SPIF

PRECISION PHYSICS AT COLLIDERS

Paolo Gambino

University of Torino - INFN Torino

INFN Theory Group Retreat - Santo Stefano Belbo - 12/11/23

GIORNATE DI STUDIO SULLA FISICA TEORICA 2021
INFN THEORY GROUP RETREAT

FONDAZIONE CESARE PAVESE, SANTO STEFANO BELBO (CN)
20-21NOVEMBRE, 2021

Outline

- The group
- Precision physics at LHC
- Precision flavour physics

The group


Paolo T


Giovanni


Colomba


Ezio


Raquel


Leonardo


Simon


Alexandre


Sandro


Lorenzo


Martin


Jakub

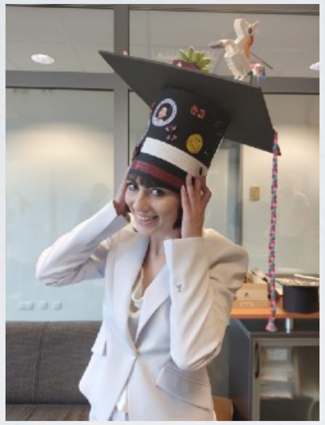

Paolo G

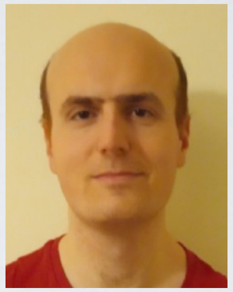
Physics

- Calculation of multi-loop virtual amplitudes
- Factorisation of QCD amplitudes and cross sections in the infrared, structure of infrared anomalous dimensions at high orders, resummation of large logarithms (threshold, p_T, …) for LHC observables
- Subtraction of infrared divergences for general collider observables at NNLO
- Production and decay of vector bosons at LHC
- Codes for phenomenology: Phantom - Recola - MadGraph5_aMC@NLO
- Precision determination of the CKM elements, the V_{cb} puzzle
- Studies of the flavour anomalies ($b \to c\tau\nu$ and $b \to s\ell^+\ell^-$) and EDMs
- Inclusive semileptonic decays on the lattice

Loop amplitudes and precision QCD

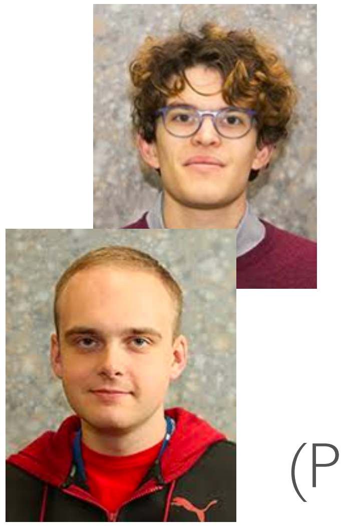

Simon Badger


PD (**FARE2020**):
Colomba Brancaccio
(PhD, Aachen)
10/23 - 09/25


MCF (**MCSA global, Zurich**)
Giulio Falcioni
10/24 - 9/27

PD (**PRIN23 w/ P.T.**):
TBC
01/24 - 12/24

JetDynamics ERC 6/18 - 11/23


Sarandrea
(PhD 6/2023)

Krys
(PhD 11/2023)

Ekta → Bonn (5yr)
Zoia → CERN/Zurich (MC+Ambizione)
Ahmed → Regensburg (J. Prof)
Becchetti → Bologna
Moodie → Industry

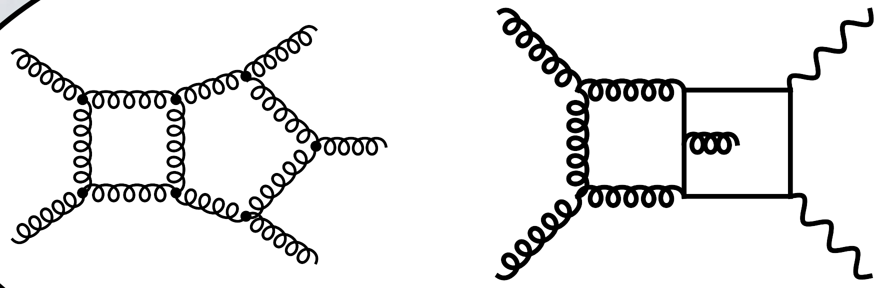
new IS:

Amplitudes

analytic structure, loop methods
and perturbative gravity

LNF (Del Duca, RN)
NA (Tramontano)
BO (Peraro)
PA (Mastrolia)
RO (Bonciani)

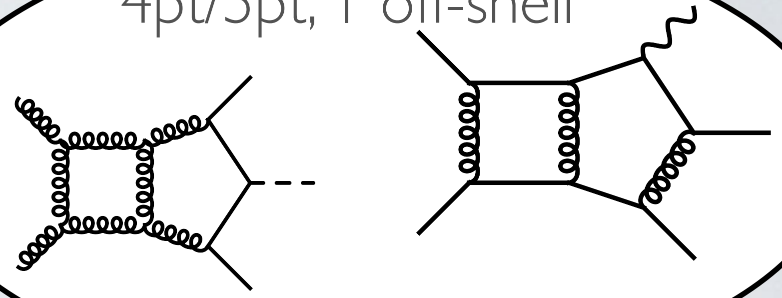
massless 5pt



pp→γ+2j

JHEP 10 (2023) 071

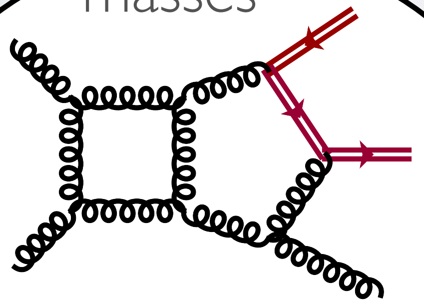
4pt/5pt, 1 off-shell



pp→Wγj JHEP 05 (2022) 035

eμ→eμj JHEP 11(2023) 041

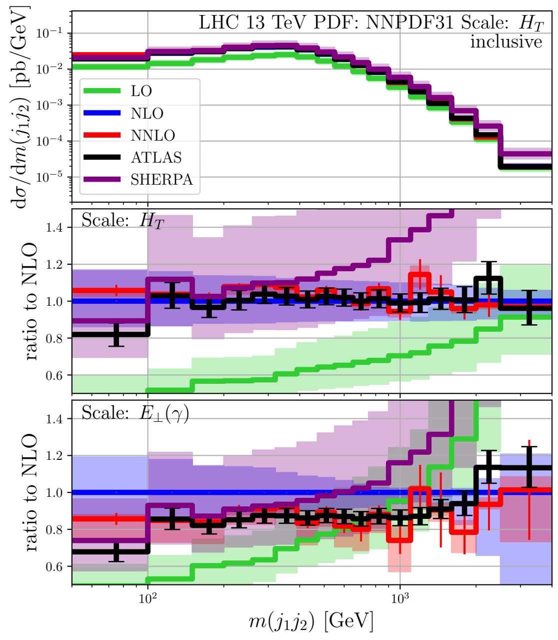
masses



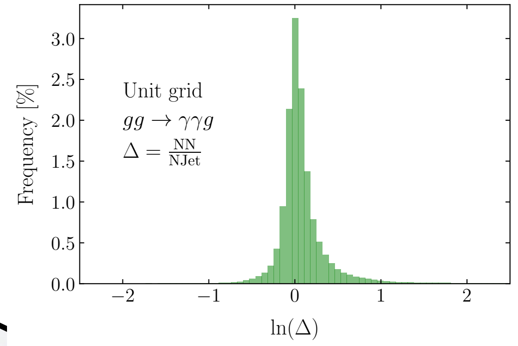
towards pp→ttj

JHEP 06 (2022) 066

JHEP 01 (2023) 156

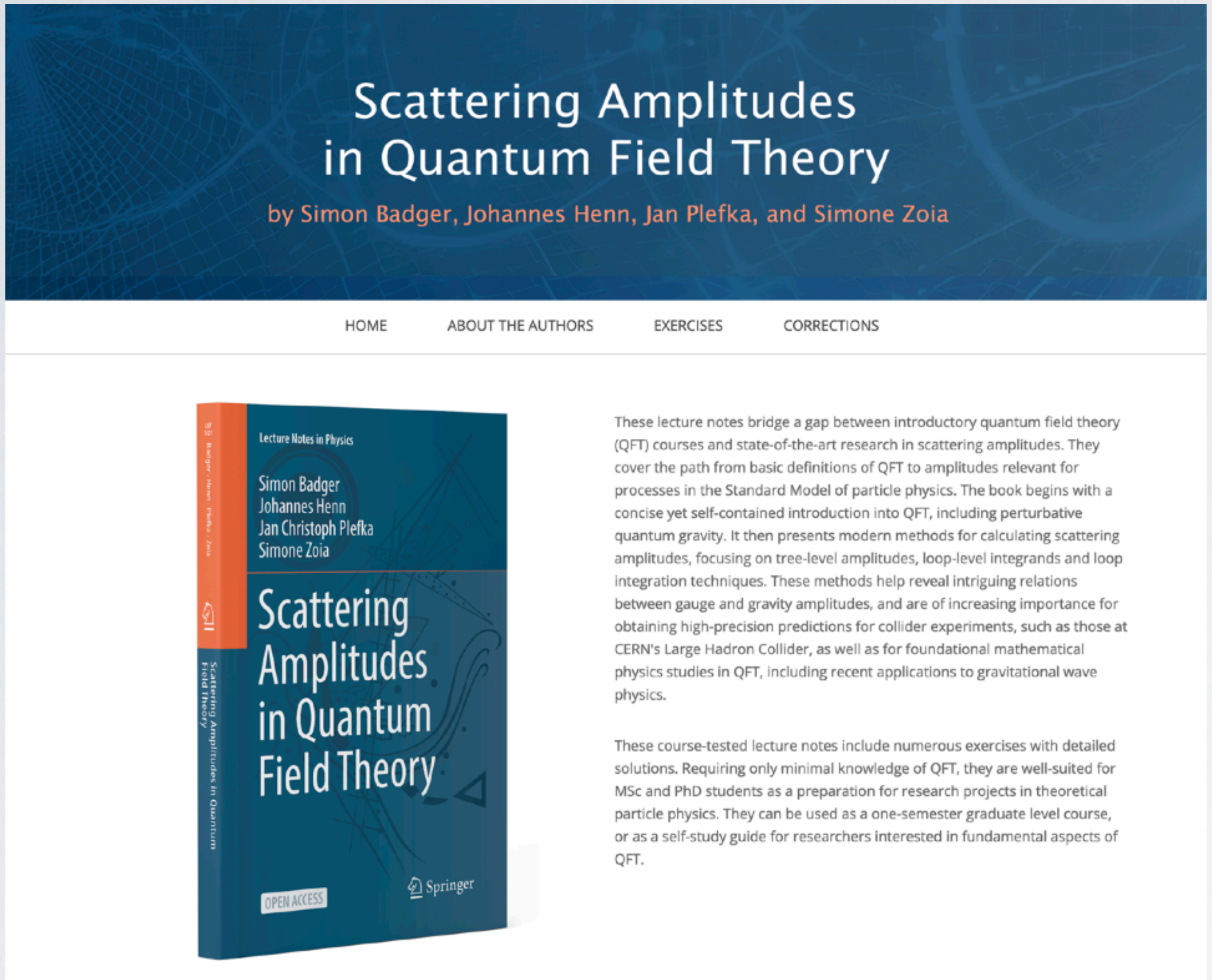


precision dσ



optimising simulations with NN

SciPost Phys.Core 6 (2023) 034



Scattering Amplitudes in Quantum Field Theory

by Simon Badger, Johannes Henn, Jan Plefka, and Simone Zoia

These lecture notes bridge a gap between introductory quantum field theory (QFT) courses and state-of-the-art research in scattering amplitudes. They cover the path from basic definitions of QFT to amplitudes relevant for processes in the Standard Model of particle physics. The book begins with a concise yet self-contained introduction into QFT, including perturbative quantum gravity. It then presents modern methods for calculating scattering amplitudes, focusing on tree-level amplitudes, loop-level integrands and loop integration techniques. These methods help reveal intriguing relations between gauge and gravity amplitudes, and are of increasing importance for obtaining high-precision predictions for collider experiments, such as those at CERN's Large Hadron Collider, as well as for foundational mathematical physics studies in QFT, including recent applications to gravitational wave physics.

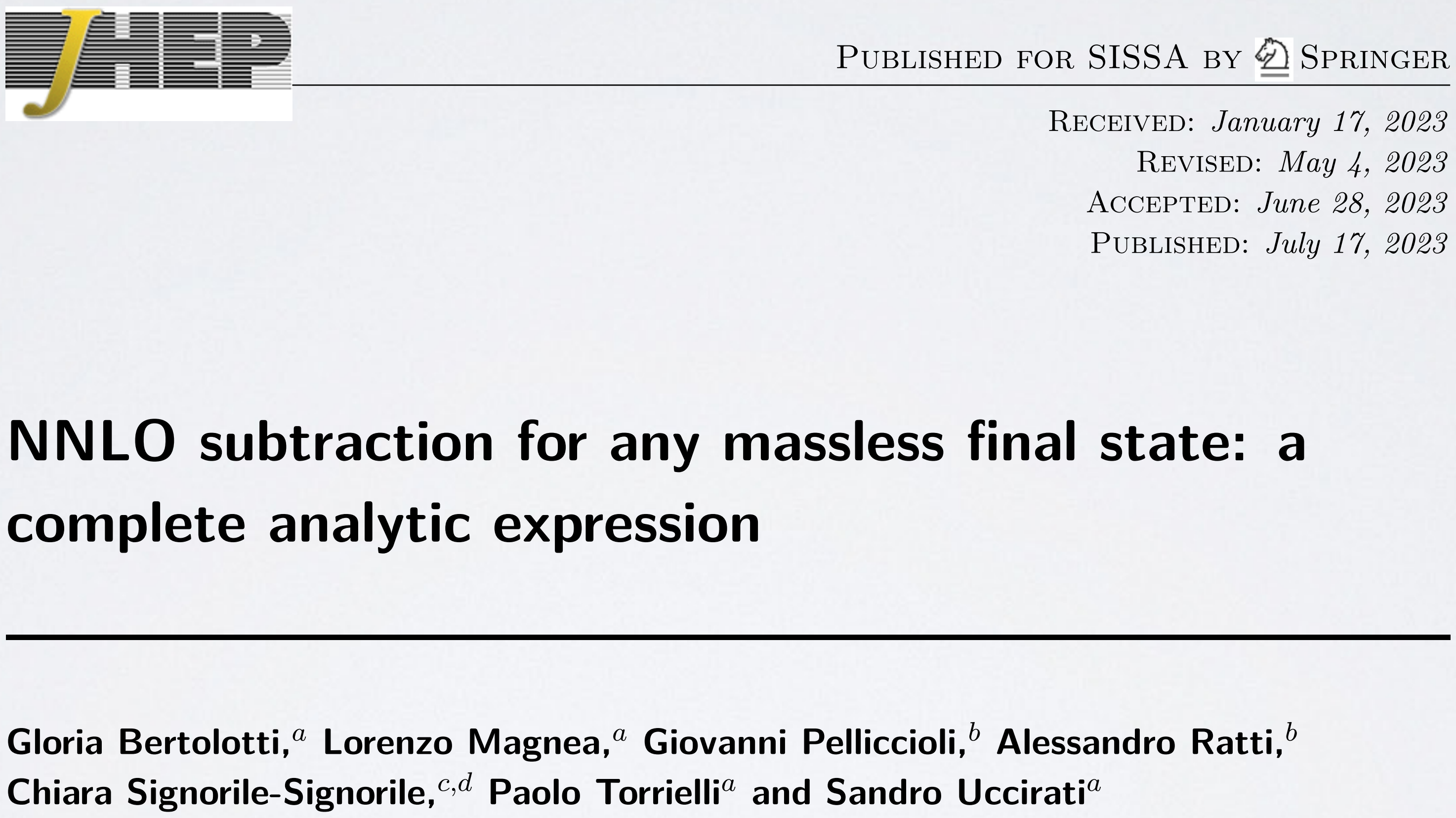
These course-tested lecture notes include numerous exercises with detailed solutions. Requiring only minimal knowledge of QFT, they are well-suited for MSc and PhD students as a preparation for research projects in theoretical particle physics. They can be used as a one-semester graduate level course, or as a self-study guide for researchers interested in fundamental aspects of QFT.

