Top quark mass, strong coupling and other problems

(LHC experimentalist's view)

Katerina Lipka

Standard Model @ Ultimate Precision

HELMHOLTZ
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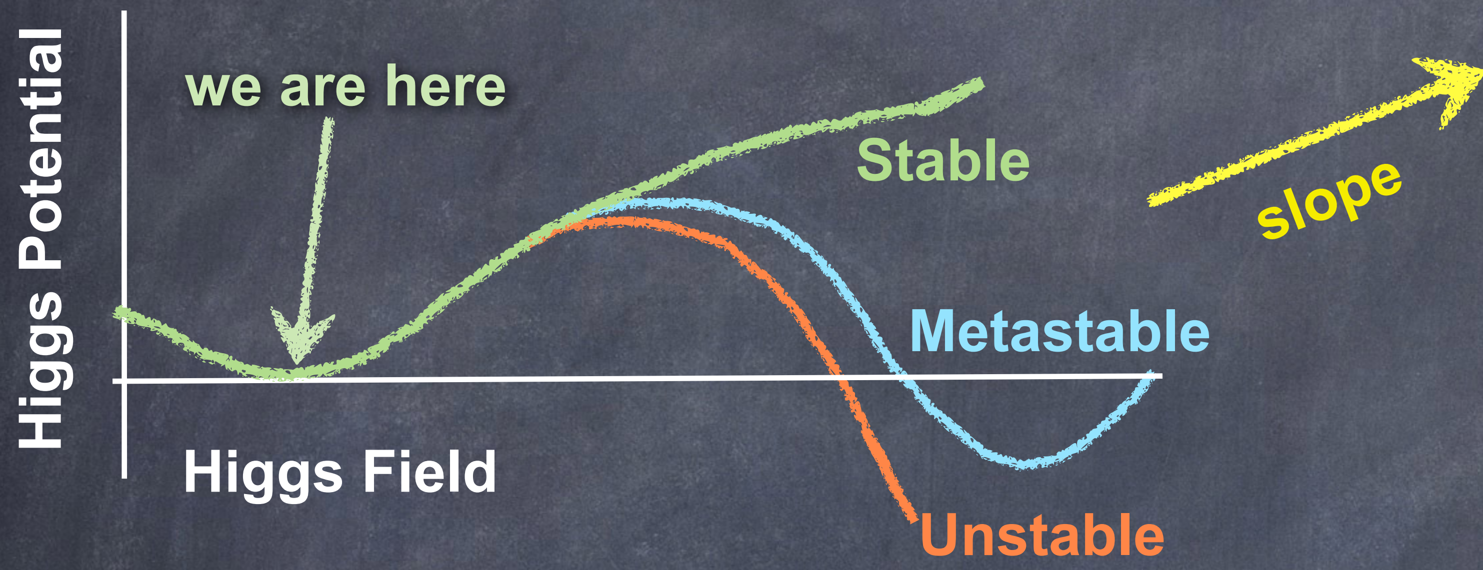
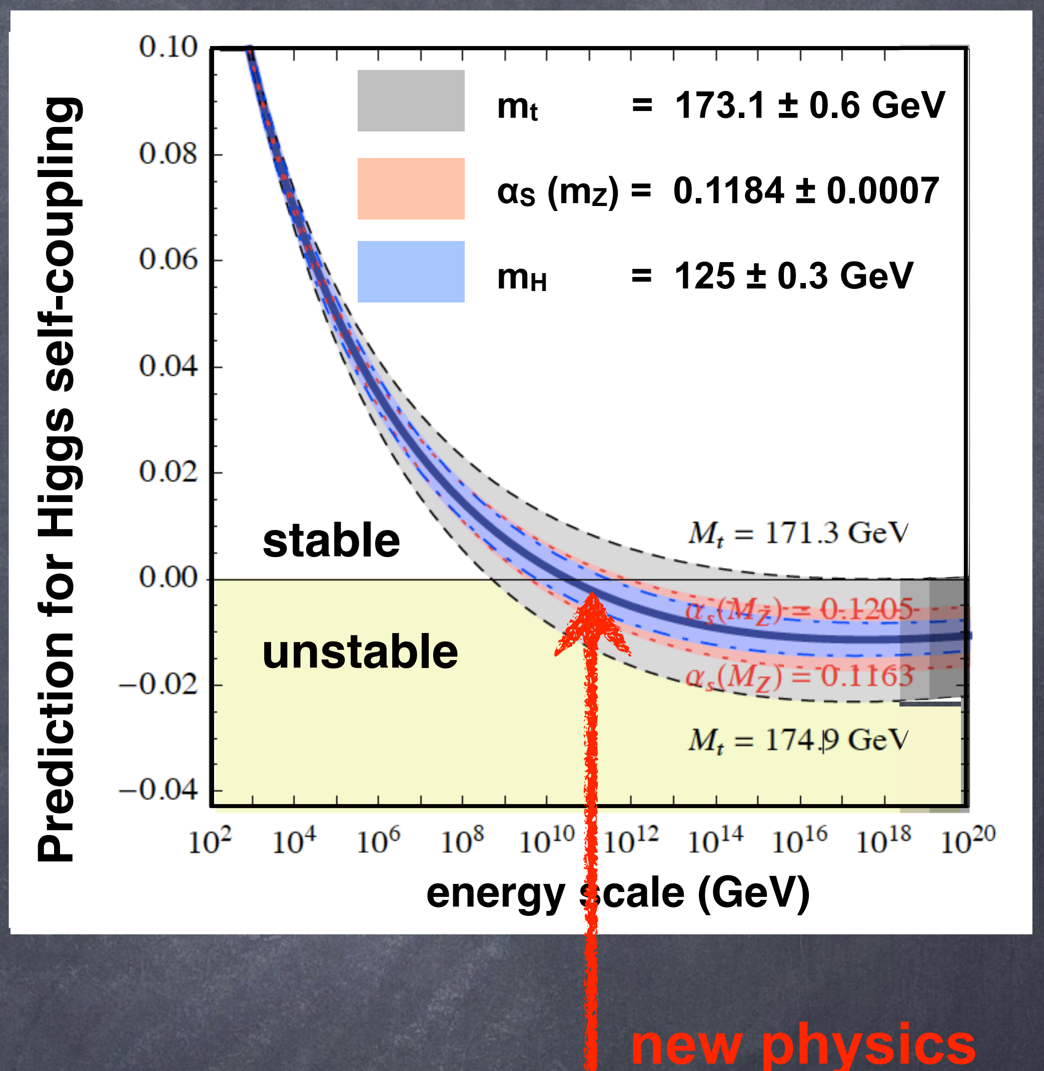
Pillars of SM vacuum stability

EW vacuum stability: Higgs quartic coupling $\lambda > 0$

e.g. G.Degrassi et al, JHEP 1208 (2012) 098





Value and precision of m_t and $\alpha_S(m_Z)$ drive the vacuum stability rather than m_H

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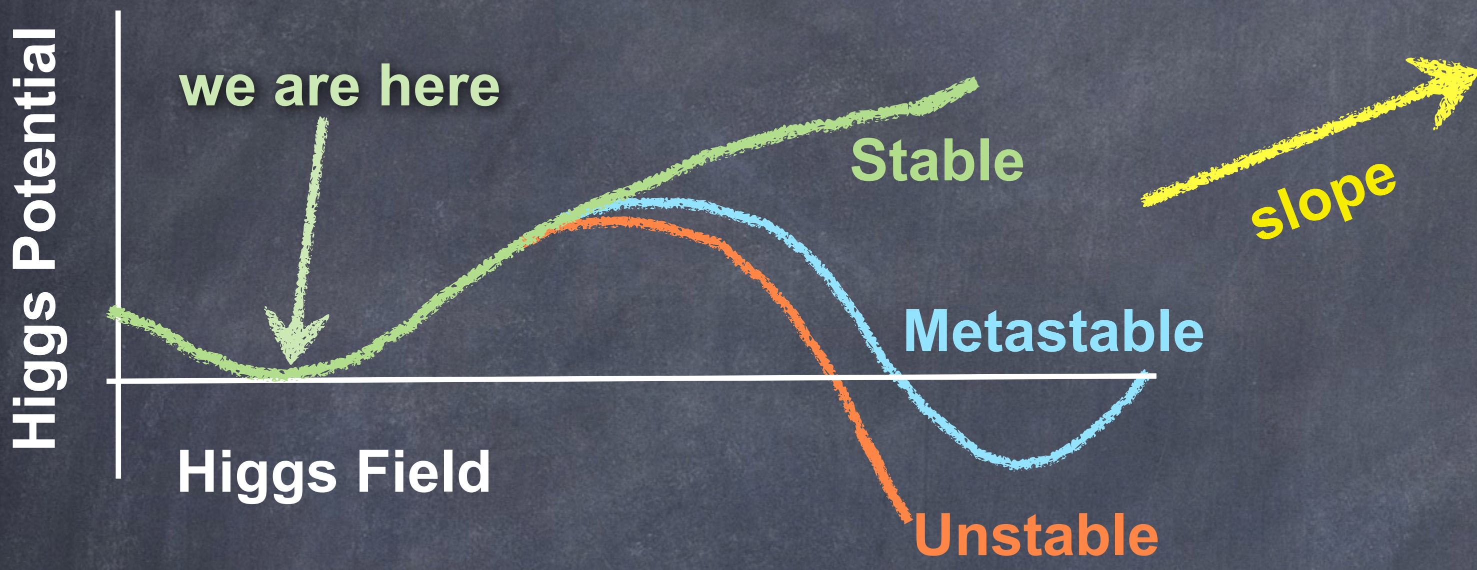
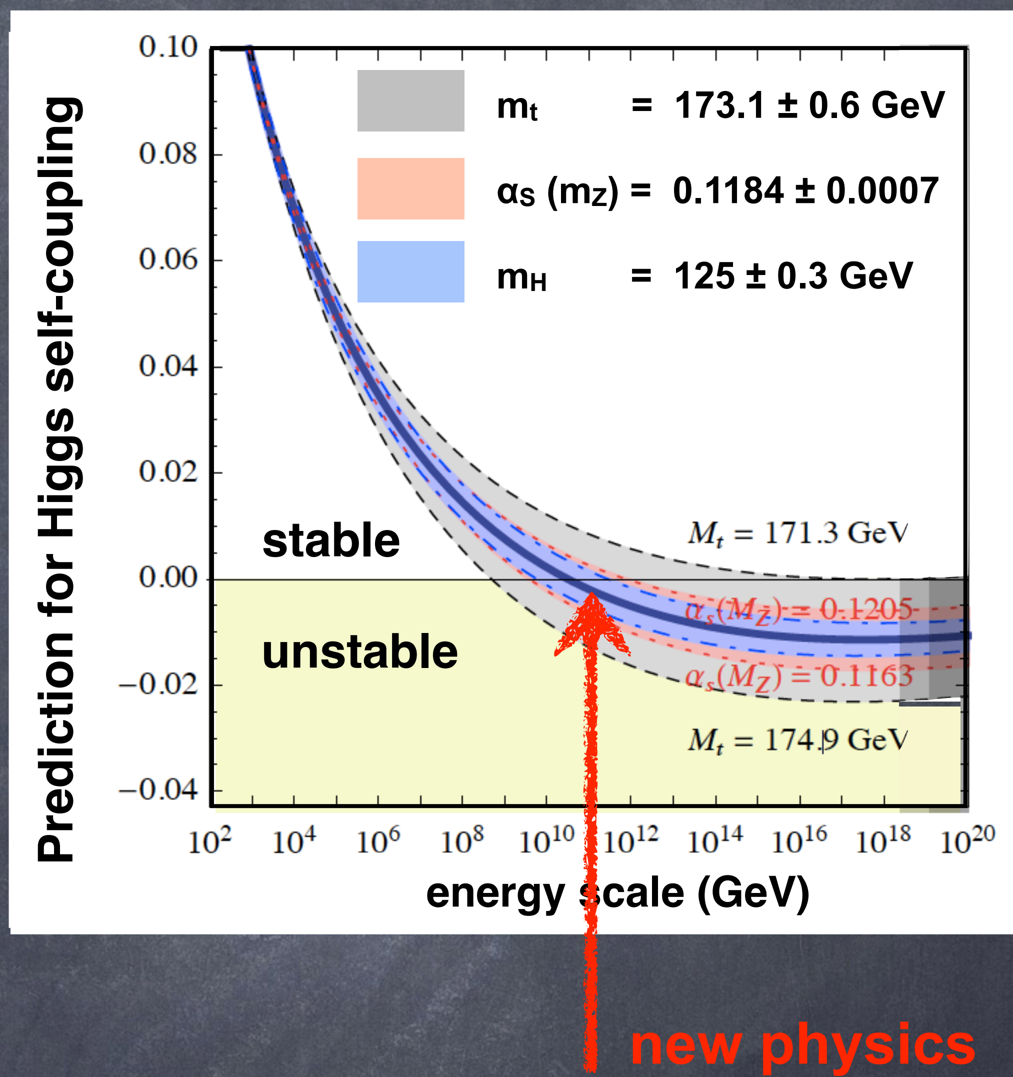




Value and precision of m_t and $\alpha_S(m_Z)$ drive the vacuum stability rather than m_H

problem 1: m_t and $\alpha_S(m_Z)$ values need to be extracted experimentally

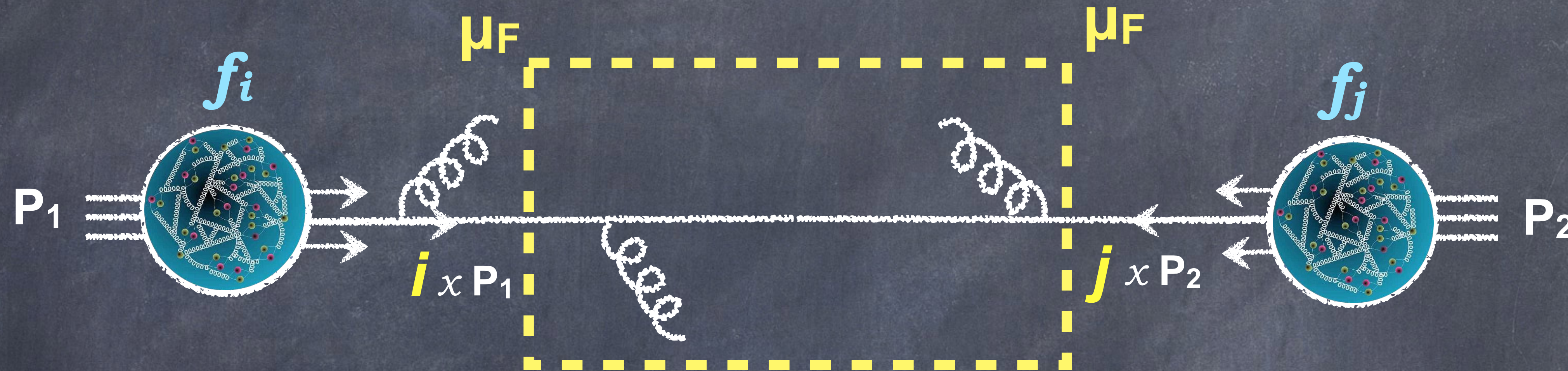
problem 2: m_t and $\alpha_S(m_Z)$ are not "observables", can not be 'measured' directly

problem 3: both m_t and $\alpha_S(m_Z)$ enter predictions for e.g. $t\bar{t}$ production in pp

problem 4: @ LHC, both m_t and $\alpha_S(m_Z)$ correlated with proton parton distributions

