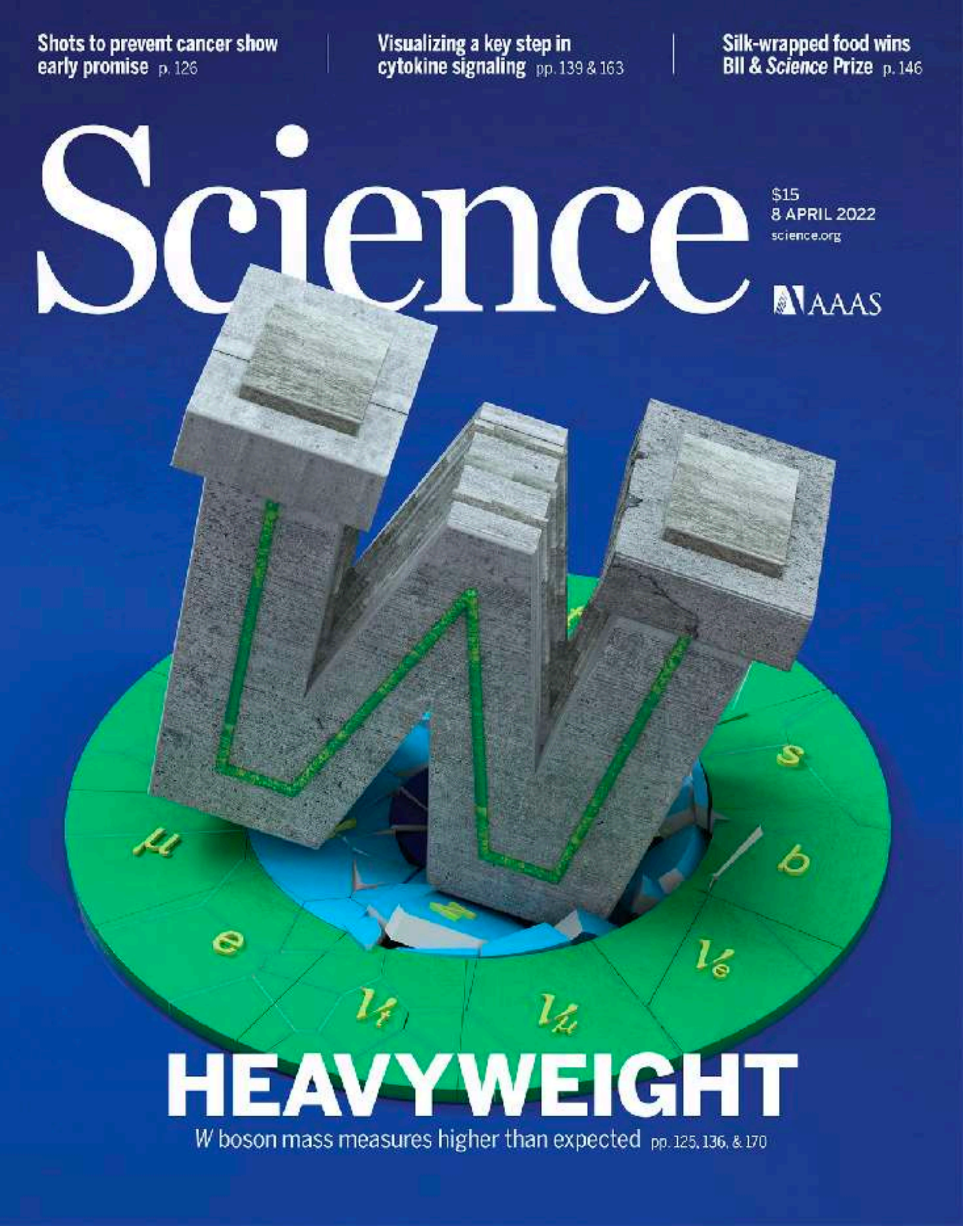


L. Chen, et al., 2204.05225

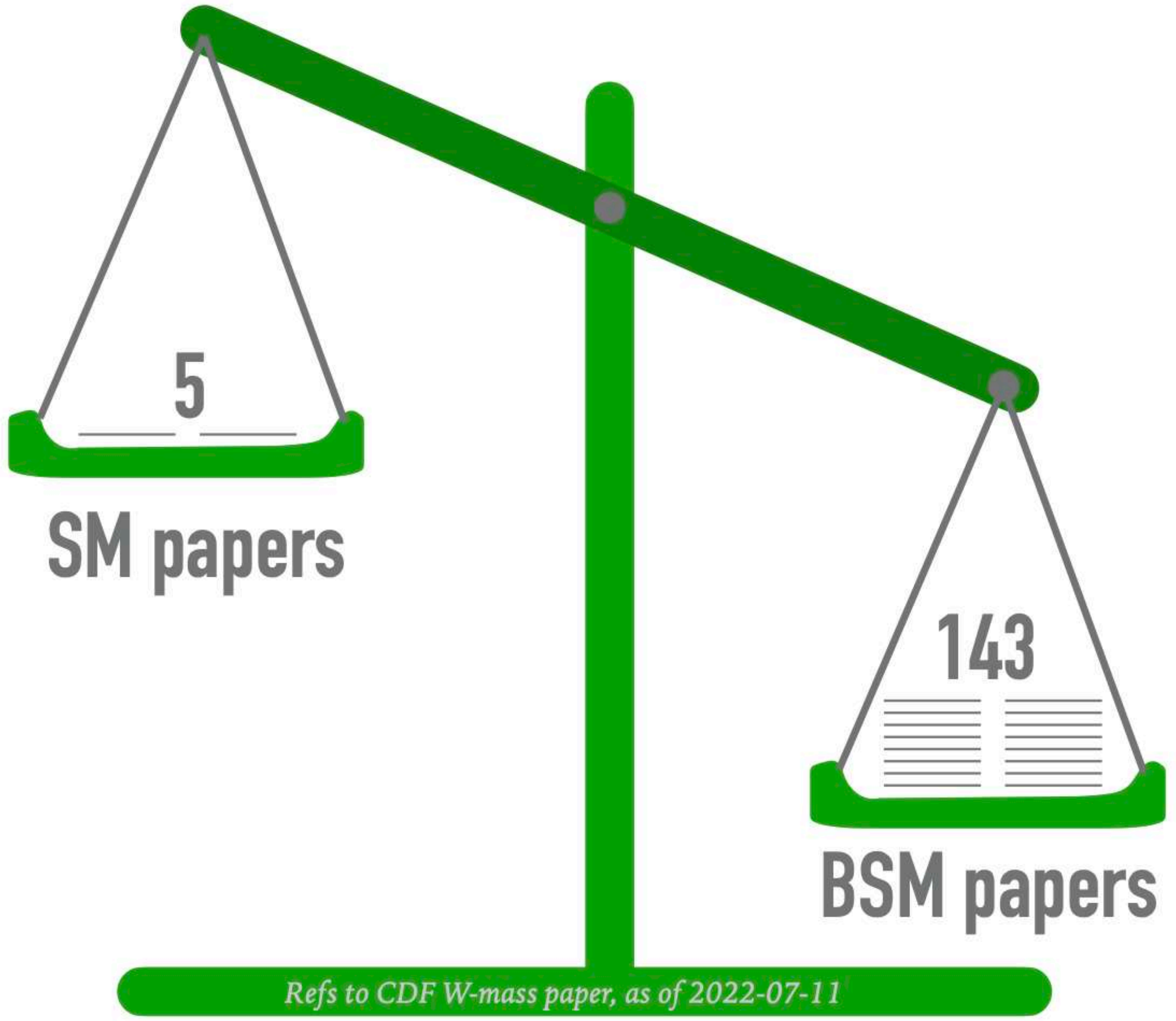


- Simultaneous probing Higgs-quark coupling and Higgs-Z coupling
- Discovery channel for H → bb
- Also used to constraint Higgs-charm coupling