in print soon…(Jan '24)

Open Access Lecture Notes

https://arxiv.org/abs/2306.05976

THE SUBTRACTION PROBLEM



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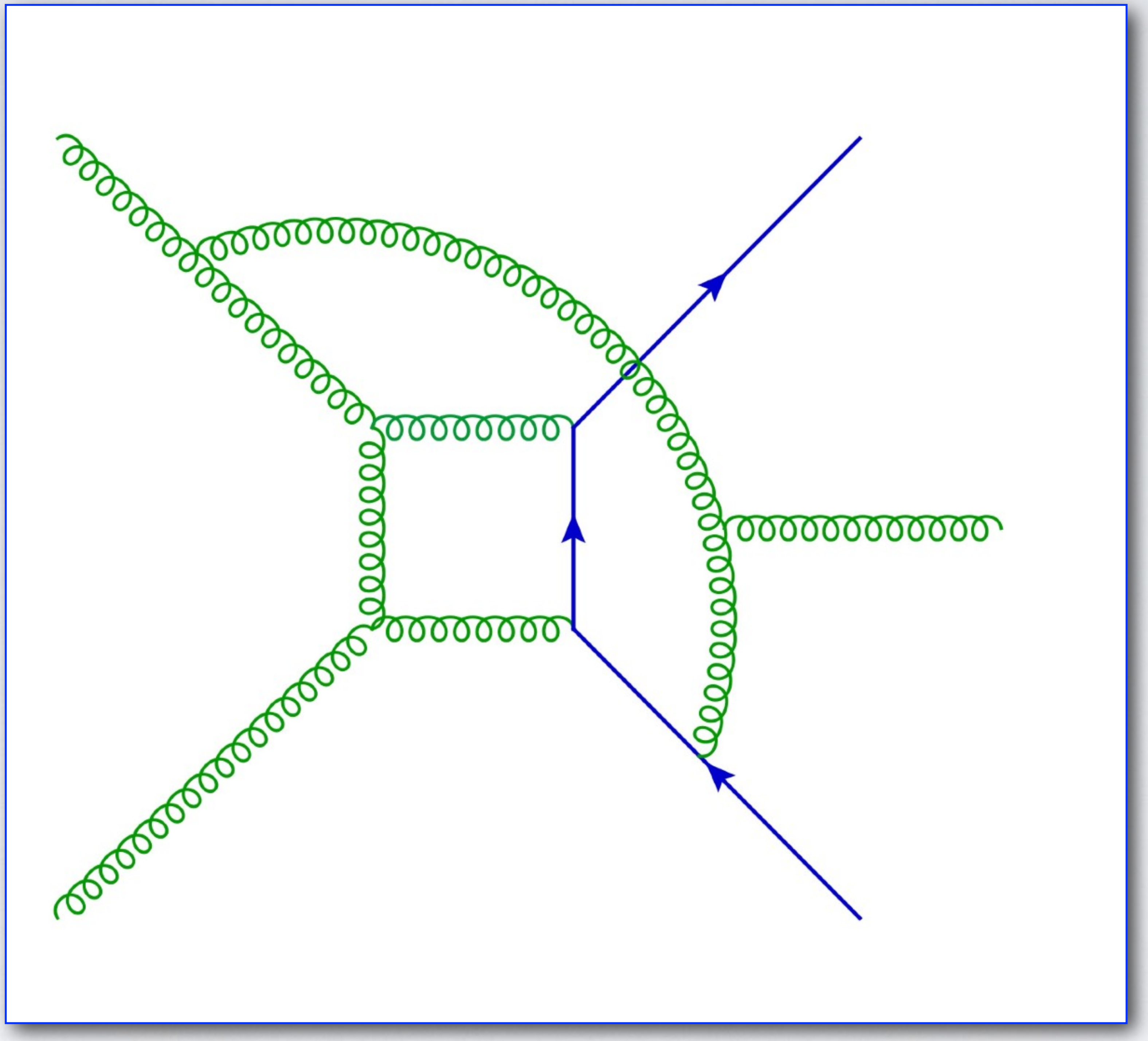
NNLO subtraction for any massless final state: a complete analytic expression

Gloria Bertolotti,[a] **Lorenzo Magnea,**[a] **Giovanni Pelliccioli,**[b] **Alessandro Ratti,**[b]
Chiara Signorile-Signorile,[c,d] **Paolo Torrielli**[a] **and Sandro Uccirati**[a]