Proton-proton collisions at the LHC

Parton Distribution Functions $f_{i,j}(Q^2, x)$ **of both protons enter factorisation**



$$\sigma_{pp\to X} = \sum_{ij} f_i(x_1, \mu_F^2) \times f_j(x_2, \mu_F^2) \otimes \hat{\sigma}_{ij\to X}(x_1, x_2, \alpha_S(\mu_R), \frac{Q^2}{\mu_R}, \frac{Q^2}{\mu_F})$$

fitted to experimental data

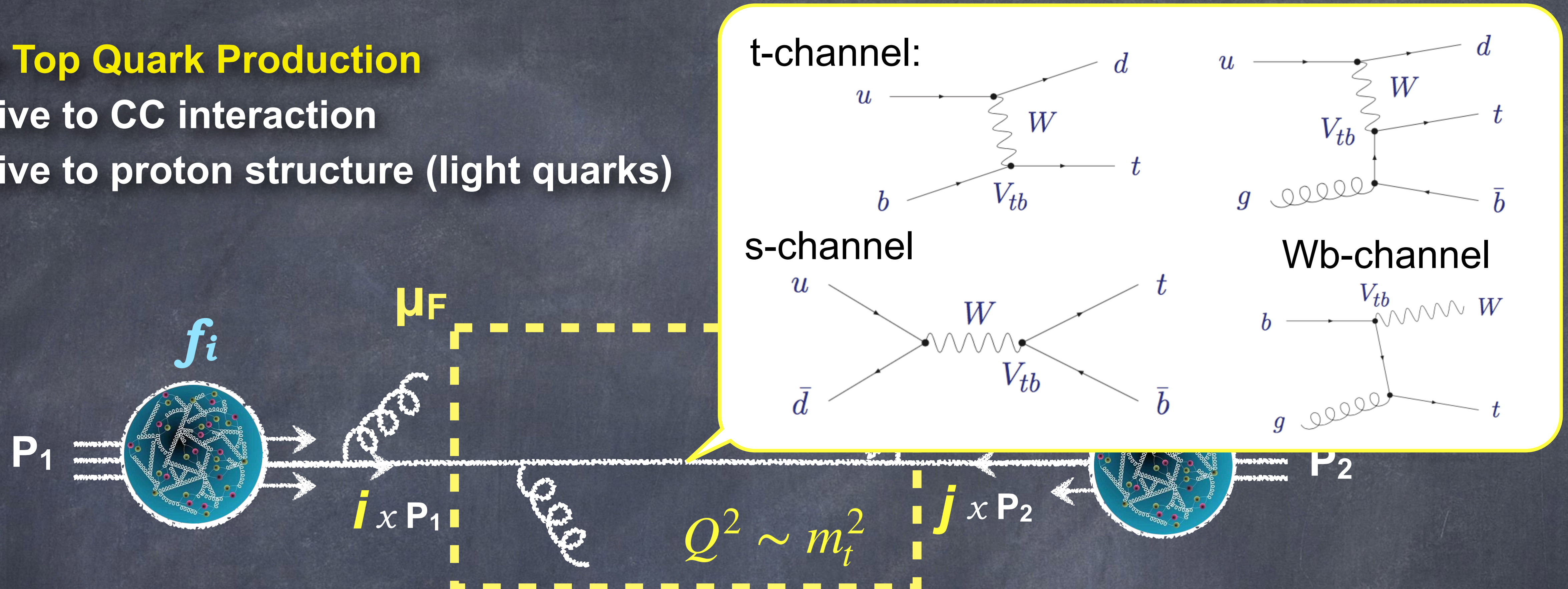
DGLAP

Top quark production at the LHC

Single Top Quark Production

sensitive to CC interaction

sensitive to proton structure (light quarks)



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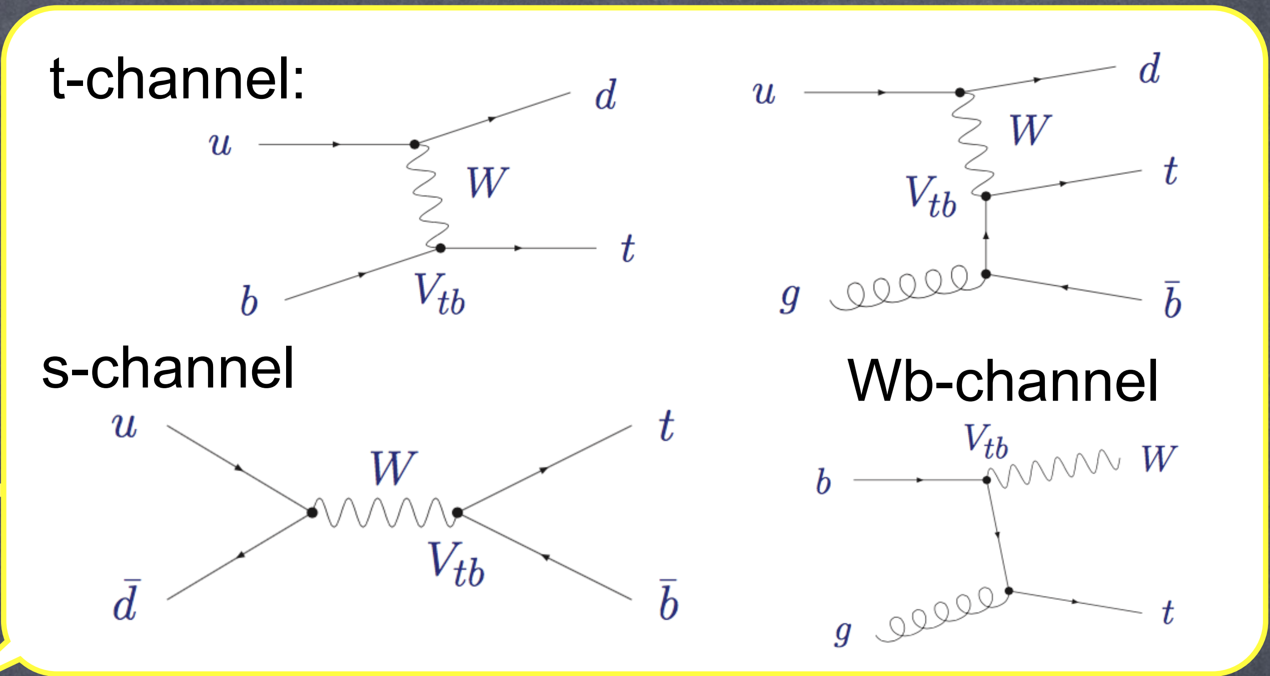
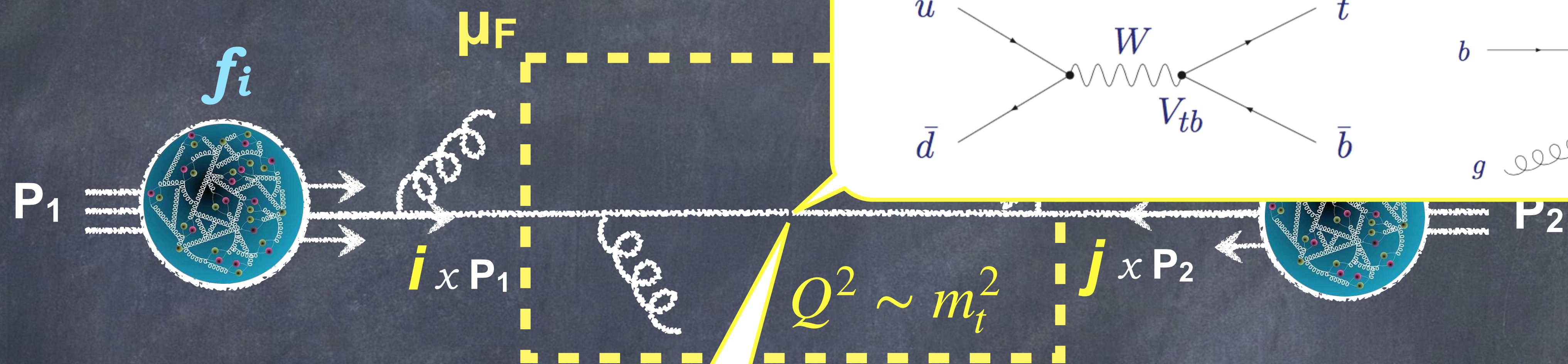
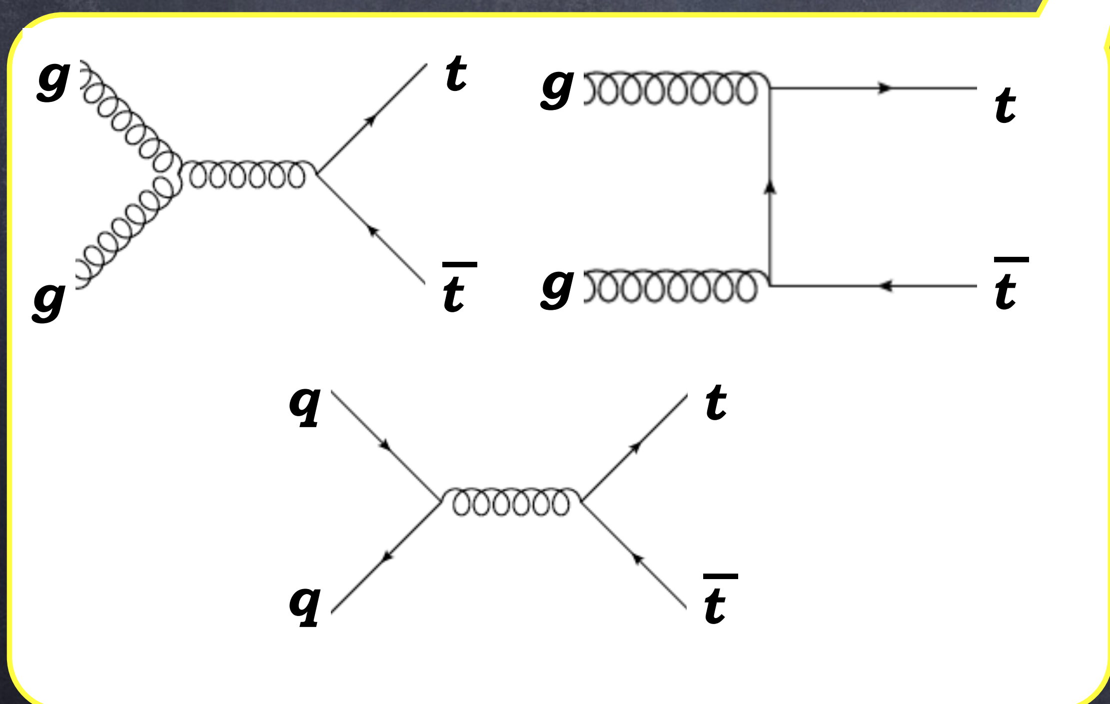






Top Quark-Antiquark Pair Production

> 85% gluon-gluon fusion

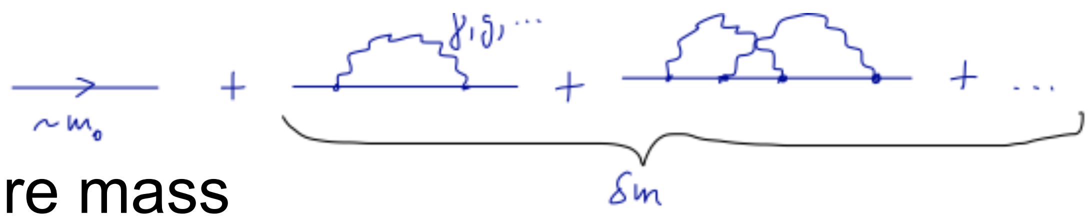
predictions available to NNLO precision

predicted $\sigma_{t\bar{t}}$ depends on:

- gluon distribution $g(x)$
- $\alpha_S(m_Z)$
- top quark mass m_t

Top quark mass m_t in QFT

Beyond LO: bare-mass term in Lagrangian receives self-energy corrections δm



bare mass

Renormalised mass $m_R = m_0 + \delta m$

@ scale μ

- **not a unique physical parameter, needs to be defined through renormalisation schemes**
- **plays a role similar to the couplings of the SM Lagrangian**

[for more details see e.g. Hoang, arXiv:2004.12915, CMS Collaboration, arXiv:2403.01313]

Top quark mass m_t in QFT

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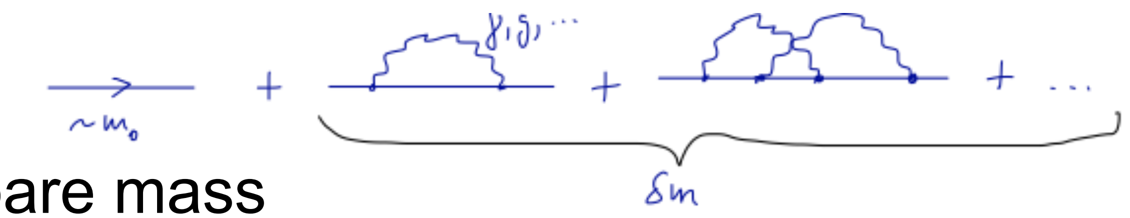

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NB: Formally, cross section predictions are independent of a choice of renormalisation scheme

in practice, can be made only at some finite truncation order in perturbation theory:
→ for a particular observable, only certain scheme choices are adequate
(so that the scheme assures absorption of quantum corrections in m_t - dependence)

Example: choice of renormalisation scheme for m_t — dominant uncertainty in the predictions for Higgs-boson or 2-Higgs production *[J. Mazzitelli, arXiv:2206.14667]*

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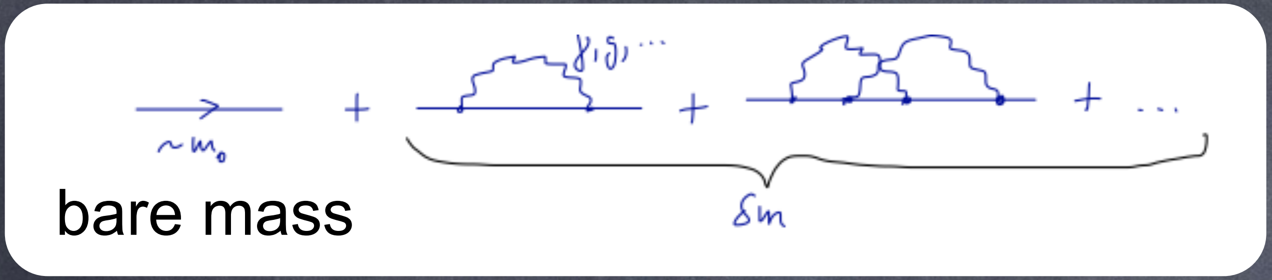

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m_t **renormalisation schemes:**

- **pole mass scheme**
- **modified minimal-subtraction ($\overline{\text{MS}}$) scheme** (renormalisation scale μ_m)
- **low-scale short-distance mass (MSR) scheme** (renormalisation scale R) *[A. Hoang et al 1704.01580]*

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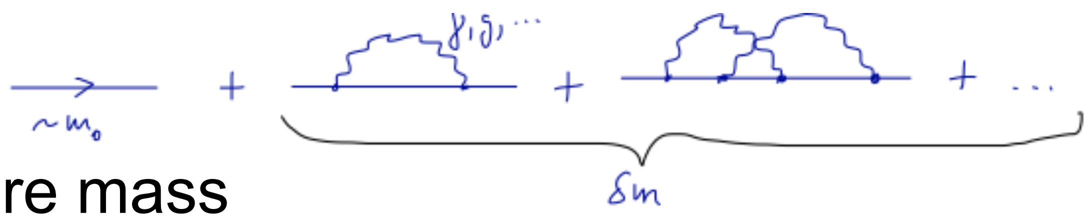

bare mass

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m_t **renormalisation schemes:**

- **pole mass scheme $m_t = m_t^{pole}$**

Defined as the **pole of the top-quark propagator** (in the approximation of a free particle)

can be formally defined **at any order**

(its colour does not prohibit the definition of the top quark as an "asymptotic state" in pQCD)

[Tarrach, Nucl. Phys. B 183 (1981) 384;
Kronfeld, hep-ph/9805215]

Concept of an asymptotic "top particle" unphysical (assumes δm can be distinguished from the real radiation at arbitrarily small scales)

→ Intrinsic ambiguity of 110–250 MeV (***renormalon problem***)

[Beneke, Marquard, Nason, Steinhauser, arXiv:1605.03609;
Hoang, Lepenik, Preisser, arXiv:1706.08526.]