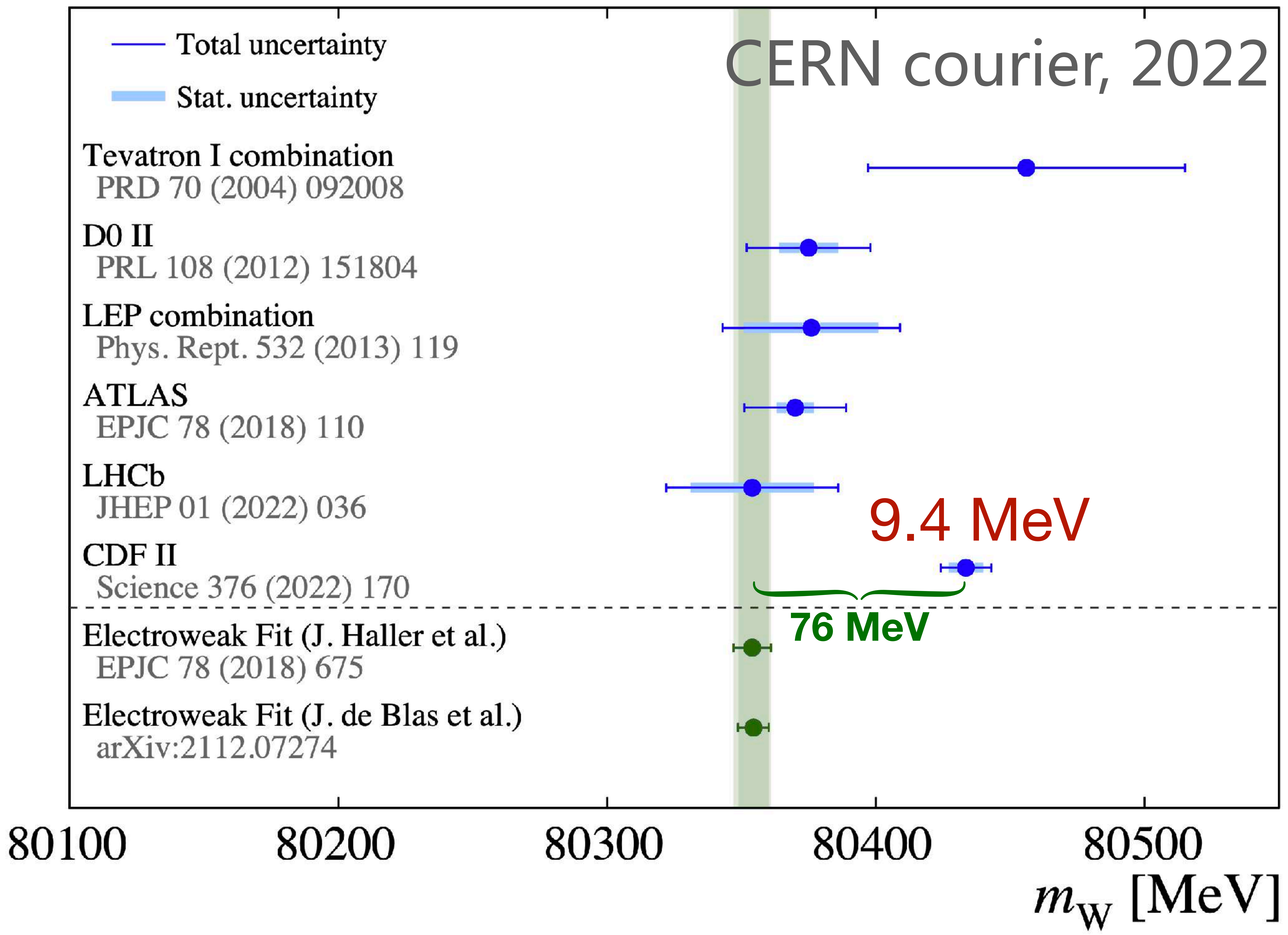


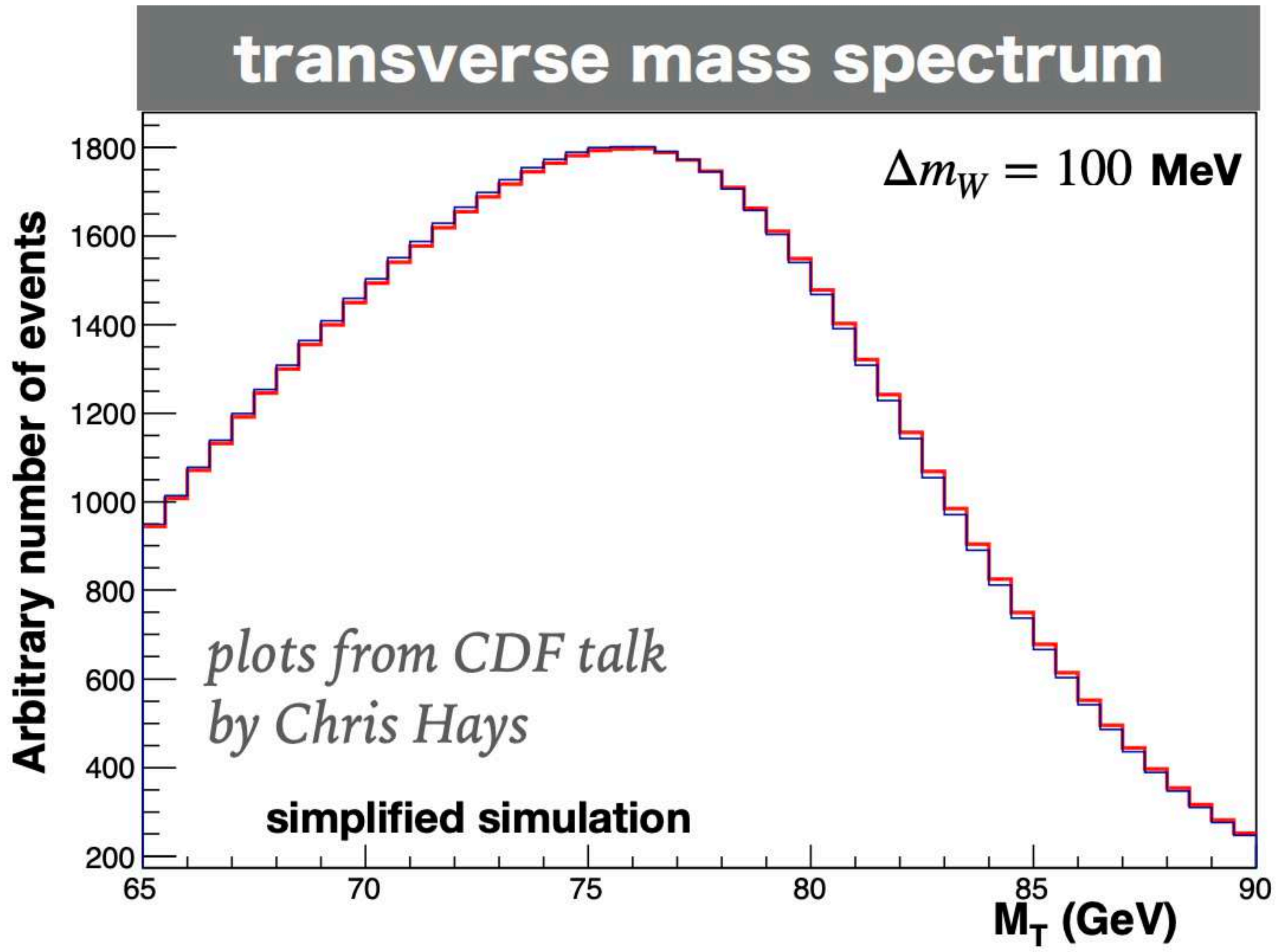
Weighing the W boson, precisely

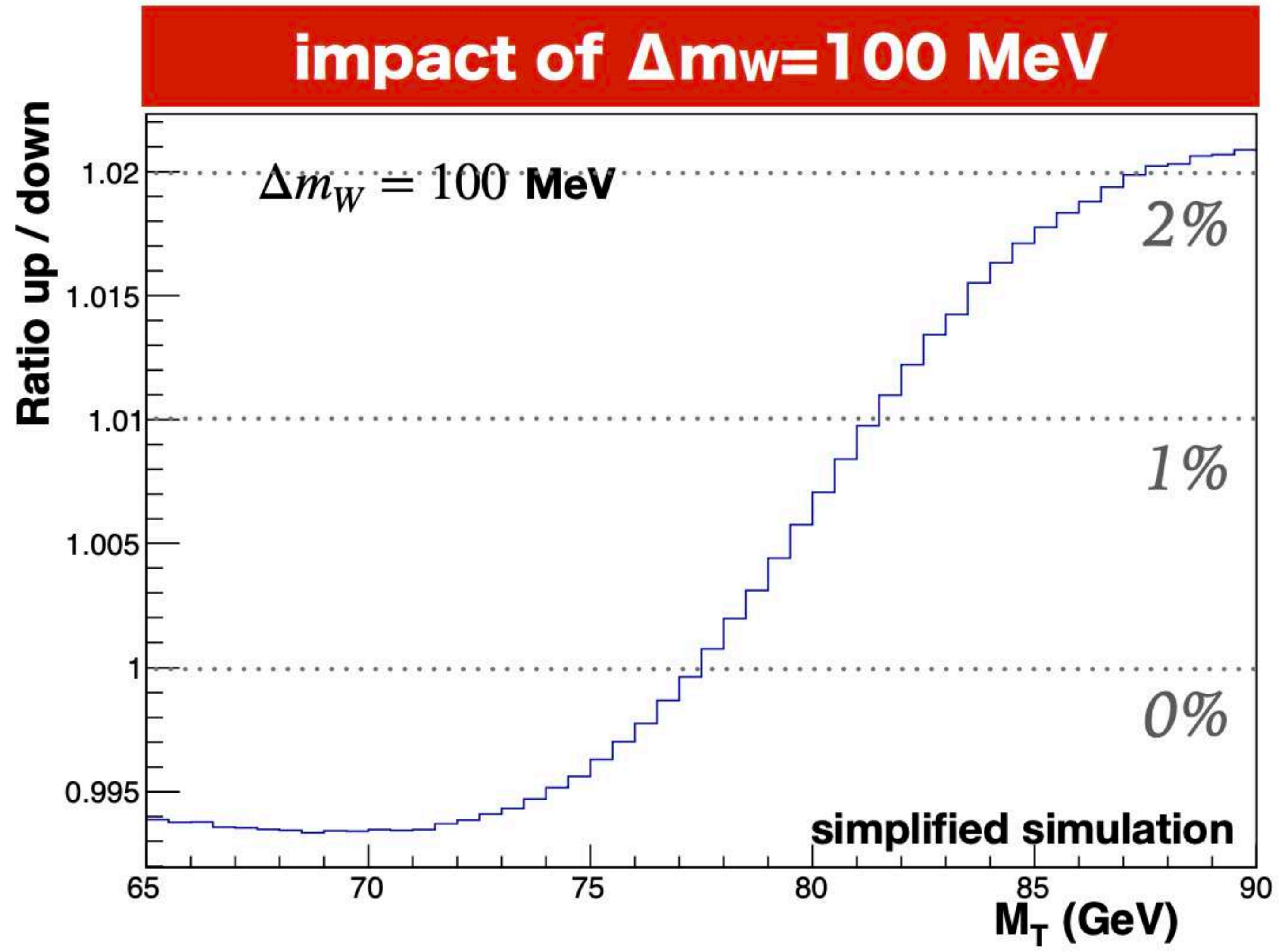


credit: Gavin Salam

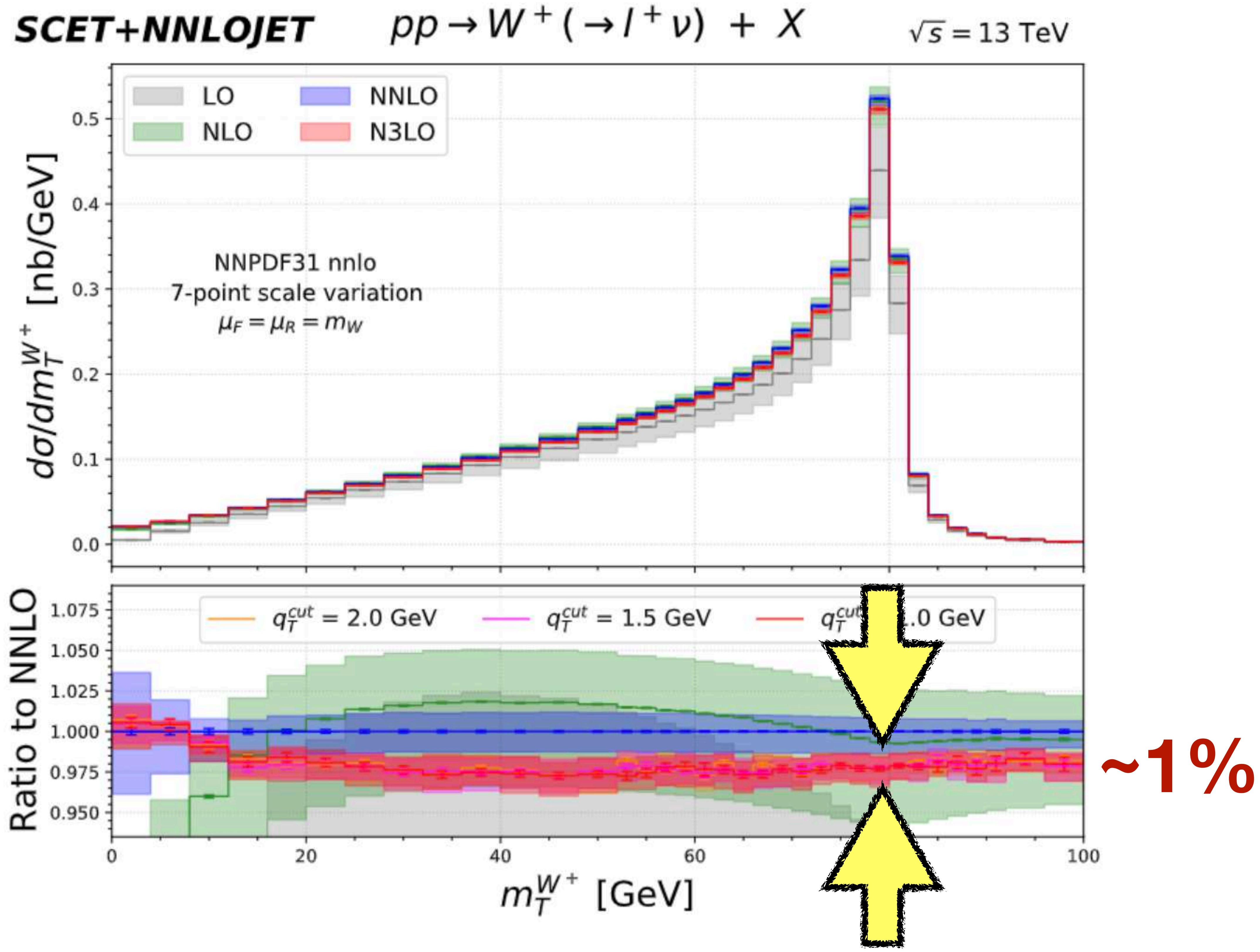
10 MeV precision requires ~0.1% control on distribution

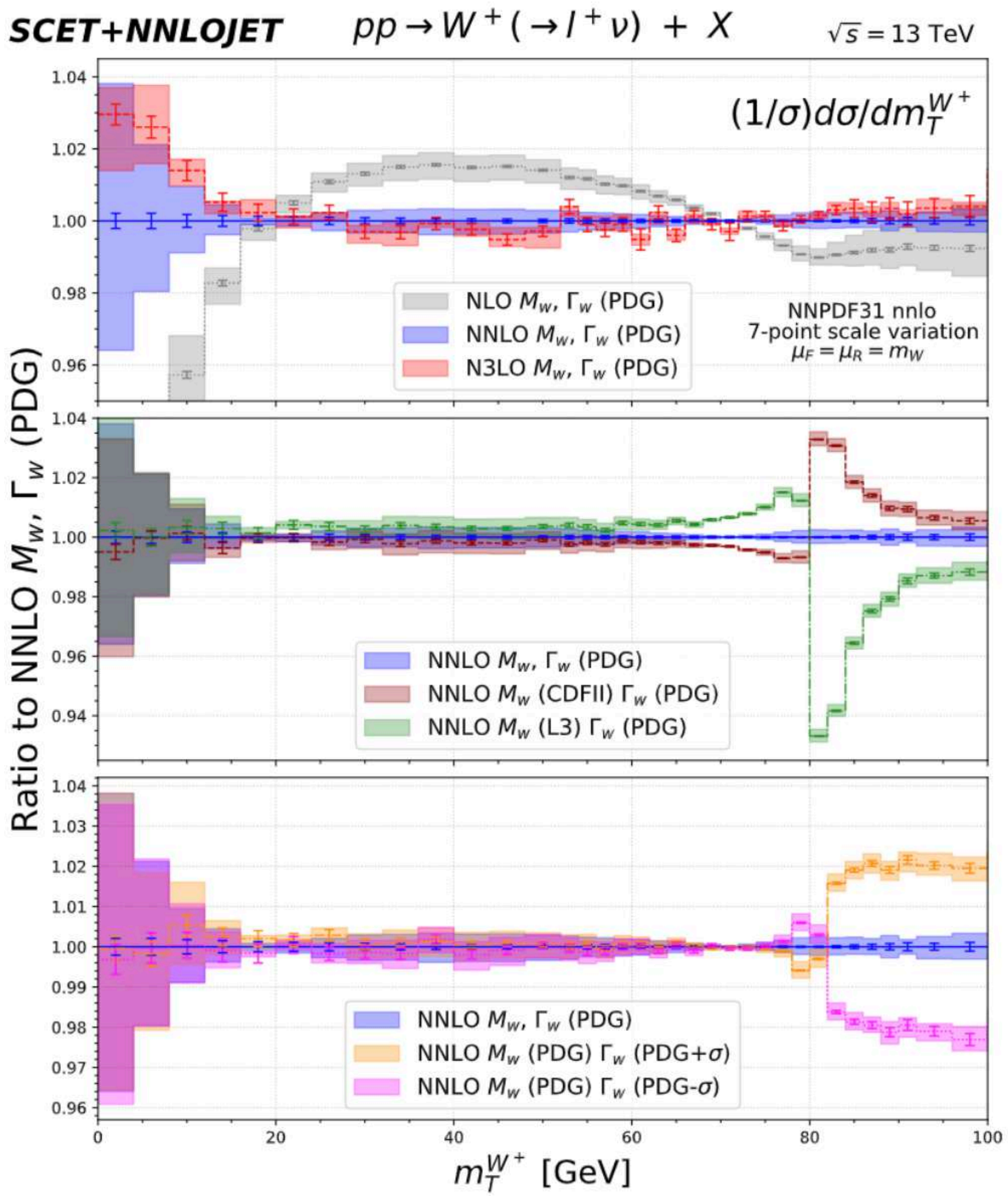






W transverse mass distribution at N3LO





- First N3LO prediction for W transverse mass distribution
- 1% shape uncertainty translate naively to 100 MeV uncertainty in W mass
- Normalized shape much more accurate, ~0.3%. Not enough to explain CDF anomaly

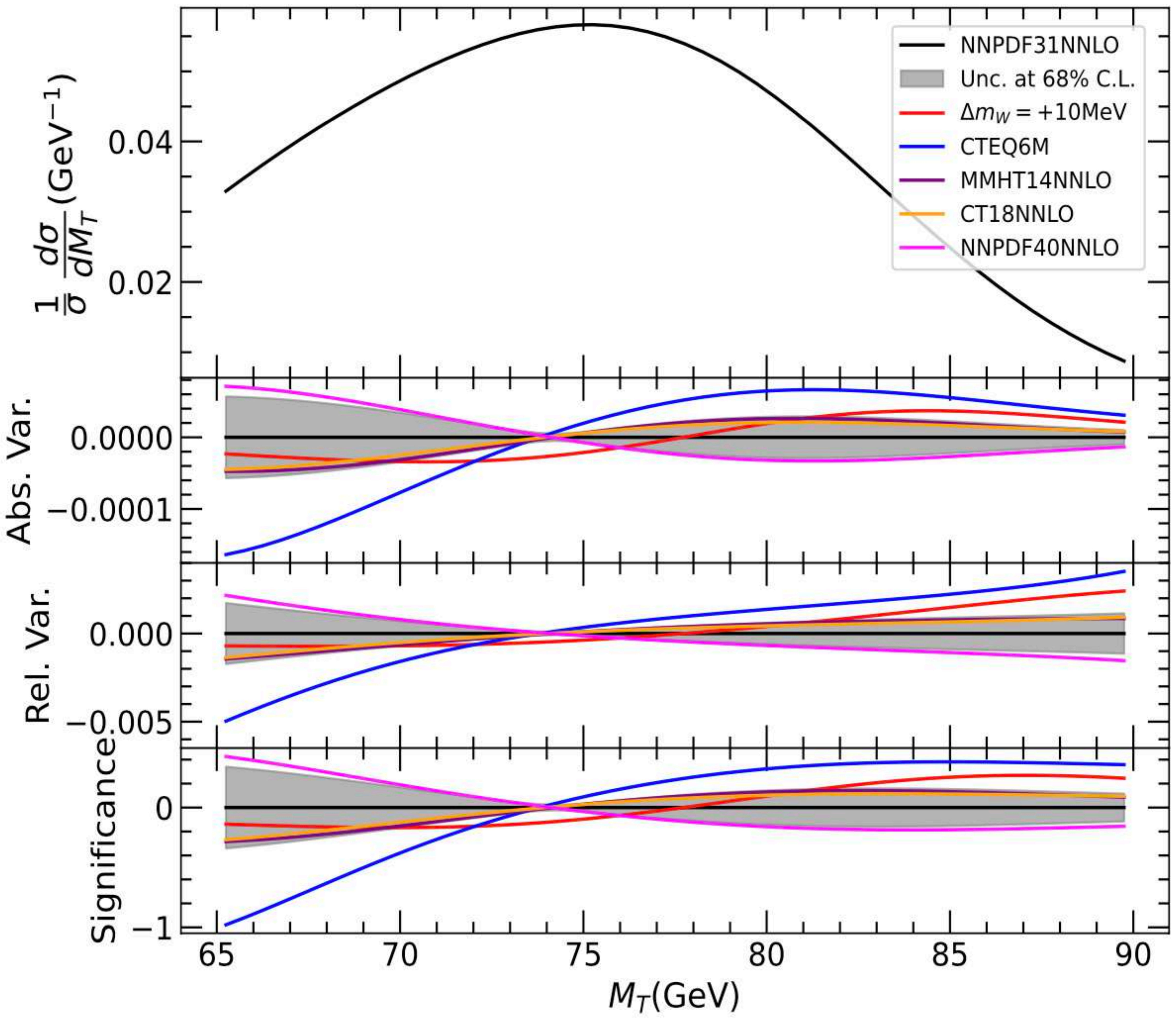
X. Chen, Gehrmann, Glover, Huss, T.Z. Yang, HXZ, 2205.11426

PDF impact to W mass

δM_W in MeV	sta.	NNPDF3.1	CT18	MMHT14	NNPDF4.0	MSHT20
$\langle M_T \rangle$(LO)	–	$0^{+8.3}_{-8.3}$	$-1.0^{+8.3}_{-11.4}$	$-3.3^{+7.4}_{-4.2}$	$+7.8^{+5.1}_{-5.1}$	$-3.1^{+6.7}_{-5.7}$
χ^2 fit (LO)	8.0	$0^{+7.6}_{-7.6}$	$-1.0^{+5.4}_{-8.6}$	$-3.3^{+6.1}_{-3.0}$	$+8.0^{+3.7}_{-3.7}$	$-3.0^{+5.0}_{-4.0}$
$\langle M_T \rangle$(NLO)	–	$0^{+5.9}_{-5.9}$	$-4.2^{+8.8}_{-13.3}$	$-5.0^{+6.7}_{-5.3}$	$+6.9^{+6.2}_{-6.2}$	$-7.6^{+7.9}_{-6.7}$
χ^2 fit (NLO)	8.0	$0^{+4.2}_{-4.2}$	$-4.3^{+5.4}_{-10.1}$	$-5.1^{+4.8}_{-3.4}$	$+7.1^{+4.5}_{-4.5}$	$-7.8^{+5.7}_{-4.5}$
CDF	9.2	$0^{+3.9}_{-3.9}$	–	–	–	–

- spread of predictions from different PDF sets can be larger than the PDF uncertainty predicted by a specific PDF set

- PDF variations can not explain CDF discrepancy



J. Gao, D.Y. Liu, K.P. Xie, 2205.03942

Update from ResBos2 for W mass measurement

- One comment to CDF measurement is that they used an previous version of ResBos, which does not match the best QCD accuracy (N3LL)

