Precision Calculations in QCD

Bahman Dehnadi

Deutsches Elektronen-Synchrotron

Theory Fellows Meeting, Dec 3th 2019, Hamburg, Germany

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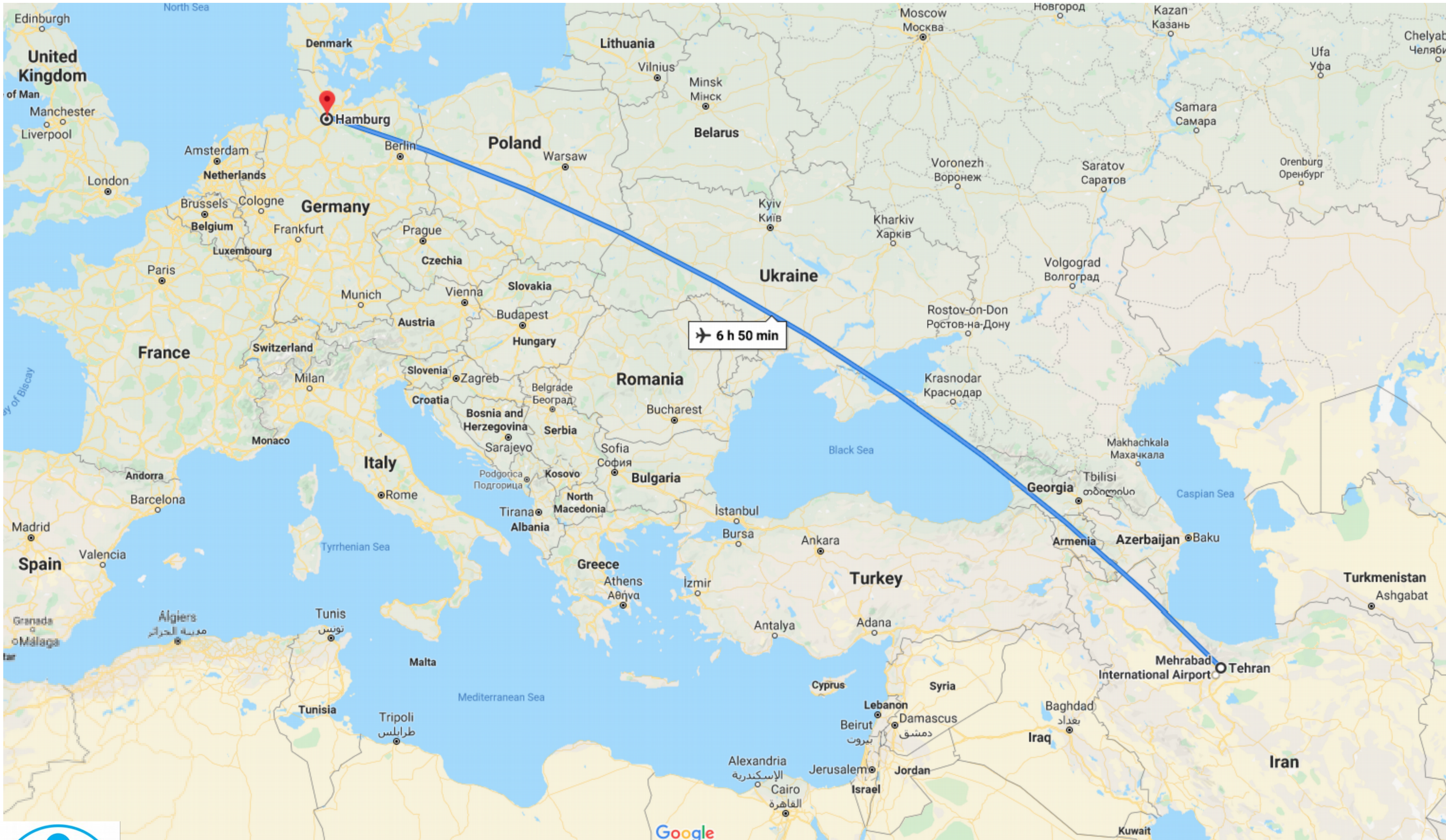
About me...