Top quark mass m_t in QFT

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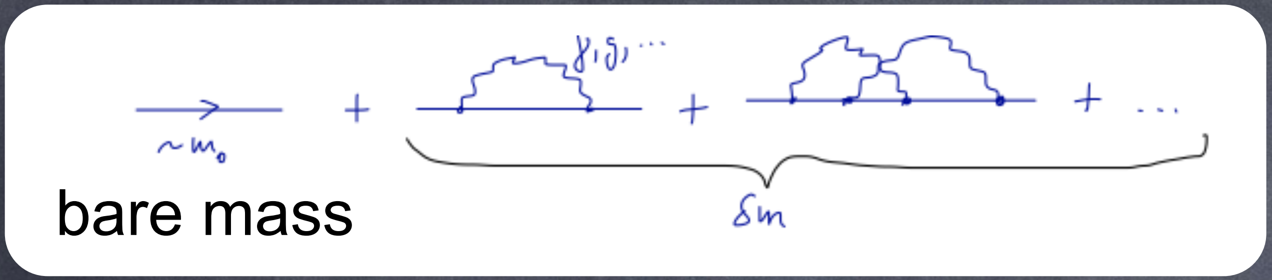

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  implies dependence on mass-renormalisation scale: $m_t(\mu_m)$,
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Top quark mass m_t in QFT

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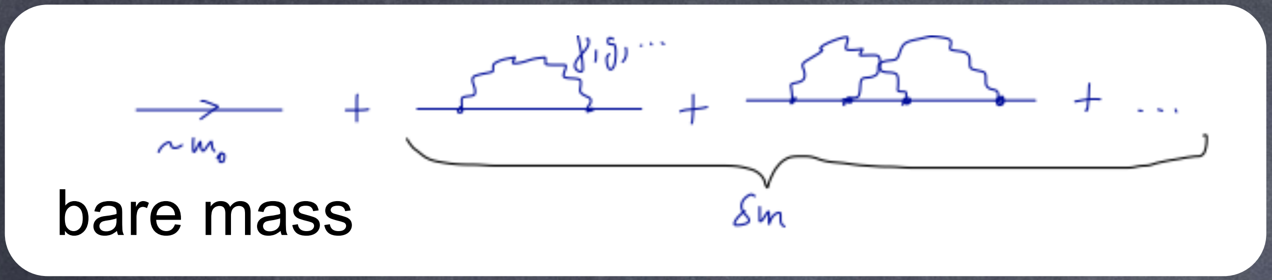

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- **low-scale short-distance mass (MSR) scheme** (renormalisation scale R)

  interpolates between the m_t^{pole} and the MS schemes:

  - $m_t^{MSR}(R)_{R\sim m_t(m_t)} \longrightarrow m_t(m_t)$
  - $m_t^{MSR}(R)_{R\to 0} \longrightarrow m_t^{pole}$

Top quark mass m_t in QFT

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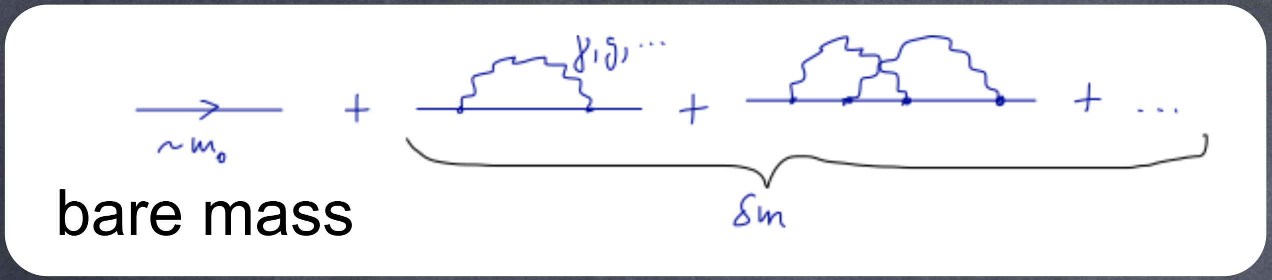

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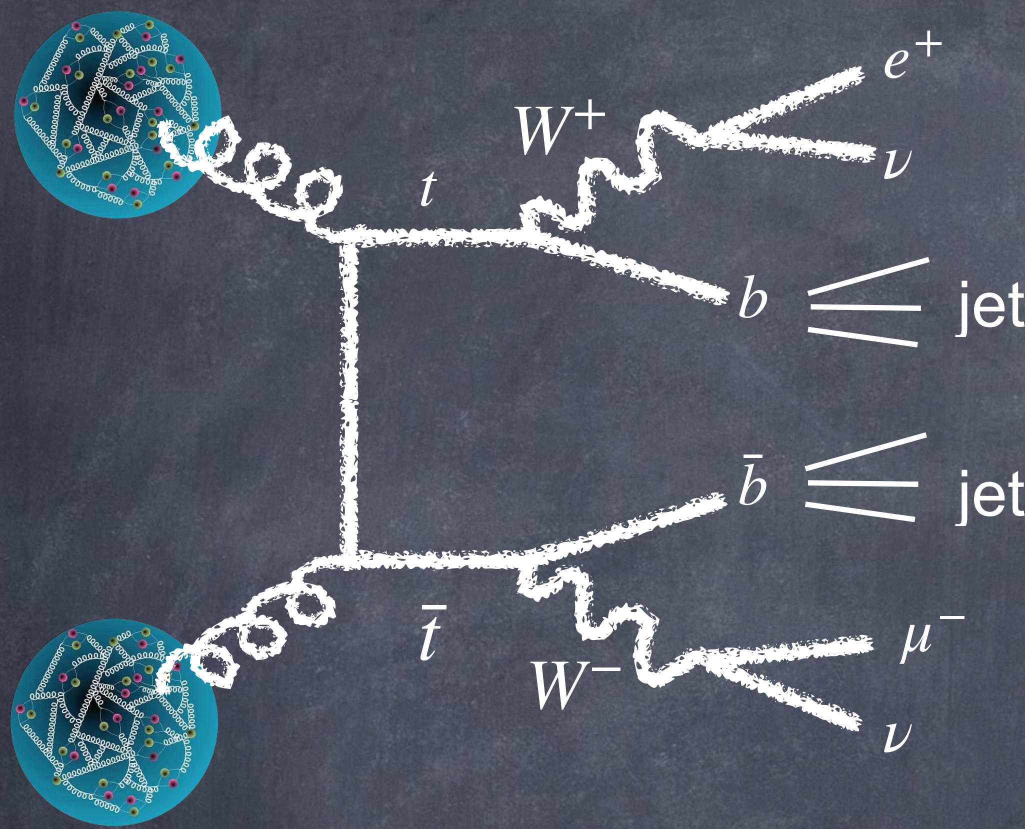
both schemes do not have the renormalon ambiguity (more physical treatment of δm)

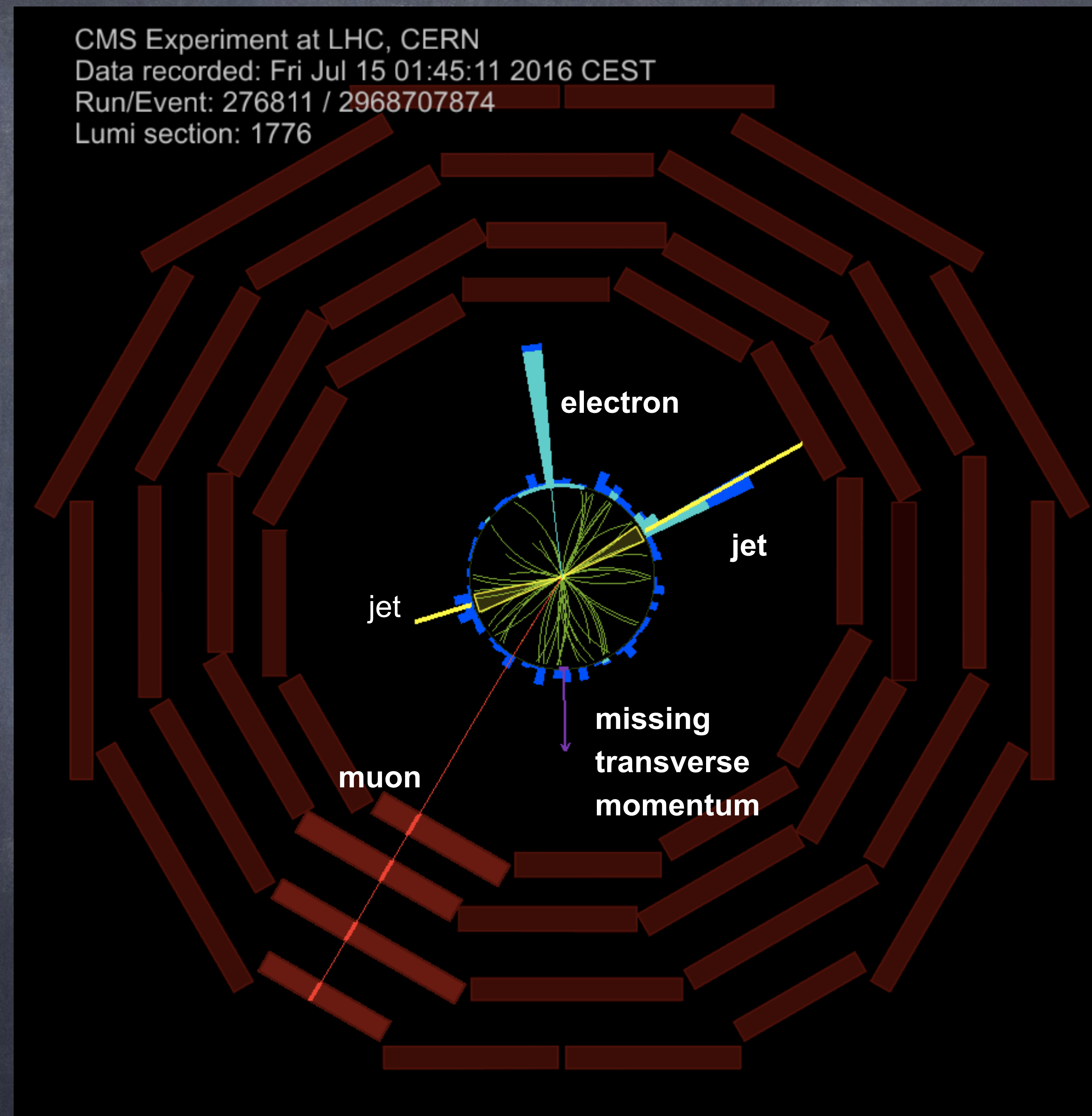
μ_m and R : energy scales, above which the self-energy corrections are absorbed into the mass,
below these scales, the real and virtual corrections are treated unresolved

A proper choice of the scheme or of the renormalisation scales is not straightforward in context of numerical predictions [e.g. calculations for top quark production @ LHC]

→ need to account for correlations with renormalisation scales related e.g. to α_S and PDFs

How does an experiment *see* top quarks ?





W boson:

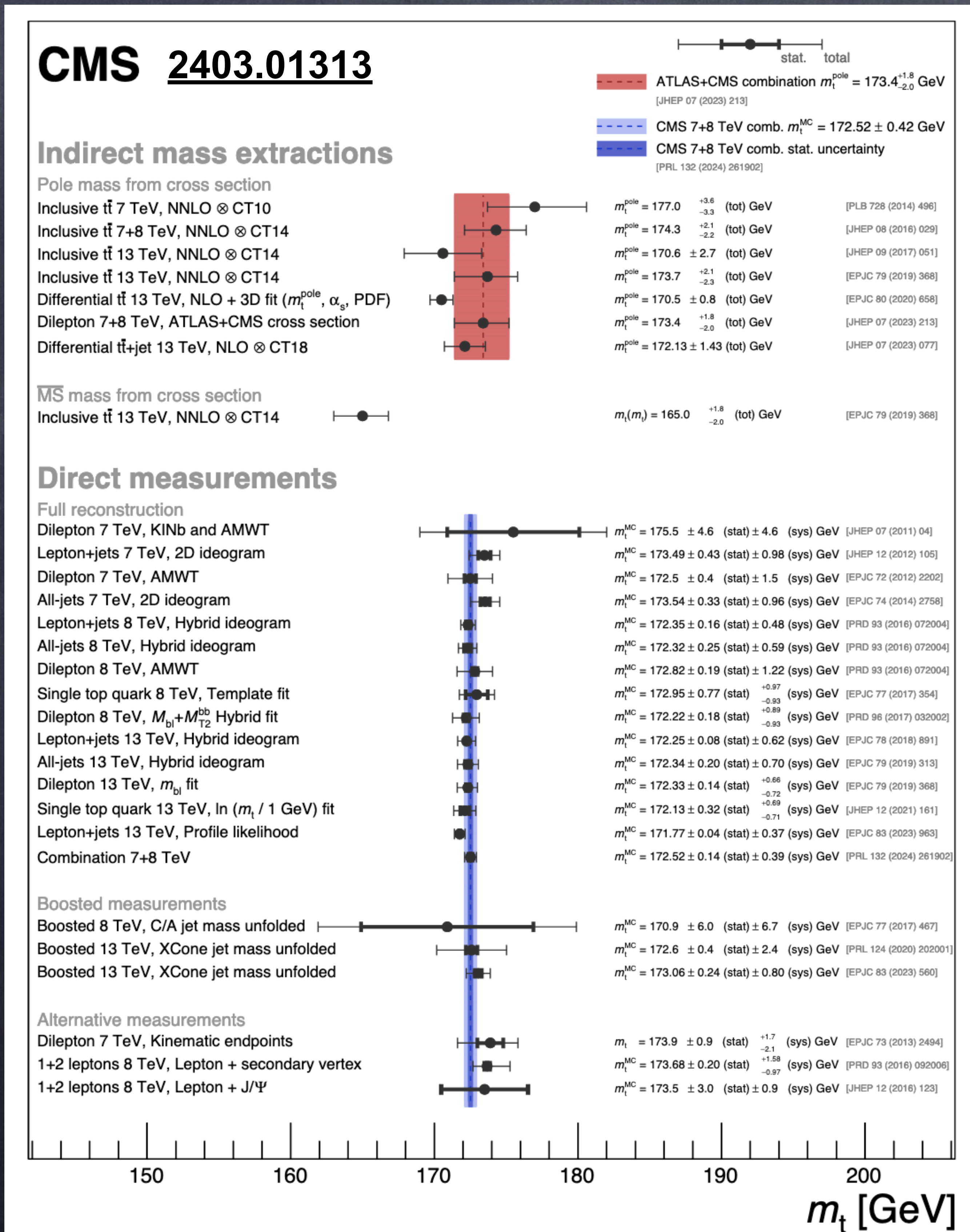
- high-p_T leptons,
  isolation in tracker + calorimeters