Sudakov factor

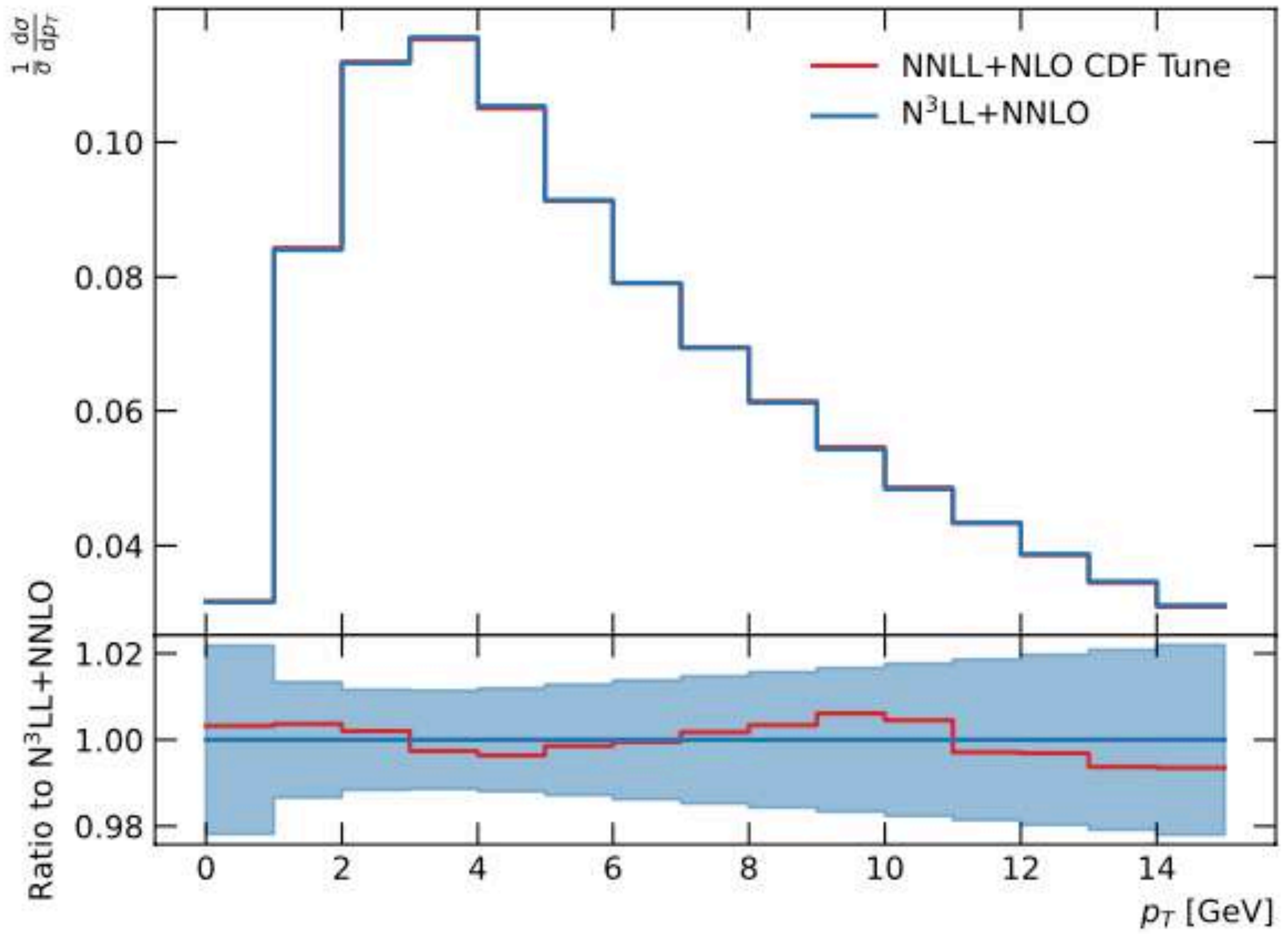
$$S(b) = \int_{C_1^2/b^2}^{C_2^2 Q^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2}\left[\ln\left(\frac{C_2^2 Q^2}{\bar{\mu}^2}\right) A(\bar{\mu}, C_1) + B(\bar{\mu}, C_1, C_2)\right]$$

Henn, Korchemsky, Mistlberger, 1911.10174
von Manteuffel, Panzer, Schabinger, 2002.04617

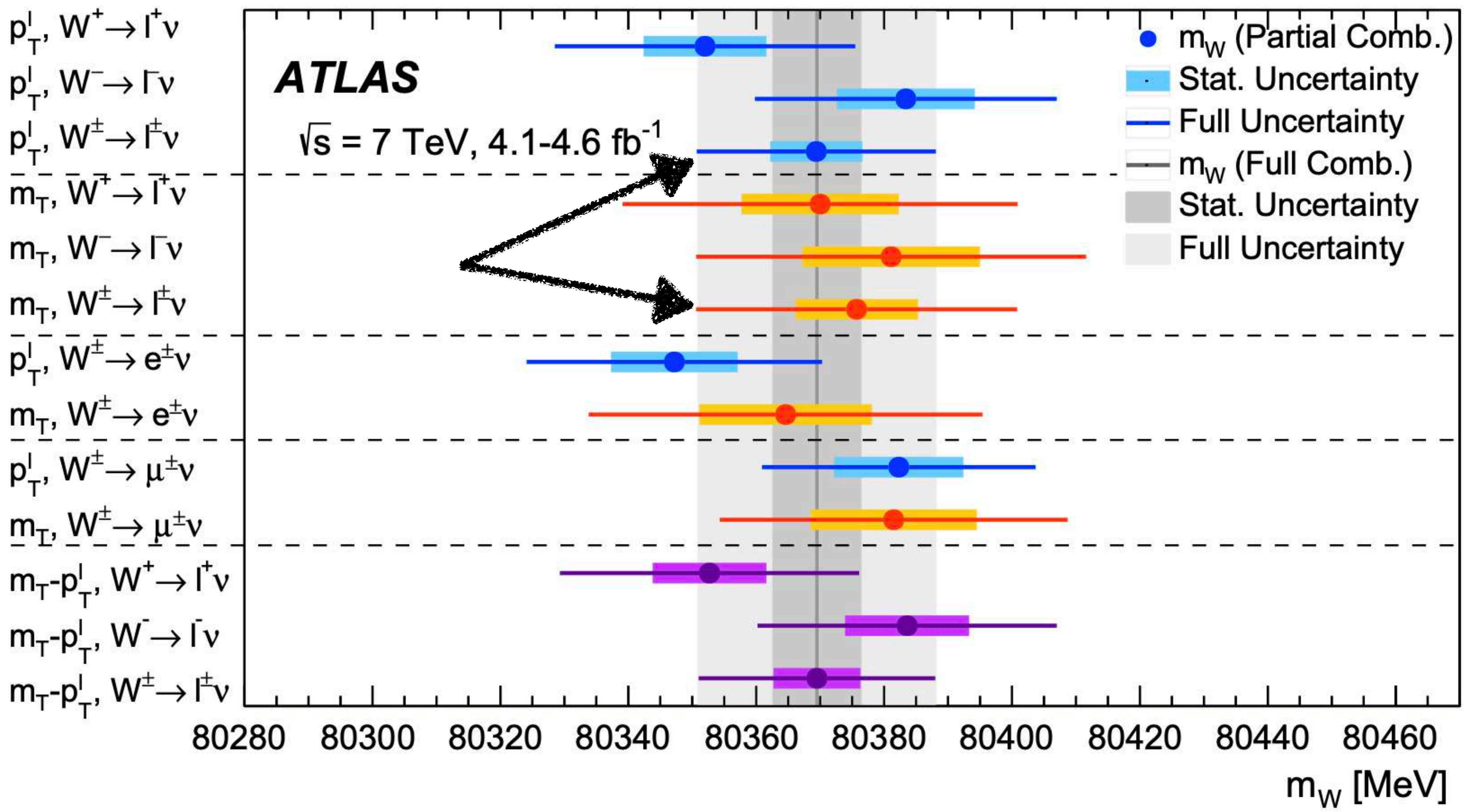
Y. Li, HXZ, 1604.01404

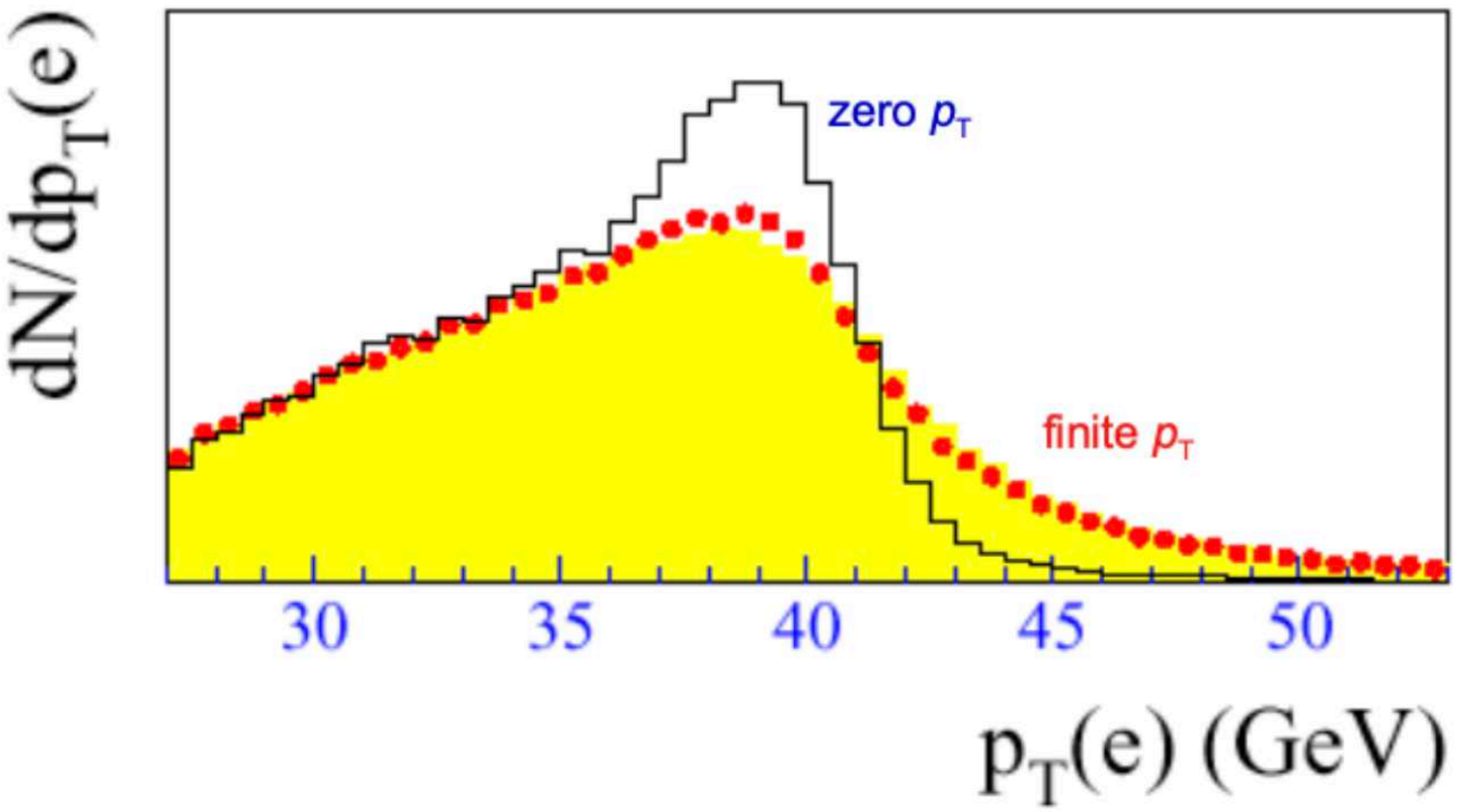
The recent CDF W mass measurement of 80,433 ± 9 MeV is the most precise direct measurement. However, this result deviates from the Standard Model predicted mass of 80,359.1 ± 5.2 MeV by 7σ. The CDF experiment used an older version of the ResBos code that was only accurate at NNLL+NLO, while the ResBos2 code is able to make predictions at N^{3}LL+NNLO accuracy. We determine that the data-driven techniques used by CDF capture most of the higher order corrections, and using higher order corrections would result in a decrease in the value reported by CDF by at most 10 MeV.

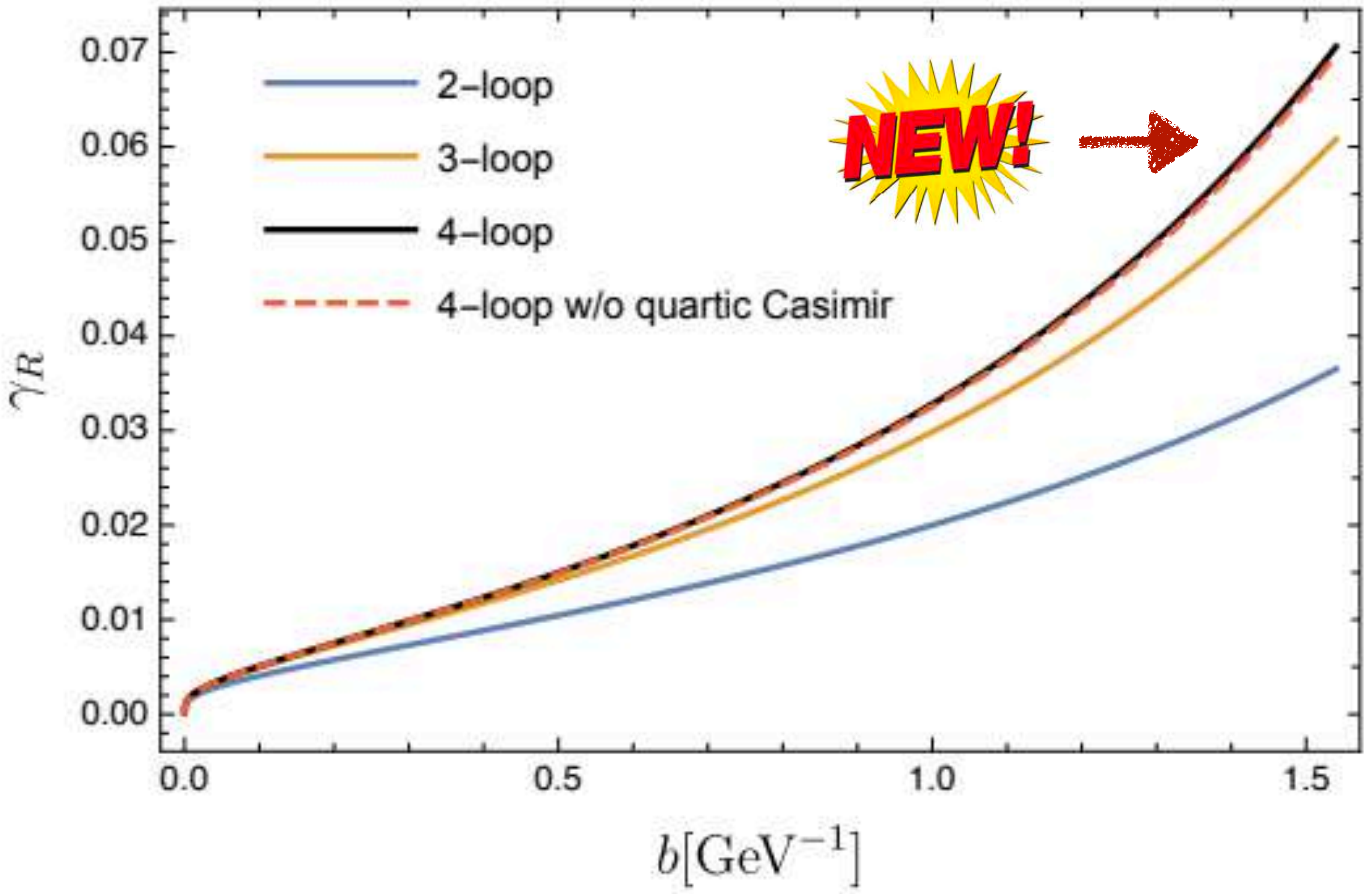
J. Issacson, Y. Fu, C.-P. Yuan, 2205.02788