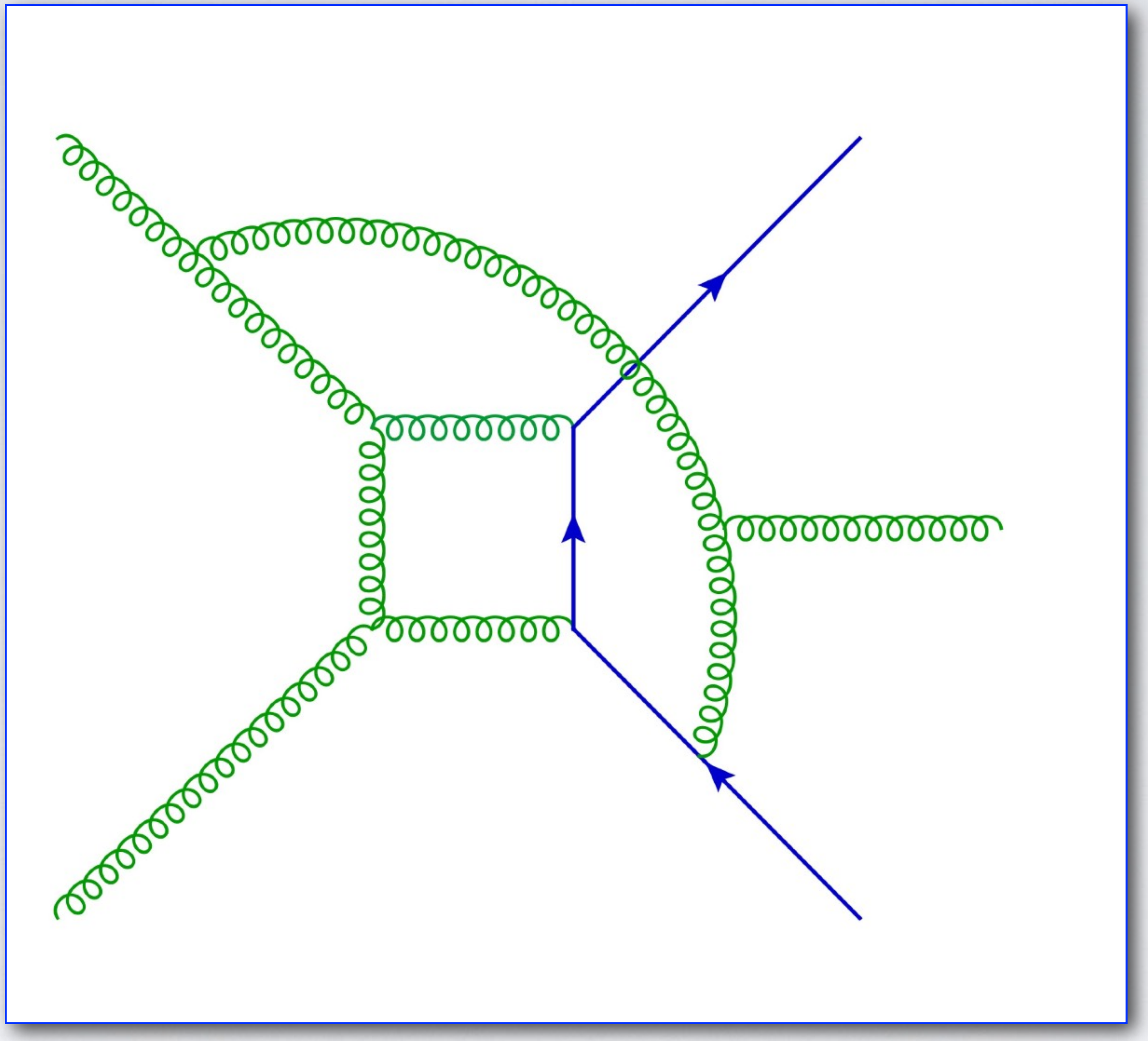
Local Analytic Sector Subtraction

Pictorial infrared



A diagram contributing a double-virtual NNLO correction to t-tbar-jet production

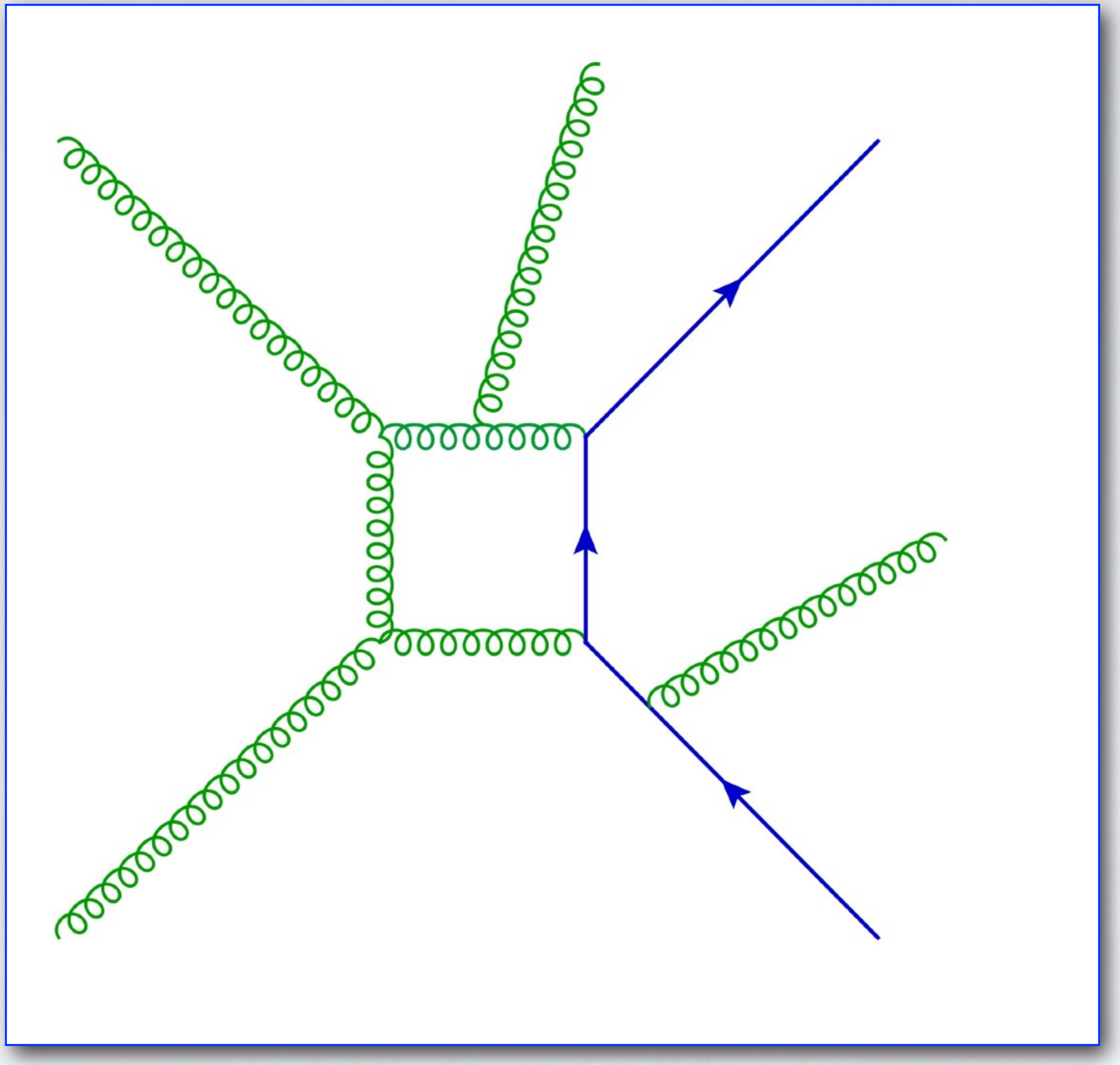
Pictorial infrared



$$\frac{1}{\epsilon^4}$$

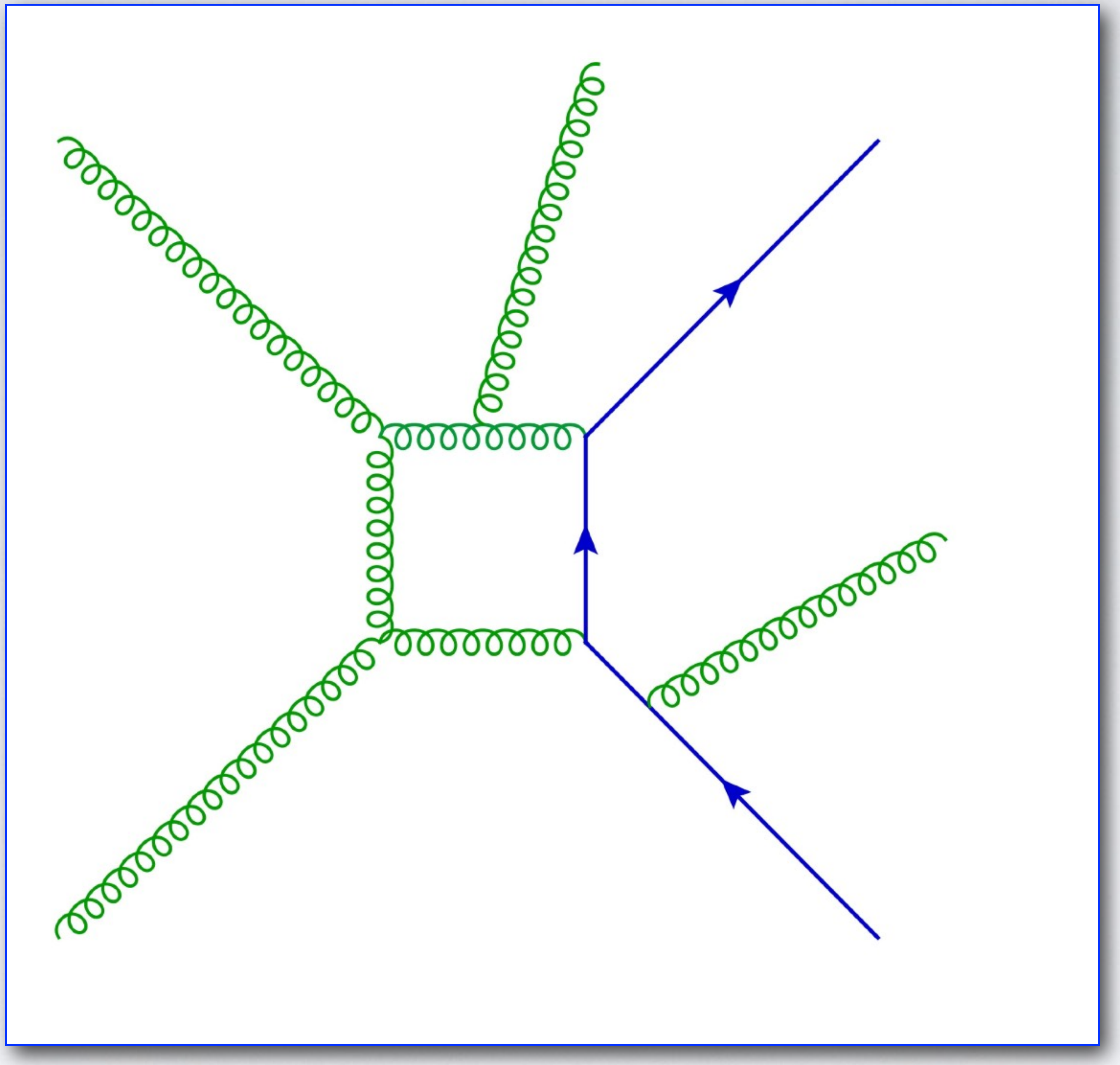
A diagram contributing a double-virtual NNLO correction to t-tbar-jet production

Pictorial infrared



A diagram contributing a real-virtual NNLO correction to t-tbar-jet production

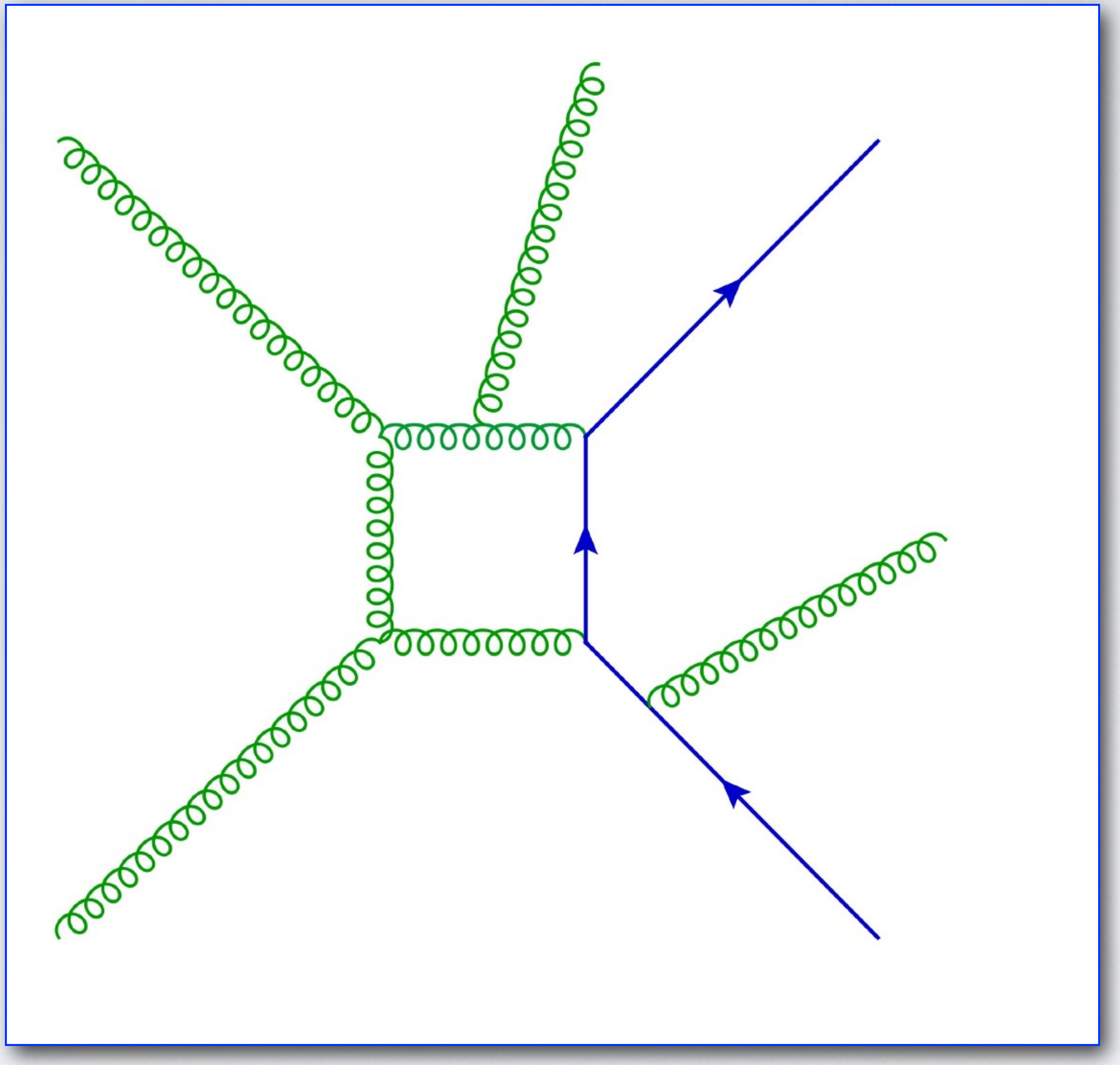
Pictorial infrared



$$\frac{1}{\epsilon^2}$$

A diagram contributing a real-virtual NNLO correction to t-tbar-jet production

Pictorial infrared

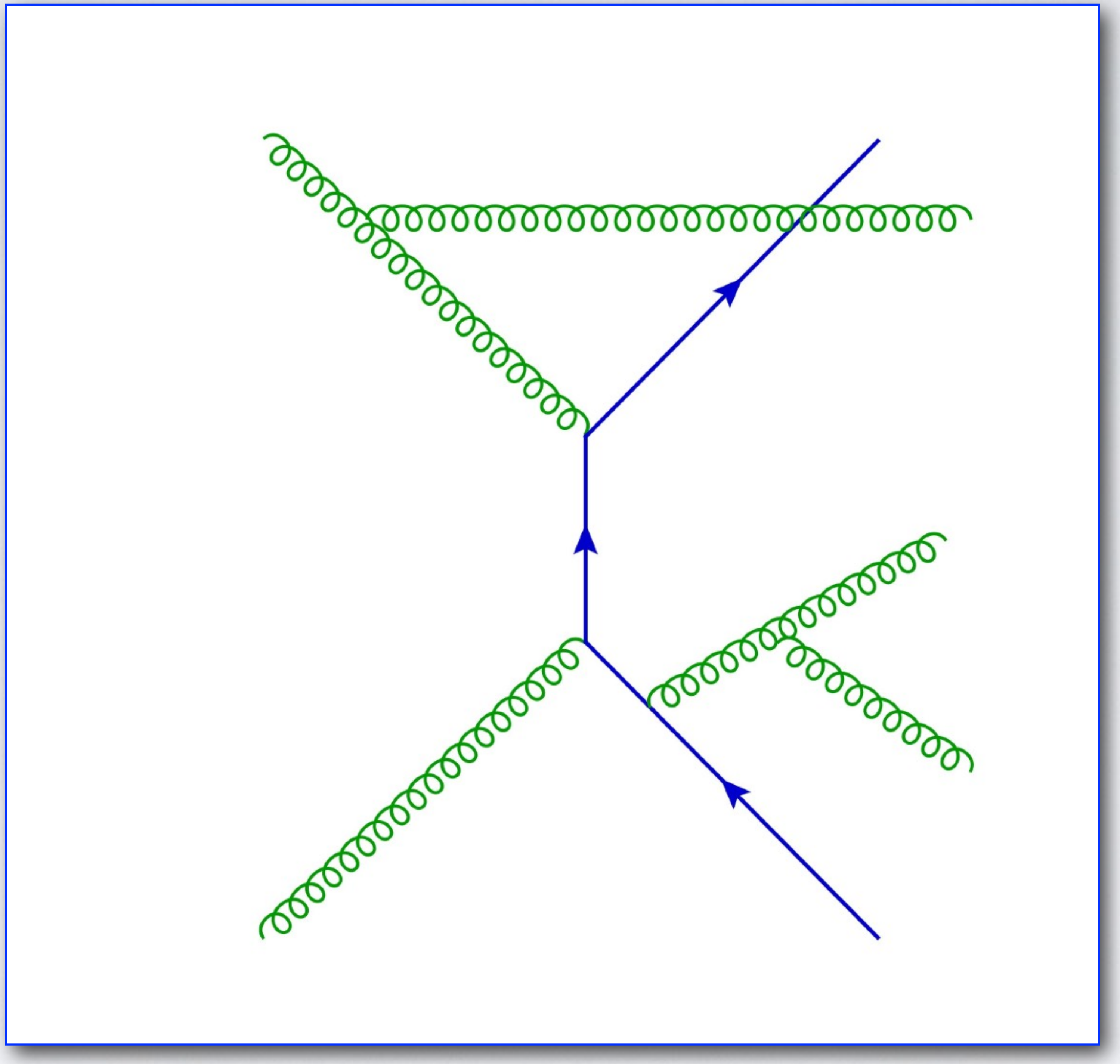


$$\frac{1}{\epsilon^2}$$

$$\frac{dE}{E}\,\frac{dk_\perp}{k_\perp}$$

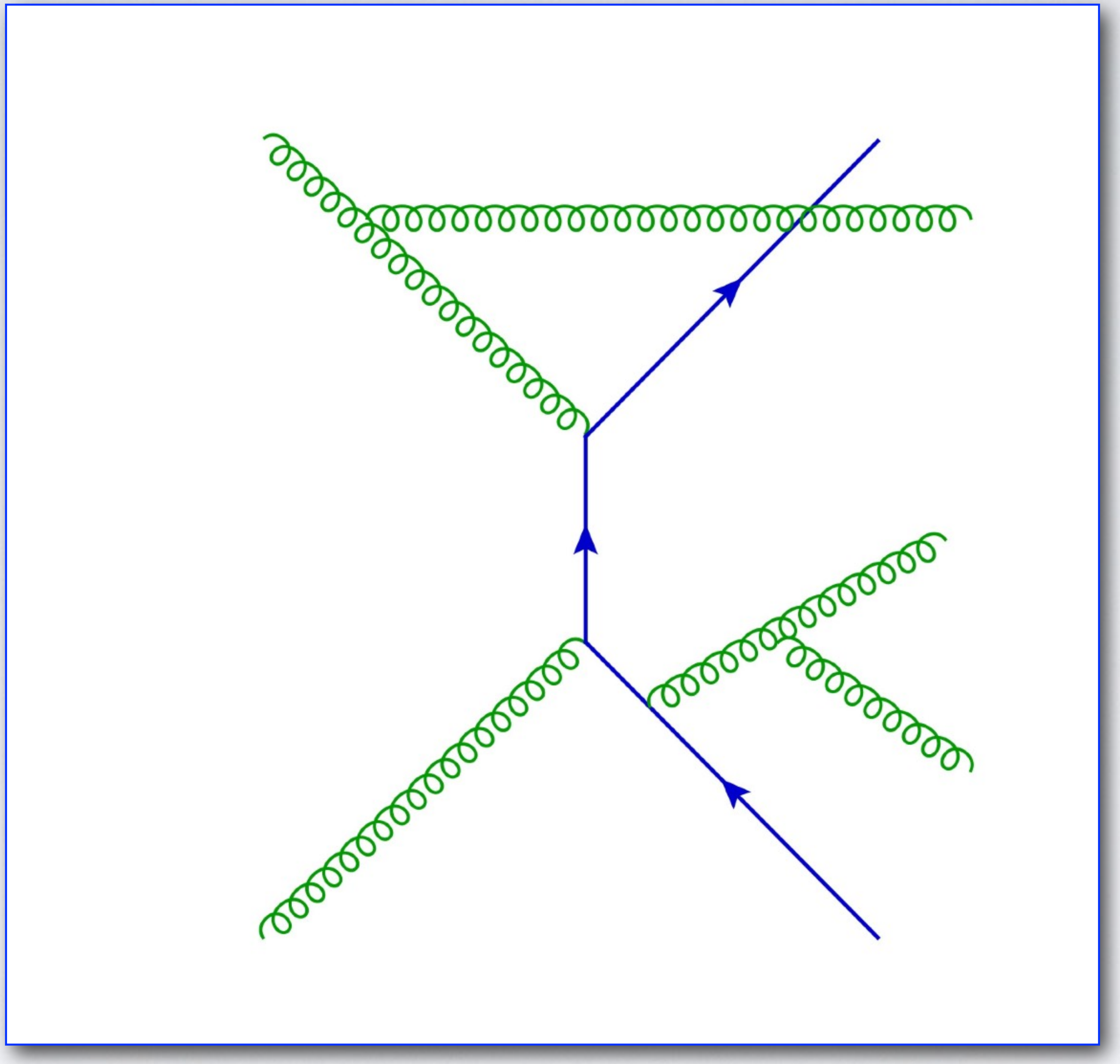
A diagram contributing a real-virtual NNLO correction to t-tbar-jet production