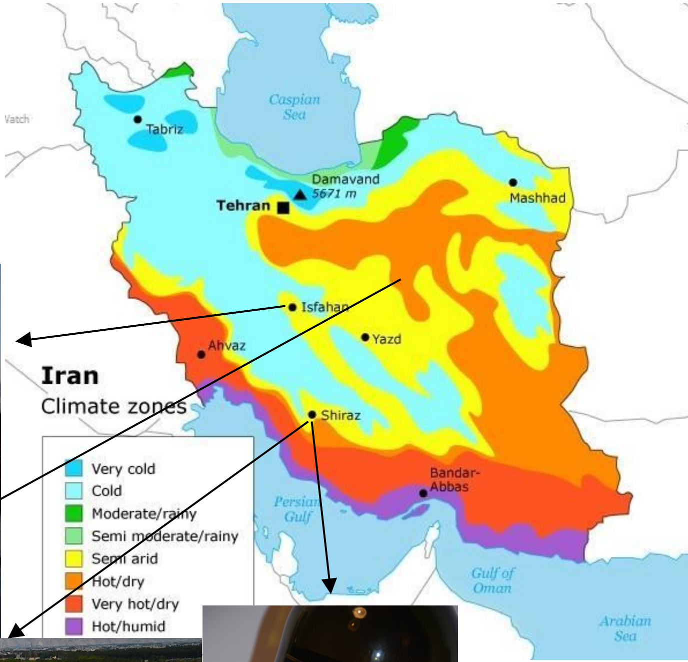
- I am from Tehran, Iran (4,404 Km away)



About Iran

Some Facts

- Muslims, Zoroastrians, Christians and Jews are living “peacefully”
- Two salt deserts covers 25% of Iran’s land area
- Iran has the third highest number of UNESCO world sites in Asia



About me...

Academic Carrier

- 2012 – 2016 PhD from University of Vienna under supervision of Andre Hoang
- 2016 – 2019 First postdoc at University of Siegen
- Since Oct. 2019 Second postdoc at DESY, Hamburg

Hobbies

- Playing persian music (Kamanche)
- Dancing *LiNdY HoP*

Research Overview

- Charm and Bottom Quark Mass Determinations from QCD Sum Rules
  [BD, A.H. Hoang, V. Mateu, I. W. Stewart, S. M. Zebarjad (2013)]
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- Top Quark Mass Calibration for Monte-Carlo Event Generators
  [M. Beutenschoen, BD, A.H. Hoang, V. Mateu, I. W. Stewart (2016)]
- Automated Calculation of N-jet Soft Functions at NNLO
  [G. Bell, BD, T. Mohrmann, R. Rahn (2018)]
- Inclusive Top Quark Pair Production at Future Linear Colliders
  [BD, A.H. Hoang, V. Mateu, M. Stahlhofen, A. Widl (to appear soon)]
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  [G. Bell, BD, J. Piclum, B. Lange (w.i.p.)]

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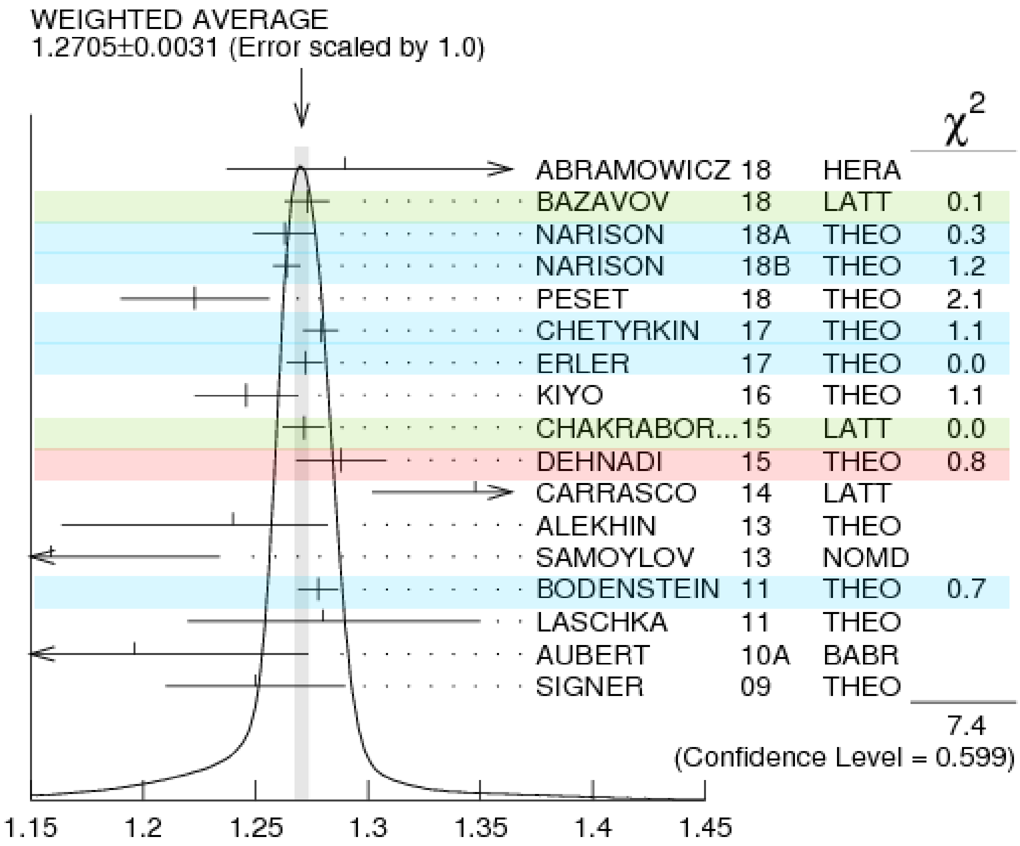
Charm and Bottom Quark Masses