W boson mass measurement at the LHC



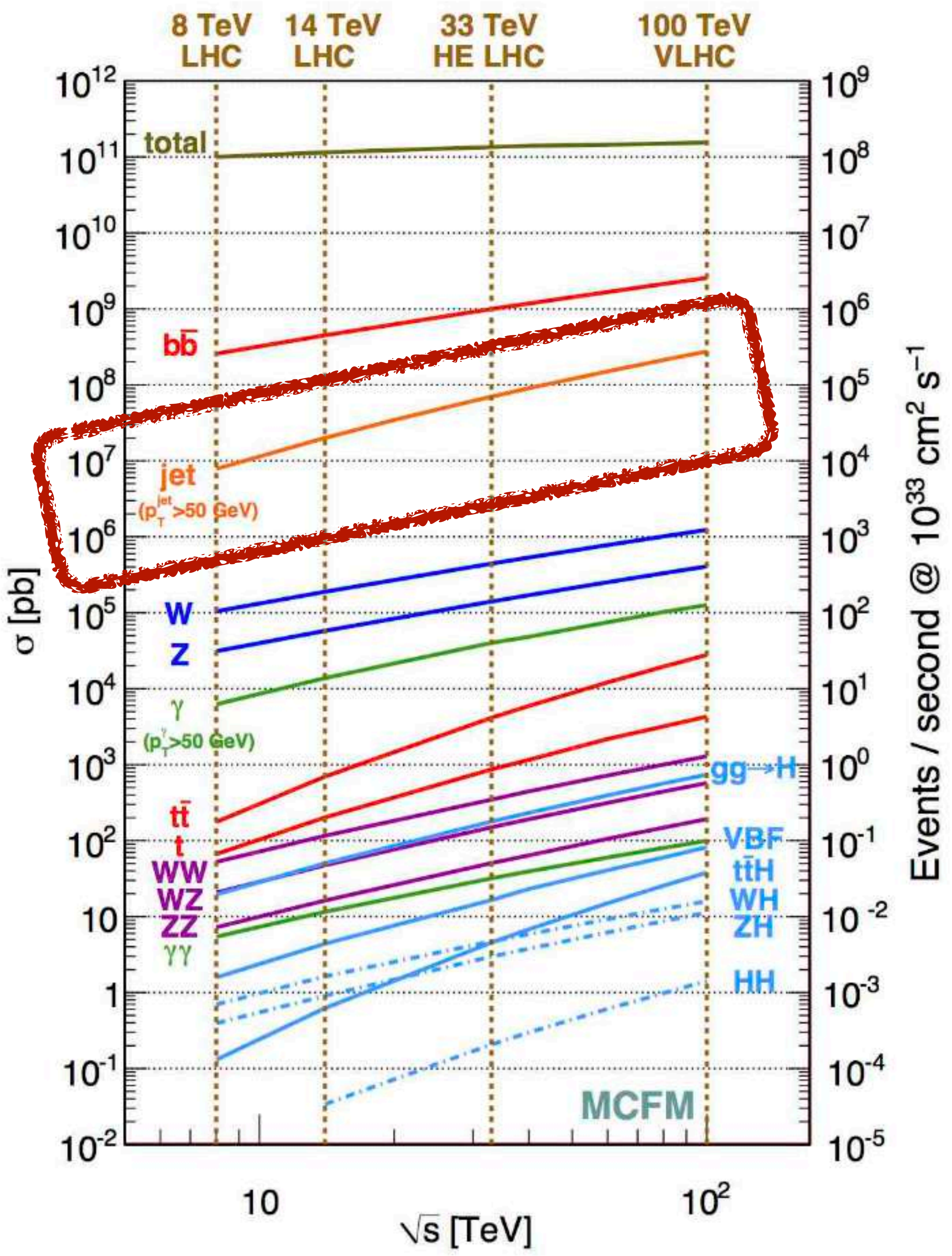


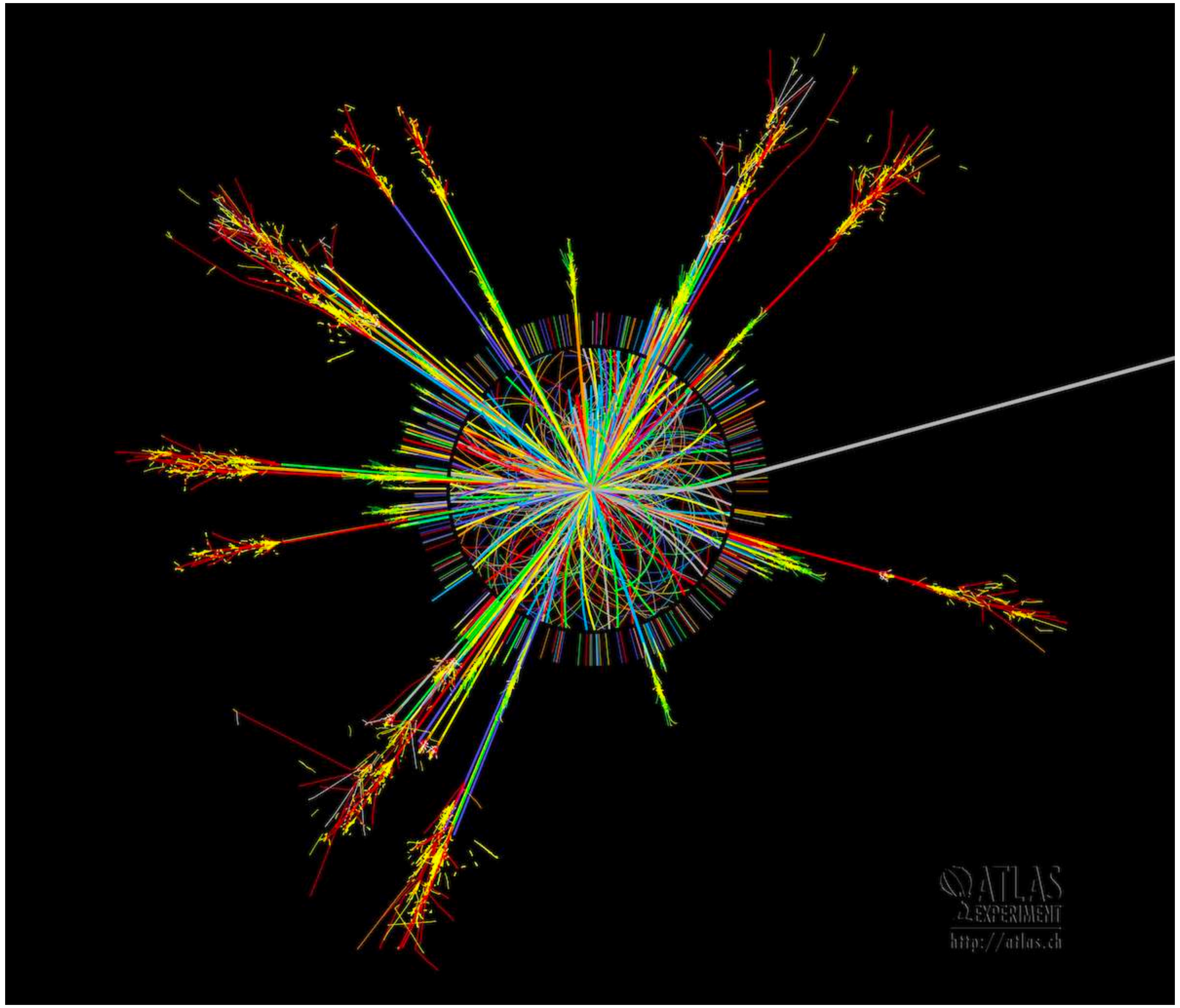


Moult, HXZ, Y.J. Zhu, 2205.02242

Duhr, Mistlberger, Vita, 2205.02249

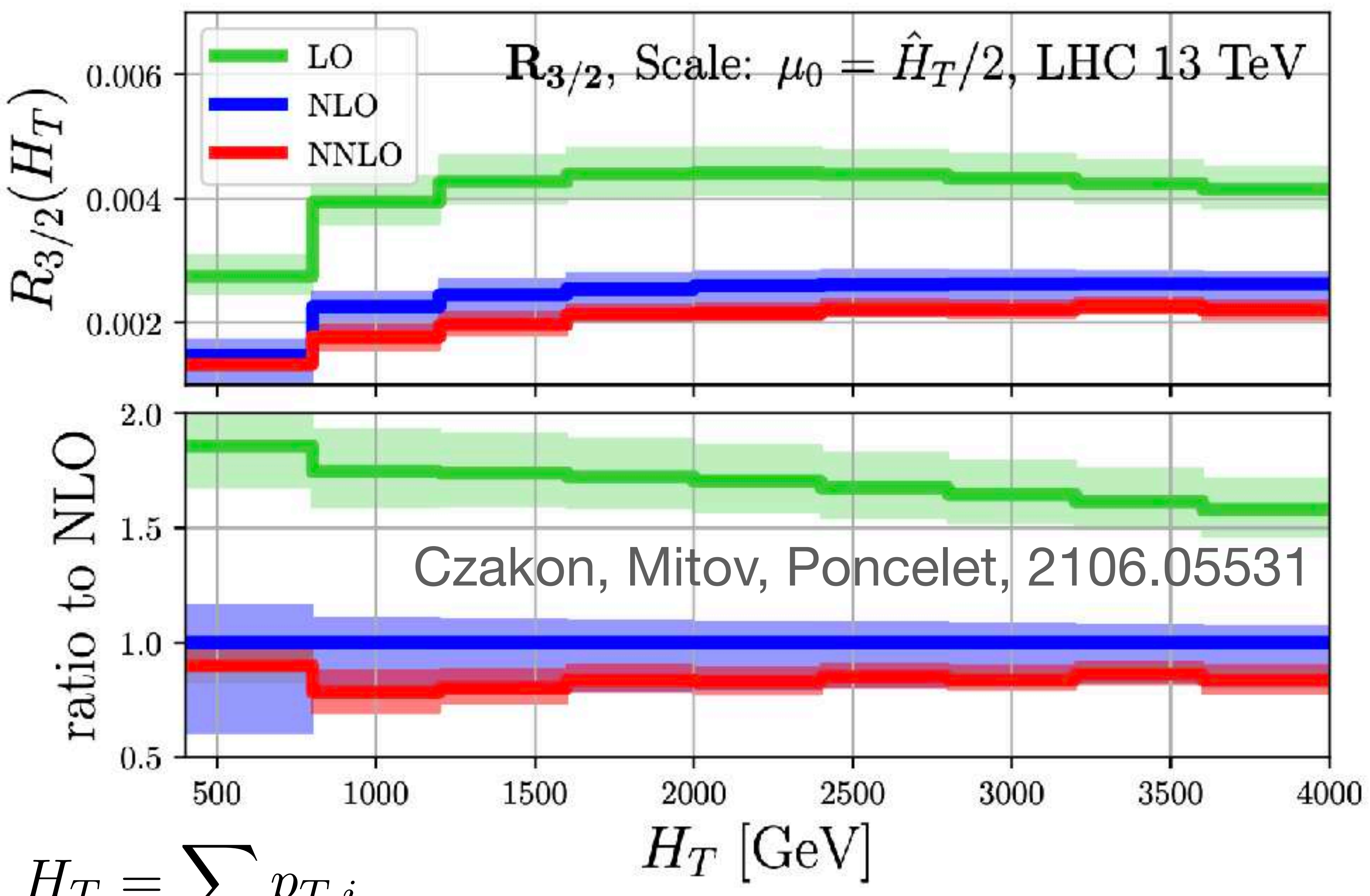
- LHC aims for 10 MeV uncertainty
- Current theory uncertainties ~ 100 MeV
- Much theoretical efforts are needed: (1) N4LL resummation; (2) power corrections; (3) non-perturbative TMD; (4) QCD+EW