Pictorial infrared



A diagram contributing a double-real NNLO correction to t-tbar-jet production

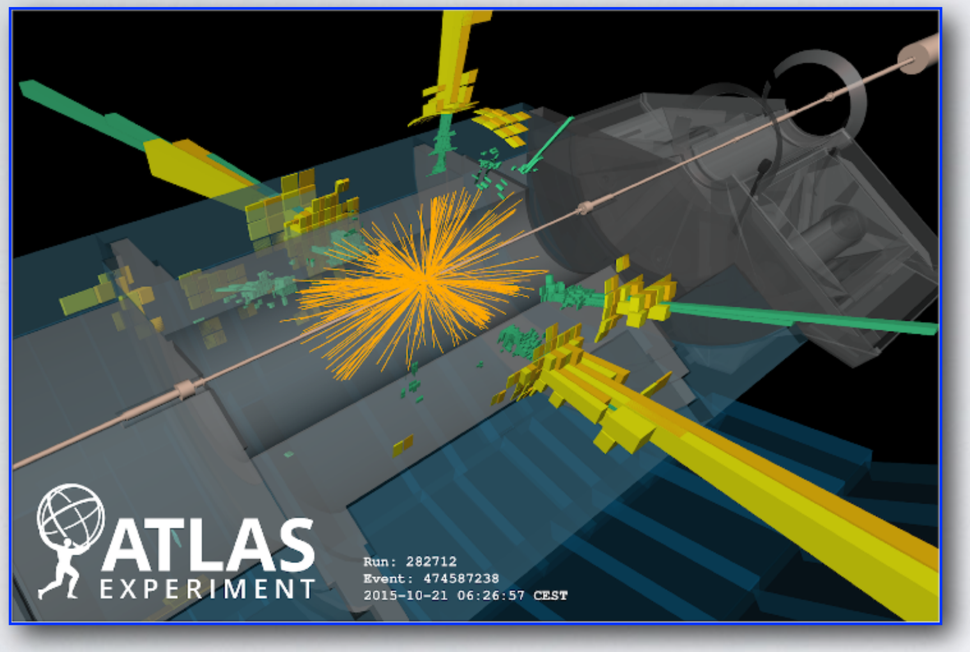
Pictorial infrared

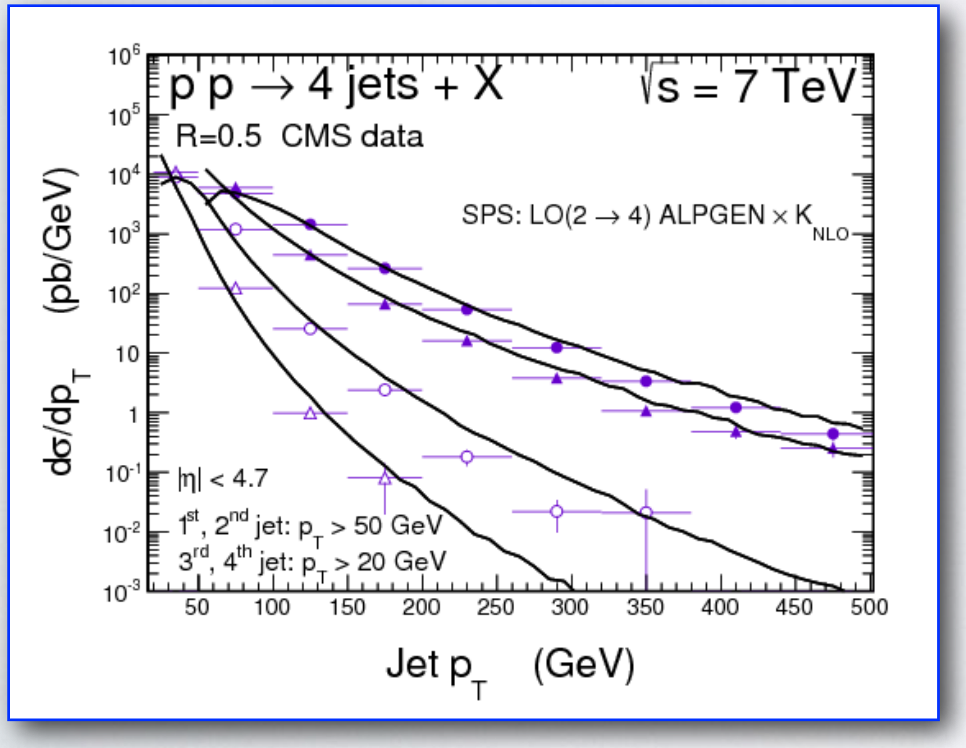


$$\left(\frac{dE}{E}\,\frac{dk_\perp}{k_\perp}\right)^2$$

A diagram contributing a double-real NNLO correction to t-tbar-jet production

The subtraction problem





- Infrared divergences (soft and collinear) cancel between configurations with different numbers of particles
- Collider observables are algorithmically complex and need elaborate phase-space constraints.
- Divergences must be canceled analytically before performing numerical integrations.
- Existing subtraction algorithms beyond NLO are computationally very intensive.
- LHC is now a precision machine: we are interested in subtraction for complicated process at very high orders.
- The factorisation of virtual corrections contains all-order information, not fully exploited.
- The structure of virtual singularities can be used as an organising principle for subtraction.

A complex final state at NLO

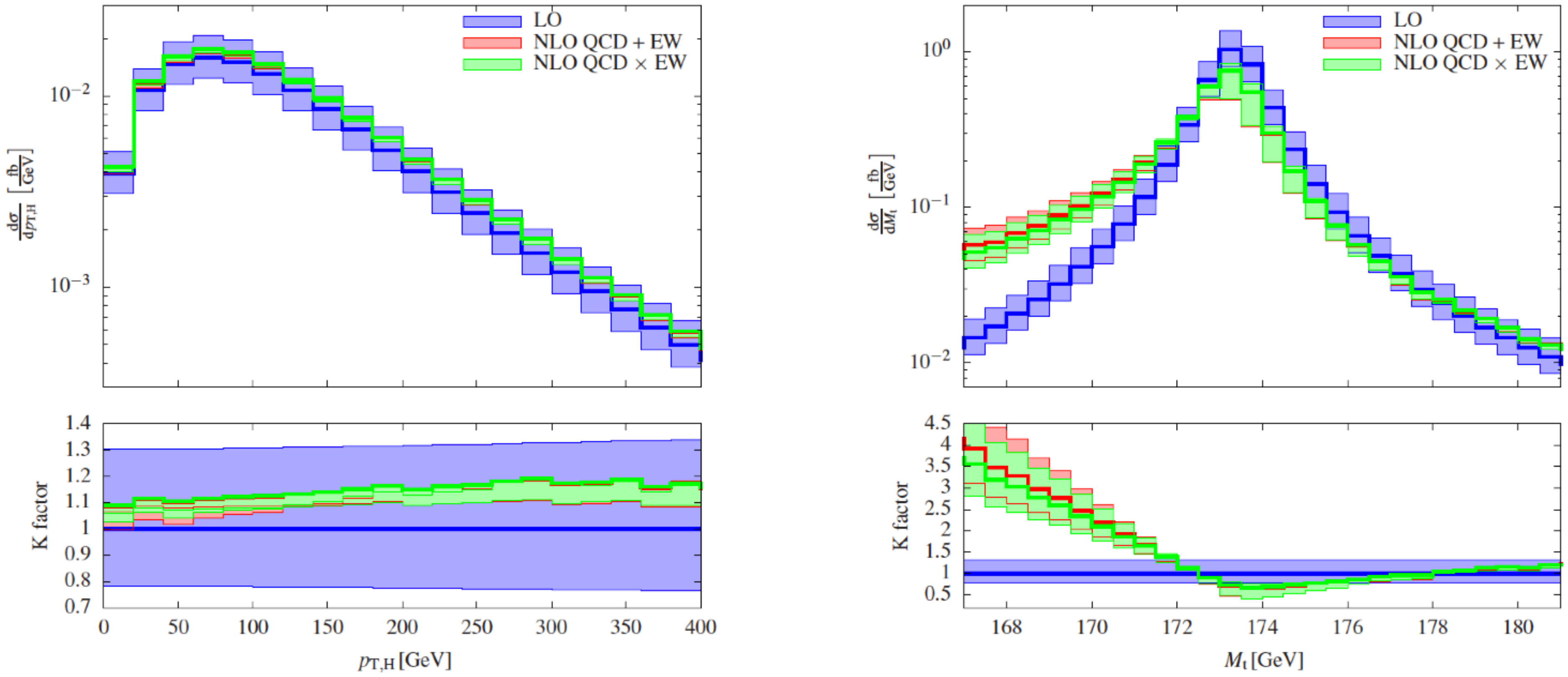
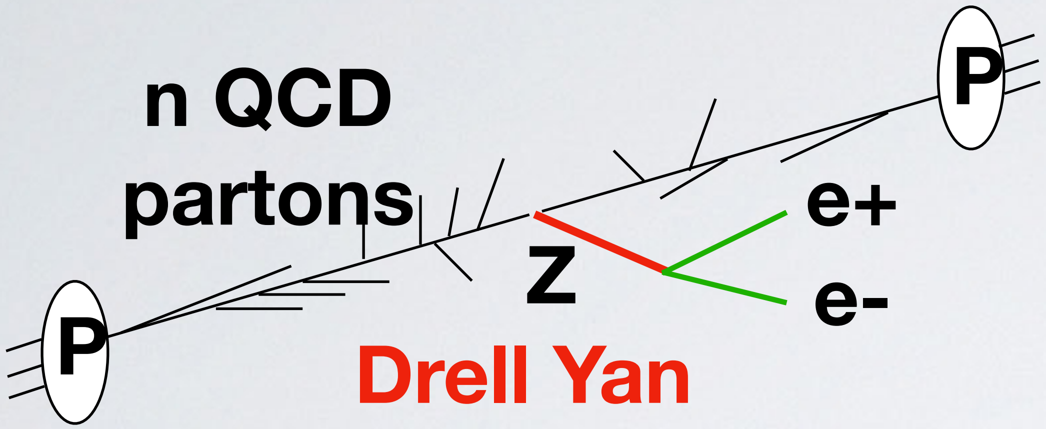
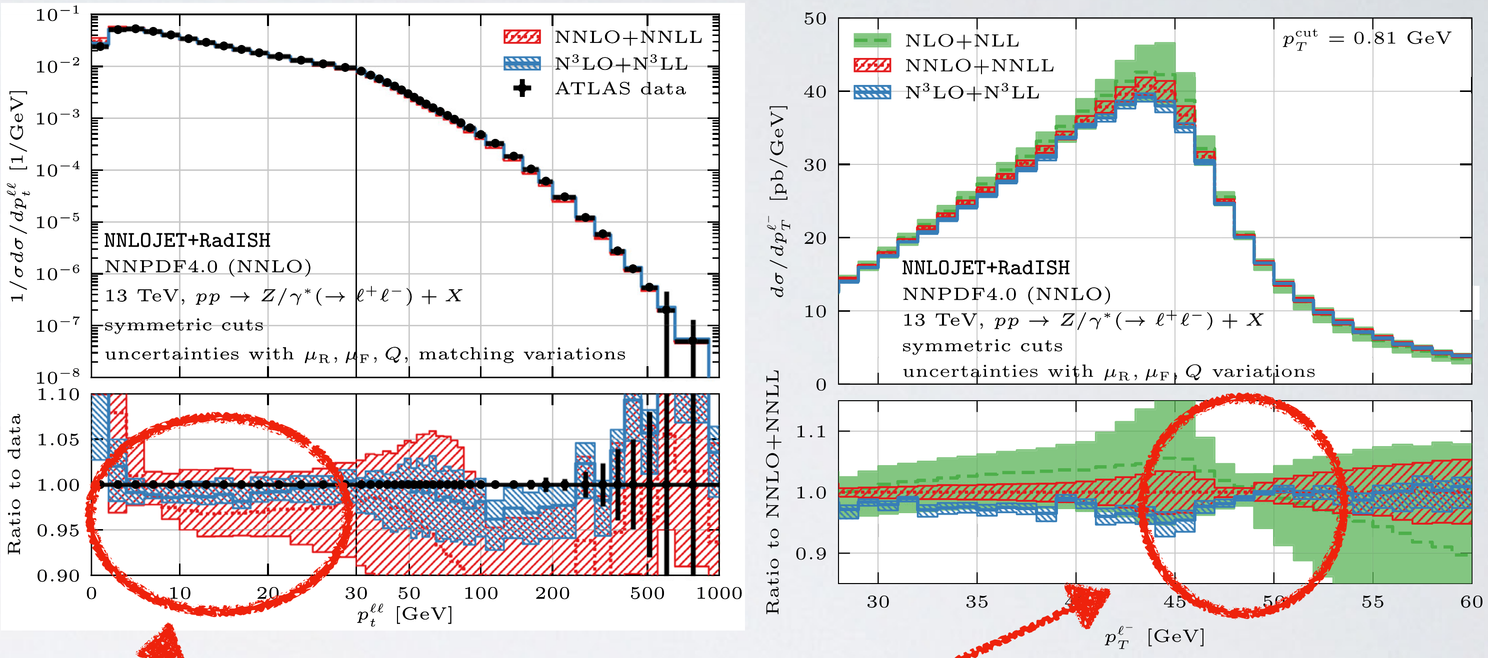


Figure 3: Differential distributions for $pp \to e^+\nu_e\mu^-\overline{\nu}_\mu b\overline{b}H$ at the LHC running at 13TeV [17]: transverse momentum of the Higgs boson (left) and invariant mass of the reconstructed top quark (right). Both the additive and the multiplicative combination of the NLO EW and QCD corrections are shown.

A. Denner, J.-N. Lang, M. Pellen, S. Uccirati - arXiv 1912.08493

HIGH-ACCURACY RESUMMATIONS AT LHC



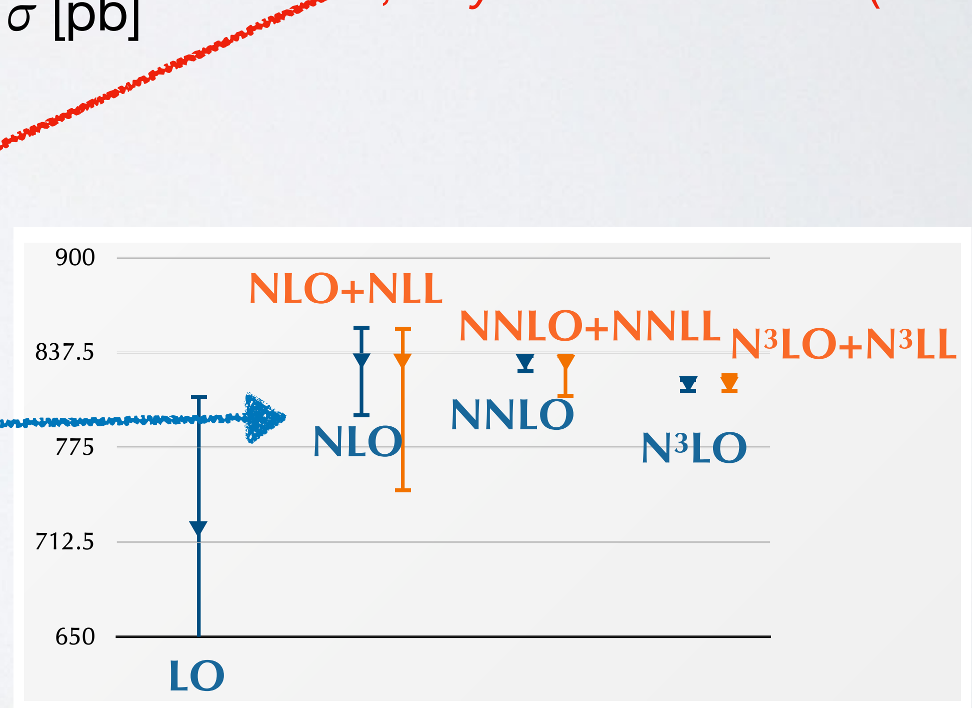


- Sum contribution from arbitrary number of soft/collinear (= IR) QCD partons

Chen et al, *Phys.Rev.Lett*. 128 (2022) 25

- Differential predictions reliable where fixed-order QCD pert. theory is spoiled by multiple IR radiation

- Calculation of cross section within experimental cuts up to N3LO in QCD using resummation ingredients



- Applications to Higgs physics, W-mass extraction, PDF determination, …

Paolo Torrielli

PRECISION FLAVOUR PHYSICS

Tests of the ***flavour structure*** of the SM: 3 generations of up and down quarks with different masses, mixing with each other via charged current.