- negative vectorial sum p_T of
  reconstructed particles (missing p_T)

b-tagged jets:

based on large mass and long lifetime of B-hadrons

Results on the top quark mass



CMS Collaboration, arXiv:2403.01313

two classes:

"indirect"

"direct"

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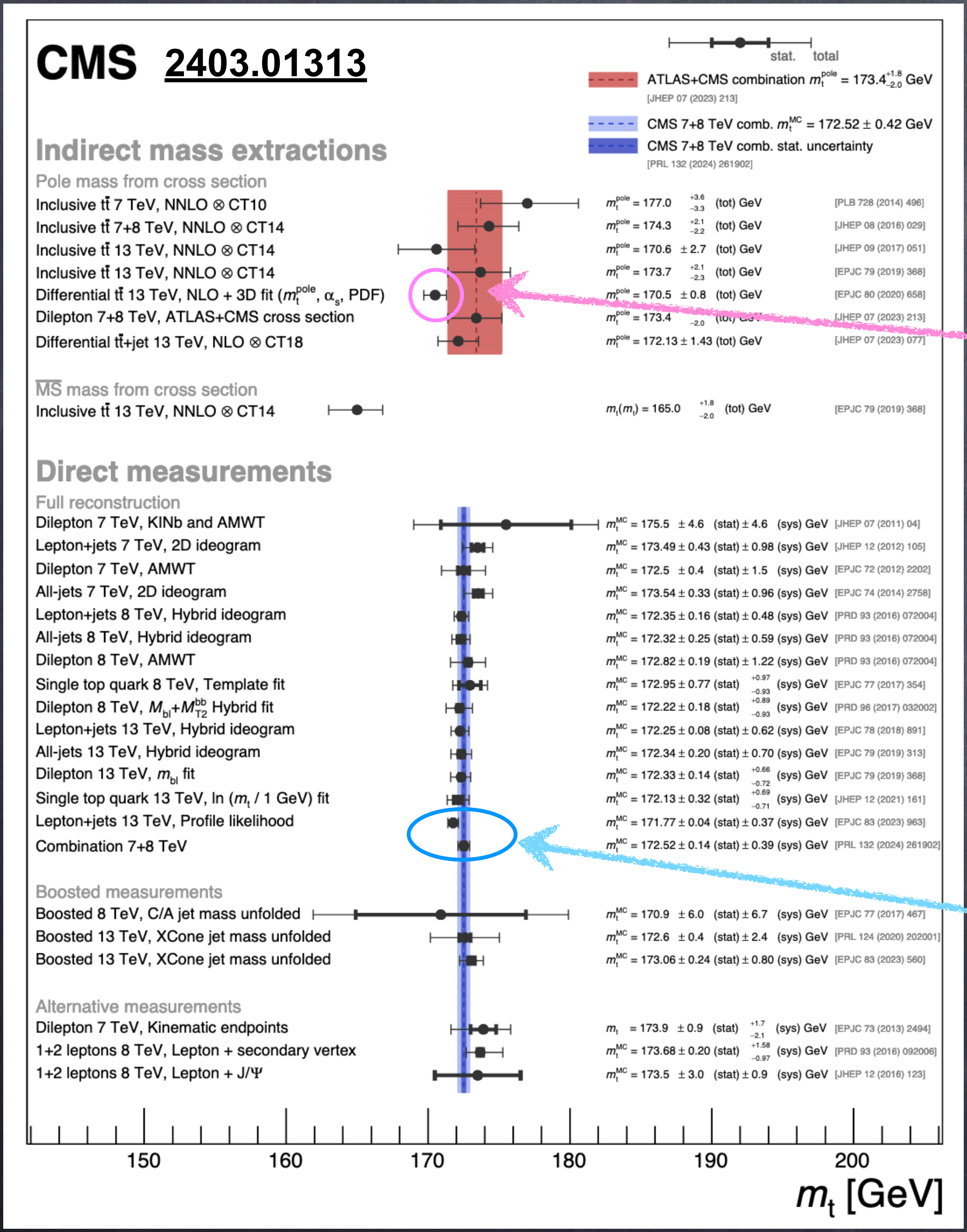


CMS Collaboration, arXiv:2403.01313

two classes:

“indirect”

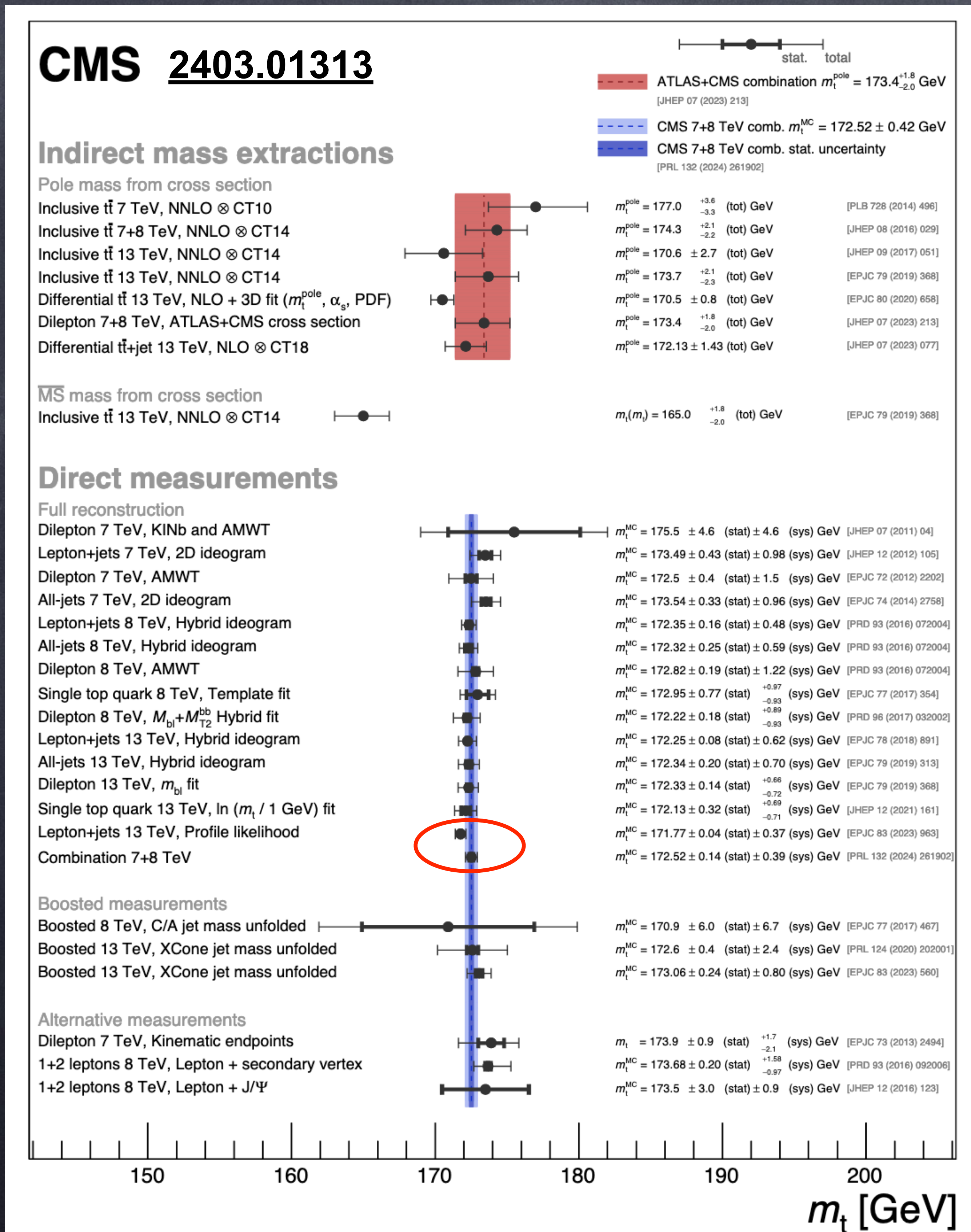
best precision 800 MeV

“direct”

seems doing best ?

claims precision ~ 400 MeV

Results on the top quark mass



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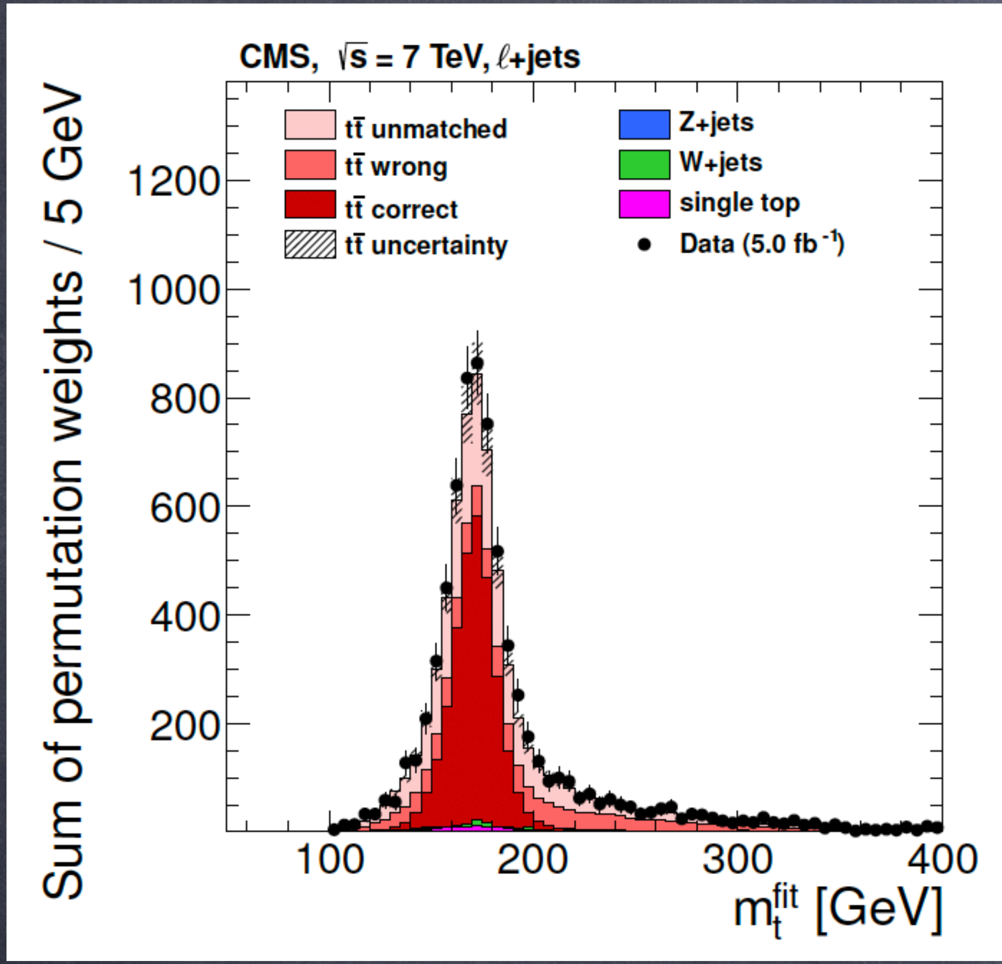
Is the measured quantity well defined?

Is its uncertainty fully understood?

Direct measurement

based on the picture of the top quark as a free particle

(invariant mass of the decay products directly related to the mass of “top quark particle”)



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kinematic fit using 3-momenta of the decay products

peak position is used as an estimator of m_t

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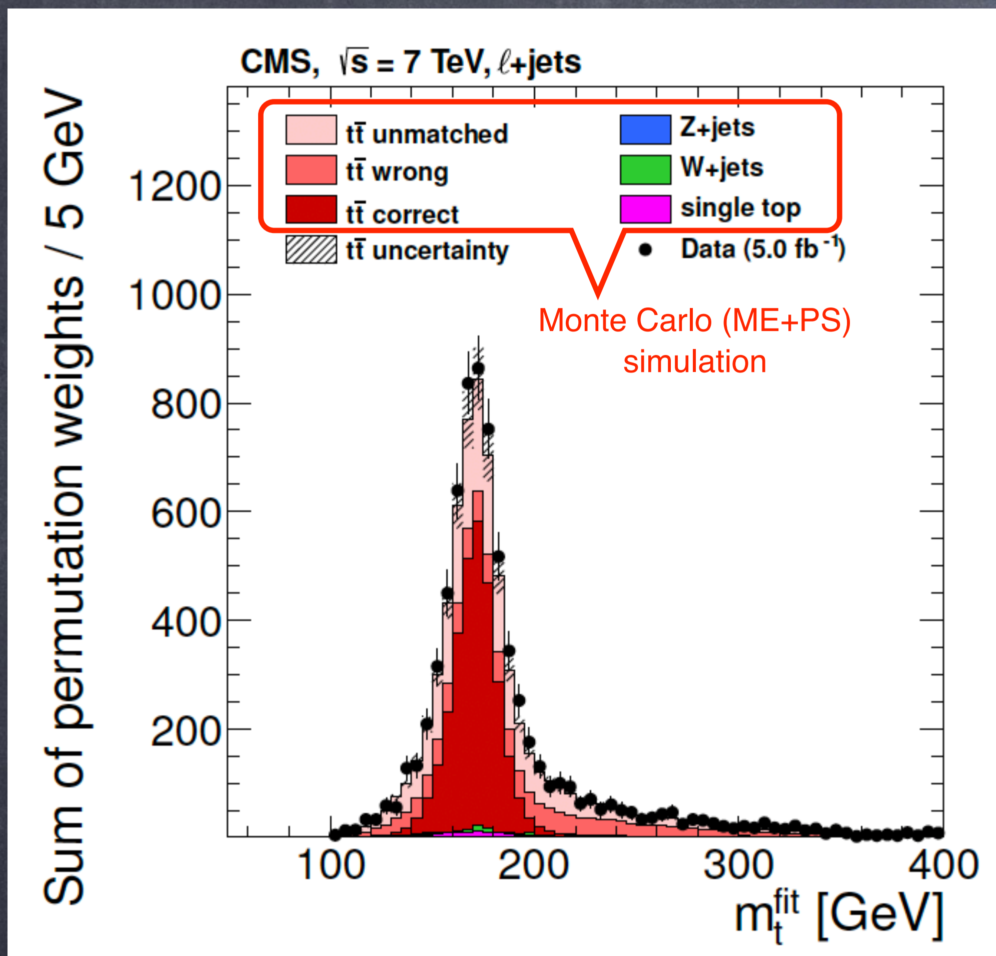
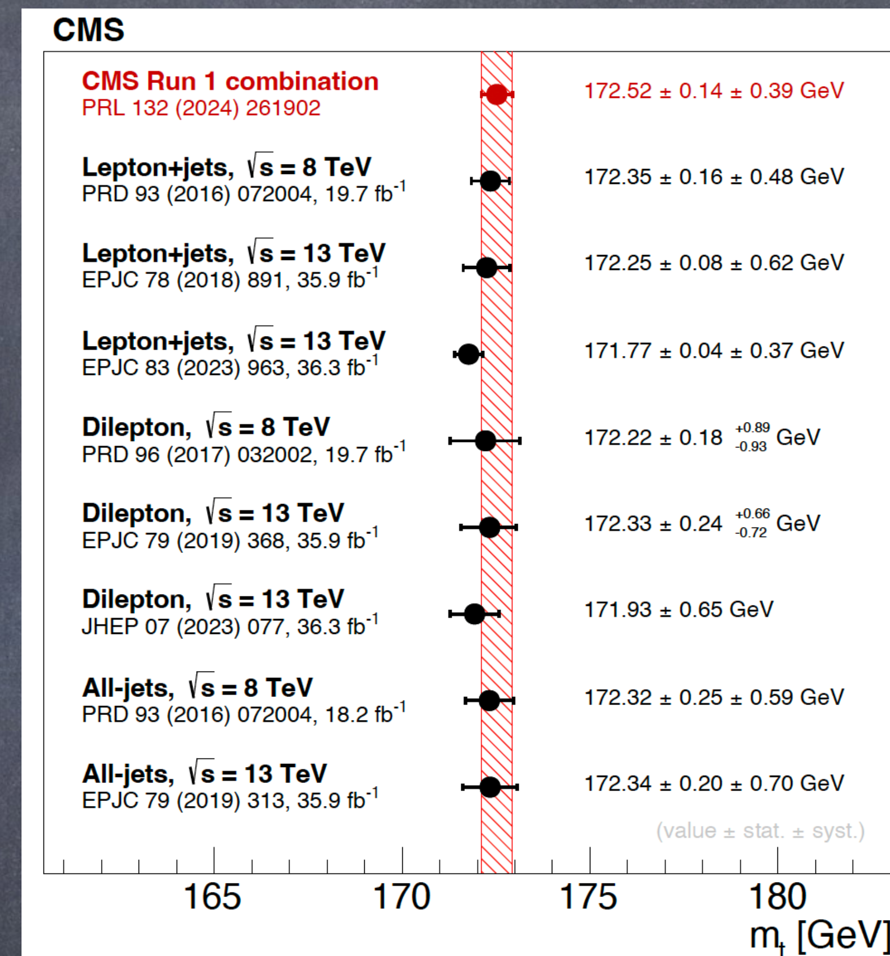