Charm Quark Mass

$$\overline{m}_c(\overline{m}_c) = 1.27 \pm 0.02\,\mathrm{GeV}$$

[PDG 2019]



- **Most precise** determinations:
  - QCD sum rules → $M_n^{\exp} = \int_{4m^2}^{\infty} \frac{\mathrm{d}s}{s^{n+1}} R_{e^+e^- \to c\bar{c}+X}(s)$
  - Lattice

[Taken from PDG 2019]

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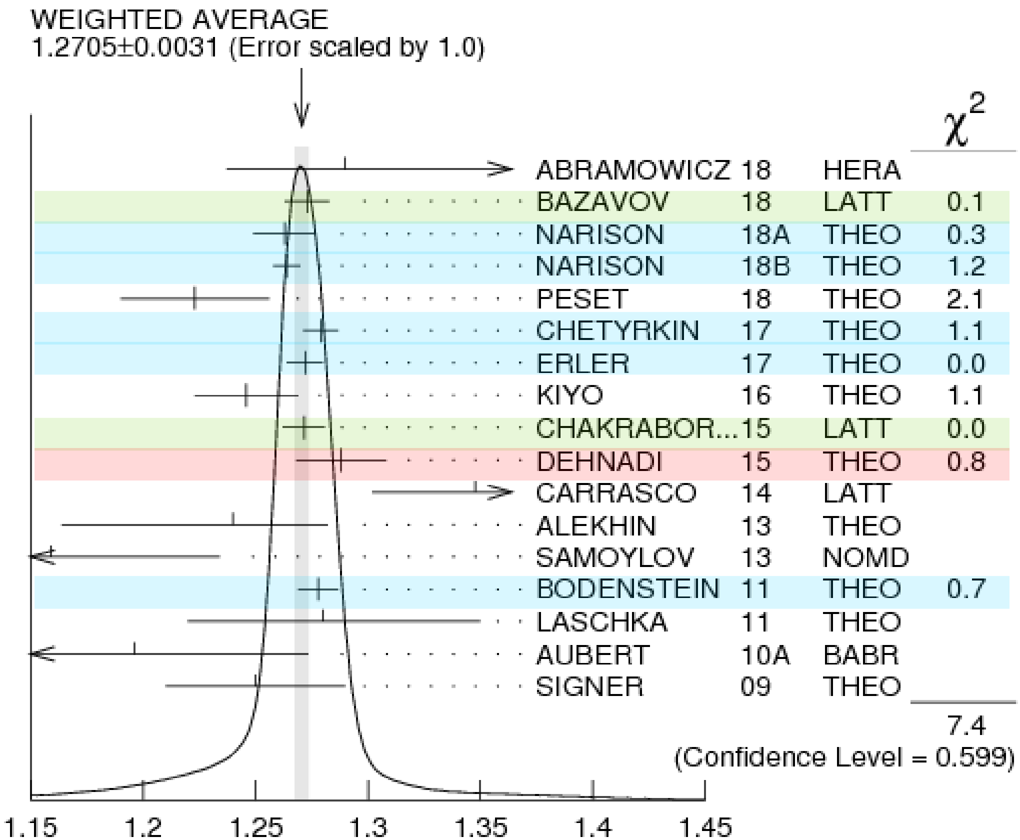