The unitary 3x3 Cabibbo-Kobayashi-Maskawa (CKM) parametrises the mixing and leads to CP violation in the SM.

$$\hat{V}_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\hat{V}^{\dagger}_{\text{CKM}} \hat{V}_{\text{CKM}} = 1$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

first row

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1$$

second row etc.

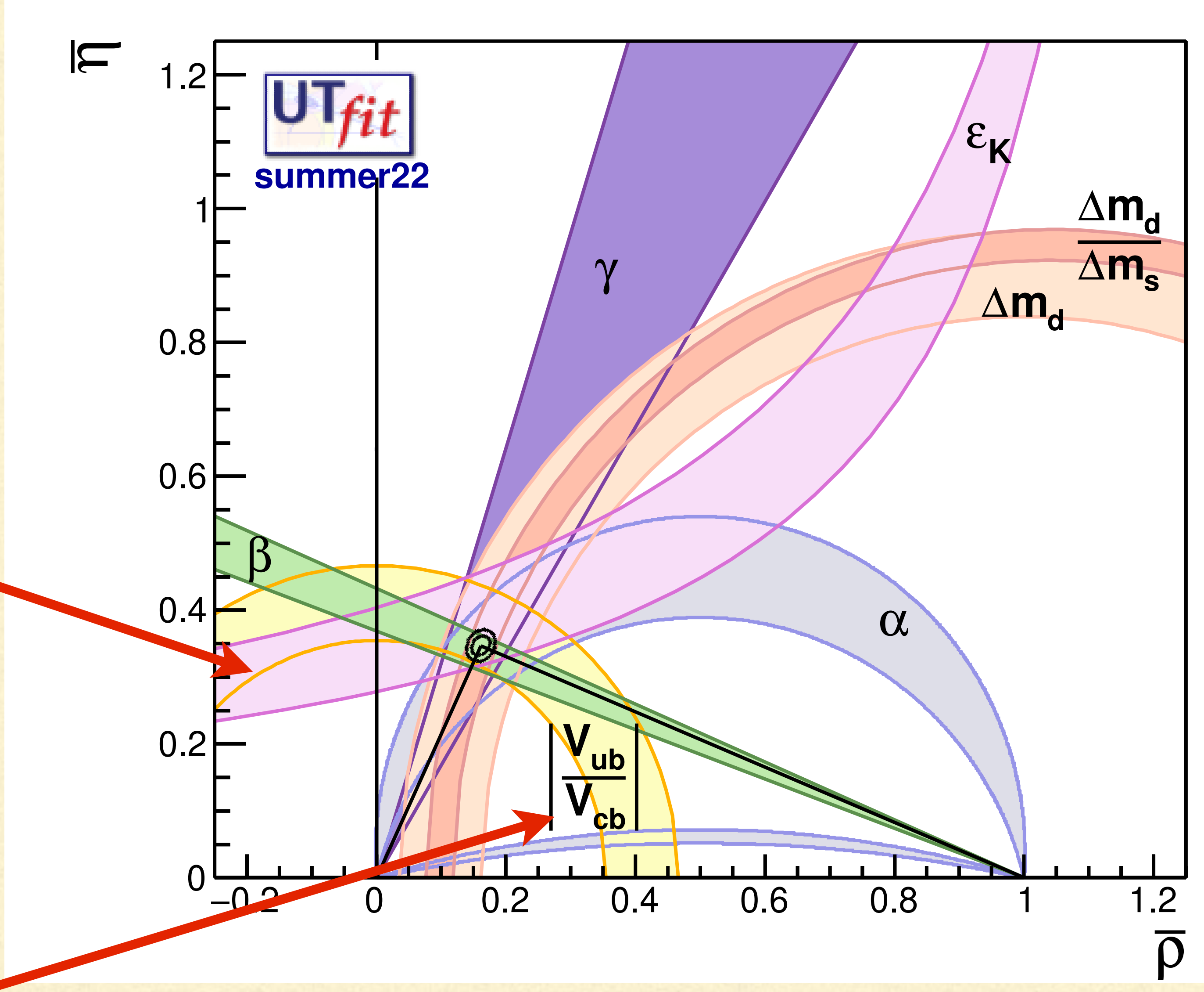
New Physics could manifest itself as violation of unitarity, or shift Flavour Changing Neutral Currents (loop induced in the SM) like $b \to s\gamma$, B and K mixing, etc

Hierarchical structure of CKM matrix ⇒ can probe $\Lambda_{NP} \gg \Lambda_{EW}$

The importance of $|V_{cb}|$

An important CKM unitarity test is the Unitarity Triangle (UT) formed by

$$1+\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}+\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}=0$$



V_{cb} plays an important role in UT

$$\varepsilon_K \approx x|V_{cb}|^4 + \ldots$$

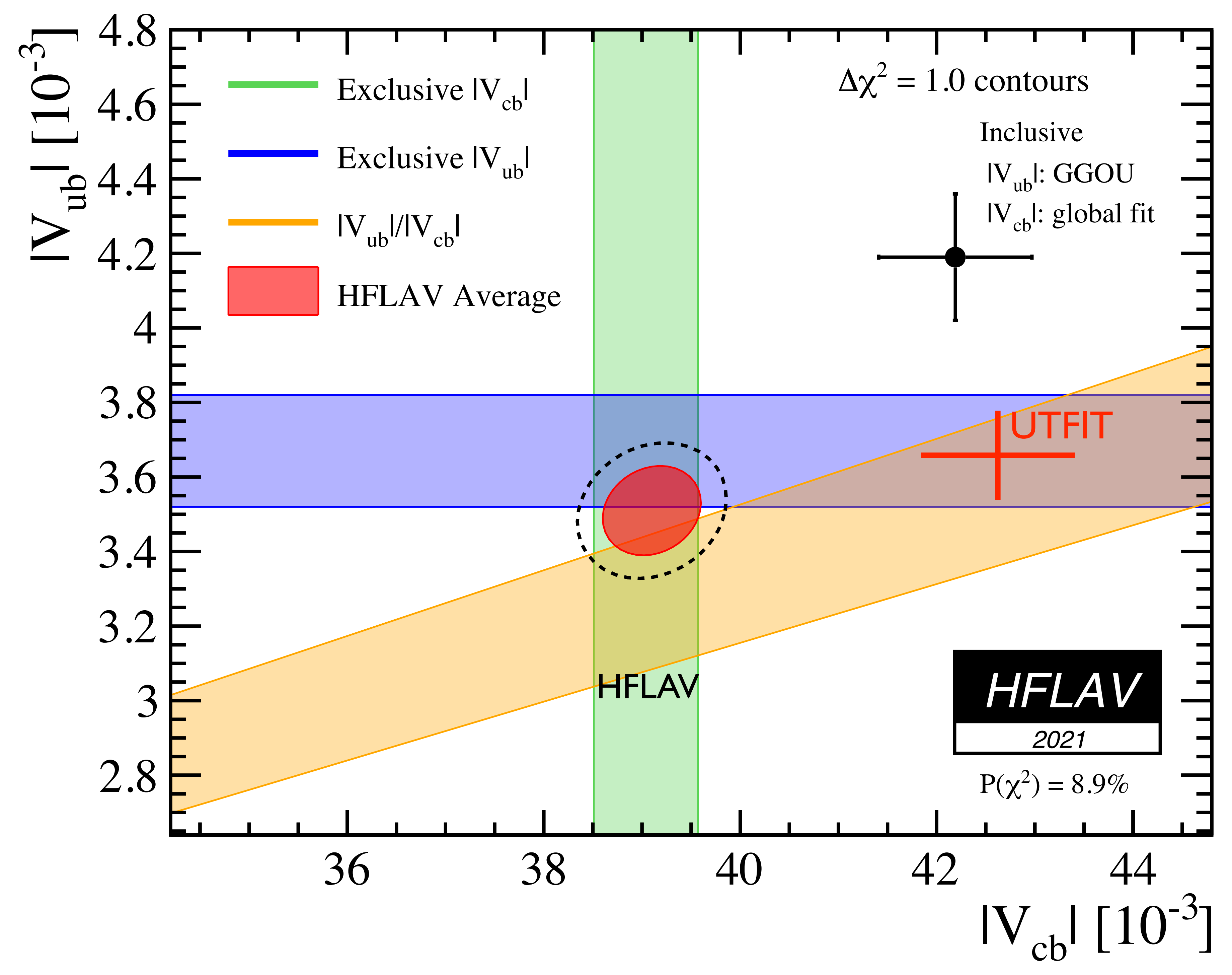
and in the prediction of FCNC:

$$\propto |V_{tb}V_{ts}|^2 \simeq |V_{cb}|^2\left[1+O(\lambda^2)\right]$$

where *it often dominates the theoretical uncertainty.*
V_{ub}/V_{cb} constrains directly the UT

Our ability to determine precisely V_{cb} is crucial for indirect NP searches

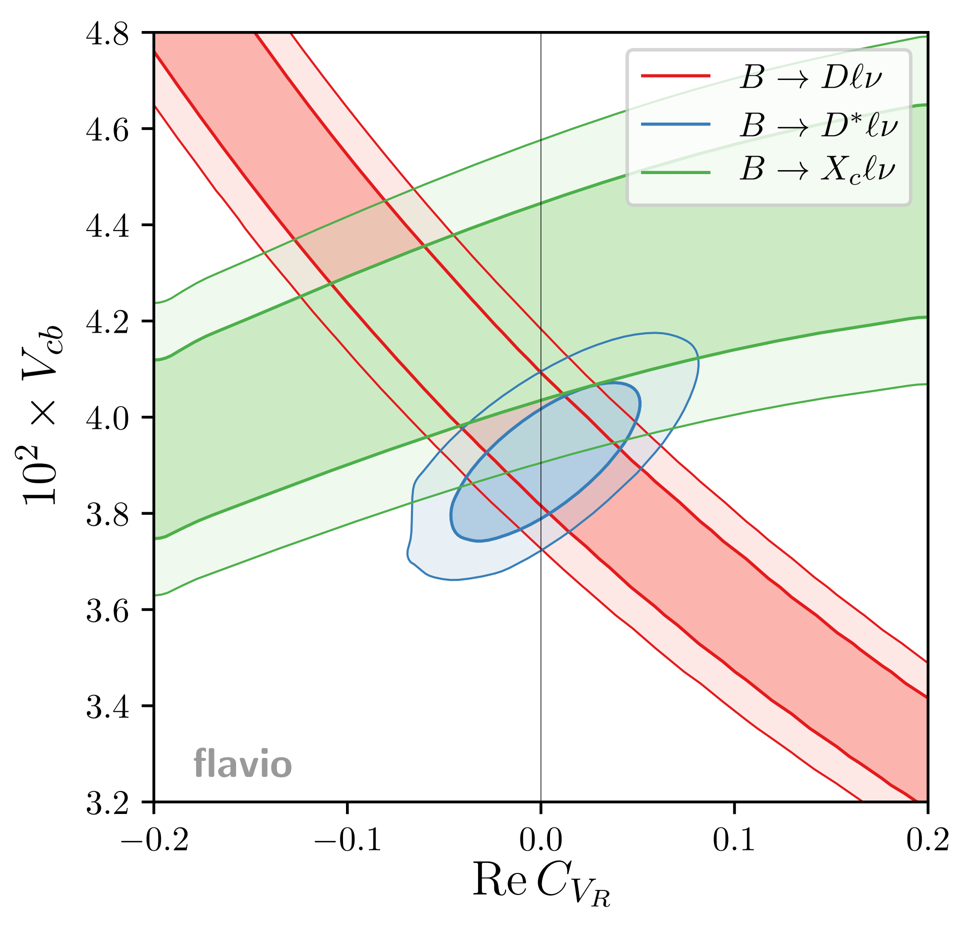
Since many years the inclusive and exclusive determinations of $|V_{cb}|$ and $|V_{ub}|$ diverge

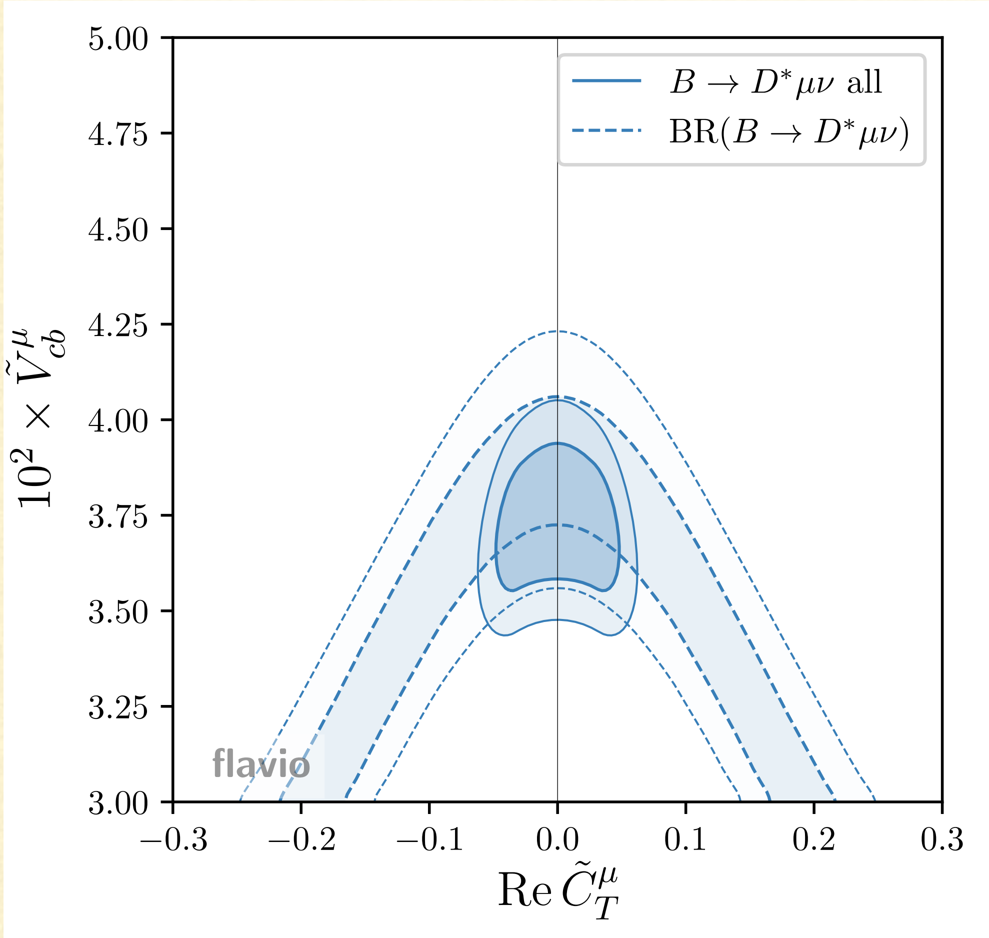


The puzzle. Do we believe these errors?