CMS Collaboration, arXiv:2403.01313

Relies on MC simulations for the modelling of the decay topologies + experimental effects

Result : m_t^{MC} **, top-quark mass parameter used in the particular MC simulation**

Based on the most m_t^{MC}- sensitive observables → highest experimental precision

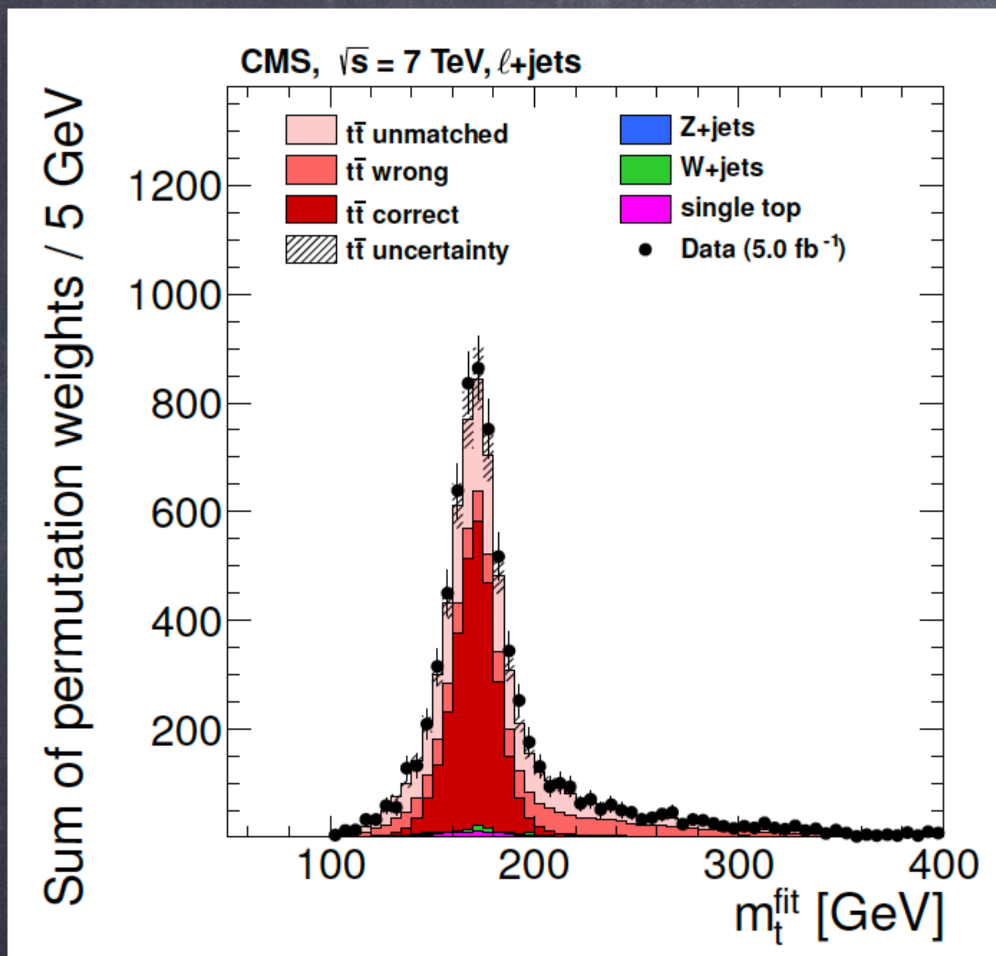
Limitation of the MC simulations → **conceptual uncertainty** in relation $m_t \propto m_t^{MC}$

NB: a theoretical problem!

Meaning of m_t^{MC}

Related to accuracy and implementation of PS and the top quark decay ME

Control m_t^{MC} at NLO needs at least NLL for the PS evolution + NLO for decay



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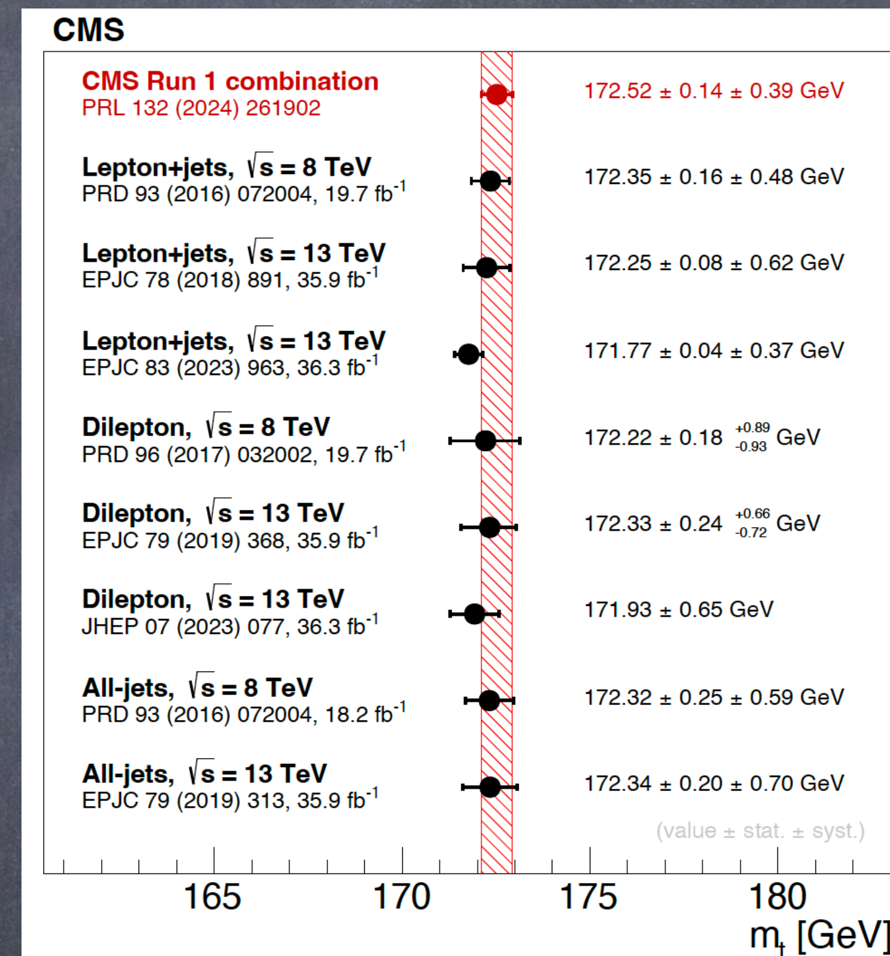

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Conceptually : $m_t^{MC} - m_t^{pole} = -2/3\ Q_0^2\ \alpha_S(Q_0^2)$ *[Hoang, Plartzer, Samitz, arXiv:1807.06617]*

$\downarrow$

transverse momentum shower cutoff of the coherent branching algorithm

State-of-the-art MC: $Q_0^2 \sim 1$ *GeV,* $m_t^{MC} - m_t^{pole} \approx 0.5$ *GeV*

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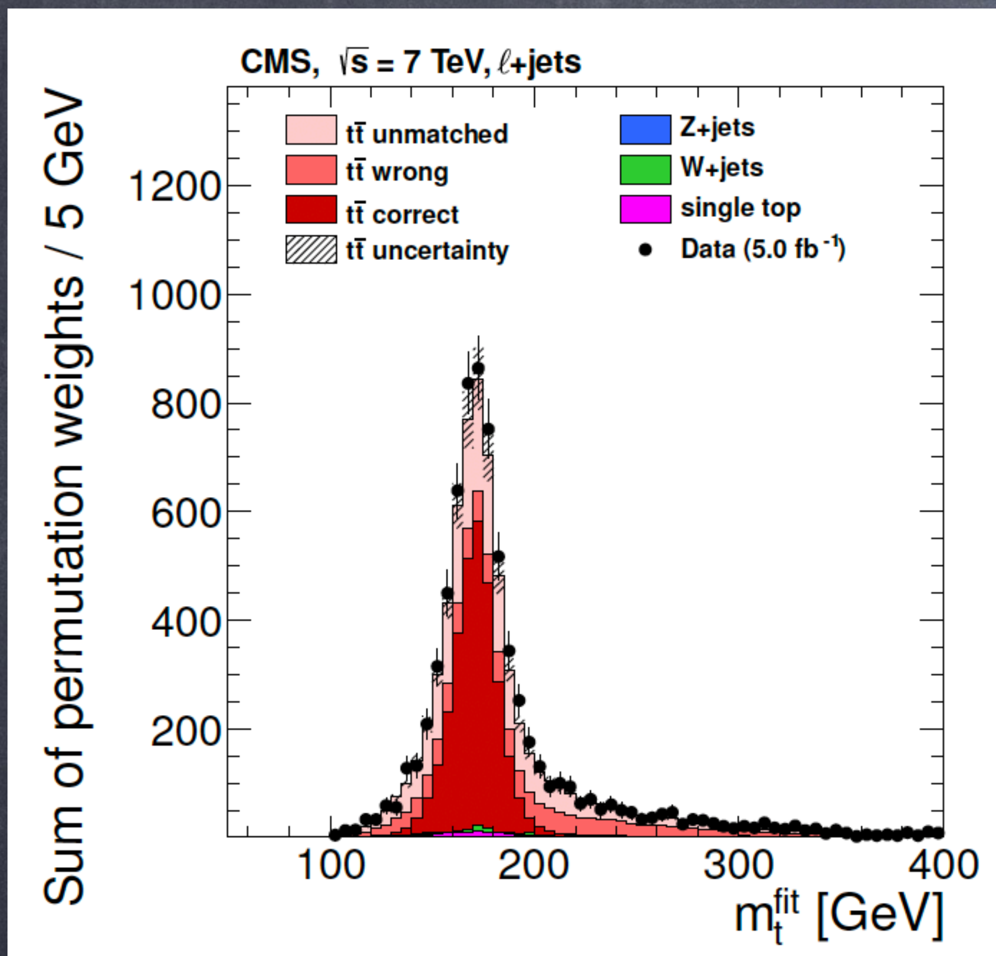

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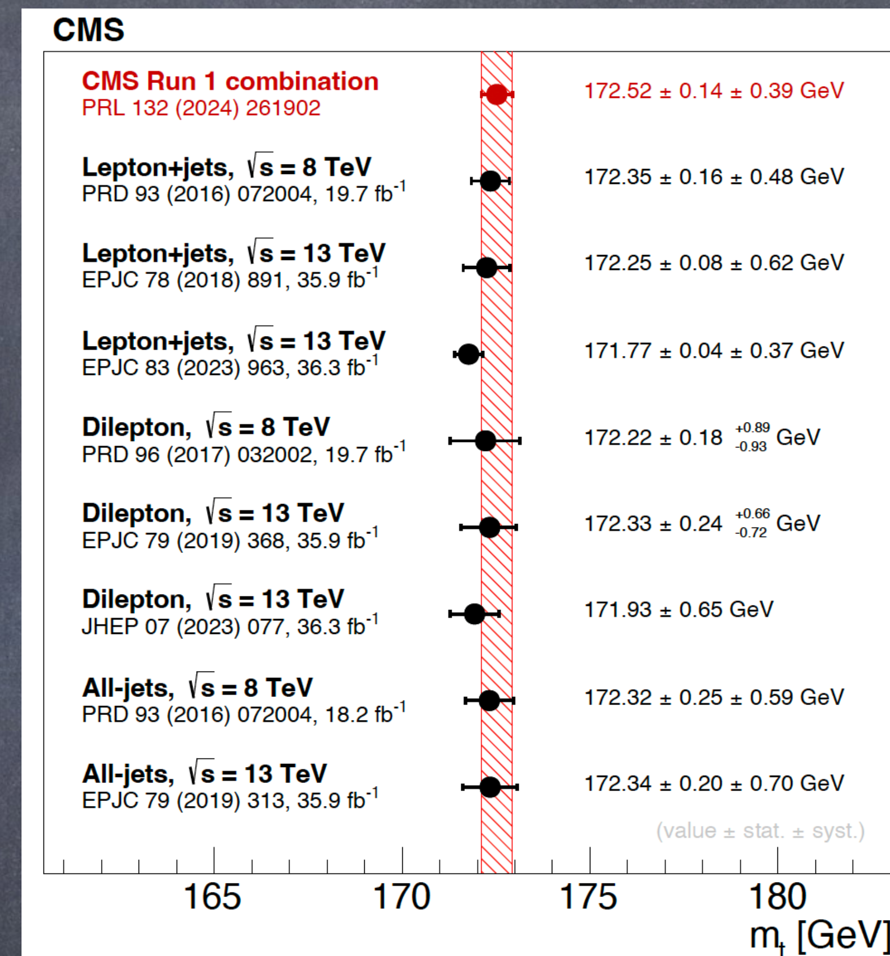