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- How much **reliable?**
  - ✘ Relied heavily on theoretical input (**significant modeling** uncertainties)
  - ✘ **Same algorithms** & perturbative series
  - ✘ **Common** method for estimating **Unc.**
  - ✘ **Consistency to each other** for justification

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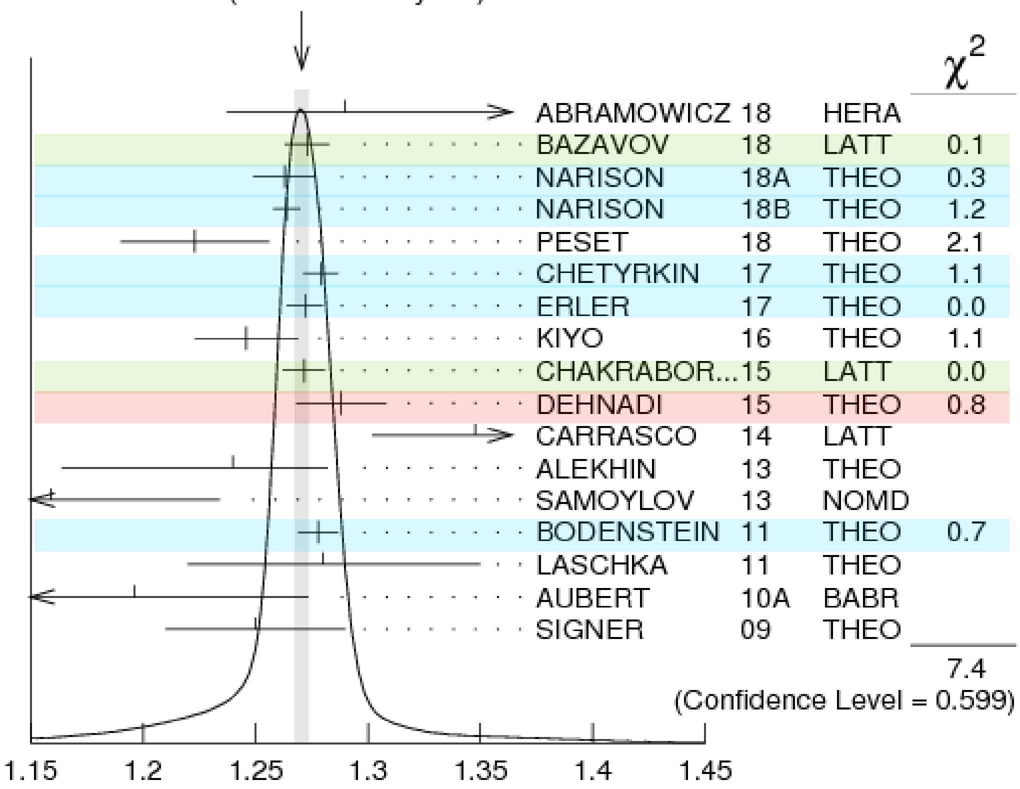