NEW PHYSICS?

Jung & Straub, 1801.01112



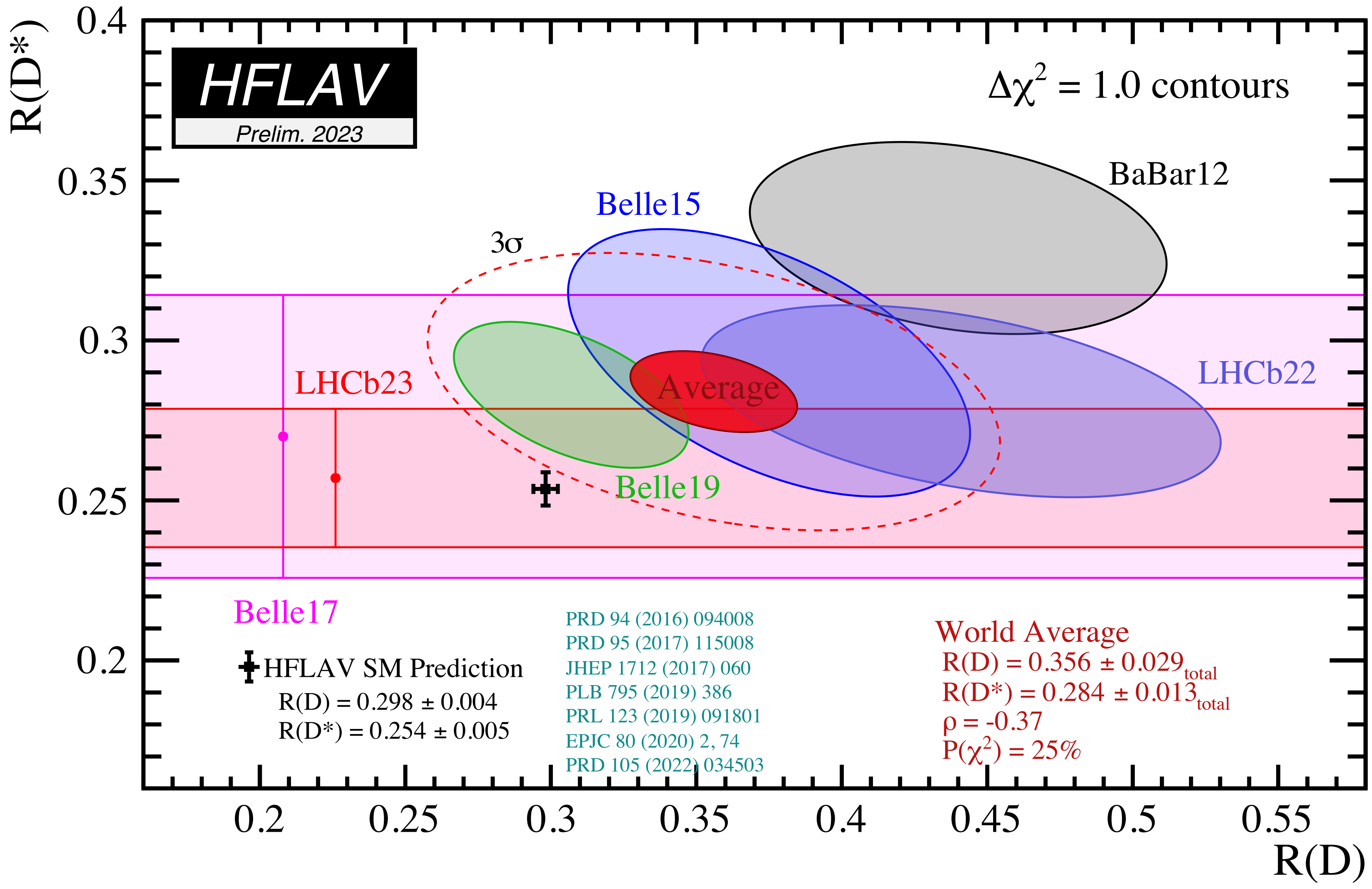


Differential distributions constrain NP strongly, SMEFT interpretation incompatible with LEP data: Crivellin, Pokorski, Jung, Straub…

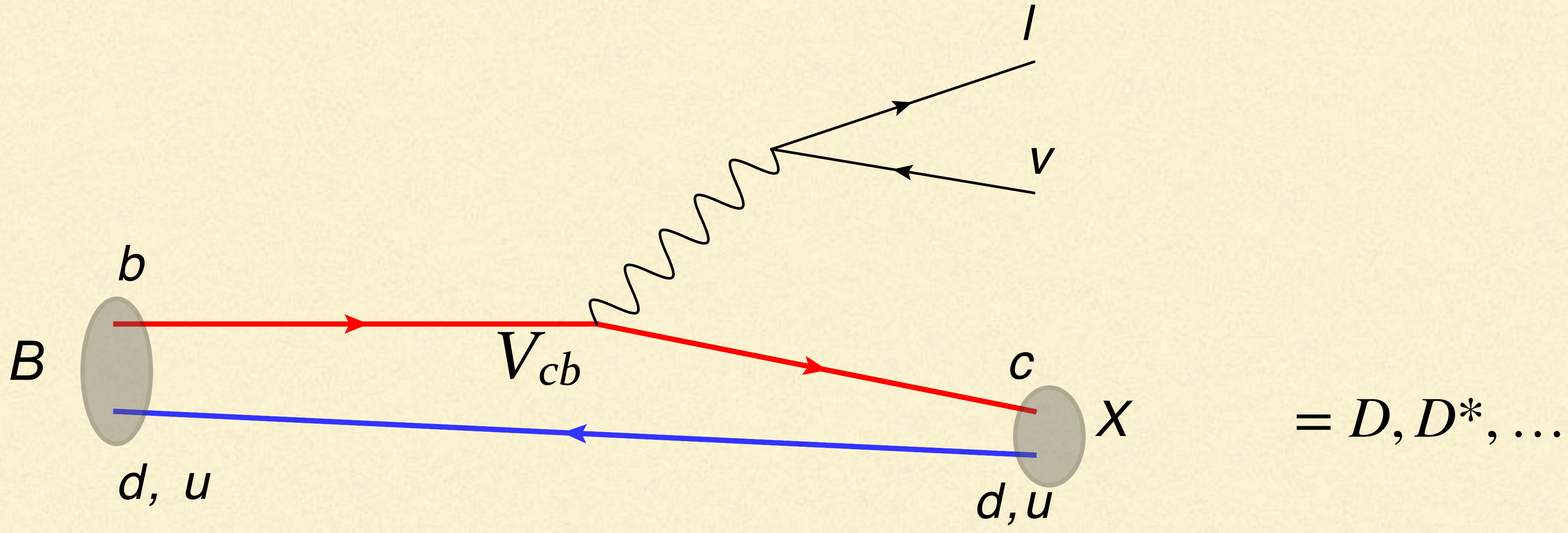
VIOLATION of LFU with TAUS?

$$R\left(D^{(*)}\right) = \frac{\mathcal{B}\left(B \to D^{(*)}\tau\nu_\tau\right)}{\mathcal{B}\left(B \to D^{(*)}\ell\nu_\ell\right)}$$

SM predictions
based on
same theory
as V_{cb} extraction



EXCLUSIVE DECAYS



$= D, D^*, \ldots$

There are 1(2) and 3(4) FFs for D and D* for light (heavy) leptons, for instance

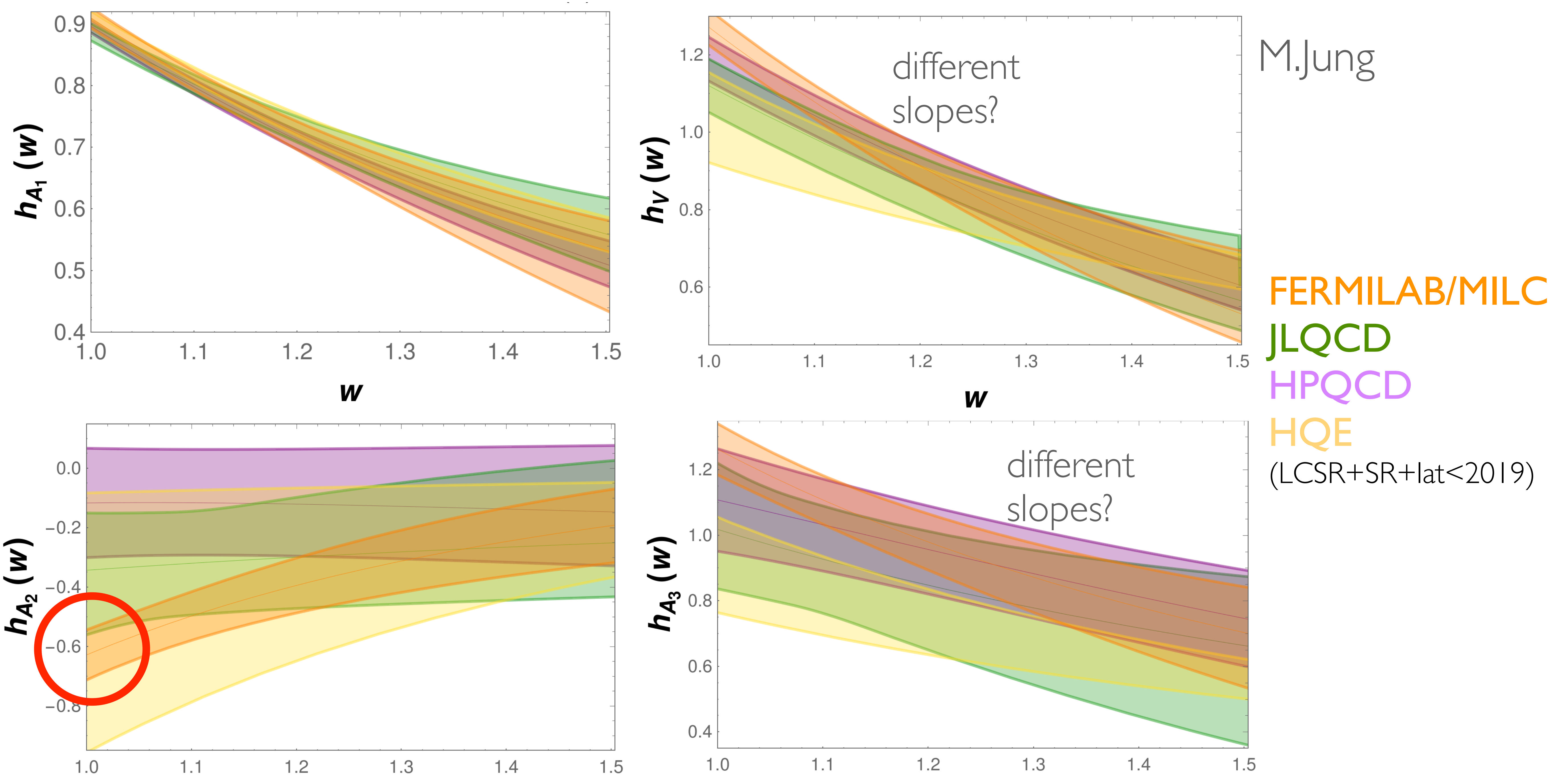
$$\langle D(k)|\,\bar{c}\gamma^{\mu}b\,|\bar{B}(p)\rangle = \left[(p+k)^{\mu} - \frac{M_B^2 - M_D^2}{q^2}q^{\mu}\right] f_{+}^{B\to D}(q^2) + \frac{M_B^2 - M_D^2}{q^2}q^{\mu} f_0^{B\to D}(q^2)$$

Information on FFs from LQCD (at high q^2), LCSR (at low q^2), HQE, exp, extrapolation, unitarity constraints, …

A ***model independent parametrization*** is necessary

LATTICE FORM FACTORS AT NONZERO RECOIL

2105.14019, 2112.13775, 2304.03137



M.Jung

BGL fits with weak unitarity. Relatively good agreement, but not in ratios!

OUR BGL FITS

Jung, Schacht, PG in progress

With Belle 2018 only

FNAL/MILC

$|V_{cb}|=39.4(9)\ 10^{-3}$ $(\chi^2_{min}=50)$ *using only total rate* $|V_{cb}|=42.2^{+2.8}_{-1.7}\ 10^{-3}$

JLQCD

$|V_{cb}|=40.7(9)\ 10^{-3}$ $(\chi^2_{min}=33)$ *using only total rate* $|V_{cb}|=40.8^{+1.8}_{-2.3}\ 10^{-3}$

HPQCD

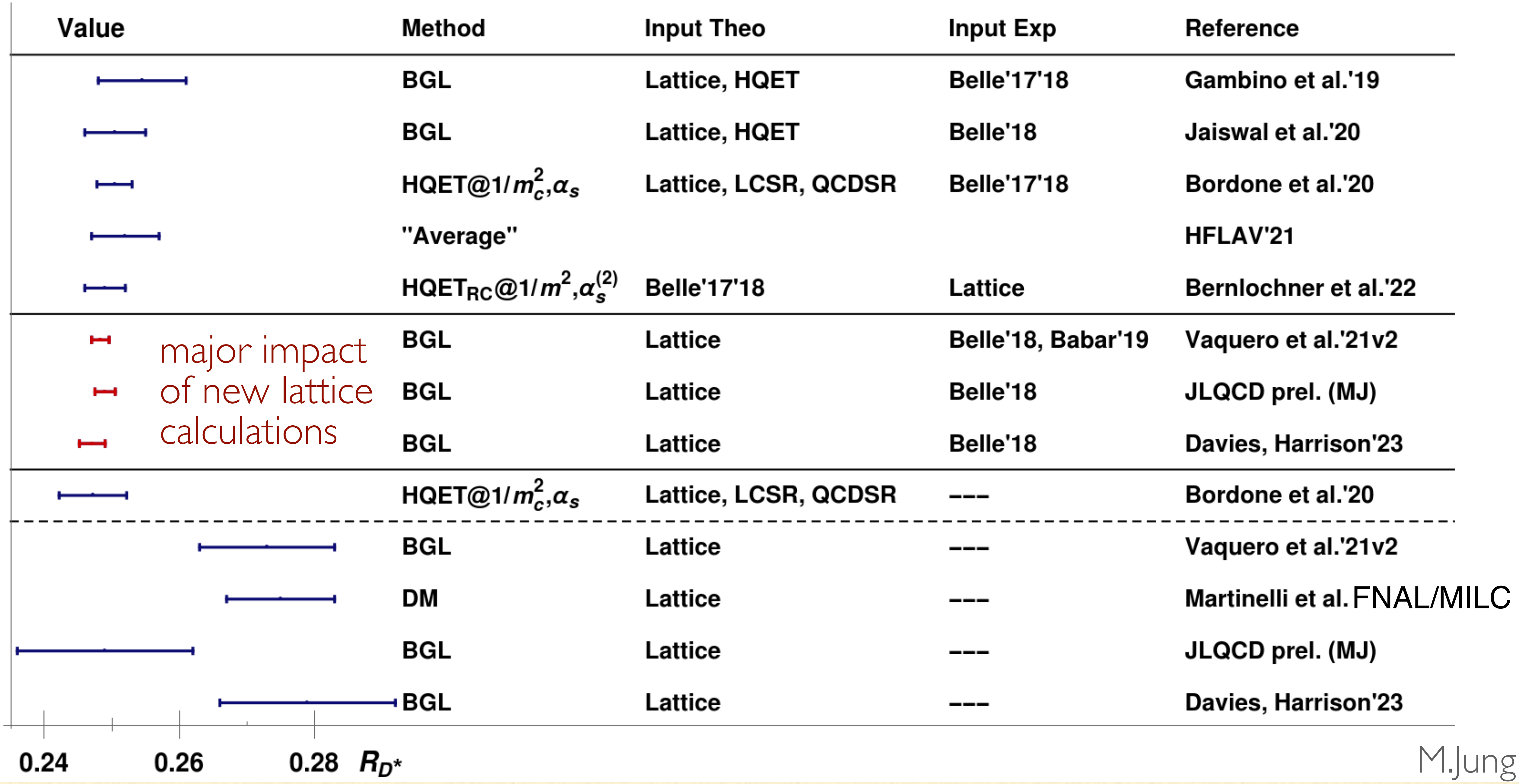
$|V_{cb}|=40.4(8)\ 10^{-3}$ $(\chi^2_{min}=50)$ *using only total rate* $|V_{cb}|=44.4\pm 1.6\ 10^{-3}$