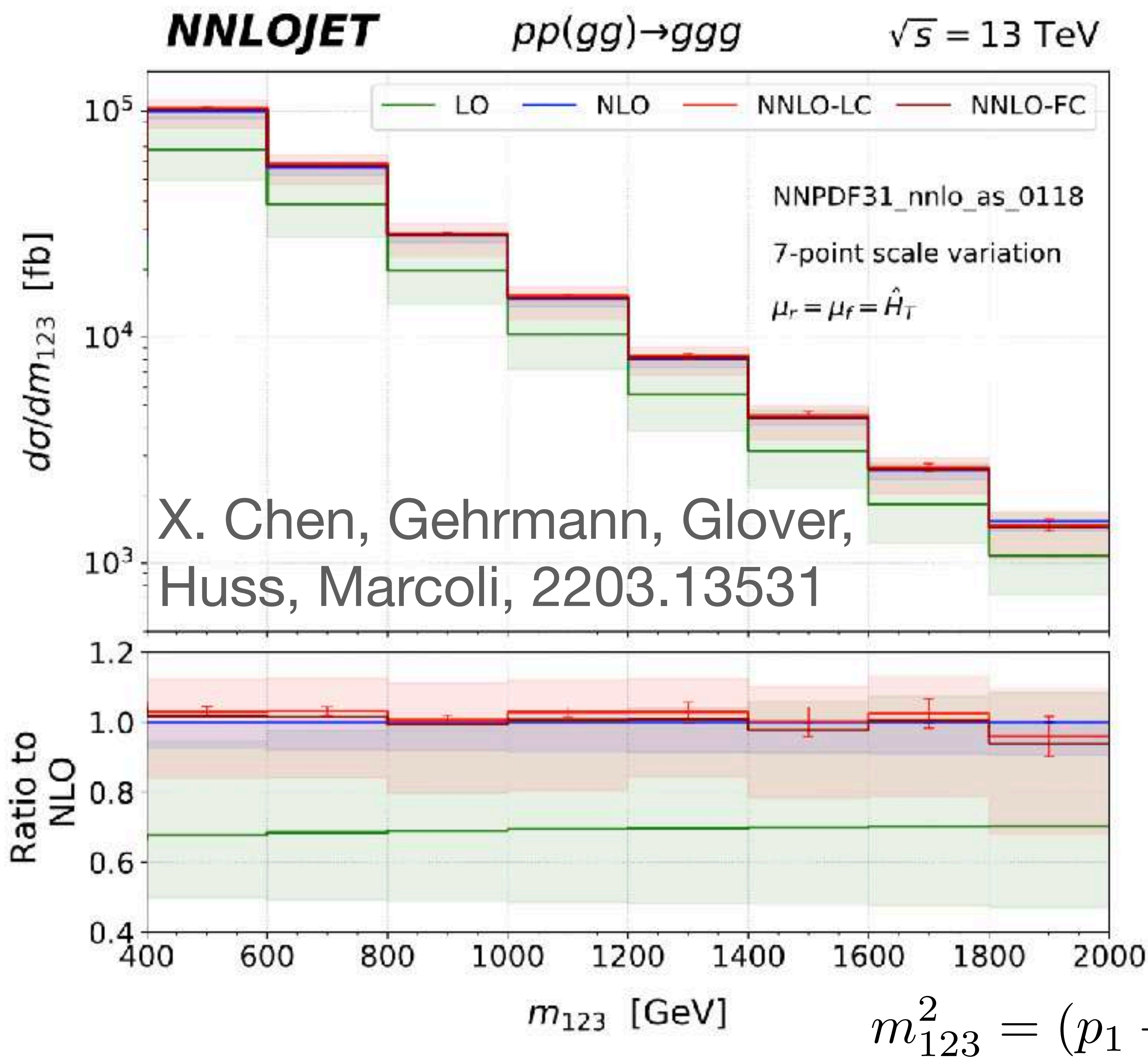


Jets and their inner structure

Three jet production at NNLO



$H_T = \sum_i p_{T,i}$



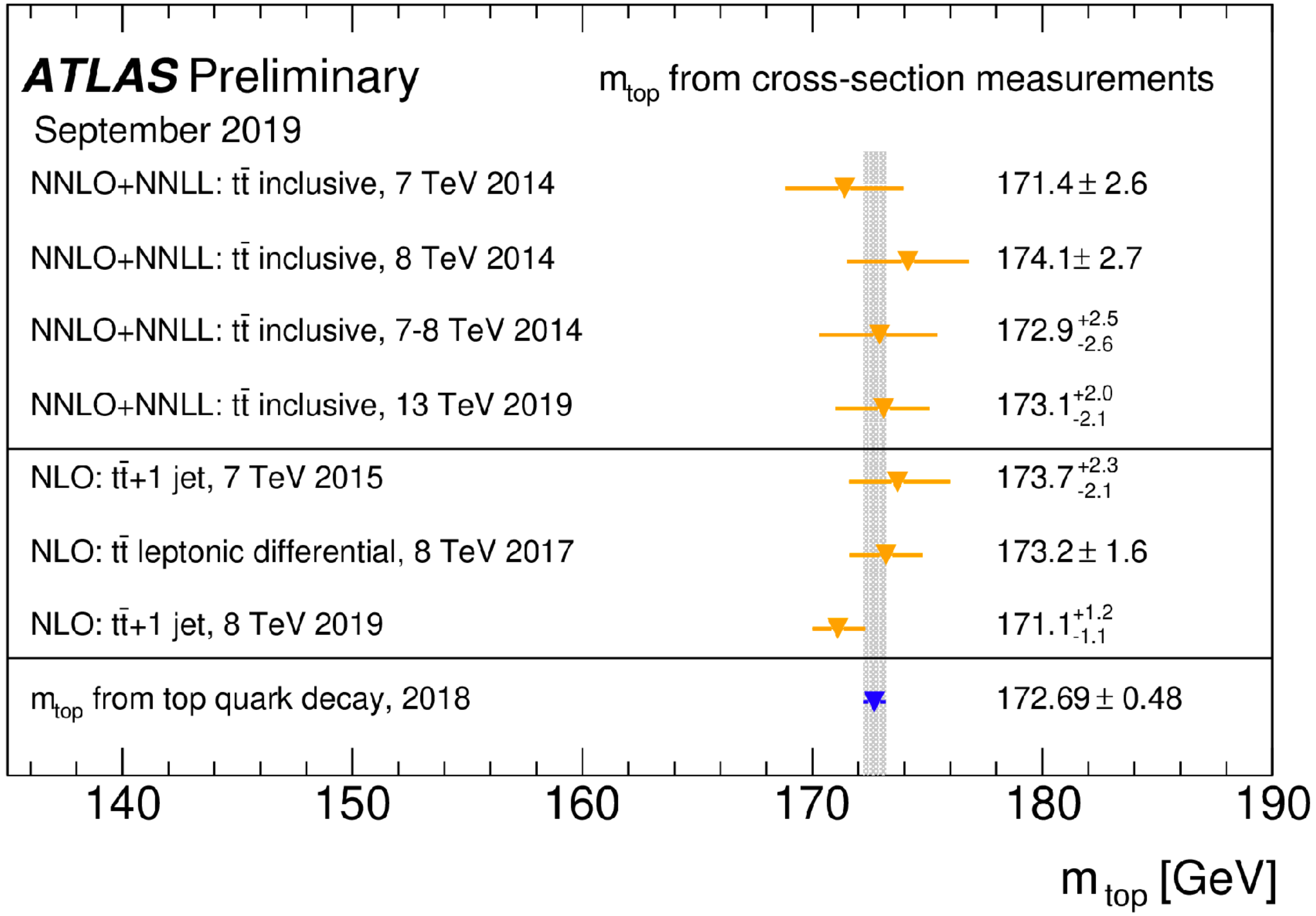
$m_{123}^2 = (p_1 + p_2 + p_3)^2$

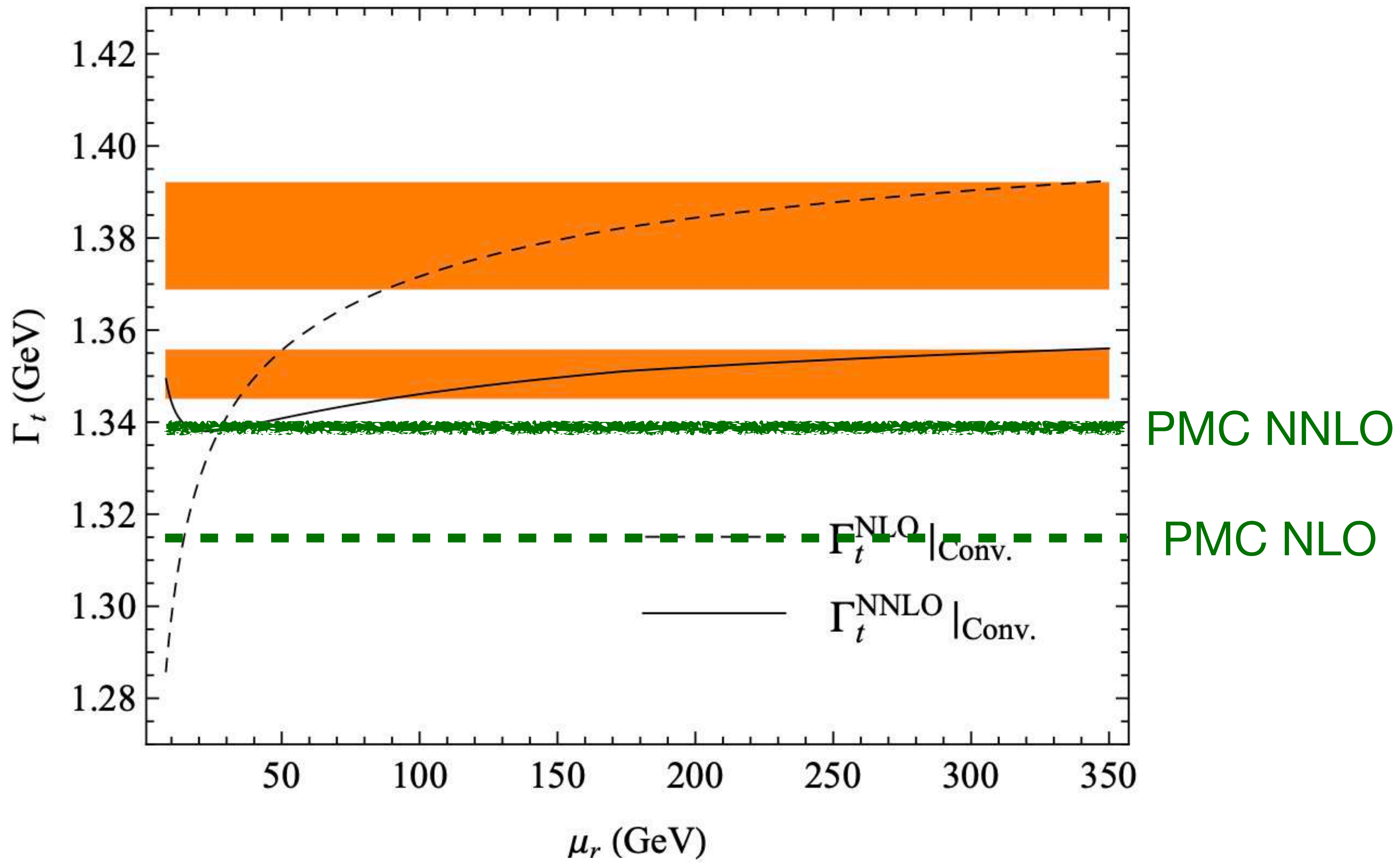
- 3/2 jet ratio is important for α_s measurement
- Giant NLO K factor. NNLO stabilize the ratio and smaller scale uncertainties
- How to better estimate scale uncertainties? (1) resummation (2) PMC scale

Top quark decay at NNLO with PMC

Principle of Maximal Conformality: absorbing all-order beta functions to α_s

R.Q. Meng, S.Q. Wang, T. Sun, C.Q. Luo, J.M. Shen, X.G. Wu, 2002.09978



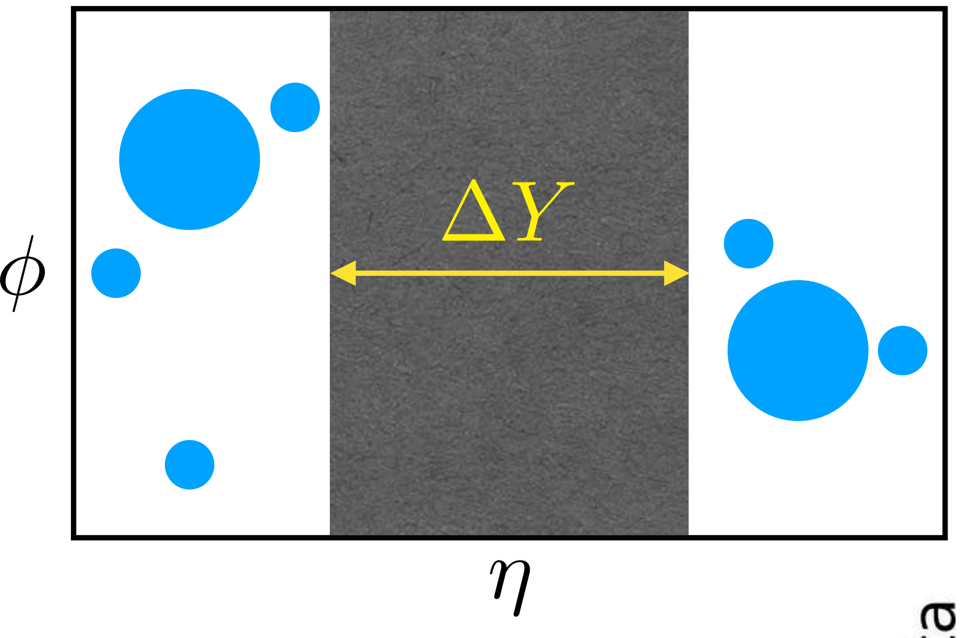


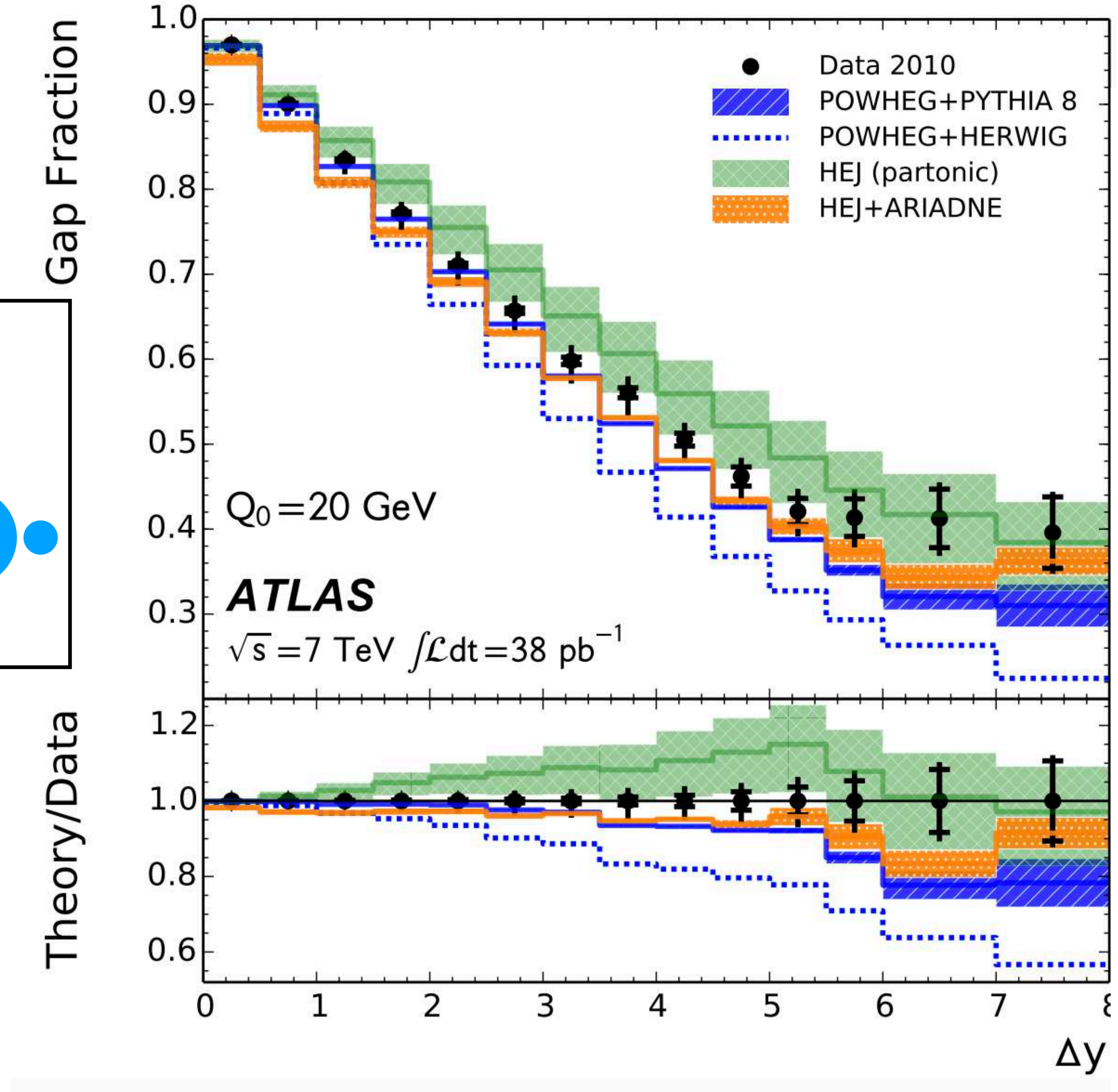
$$\Gamma_t^{\mathrm{tot}}|_{\mathrm{PMC}} = 1.3383^{+0.0275+0.0016}_{-0.0271-0.0017} \pm 0.0023\ \mathrm{GeV}$$

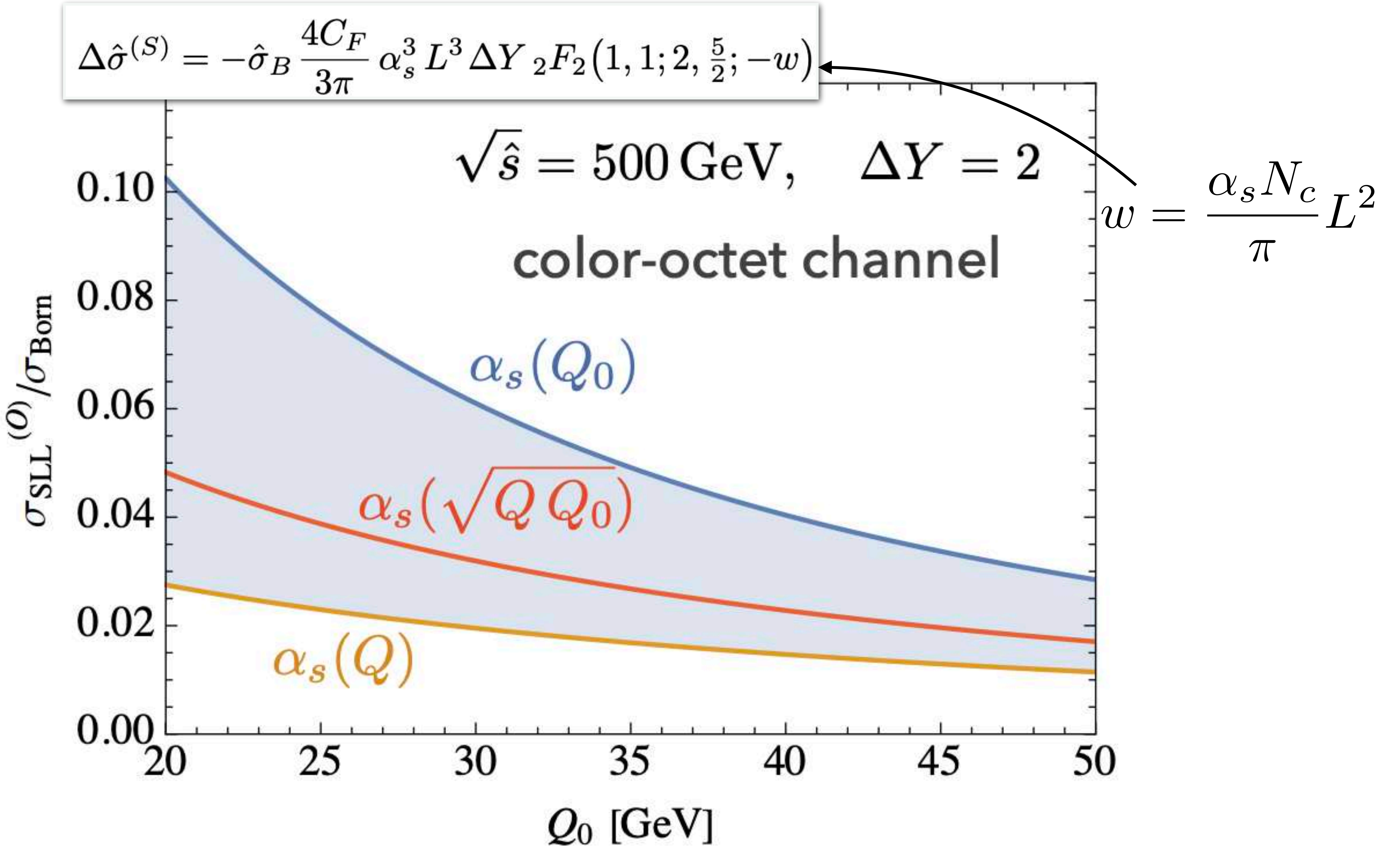
δm_t $\delta\alpha_s$ Missing higher orders

Resummation of super leading logarithms

Becher, Neubert, D.Y. Shao, 2107.01212





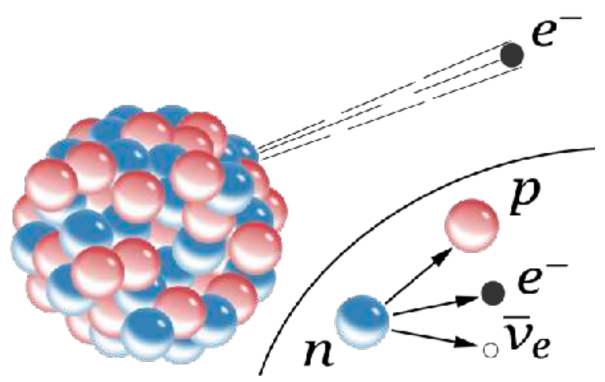


- Jets production with large rapidity gap is important in VBF Higgs production, as well as probing BFKL dynamics.
- It has been known for 15 years the existence of a class of super-leading logarithms in non-global observables [J. Forshaw, A. Kyrieleis, M. Seymour]. Five-loop explicit calculation available, but no resummation formula known. Effects not capture by parton shower.
- Recently an all-order analytic resummation formula become available, allowing for the first time estimating impacts of SLL to gap fraction.