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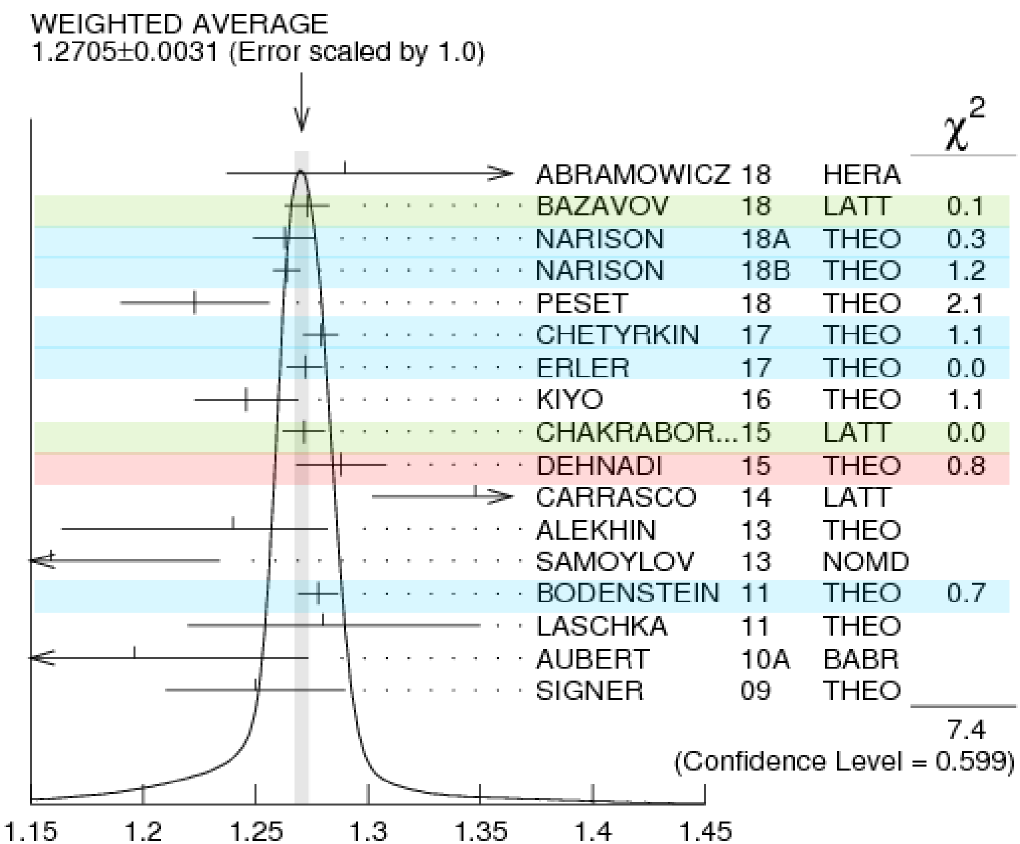
- Our results (QCD sum rules)
  - ✓ Combine **all experimental** data
  - ✓ **Different algorithms** for determining the mass
  - ✓ **New method** for estimating **Unc.** Double scale variation

Charm Quark Mass

$$\overline{m}_c(\overline{m}_c) = 1.27 \pm 0.02\,\text{GeV}$$

[PDG 2019]



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  - ✘ Relied heavily on theoretical input (**significant modeling** uncertainties)
  - ✘ **Same algorithms** & perturbative series
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  - ✘ **Consistency to each other** for justification

- Our results (QCD sum rules)

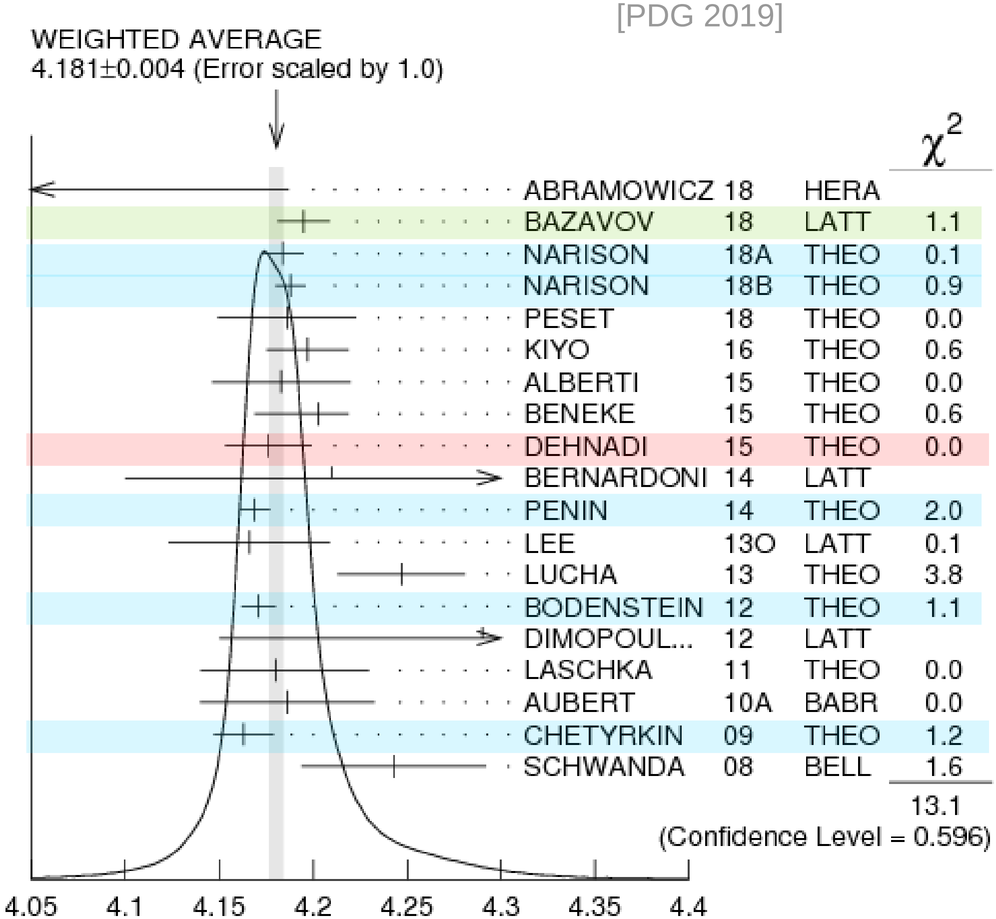
$$\overline{m}_c(\overline{m}_c) = 1.288 \pm (0.006)_{\text{stat}} \pm (0.009)_{\text{syst}} \pm (0.014)_{\text{pert}} \pm (0.010)_{\alpha_s} \pm (0.002)_{\langle GG \rangle}\ \text{GeV}$$