HPQCD and FNAL are not well compatible: adding 16 points increases χ^2 by 35

Global BGL fit to Belle18+FNAL+JLQCD+HPQCD data:

$|V_{cb}|=40.3(7)\ 10^{-3}$ $(\chi^2_{min}=91)$ *using only total rate* $|V_{cb}|=42.4(1.0)\ 10^{-3}$

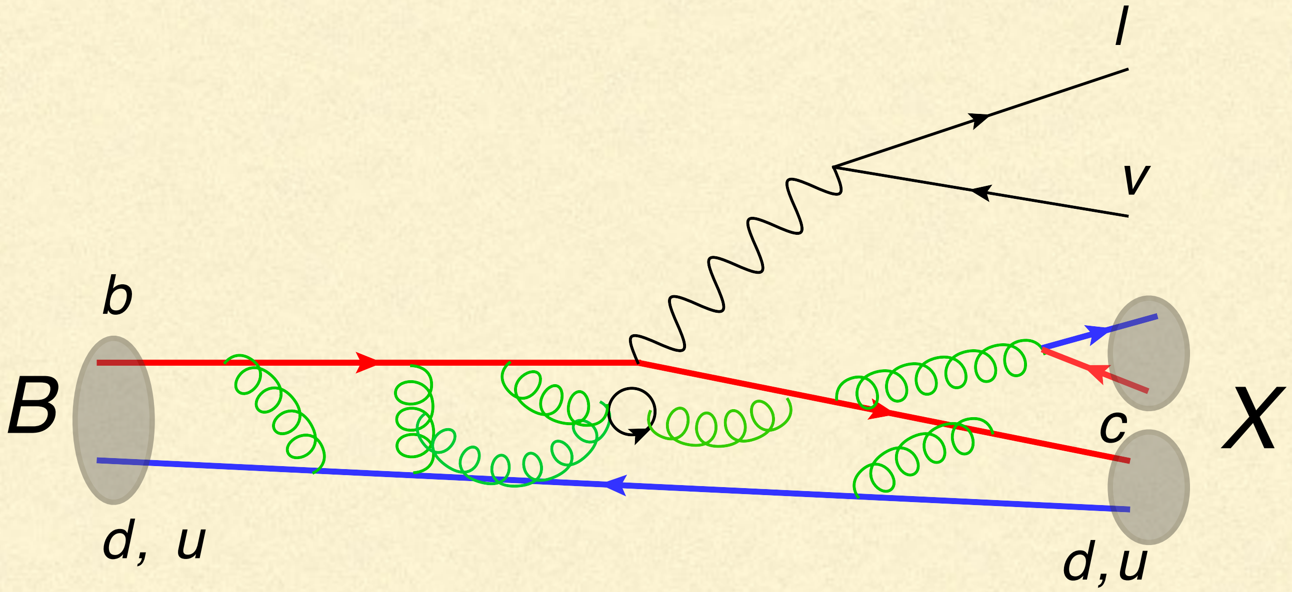
Overview over predictions for $R(D^*)$



Value	Method	Input Theo	Input Exp	Reference
	BGL	Lattice, HQET	Belle'17'18	Gambino et al.'19
	BGL	Lattice, HQET	Belle'18	Jaiswal et al.'20
	HQET@1/m_c^2,α_s	Lattice, LCSR, QCDSR	Belle'17'18	Bordone et al.'20
	"Average"			HFLAV'21
	HQET$_{RC}$@1/m^2,$\alpha_s^{(2)}$	Belle'17'18	Lattice	Bernlochner et al.'22
	BGL	Lattice	Belle'18, Babar'19	Vaquero et al.'21v2
	BGL	Lattice	Belle'18	JLQCD prel. (MJ)
	BGL	Lattice	Belle'18	Davies, Harrison'23
	HQET@1/m_c^2,α_s	Lattice, LCSR, QCDSR	---	Bordone et al.'20
	BGL	Lattice	---	Vaquero et al.'21v2
	DM	Lattice	---	Martinelli et al. FNAL/MILC
	BGL	Lattice	---	JLQCD prel. (MJ)
	BGL	Lattice	---	Davies, Harrison'23

Predictions based only on Fermilab & HPQCD lead to larger R(D*), in better agreement with exp, mostly because of the suppression at high w of the denominator. ***No reason not to use experimental data for a SM test***, especially in presence of tensions in lattice data.

INCLUSIVE DECAYS: BASICS



- ***Simple idea:*** inclusive decays do not depend on final state, long distance dynamics of the B meson factorizes. An OPE allows us to express it in terms of B meson matrix elements of local operators.

- The Wilson coefficients are perturbative, matrix elements of local ops parameterize non-pert physics: ***double series in*** $\alpha_s, \Lambda/m_b$

- Lowest order: decay of a free *b*, linear Λ/m_b absent. Depends on $m_{b,c}$, two parameters at $O(\Lambda^2/m_b^2)$, 2 more at $O(\Lambda^3/m_b^3)$ ... Many higher order effects have been computed.

A GLOBAL FIT

Finauri, PG 2310.20324

$m_b^{\rm kin}$	$\overline{m}_c(2\,\mathrm{GeV})$	μ_π^2	$\mu_G^2(m_b)$	$\rho_D^3(m_b)$	ρ_{LS}^3	$\mathrm{BR}_{c\ell\nu}$	$10^3\lvert V_{cb}\rvert$
4.573	1.090	0.454	0.288	0.176	-0.113	10.63	41.97
0.012	0.010	0.043	0.049	0.019	0.090	0.15	0.48

Includes all leptonic, hadronic, and q^2 moments

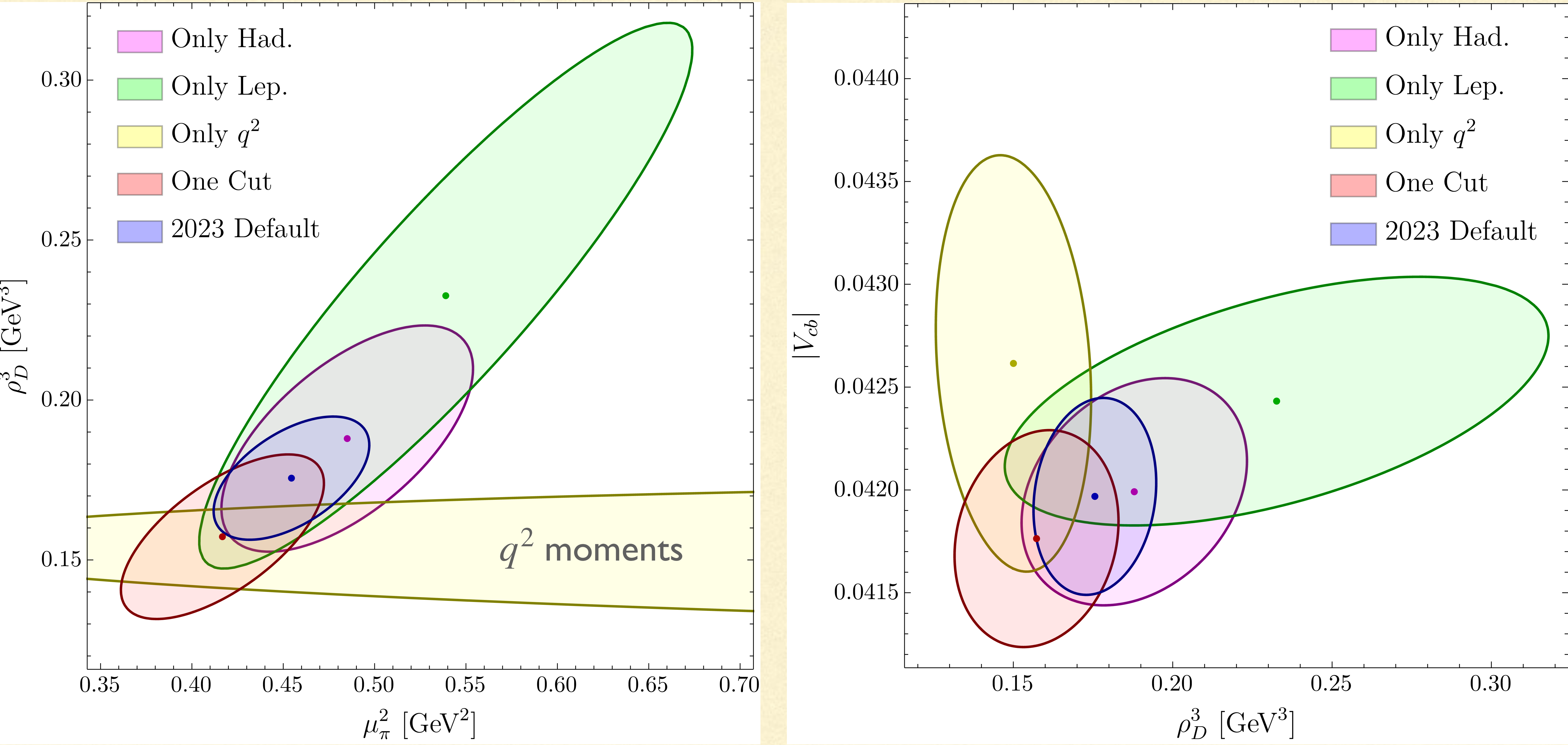
Up to $O(\alpha_s^2)$, $O(\alpha_s/m_b^2)$, $O(1/m_b^3)$ for M_X, E_ℓ moments
Up to $O(\alpha_s^2\beta_0)$, $O(\alpha_s/m_b^3)$ for q^2 moments
Subtracts QED effects beyond those computed by PHOTOS (only BaBar BR and lept moments) $\delta|V_{cb}| \sim -0.2\,\%$

Employs $\overline{m}_b(\overline{m}_b) = 4.203(11)\mathrm{GeV}$ and $\overline{m}_c(3\mathrm{GeV}) = 0.989(10)\mathrm{GeV}$(FLAG)
$\chi^2_{min}/dof = 0.55$

$$|V_{cb}| = (41.97 \pm 0.27_{exp} \pm 0.31_{th} \pm \boxed{0.25_\Gamma}) \times 10^{-3} = (41.97 \pm 0.48) \times 10^{-3}$$

comparison of different datasets

Finauri, PG 2310.20324

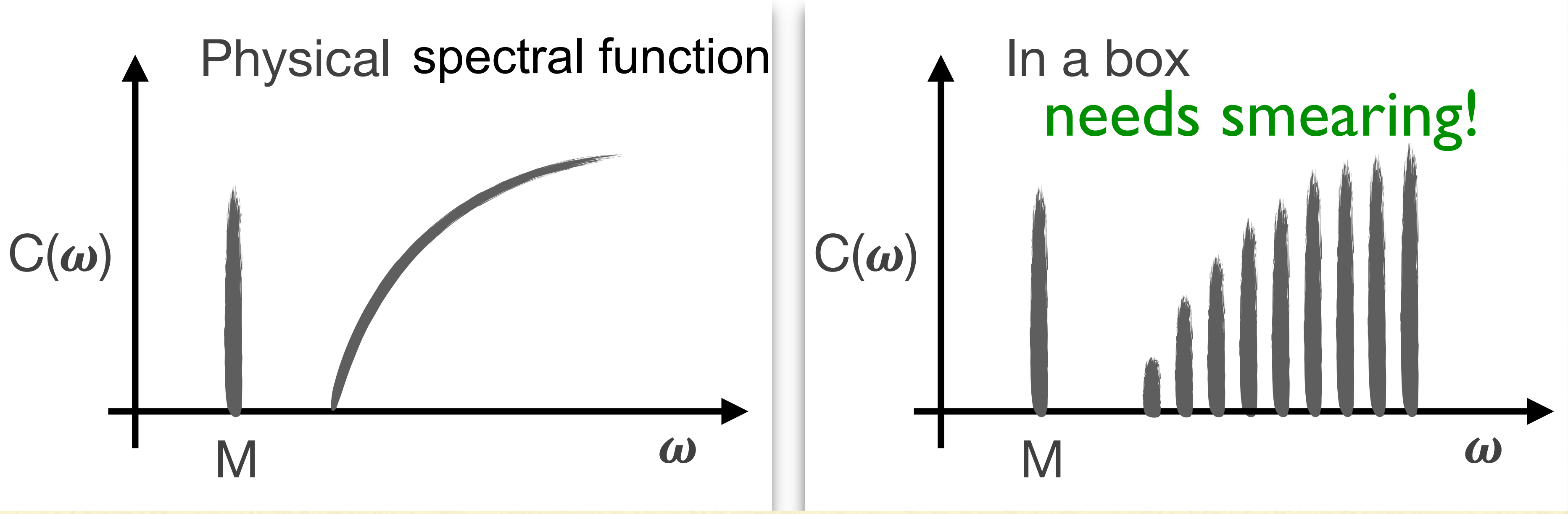


INCLUSIVE DECAYS ON THE LATTICE

Inclusive processes impractical to treat directly on the lattice. Vacuum current correlators computed in euclidean space-time are related to $e^+e^- \rightarrow$ hadrons or τ decay via analyticity. In our case the correlators have to be computed in the *B* meson, but analytic continuation more complicated: two cuts, decay occurs only on a portion of the cut associated to *B* semileptonic decays.