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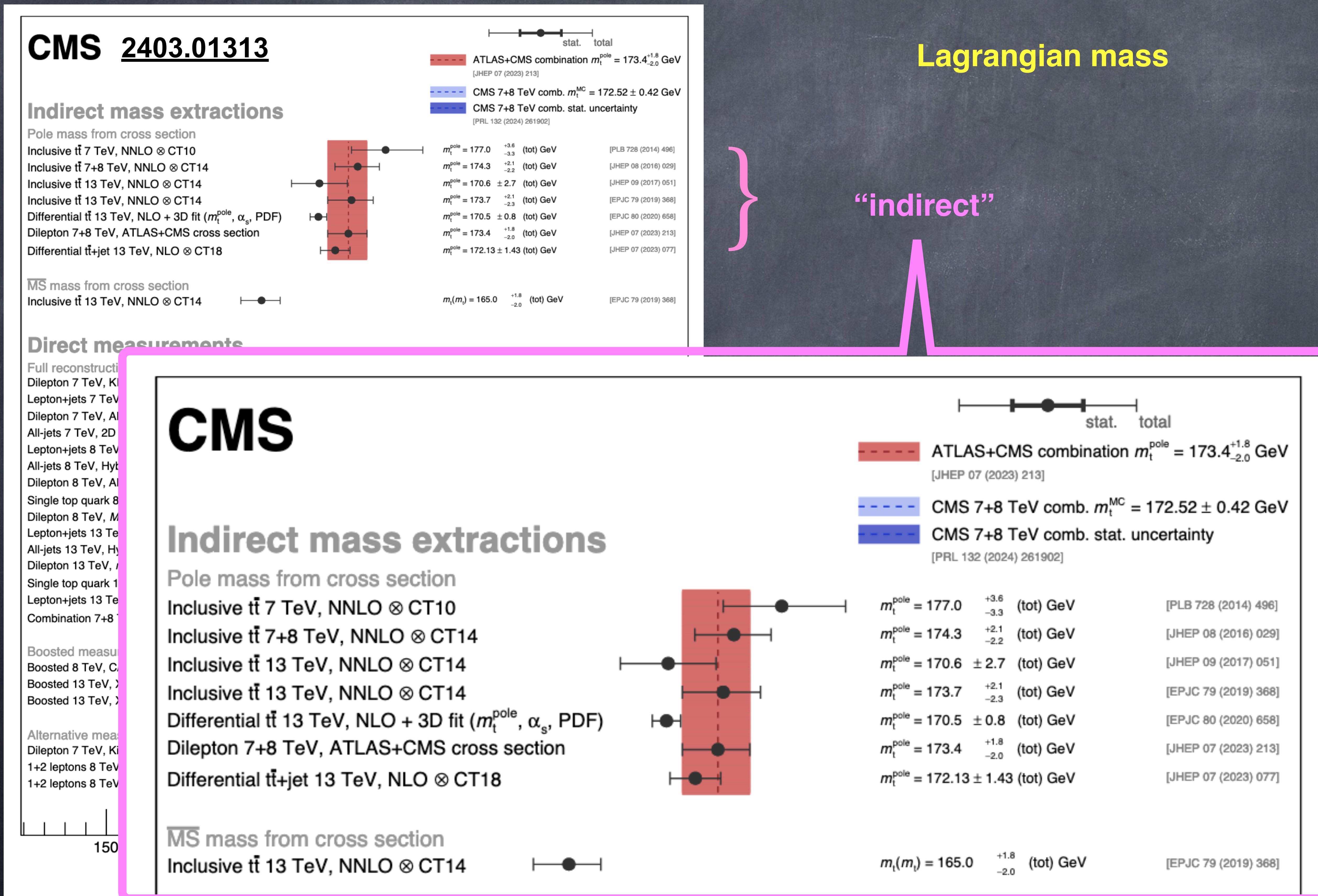
Calibration studies:

m_t^{MC} *corresponds to* m_t^{pole} *or* m_t^{MSR} *within 0.5–1.0 GeV*

[Kieseler, Lipka, Moch arXiv:1511.00841,
M. Butenschoen et al. arXiv:1608.01318
B. Dehnadi, et al arXiv:2309.00547
P. Azzi et al. arXiv:1902.04070]

Which mass to use for stability plot?



Lagrangian mass

"indirect"

CMS Collaboration, arXiv:2403.01313

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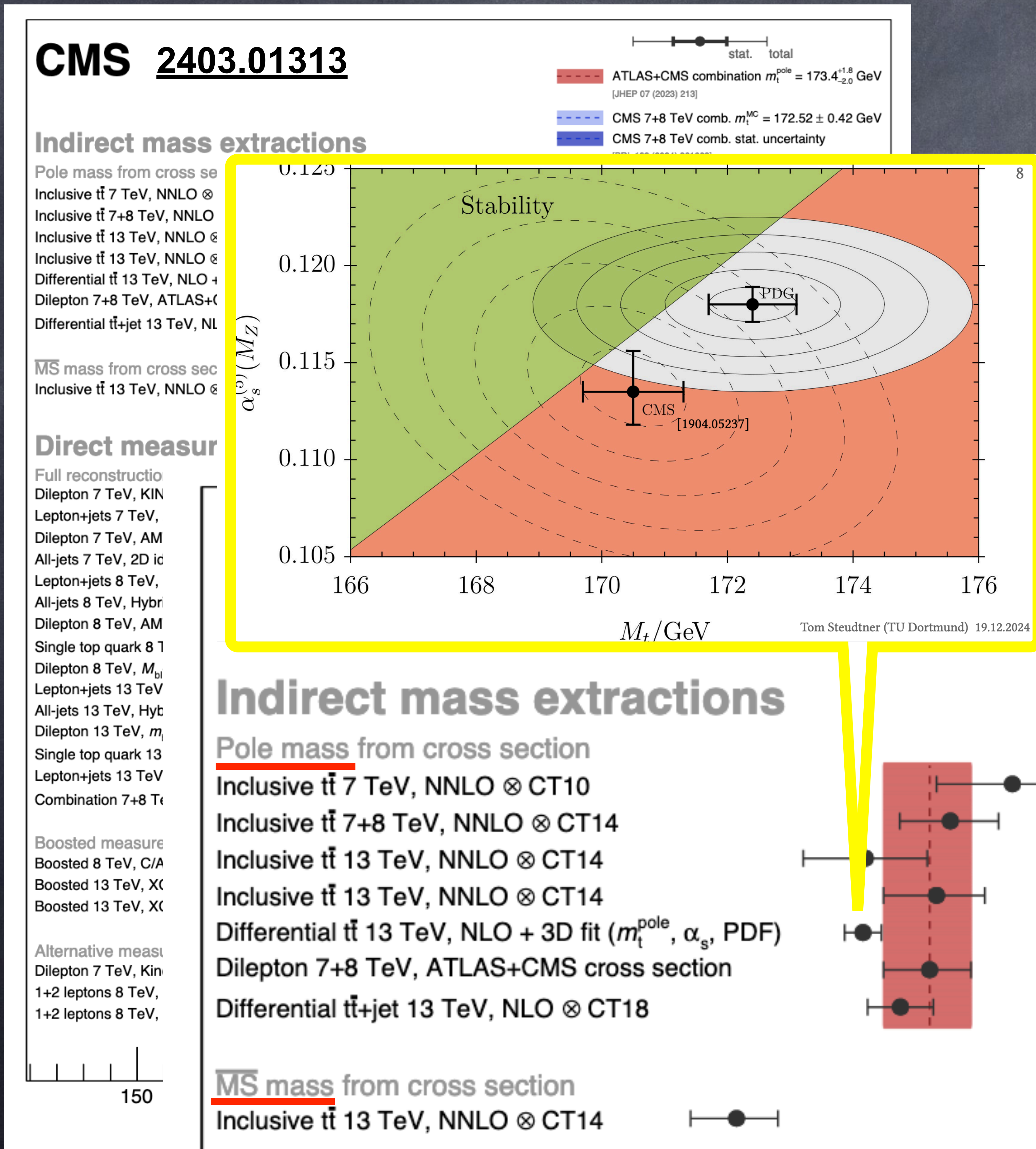
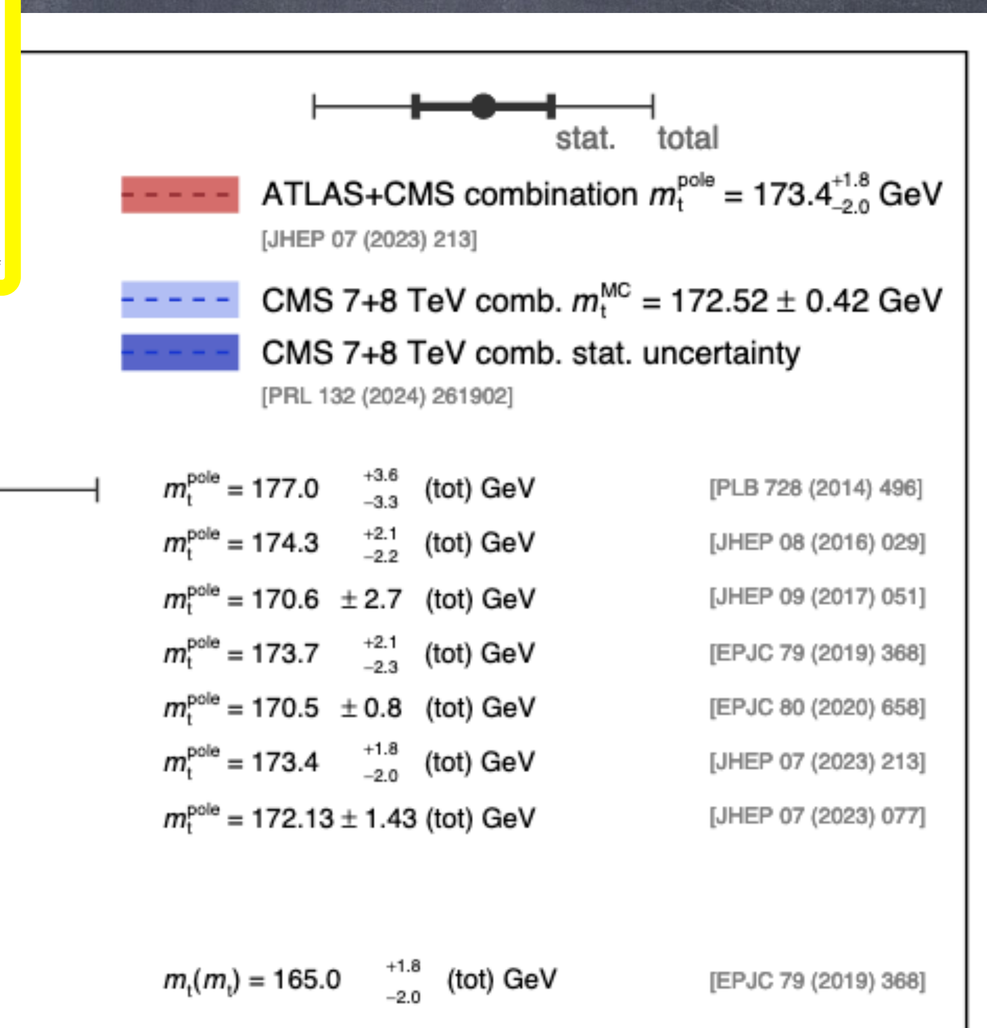




Lagrangian mass

In Tom's talk:

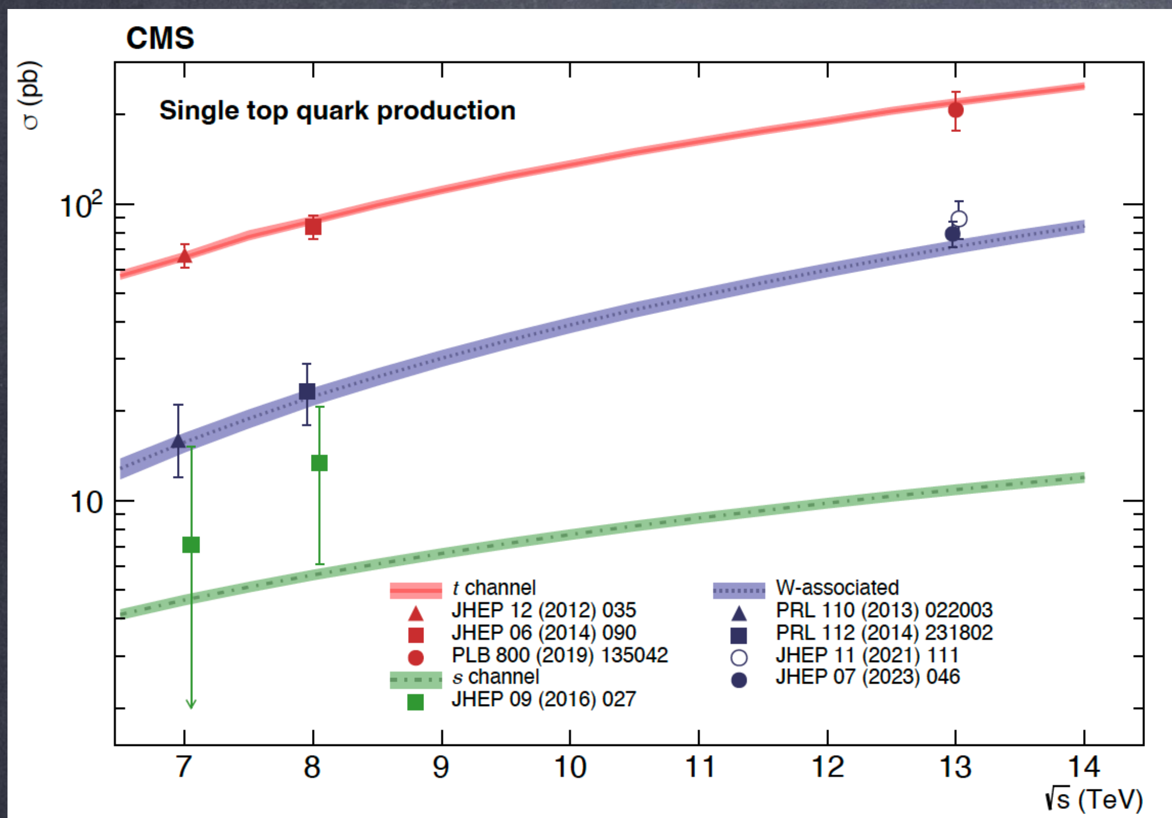
CMS NLO values of m_t^{pole} and $\alpha_S(m_Z)$ are used:

was it a good choice?