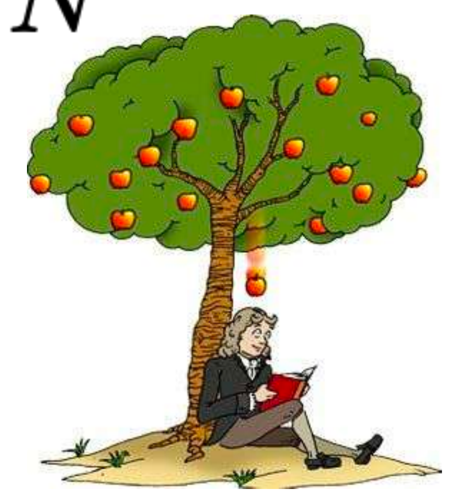
α_s from jet substructure

$$\frac{\delta\alpha}{\alpha} \simeq 10^{-10}$$

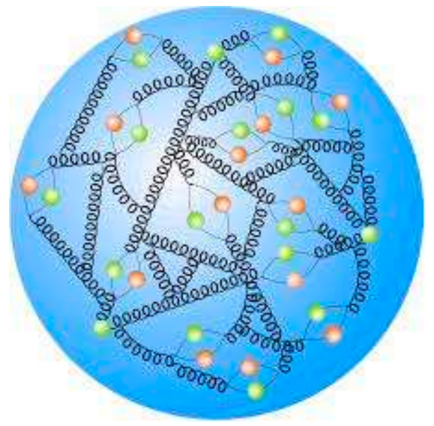
$$\frac{\delta G_F}{G_F} \simeq 10^{-8}$$



$$\frac{\delta G_N}{G_N} \simeq 10^{-5}$$



$$\frac{\delta\alpha_S}{\alpha_S} \simeq 0.01$$

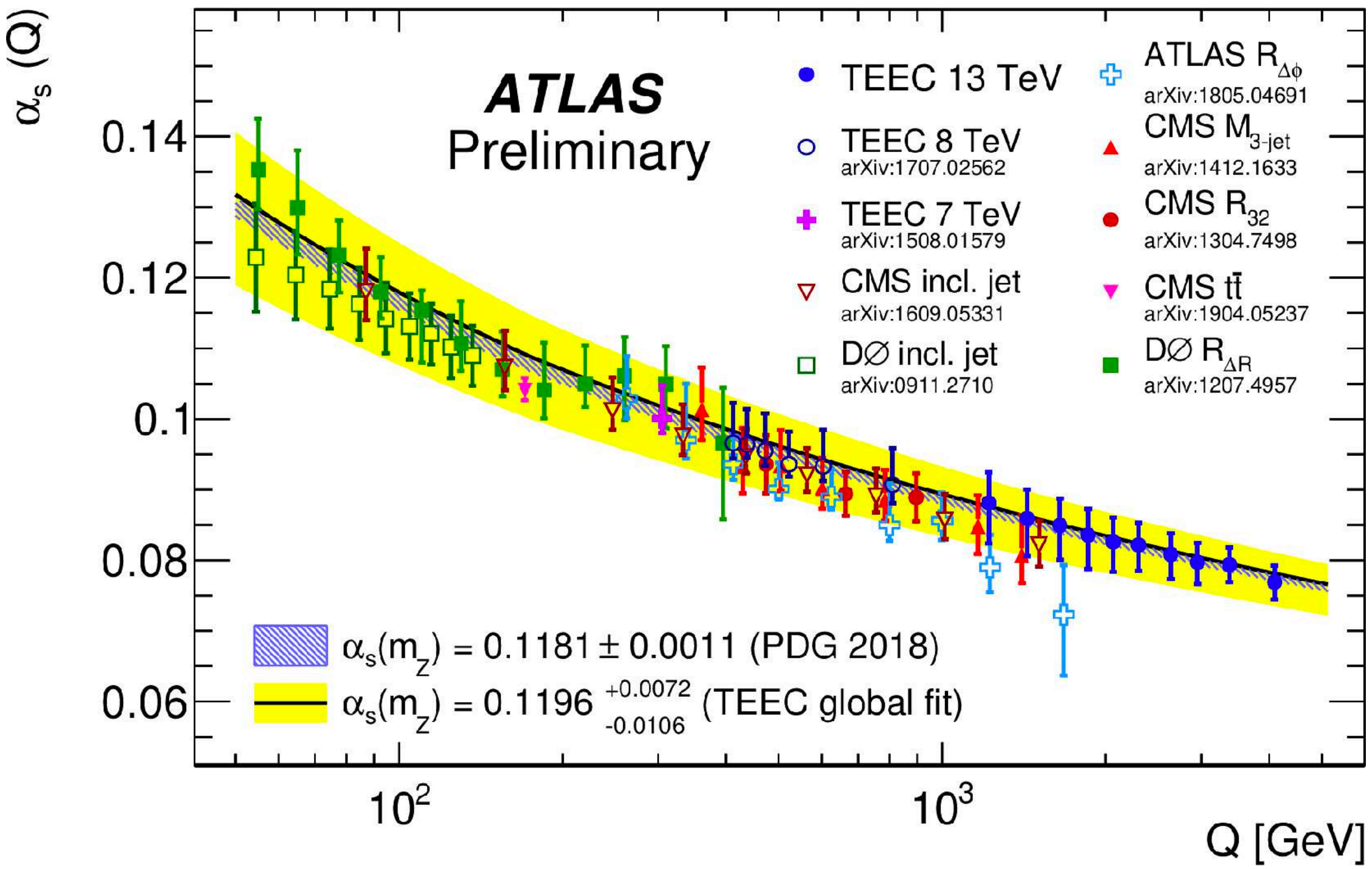


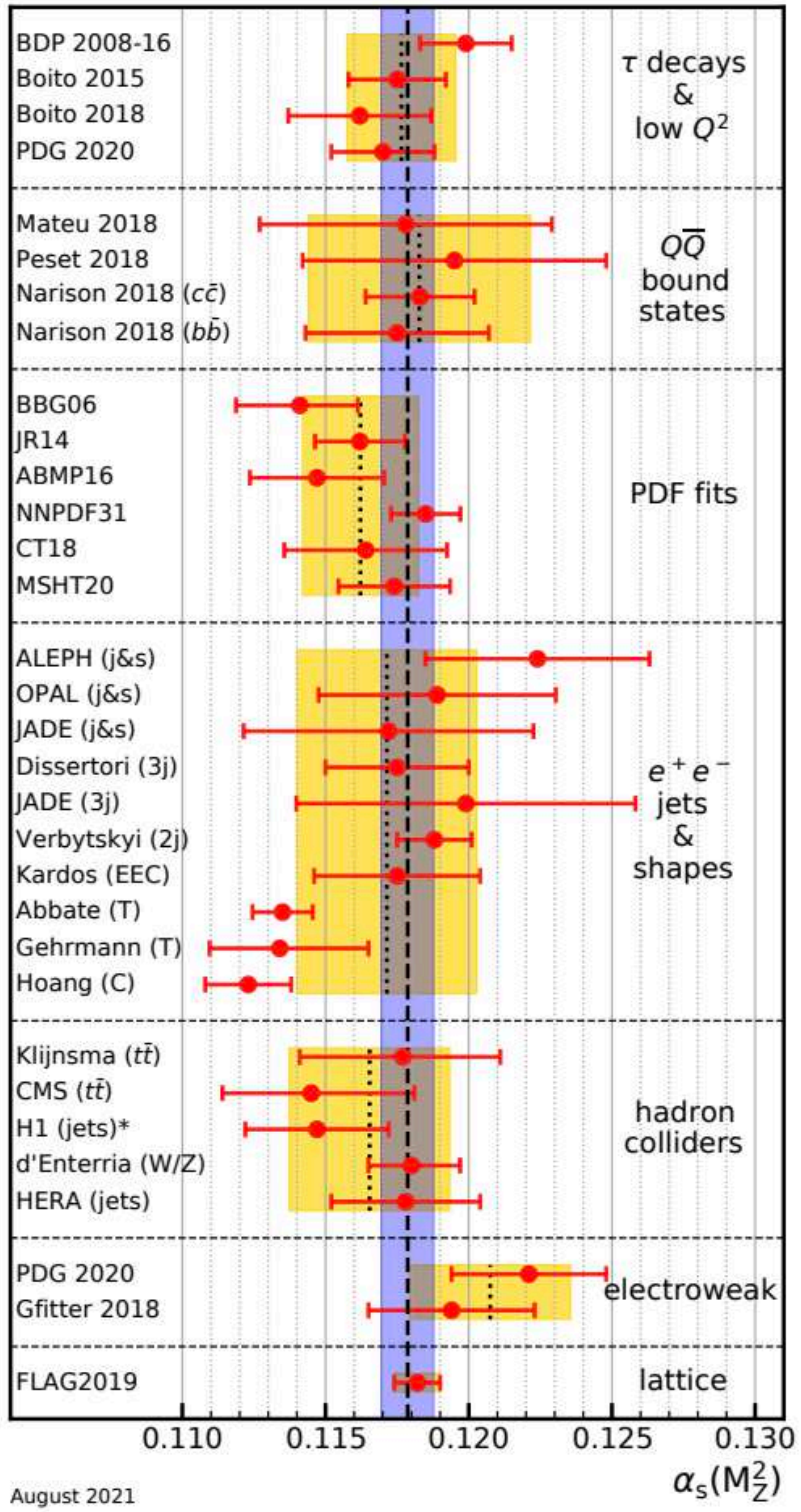
- Among the four fundamental constant, α_s have the largest uncertainty
- α_s is the single largest source of theory uncertainty in Higgs cross section prediction

α_s from jet data and discrepancy

- Current jet data, although very rich, has not show its full power in constrain α_s

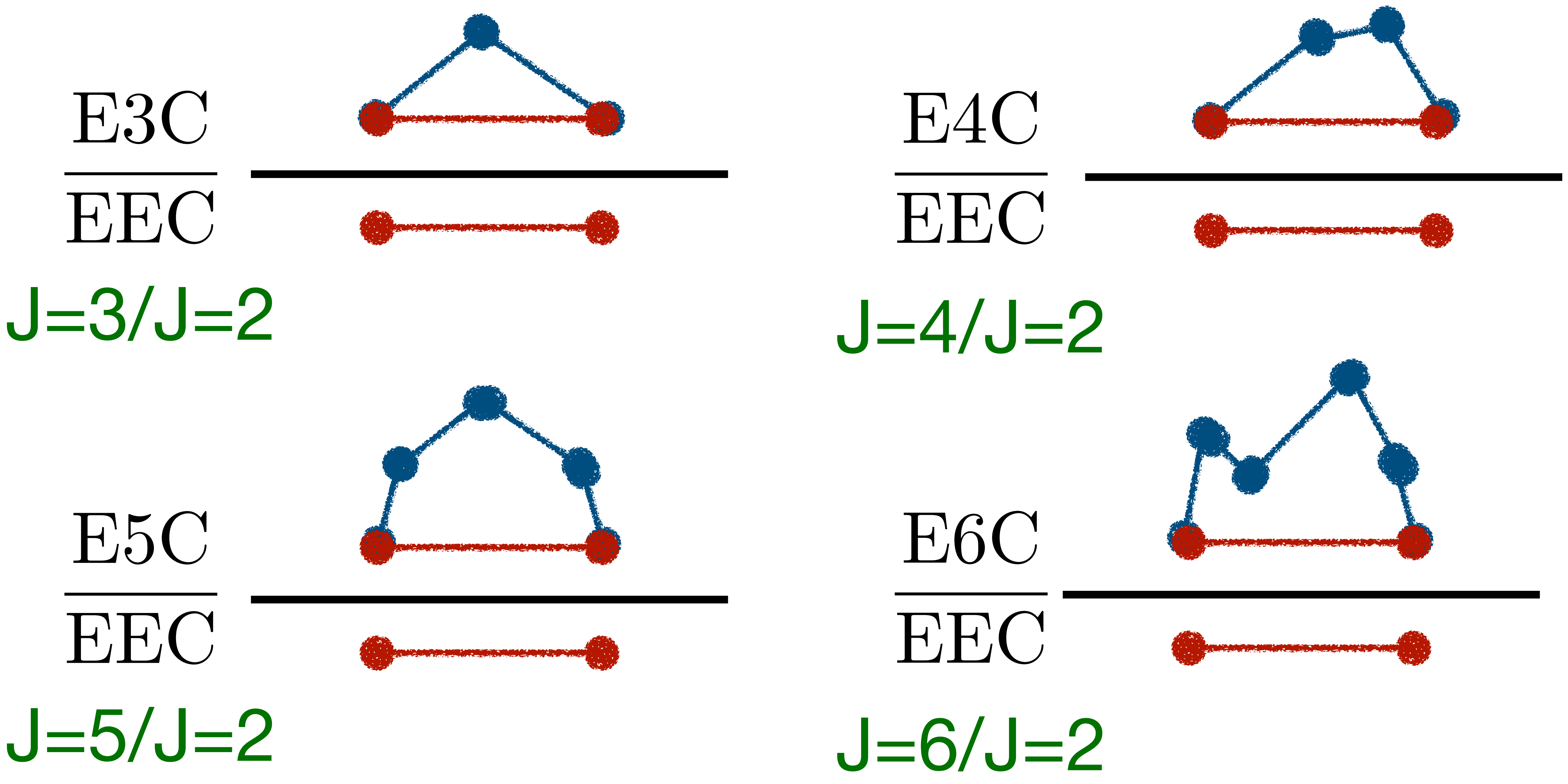
- Also long-term discrepancy in some e+e- jet fit





Non of the current jet data fit exploit jet substructure!

α_s from multi-point energy correlator

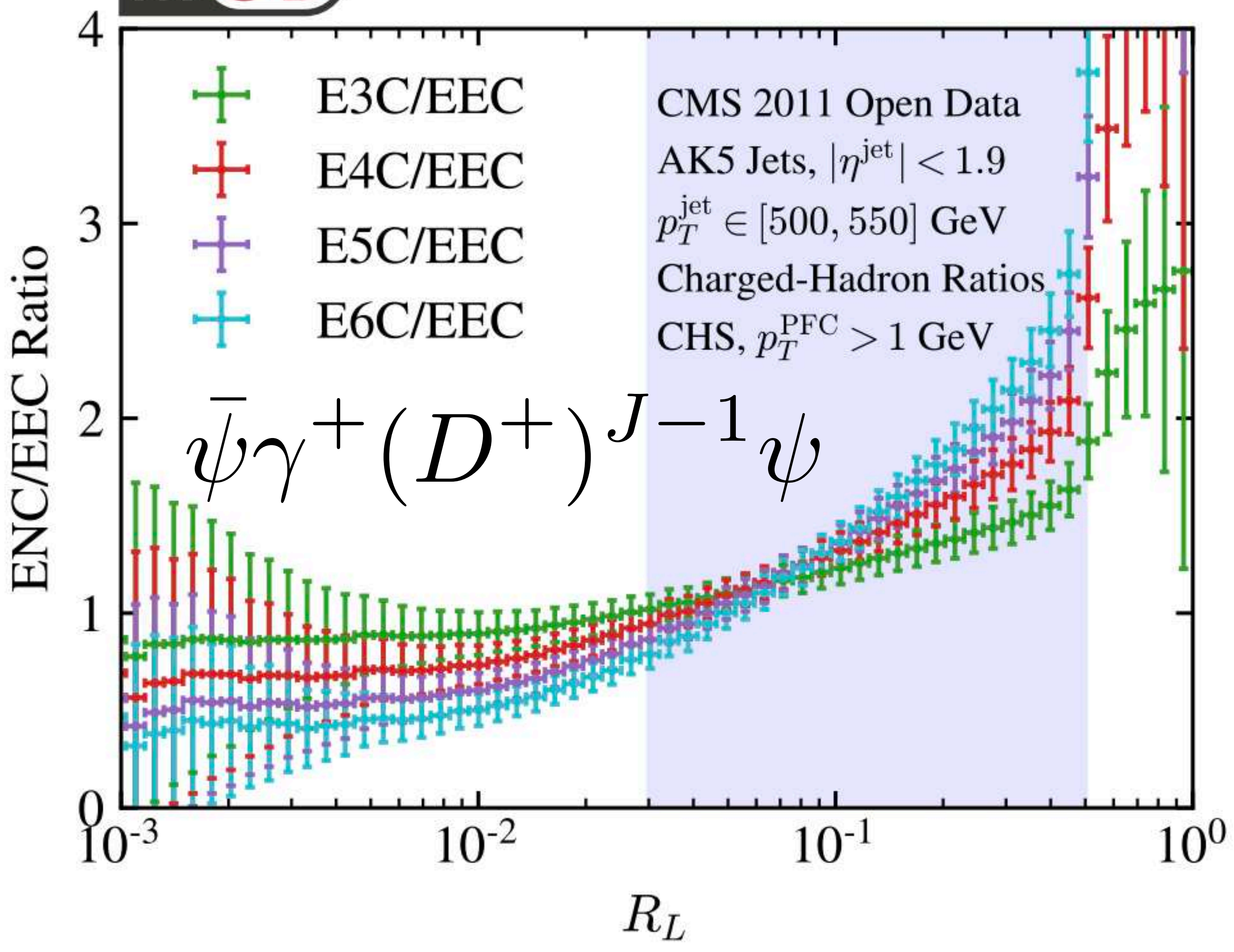


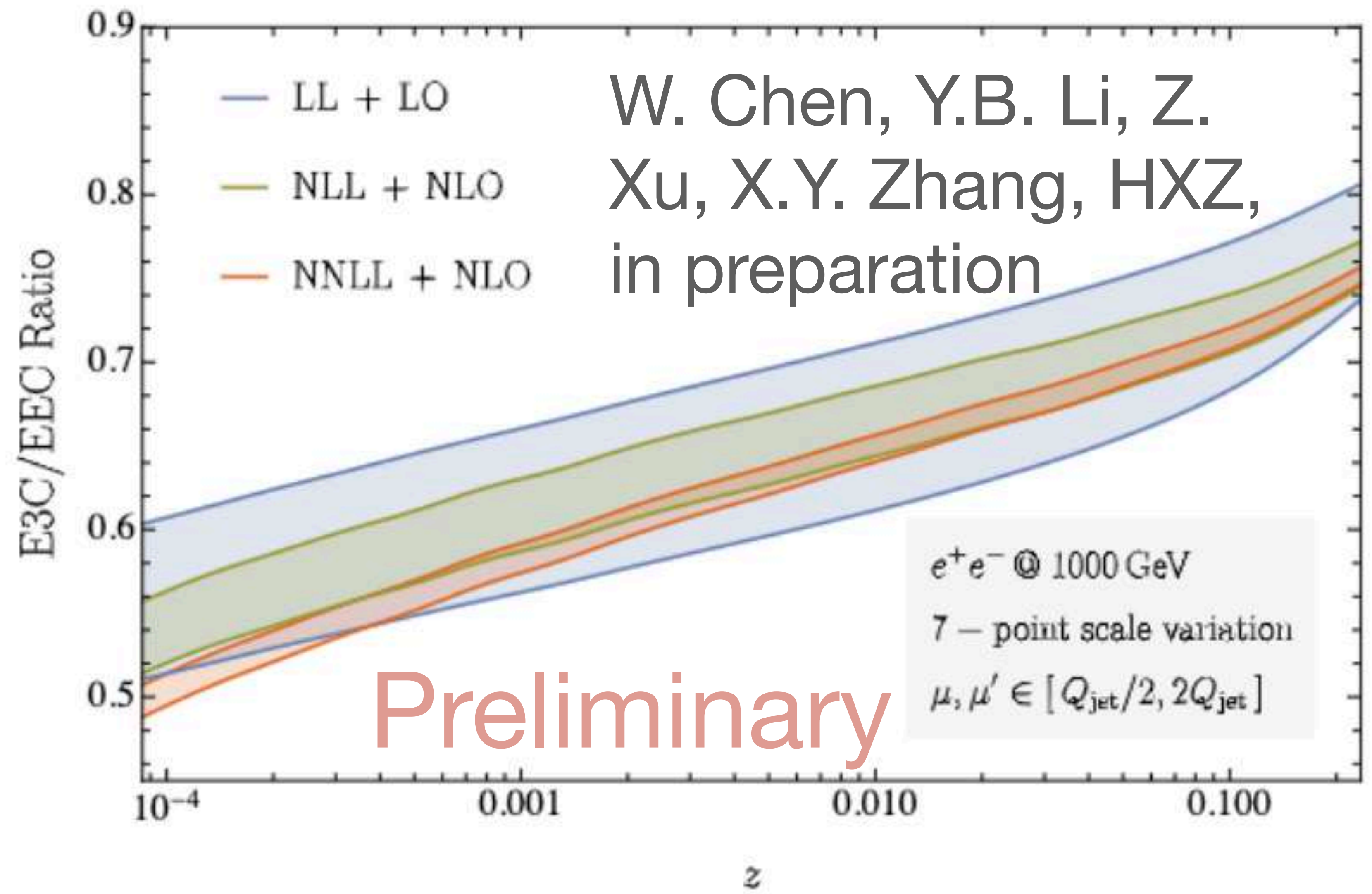
H. Chen, I. Moult, X.Y. Zhang, HXZ, 2004.11381