While the lattice calculation of the spectral density of hadronic correlators is an ***ill-posed problem***, the spectral density is accessible after smearing

Hansen, Meyer, Robaina, Hansen, Lupo, Tantalo, Bailas, Hashimoto, Ishikawa



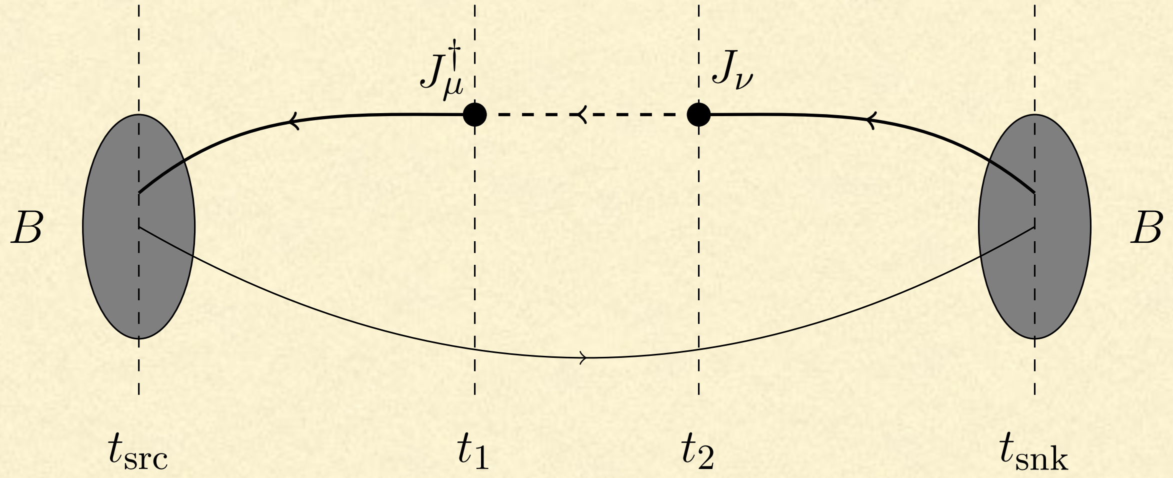
W. Jay @Snowmass workshop

A NEW APPROACH

Hashimoto, PG 2005.13730

4-point functions on the lattice are related to the hadronic tensor in euclidean

$$\sim \langle B|J^\dagger_\mu(\mathbf{x},t)J_\nu(\mathbf{0},0)|B\rangle$$

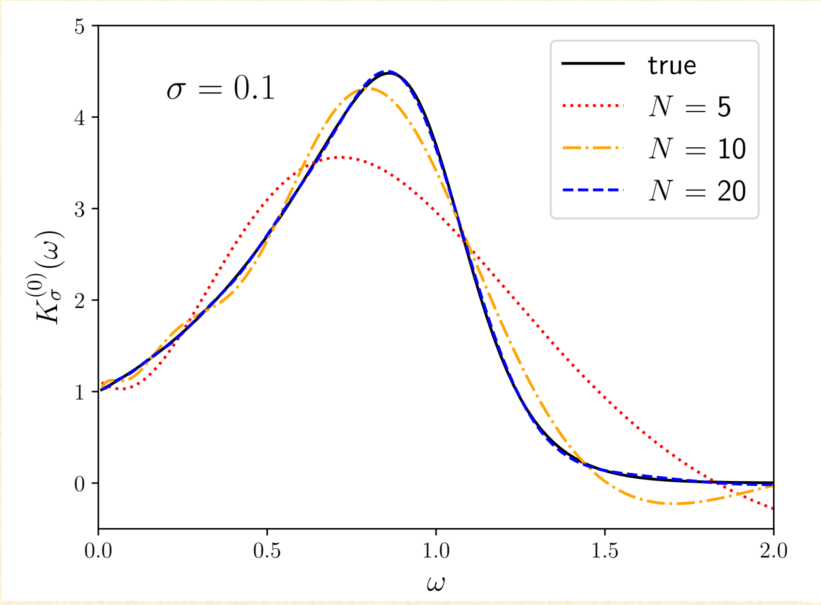


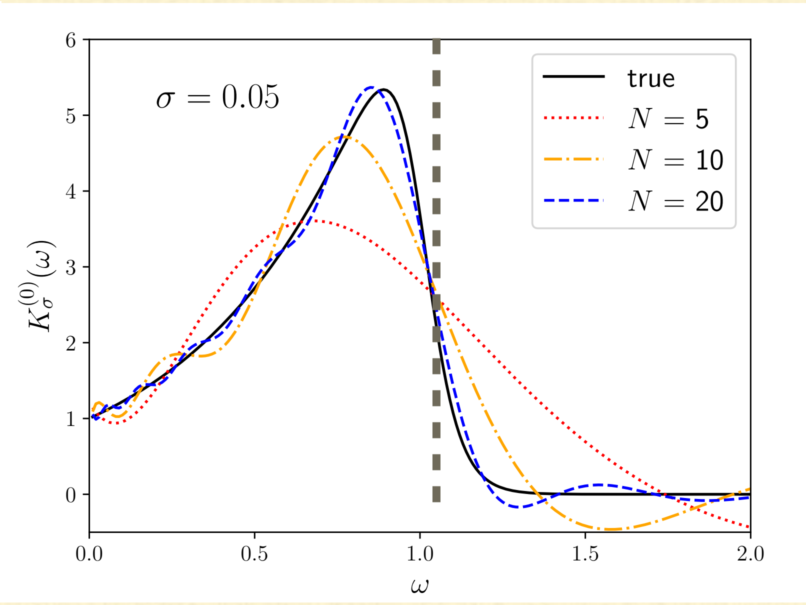
$$d\Gamma \sim L^{\mu\nu}W_{\mu\nu}, \quad W_{\mu\nu} \sim \sum_X \langle B|J^\dagger_\mu|X\rangle\langle X|J_\nu|B\rangle$$

$$\int d^3x \frac{e^{i\mathbf{q}\cdot\mathbf{x}}}{2M_B}\langle B|J^\dagger_\mu(\mathbf{x},t)J_\nu(\mathbf{0},0)|B\rangle \sim \int_0^\infty d\omega W_{\mu\nu}e^{-t\omega}$$

smearing kernel $f(\omega) = \sum_n a_n e^{-na\omega}$

The necessary smearing is provided by phase space integration over the hadronic energy, which is cut by a θ with a sharp hedge: sigmoid $1/(1+e^{x/\sigma})$ can be used to replace kinematic $\theta(x)$ for $\sigma \to 0$. Larger number of polynomials needed for small σ



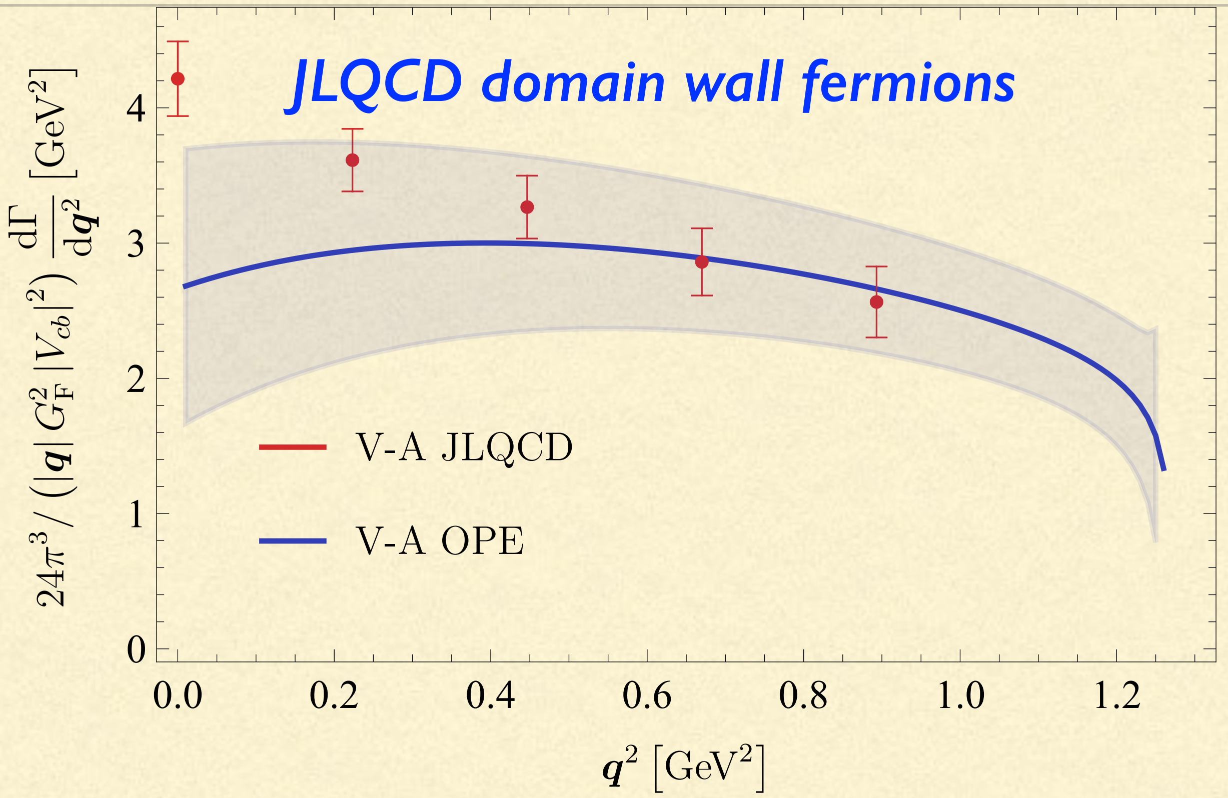


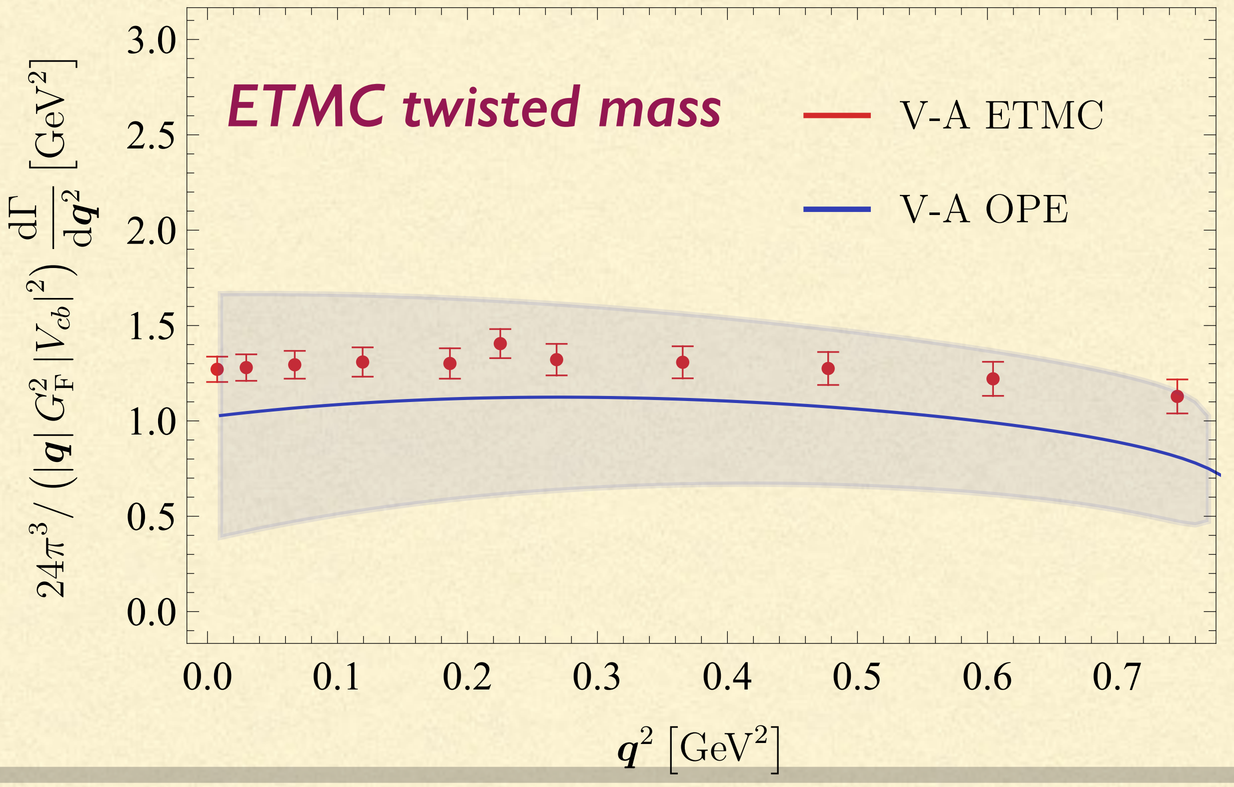
Two methods based on Chebyshev polynomials and Backus-Gilbert. Important:

$$\lim_{\sigma\to 0}\lim_{V\to\infty} X_\sigma$$

PG, Hashimoto, Maechler, Panero, Sanfilippo, Simula, Smecca, Tantalo, 2203.11762

LATTICE VS OPE





m_b^{kin} (JLQCD)	2.70 ± 0.04
$\overline{m}_c(2\ \text{GeV})$ (JLQCD)	1.10 ± 0.02
m_b^{kin} (ETMC)	2.39 ± 0.08
$\overline{m}_c(2\ \text{GeV})$ (ETMC)	1.19 ± 0.04
μ_π^2	0.57 ± 0.15
ρ_D^3	0.22 ± 0.06
$\mu_G^2(m_b)$	0.37 ± 0.10
ρ_{LS}^3	-0.13 ± 0.10
$\alpha_s^{(4)}(2\ \text{GeV})$	0.301 ± 0.006

OPE inputs from fits to exp data (physical m_b), HQE of meson masses on lattice

1704.06105, J.Phys.Conf.Ser. 1137 (2019) 1, 012005

We include $O(1/m_b^3)$ and $O(\alpha_s)$ terms

Hard scale $\sqrt{m_c^2+\mathbf{q}^2} \sim 1-1.5\,\text{GeV}$

We do not expect OPE to work at high $|\mathbf{q}|$

Twisted boundary conditions allow for any value of $\vec{q}^2$

Smaller statistical uncertainties


kia ora
ありがとう
barka
tau
bedankt
arigatô
bayarlalaa
dekuji
rahmat
grazzi
мерси
tack
sulpay
akun
aciu
tanemirt
mersi
diolch
dakujem
ngiyabonga
djiere dieuf
dhanyavad
shukriya
spas
mochchakkeram
sukriya
merci
chnorakaloutioun
dank je
teşekkü ederim
gracies
welalin
efharisto
terima kasih
gratias ago
mamnun
kop khun
najis tuke
teşekkür ederim
obrigado
misaotra
matondo
dhanyavadagalu
paldies
faafetai lava
hvala
trugarez
kam sah hamnida
koszonom
rahmet
kop khun krap
mercé
leat
nandri
gracias
krap
tapadh
sagolun
nanni
taiku
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thank you
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Баярлалаа
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謝謝
vinaka
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xiexie
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sobodi
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спасибо
murakoze