CMS Collaboration, arXiv:2403.01313

Top quark cross sections

single top



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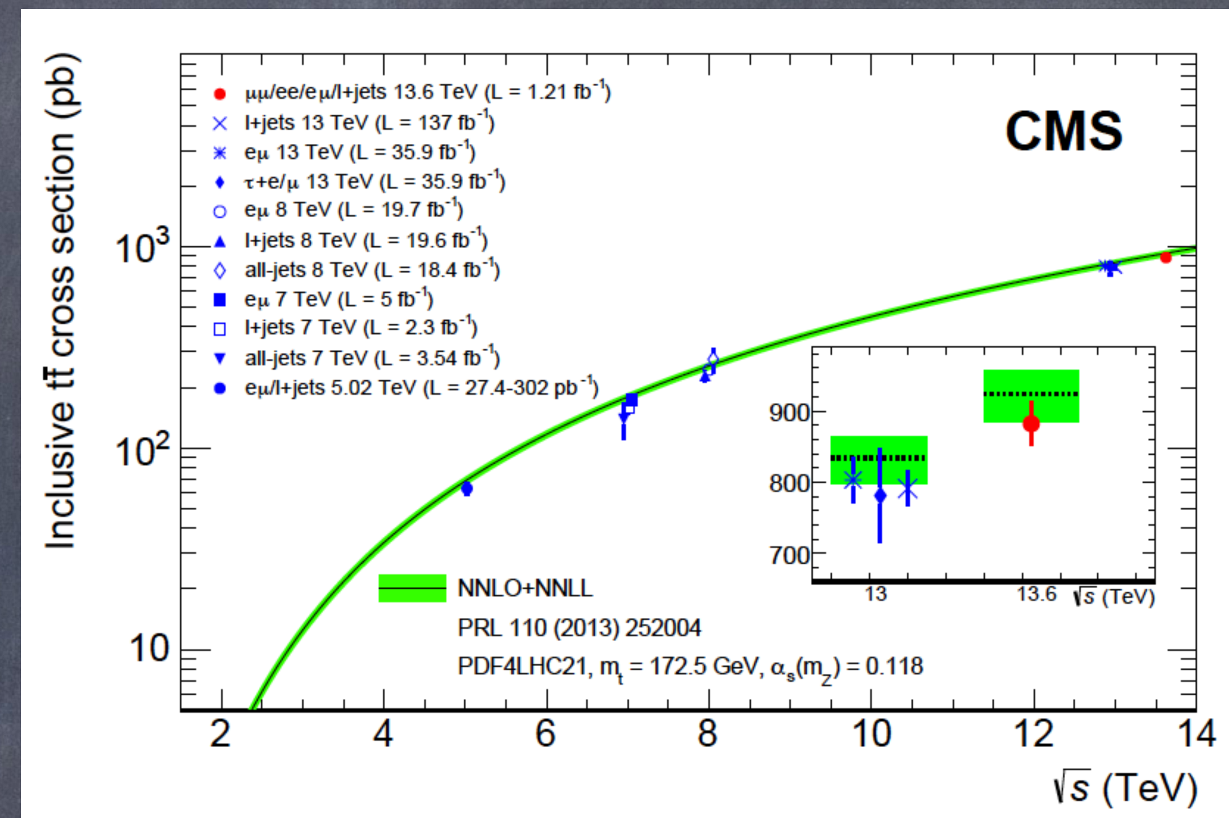
$t\bar{t}$ pair



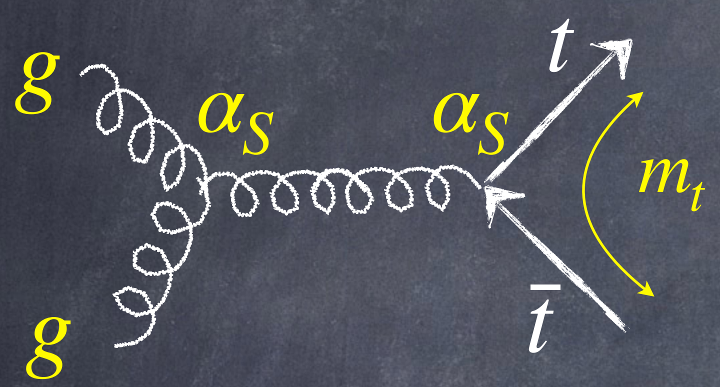
CMS Collaboration, arXiv:2403.01313

single top used for m_t^{MC} measurement, is important for future m_t extractions

mostly used for m_t extractions

Indirect extractions of m_t

m_t^{pole}, $m_t(m_t)$ or m_t^{MSR} can be extracted from inclusive $t\bar{t}$ production cross section



✓ normalisation is driven by the value of m_t , $\alpha_S(m_Z)$, $g(x)$

✓ compare measurement to prediction: extract m_t

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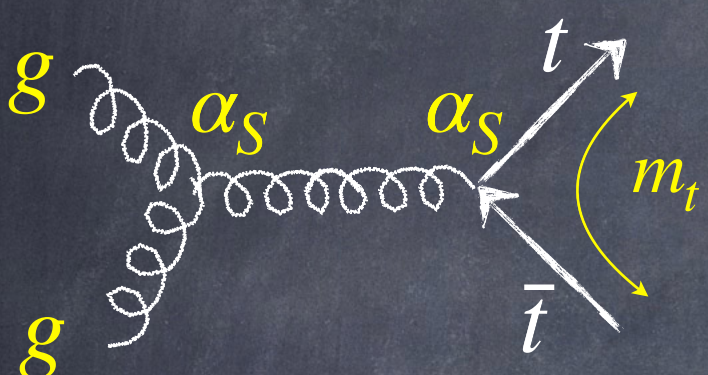

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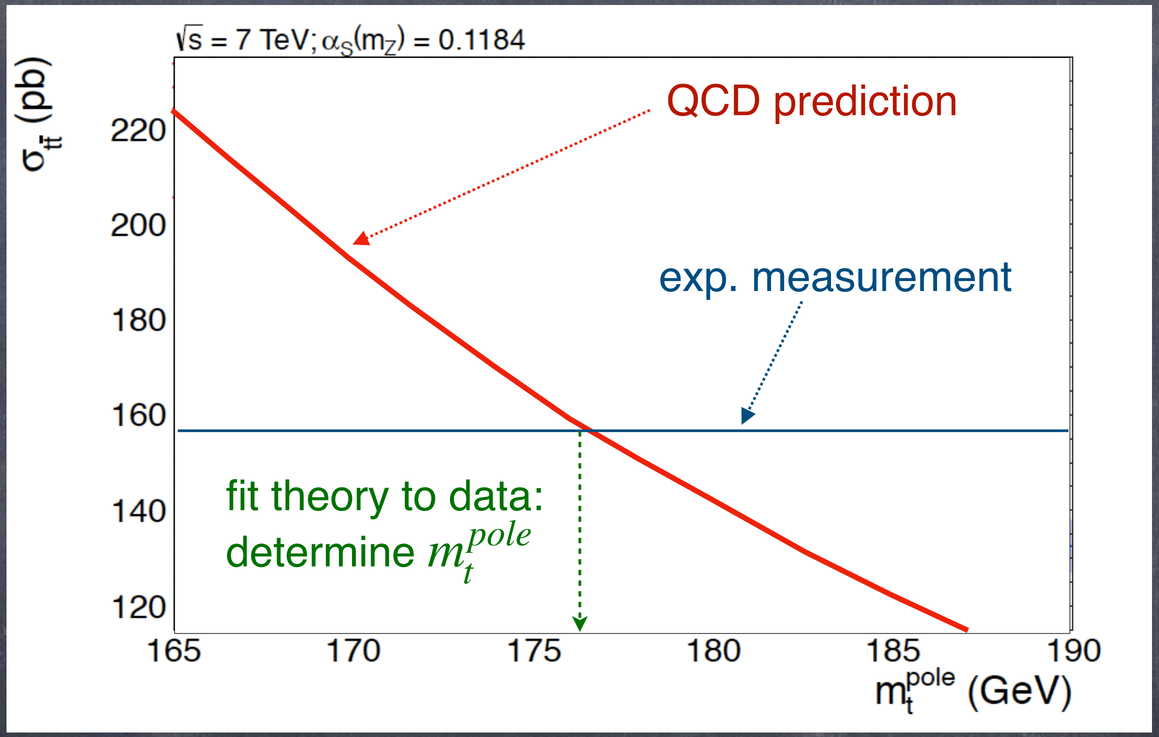
analysis strategy:



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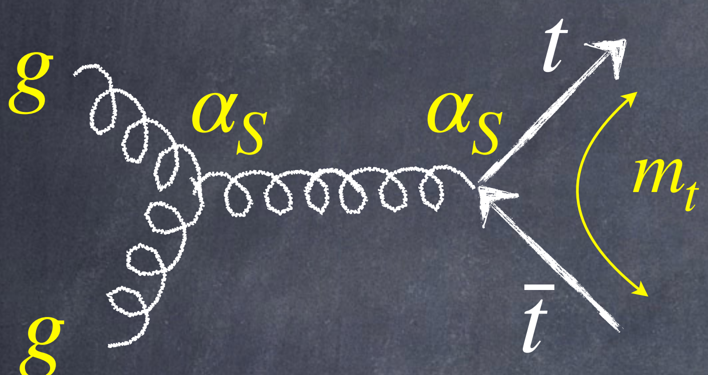

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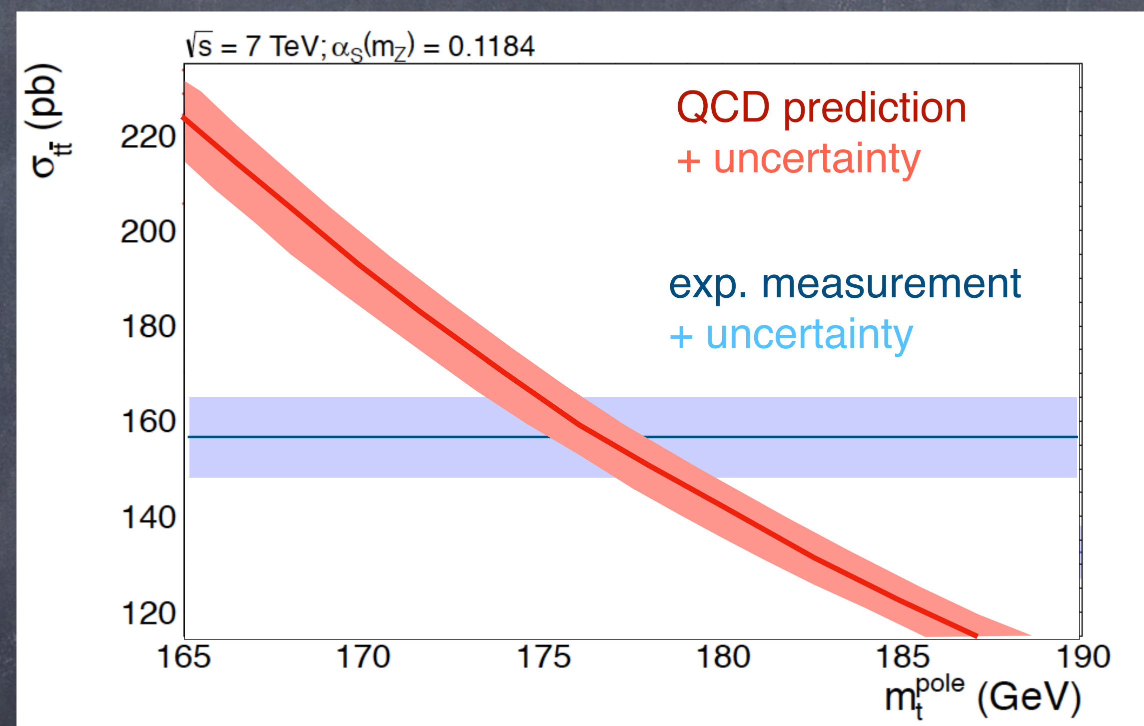

analysis strategy:

consider experimental

and theory uncertainties

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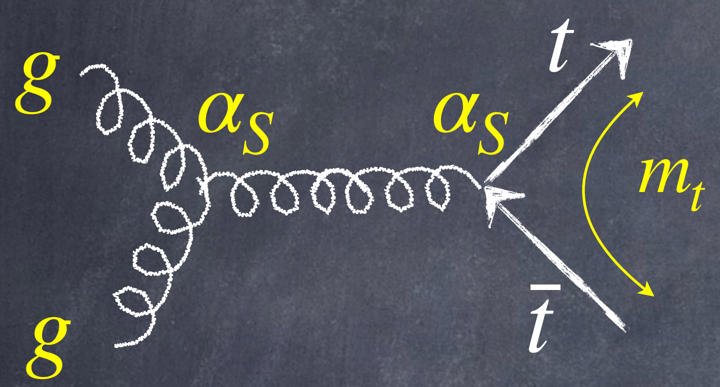

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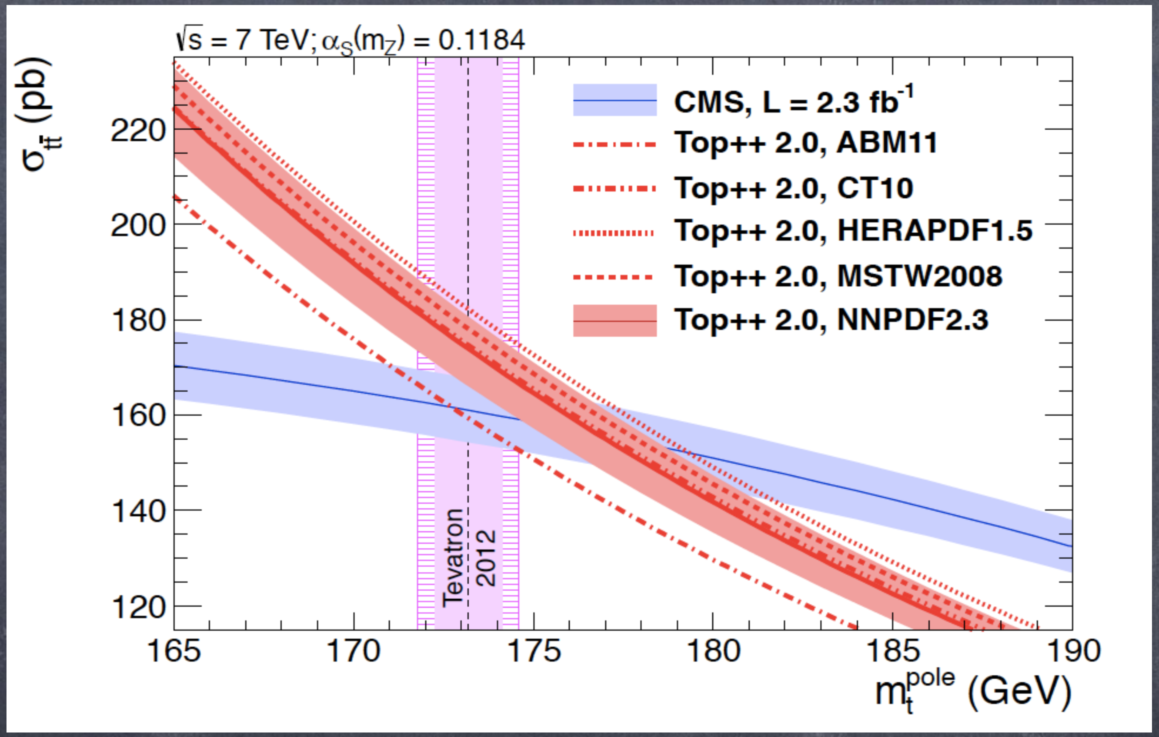