- Need to understand experimental uncertainties for multi-point correlation

- Need to improve theory prediction (work in progress)

P. Komiske, I. Moult, J. Thaler, HXZ, 2201.07800





Summary

- Remarkable progress in precision QCD and electroweak physics, driven by LHC and other high energy colliders, interfacing with modern mathematics

- Provides new understanding of QCD and quantum field theory in general

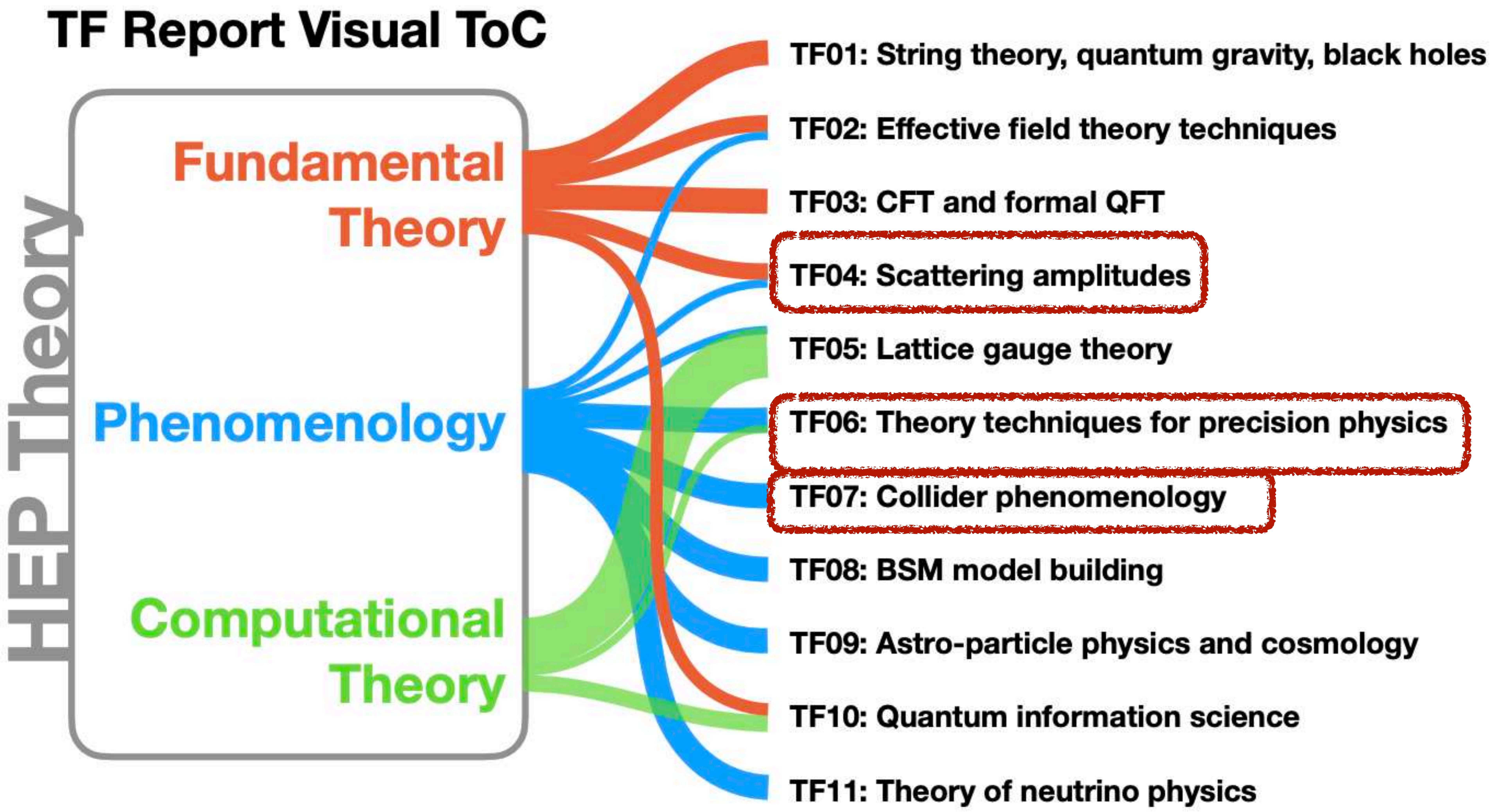
- Precision calculation and measurement has help sharpen the description of the Standard model

- In some cases precision measurement has lead to discrepancy that might due to new physics (W mass, μ g-2)

- Numerous opportunities ahead in light of high precision data in coming decade

Backup slides

Where do precision calculation stands?



Theory Frontier Snowmass report 2022

Highlights from last decade

- New perturbative and non-perturbative techniques (ranging from the double copy structure of scattering amplitudes to the advent of diverse bootstrap methods) have vastly expanded our knowledge of quantum field theory

- The discovery of gravitational waves has catalyzed rapid progress in precision calculations via scattering amplitudes and inspired the use of gravitational waves to study particle physics inaccessible via planned colliders.

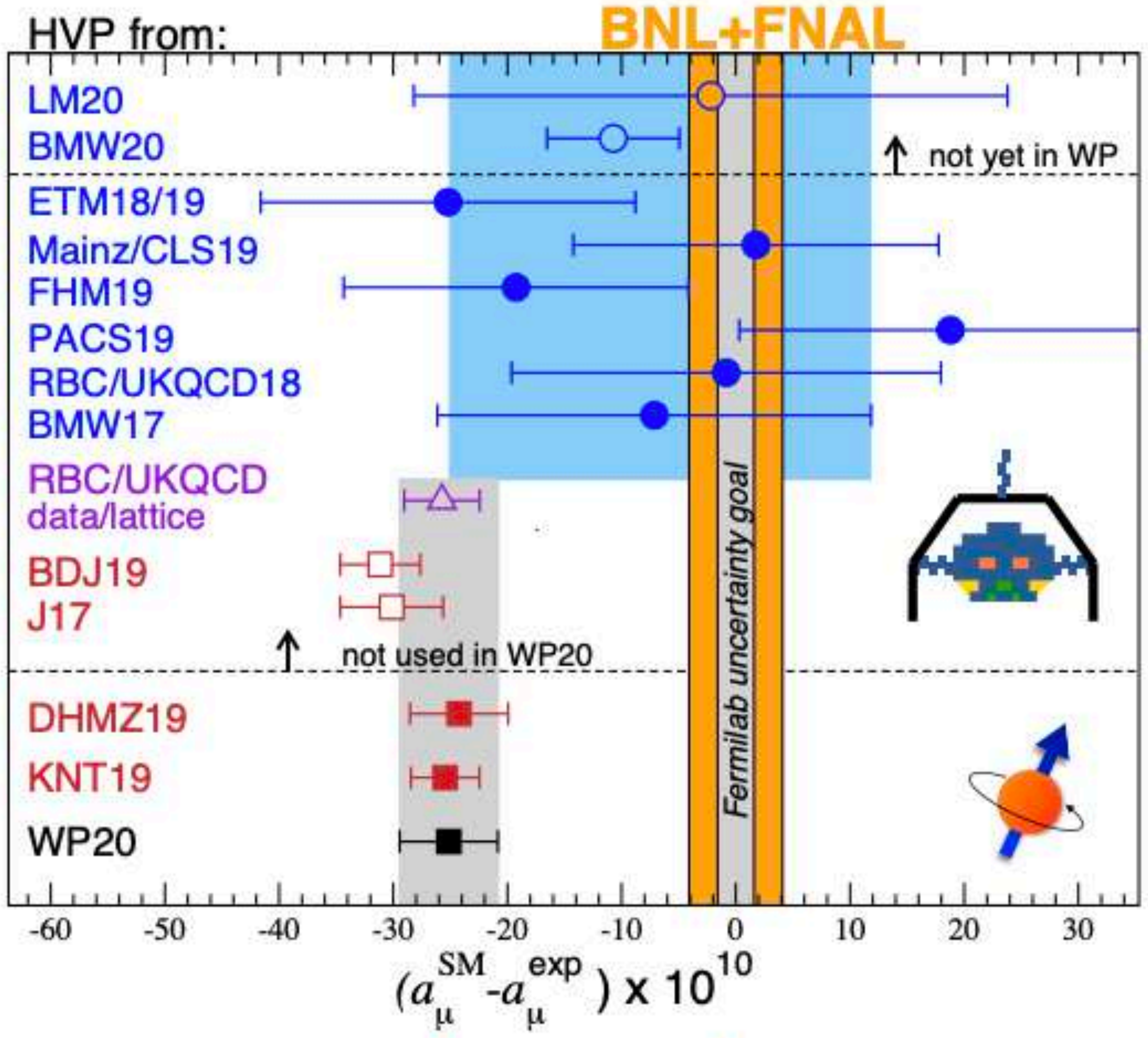
- In precision collider theory the calculation of cross sections to the NNLO and beyond in QCD has now become possible, unlocking the door to unprecedented tests of the SM.

- Collider phenomenology has led to many new collider observables including many forms of jet substructure and the emerging field of multi-point correlators, and is employing widespread innovations in computational theory to leverage machine learning and artificial intelligence.