$$\alpha_s(m_Z) = 0.1184 \pm 0.0021$$

Bottom Quark Mass

$$\overline{m}_b(\overline{m}_b) = (4.18 \pm 0.03)\,\text{GeV}$$

[PDG 2019]



- **Most precise** determinations:
  - QCD sum rules
  - Lattice

- ✘ **Similar caveats**

- Our results (QCD sum rules)

$$\overline{m}_b(\overline{m}_b) = 4.176 \pm (0.004)_{\text{stat}} \pm (0.019)_{\text{syst}} \pm (0.010)_{\text{pert}} \pm (0.007)_{\alpha_s} \pm (0.0001)_{\langle GG\rangle}\,\text{GeV}$$

$$\alpha_s(m_Z) = 0.1184 \pm 0.0021$$

[Taken from PDG 2019]

Top Quark Mass

Top Quark Mass

2019 Review of Particle Physics.
M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and 2019 update.

QUARKS

INSPIRE search

t $\quad I(J^P) = 0(1/2^+)$

Charge = $\frac{2}{3}$ e Top = +1

See related review:
Top Quark

t-QUARK MASS

t-Quark Mass (Direct Measurements)	172.9 ± 0.4 GeV (S = 1.3)
t-Quark Mass from Cross-Section Measurements	160^{+5}_{-4} GeV
t-Quark Pole Mass from Cross-Section Measurements	173.1 ± 0.9 GeV

[Taken from PDG 2019]

Top Quark Mass

2019 Review of Particle Physics.
M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and 2019 update.

t-Quark Mass (Direct Measurements)

INSPIRE search

The following measurements extract a t-quark mass from the kinematics of $t\bar{t}$ events. They are sensitive to the top quark mass used in the MC generator that is usually interpreted as the pole mass, but the theoretical uncertainty in this interpretation is hard to quantify. See the review ``The Top Quark'' and references therein for more information.

OUR AVERAGE of 172.9 ± 0.4 (GeV) is an average of top mass measurements from LHC and Tevatron Runs. The latest Tevatron average, $174.30 \pm 0.35 \pm 0.54$ GeV, was provided by the Tevatron Electroweak Working Group (TEVEWWG).

VALUE (GeV)	*DOCUMENT ID*			*TECN*	*COMMENT*
$\mathbf{172.9 \pm 0.4}$	**OUR AVERAGE** Error includes scale factor of 1.3.				
$172.25 \pm 0.08 \pm 0.62$	1	SIRUNYAN	2018DE	CMS	$\ell + \geq 4$j ($2b$)
$172.95 \pm 0.77 {}^{+0.97}_{-0.93}$	2	SIRUNYAN	2017L	CMS	t -channel single top production
$172.84 \pm 0.34 \pm 0.61$	3	AABOUD	2016T	ATLS	combination of ATLAS
$172.44 \pm 0.13 \pm 0.47$	4	KHACHATRYAN	2016AK	CMS	combination of CMS
$174.30 \pm 0.35 \pm 0.54$	5	TEVEWWG	2016	TEVA	Tevatron combination

Conceptual problem: What is m_t^{MC} ?