Theory Frontier Snowmass 2022 report

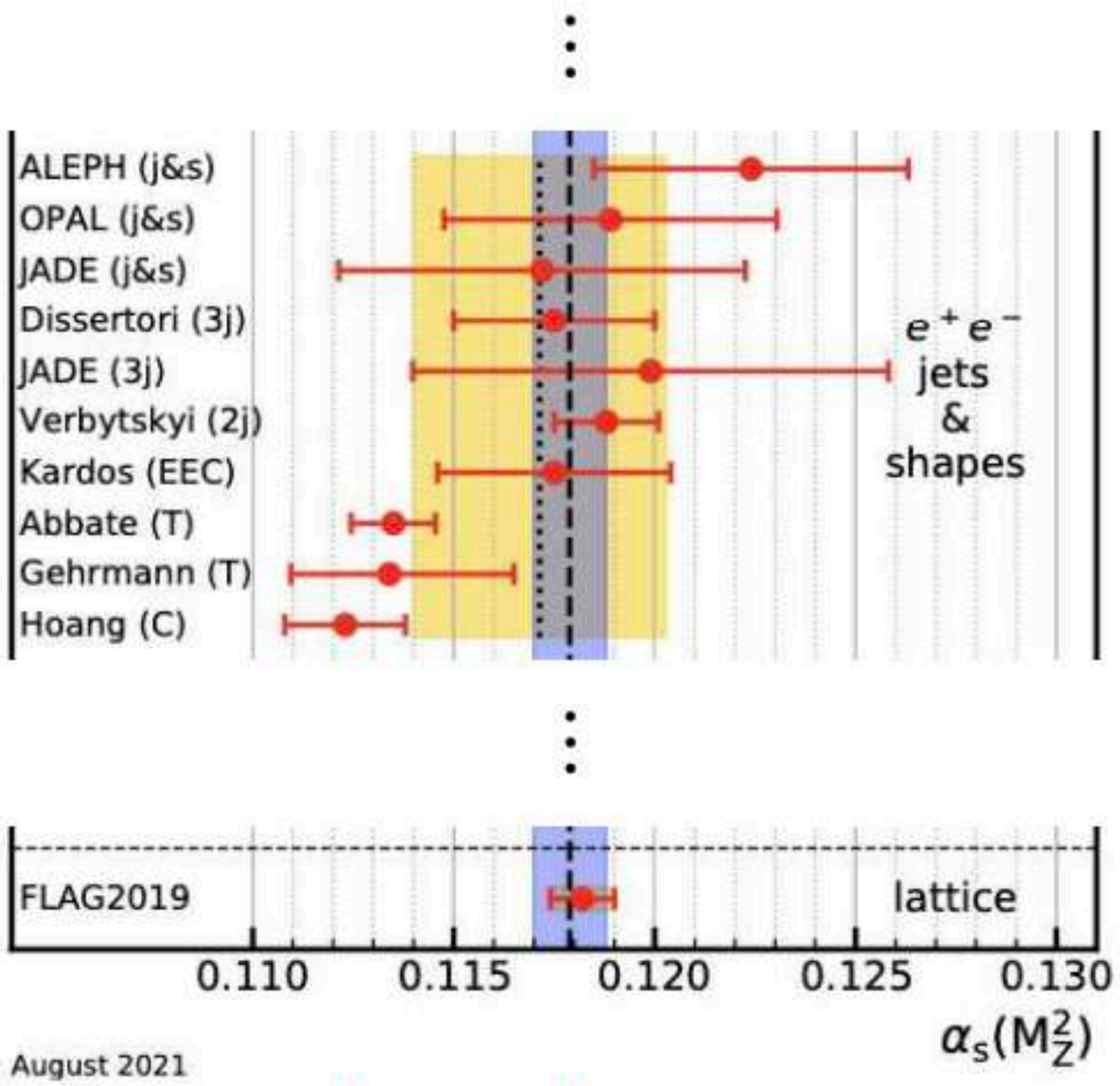
Puzzles in (Non-)Perturbative QCD

Muon Anomalous Moment



hmm…

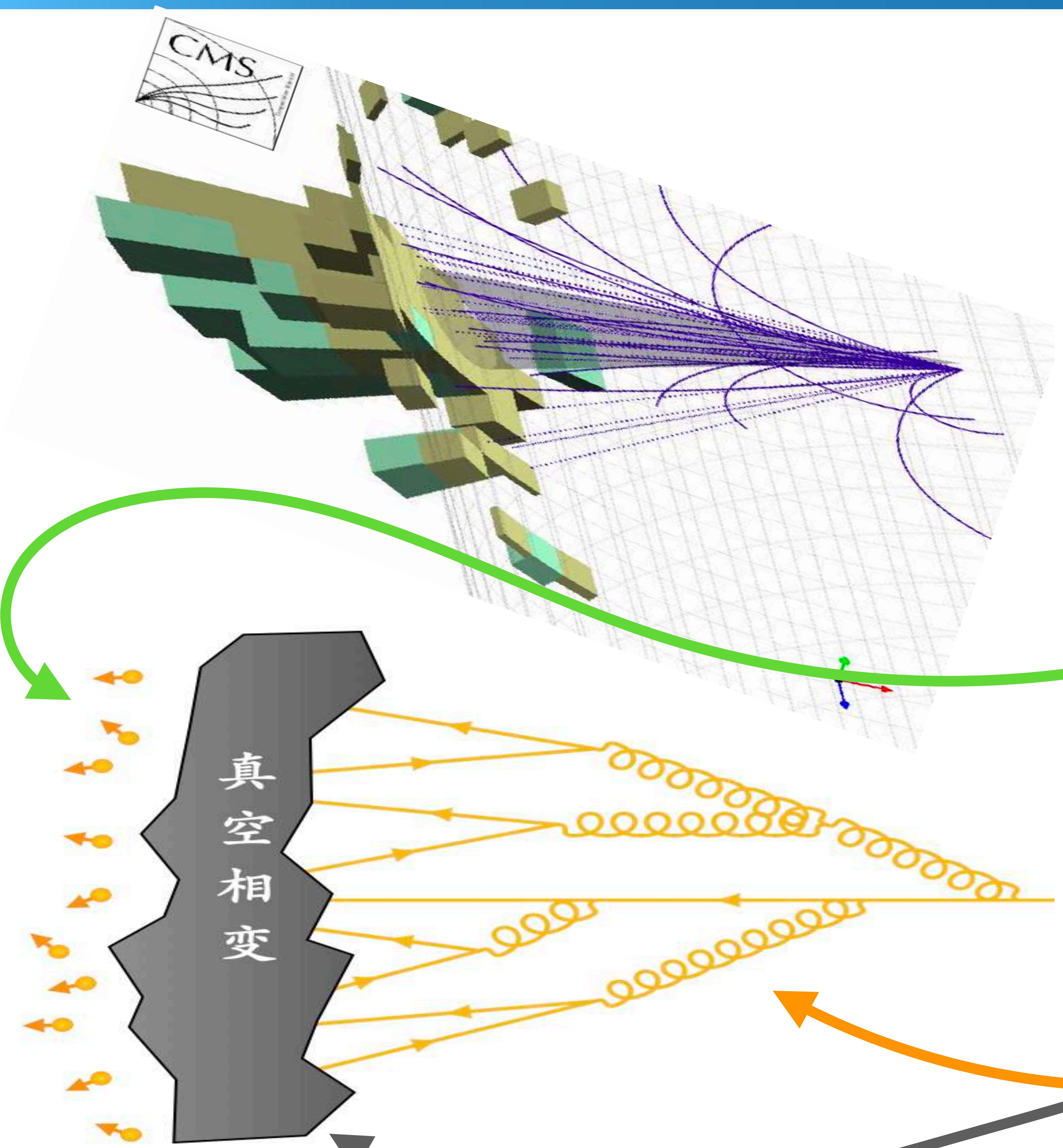
Strong Coupling Constant

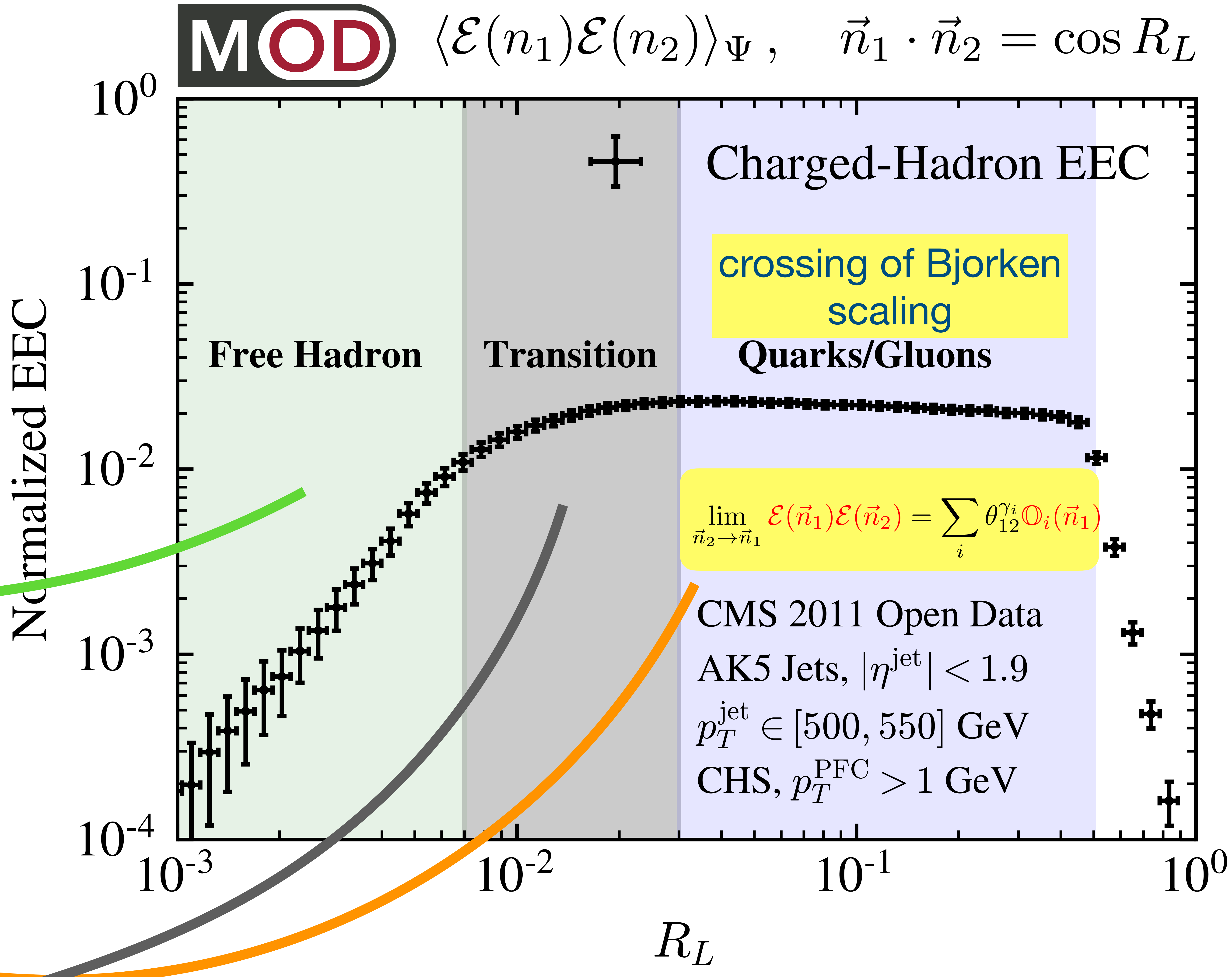


hmm…

J. Thaler, Snowmass 2022 plenary talk

New observable connecting perturbative and confinement in LHC measurement

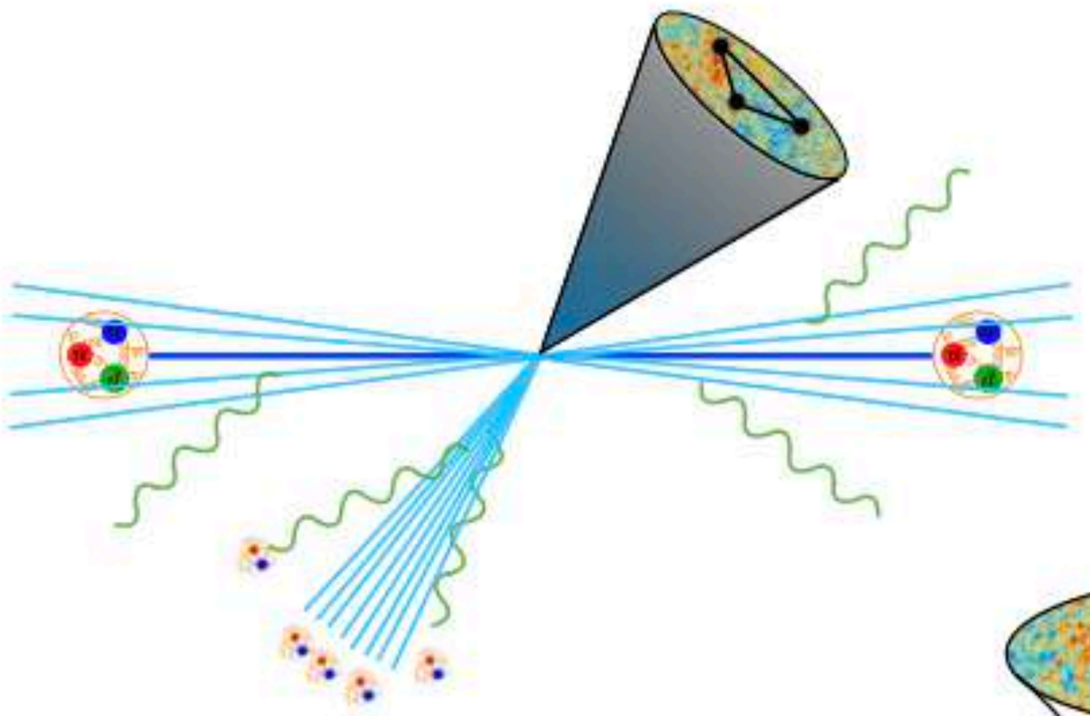


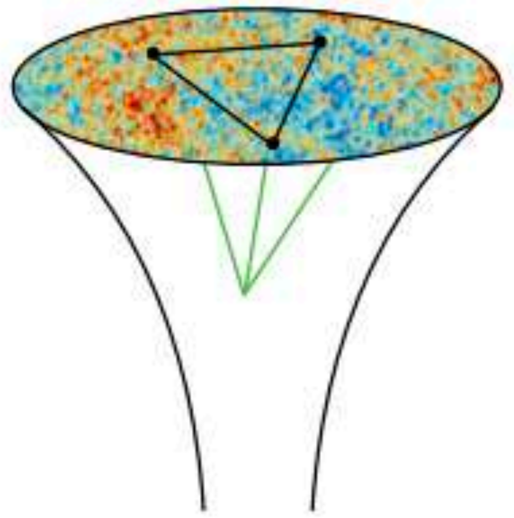


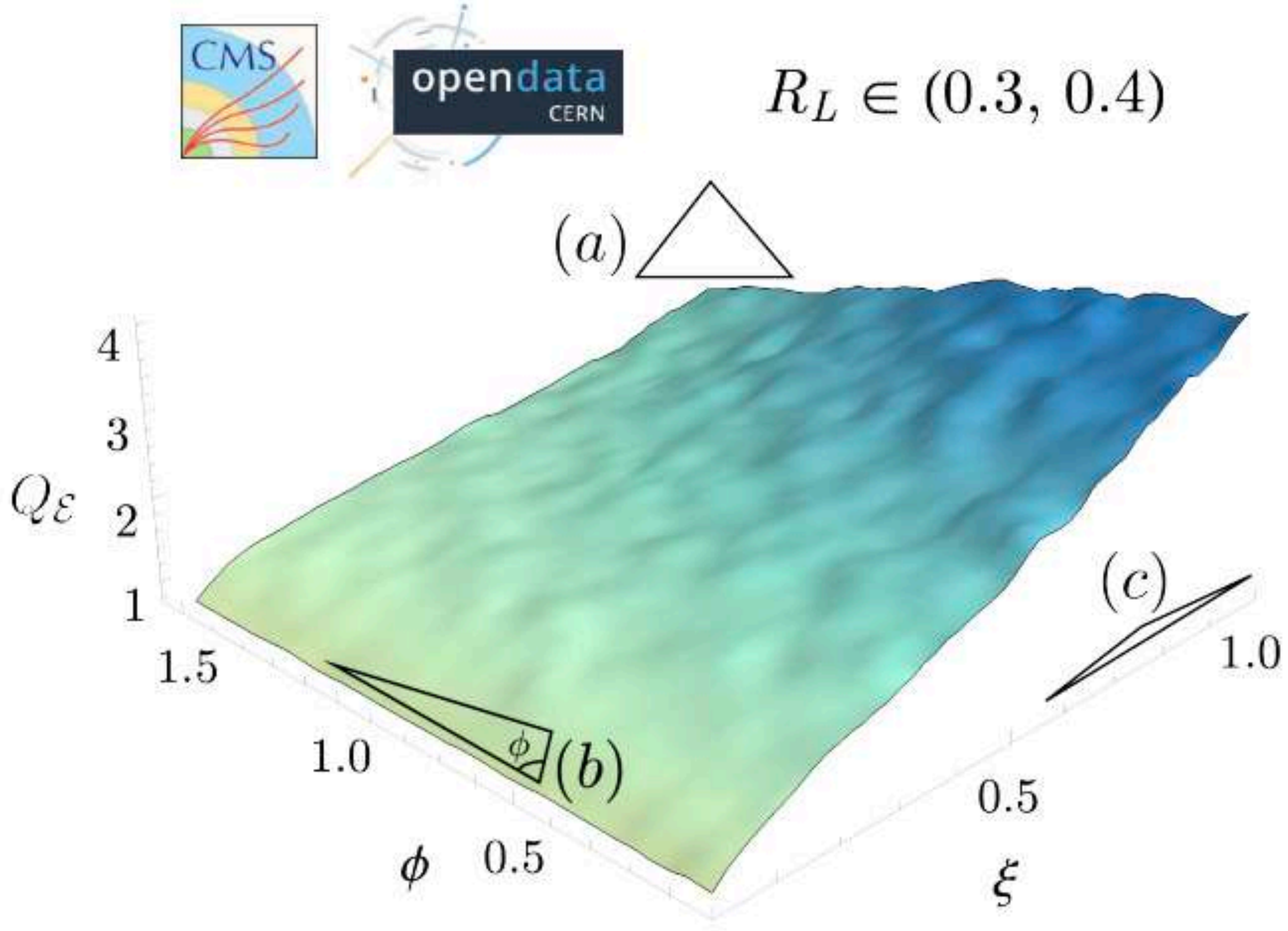
P. Komiske, I. Moult, J. Thaler, HXZ, 2201.07800

Reaching Across Disciplines

"Non-Gaussianities" in collider energy flux





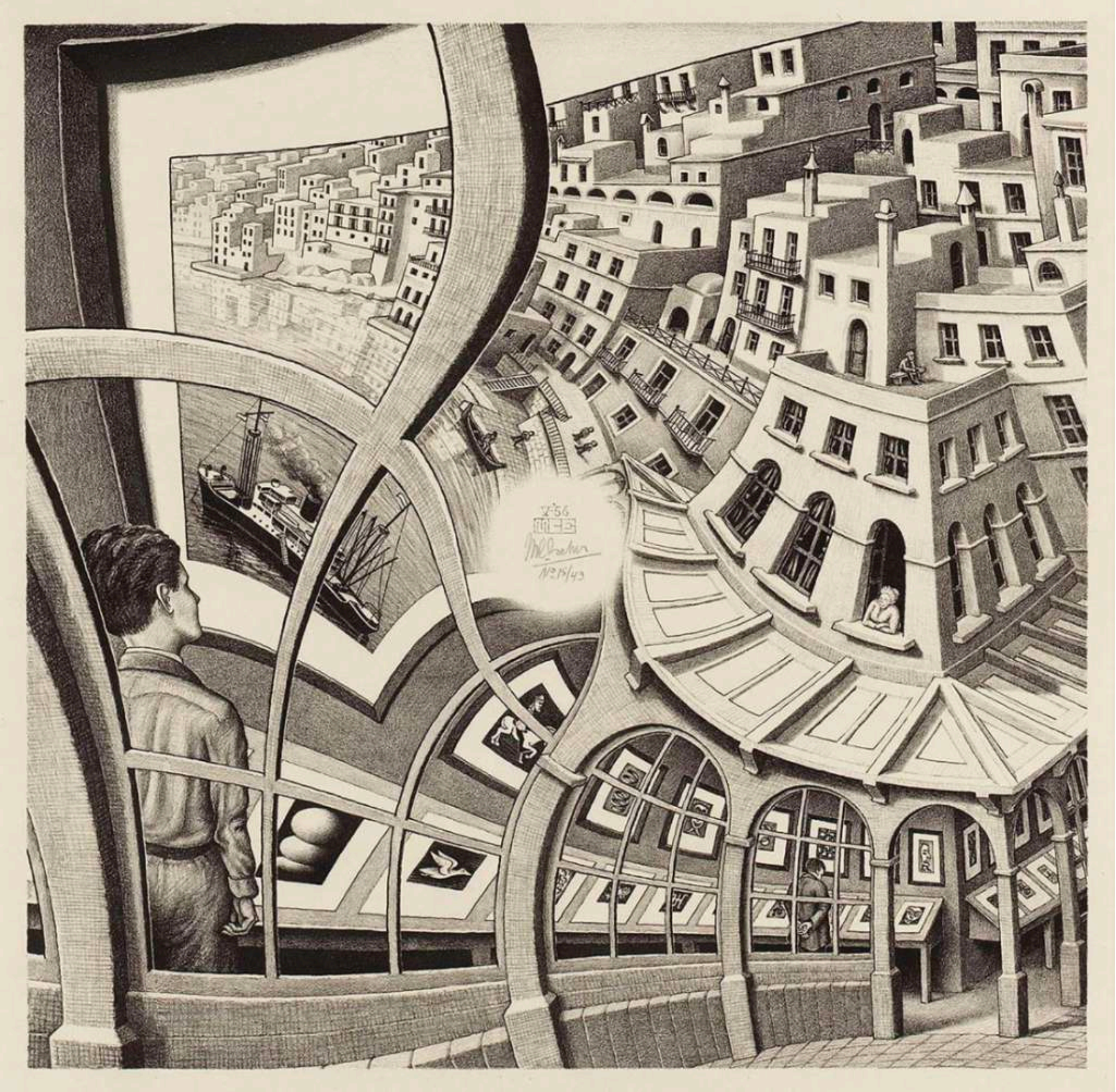


← UV to IR →

← Theory to Experiment →

Technique from collider physics and QCD	Interpreted through lens of cosmology	Computed through lens of conformal field theory	Analyzed with public collider data

← Phenomenological to Formal →



CFT in jet substructure

H. Chen, I. Moult, J. Sandor, HXZ, 2202.04085
C.-H. Chang, Simmons-Duffin, 2202.04090

H. Chen, I. Moult, J. Thaler, HXZ, 2205.02857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杭州 2022年8月22–24日
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