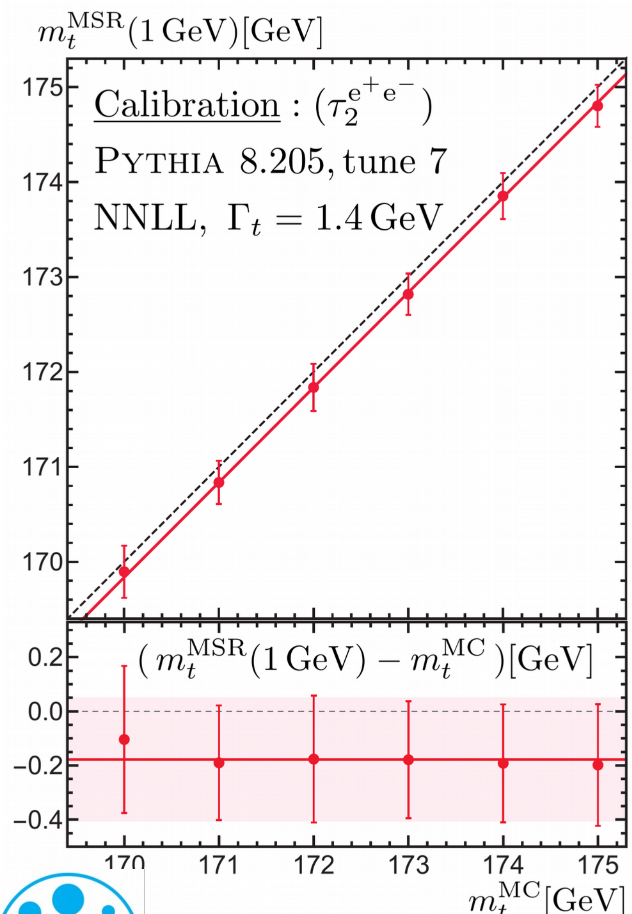
→ Additional conceptual uncertainty in m_t^{MC} ~ O(*1* GeV)

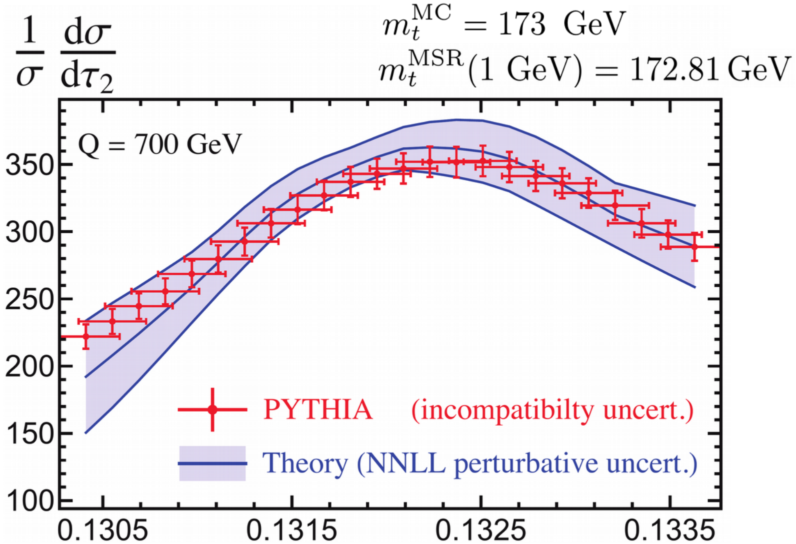
[Hoang, Stewart (2008), Hoang (2014)]

Top Quark Mass Calibration

Basic idea: calibrate the top mass
$m_t^{MC} = m_t^{short\text{-}distance} + O(1\ \text{GeV})$

[M. Beutenschoen, BD, V. Mateu, A.H. Hoang, I. W. Stewart (2016)]





Strategy for calibration:

- Strong mass-sensitive observable **(2-jettiness)**
- Accurate **analytic hadron-level QCD predictions** with full control over the quark mass-scheme dependence
- Compare to sample data from MC generators
- Find a numerical relation:

$$m_t^{\rm MC} = m_t^{\rm MSR}(1\,\text{GeV}) + (0.18 \pm 0.22)\,\text{GeV}$$

$$m_t^{\rm MC} = m_t^{\rm pole} + (0.57 \pm 0.28)\,\text{GeV}$$

N-jet soft function

N-jettiness soft function

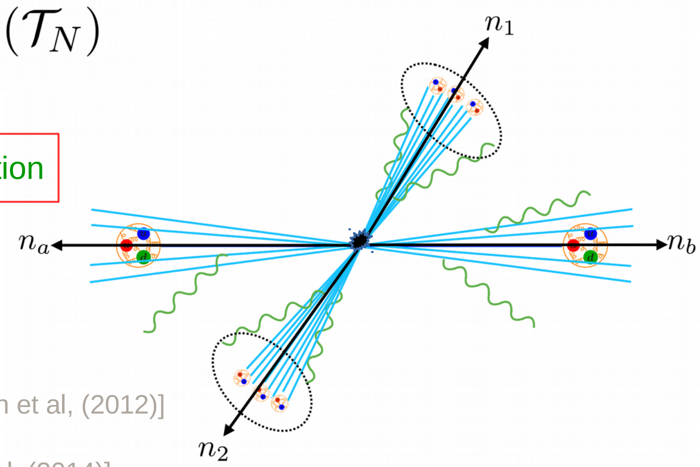
N-jettiness cross section:

[I. W. Stewart, F. J. Tackmann, W. J. Waalewijn (2010)]

factorization theorems in soft/collinear limits

$$\frac{d\sigma(X)}{d\mathcal{T}_N} = \mathbf{H} \times B_a \otimes B_b \otimes J_1 \otimes \ldots \otimes J_N \otimes S_N + \mathcal{O}(\mathcal{T}_N)$$

Hard function — Beam functions — Jet functions — N-jet soft function



Hard function: for many processes known to NNLO [Gehrmann et al, (2012)]

Beam function: known to NNLO [Gaunt et al, (2014)]

Jet function: known to NNNLO [Brüser et al. (2018)]

Soft function: for N=0,1 known to NNLO [Boughezal et al (2015), Compbell et al (2017)

Aim: calculating N-jettiness soft function for N>1 to NNLO

N-jettiness soft function

Idea: Automation

[G. Bell, BD, T. Mohrmann, R. Rahn (2018)]

- Find generic strategy to evaluate soft functions (to NNLO)
- Set up a numerical method based on universal structure of divergences
  - ✓ Isolate singularities with universal phase-space parametrization, e.g. at NLO:

$$S_{ab}(\tau,\mu) \sim \underbrace{\frac{\Gamma(-2\epsilon)}{\Gamma(-\epsilon)}}_{\text{Soft divergence}} \Big(\sqrt{n_{ab}/2}\,\tau e^{\gamma_E}\mu\Big)^{2\epsilon}$$

$$\times \int_0^1 \mathrm{d}y \int_{-1}^1 \mathrm{d}\cos\theta_1\,\mathrm{d}\cos\theta_2\,\sin^{-1-2\,\epsilon}\theta_1\,\sin^{-2-2\,\epsilon}\theta_2\,\underbrace{y^{-1+n\epsilon}}_{\text{Collinear divergences}}\underbrace{\Big[f(y,\theta_1,\theta_2)\Big]^{2\epsilon}}_{\text{Measurement function}}$$

Collinear divergences (y → rapidity measure)

  - ✓ Compute observable dependent integrations numerically

$$\int_0^1 dx\; x^{-1+n\varepsilon}\; f(x) = \int_0^1 dx\; x^{-1+n\varepsilon}\,\Big[\,\underbrace{f(x)-f(0)}_{\text{finite}}+\underbrace{f(0)}_{1/\varepsilon}\,\Big]$$

Current Research Focus

Current Research Focus

- **N-jettiness subtraction technique** for studying various **multi-jet processes**
- **Quark mass effects** in exclusive **Drell-Yan**
- Flavor Physics: **SIMBA**

The gaol is to provide a **global** $B \to X_s \gamma$ **+** $B \to X_u \ell \bar{\nu}$ **fit** using **Belle II** measurements (determine the shape function, $|V_{ub}|$, $|C_7^{\rm incl} V_{tb} V_{ts}^*|$, m_b)

Thank you for your attention!