CMS PLB 728 (2013) 496

In a real measurement

limited detector acceptance:

extrapolation to full phase space

relies on MC

(rest dependence on m_t^{MC})

choice of different PDFs +$\alpha_S(m_Z)$

$\rightarrow$ different values of predicted $\sigma_{t\bar{t}}$

[m_t correlated with $\alpha_S(m_Z)$ and $g(x)$]

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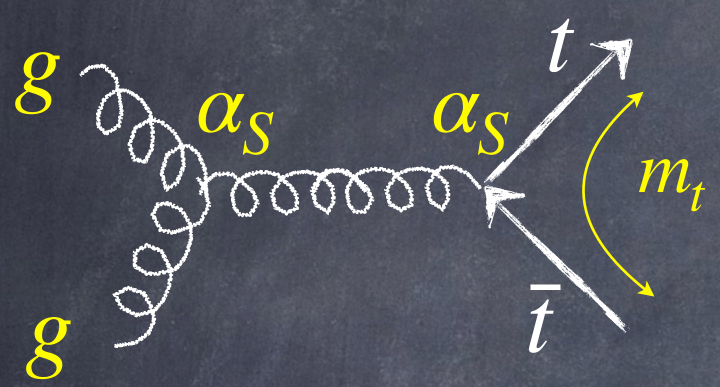

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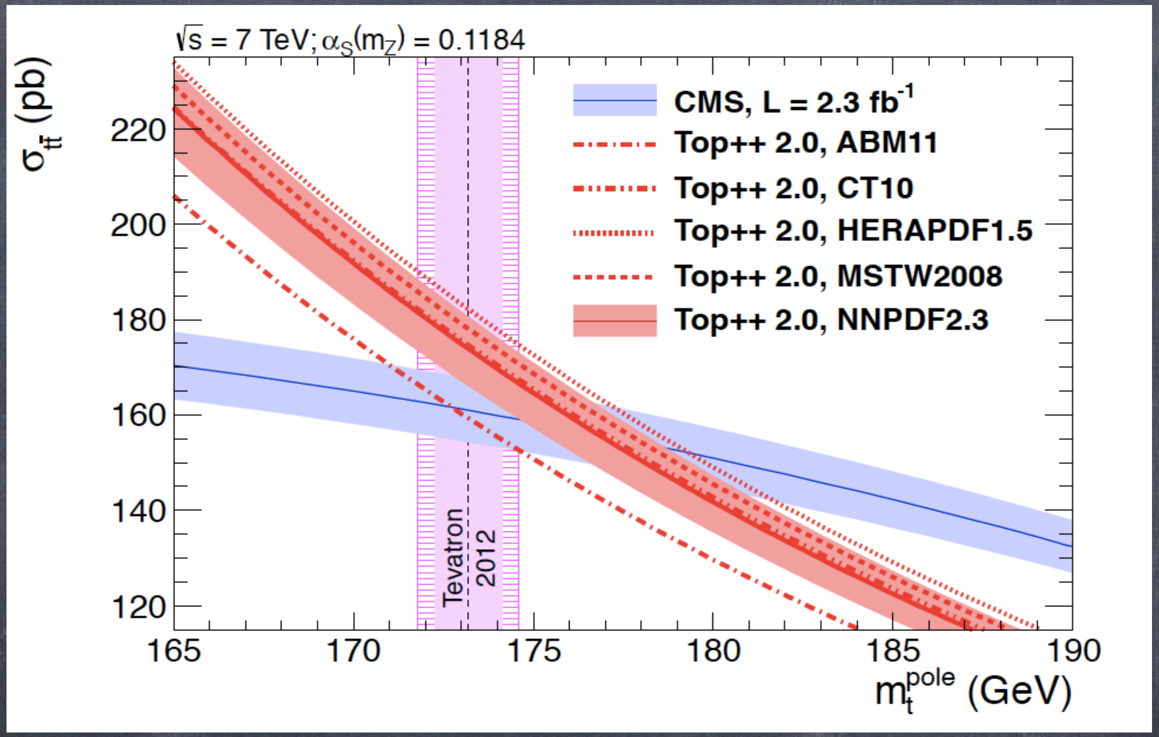


CMS PLB 728 (2013) 496

In a real measurement

limited detector acceptance:

extrapolation to full phase space

relies on MC

(rest dependence on m_t^{MC})

choice of different PDFs +$\alpha_S(m_Z)$

→ different values of predicted $\sigma_{t\bar{t}}$

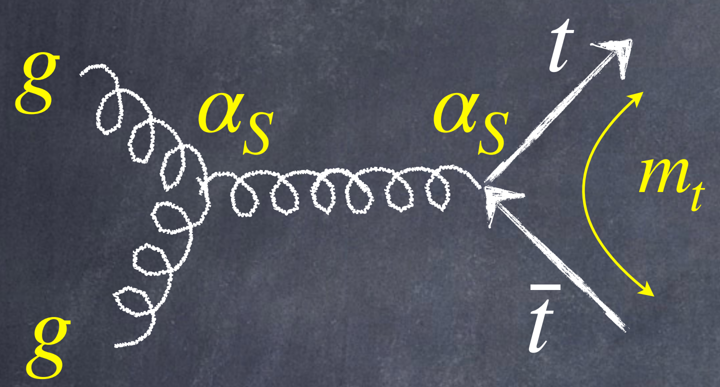
[m_t correlated with $\alpha_S(m_Z)$ and $g(x)$]

✓ additional uncertainty from rest-dependence of $\sigma_{t\bar{t}}$ on m_t^{MC}

✓ only one parameter, $g(x)$, OR α_S, OR m_t can be extracted from inclusive cross section

Indirect extractions of m_t

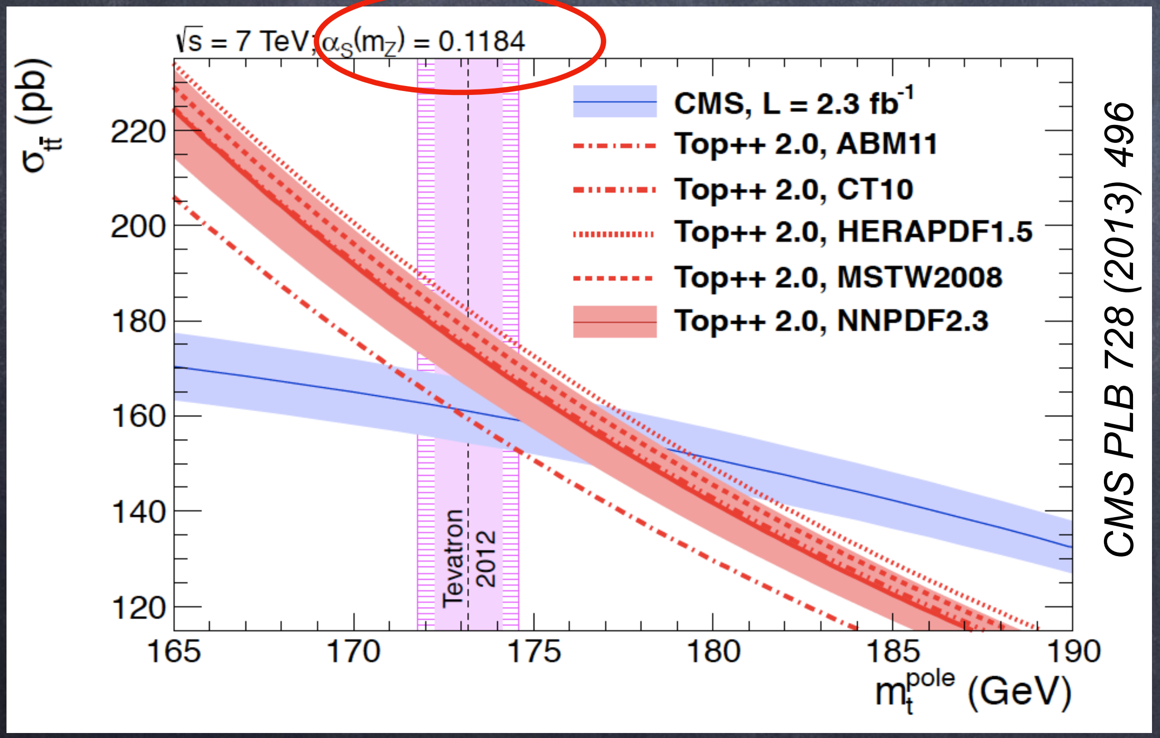
m_t^{pole}, $m_t(m_t)$ or m_t^{MSR} can be extracted from inclusive $t\bar{t}$ production cross section



✓ normalisation is driven by the value of m_t , $\alpha_S(m_Z)$, $g(x)$

✓ compare measurement to prediction: extract m_t or $\alpha_S(m_Z)$, or $g(x)$

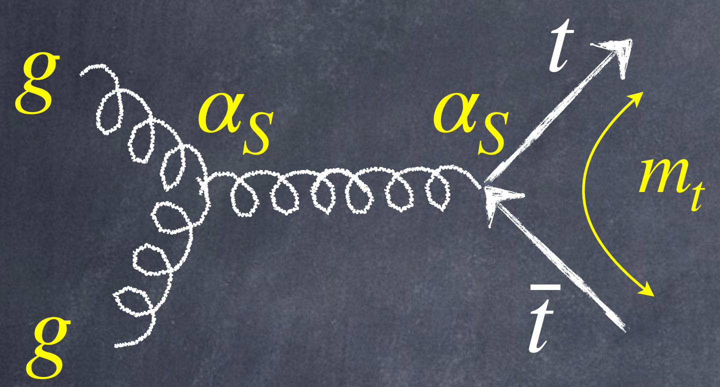
1) fix $g(x)$ AND $\alpha_S(m_Z)$



✓ m_t can be extracted

Indirect extractions of m_t

m_t^{pole}, $m_t(m_t)$ or m_t^{MSR} can be extracted from inclusive $t\bar{t}$ production cross section



✓ normalisation is driven by the value of m_t , $\alpha_S(m_Z)$, $g(x)$

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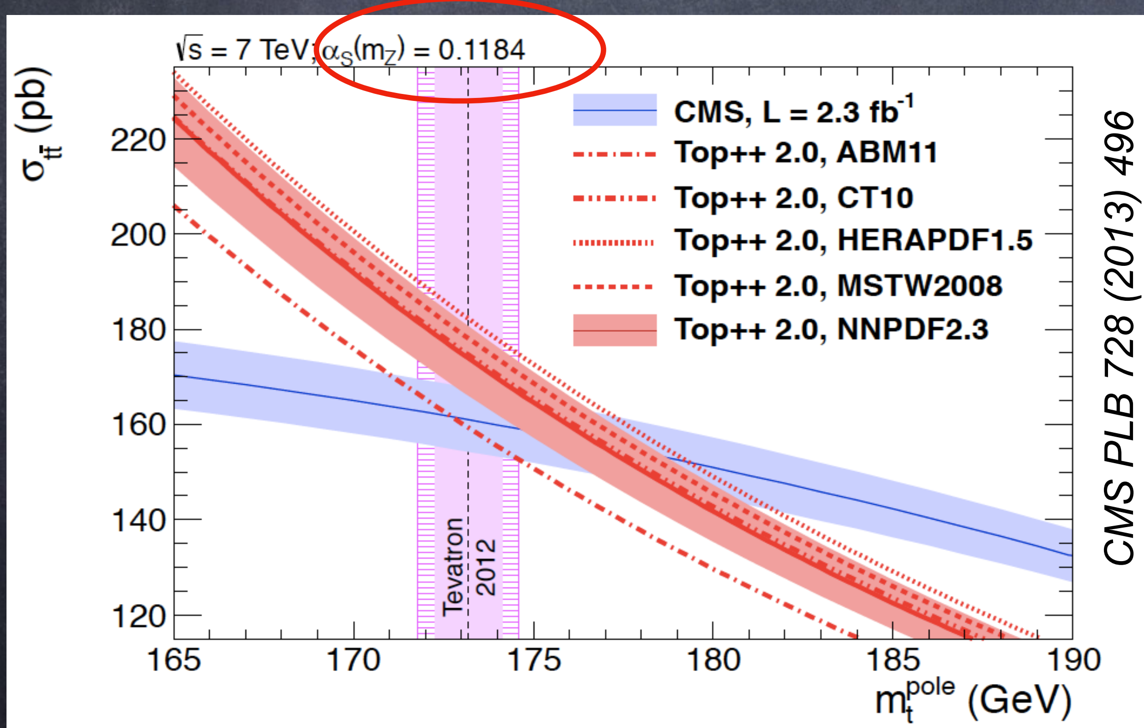
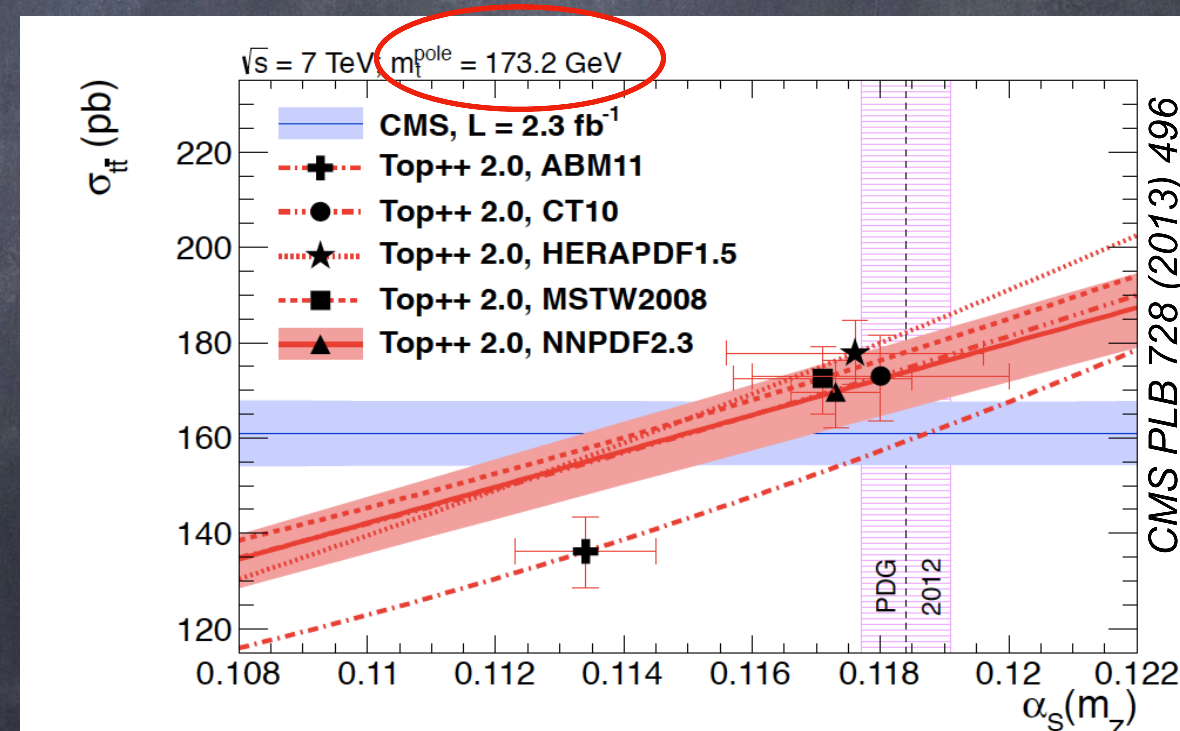


✓ m_t can be extracted

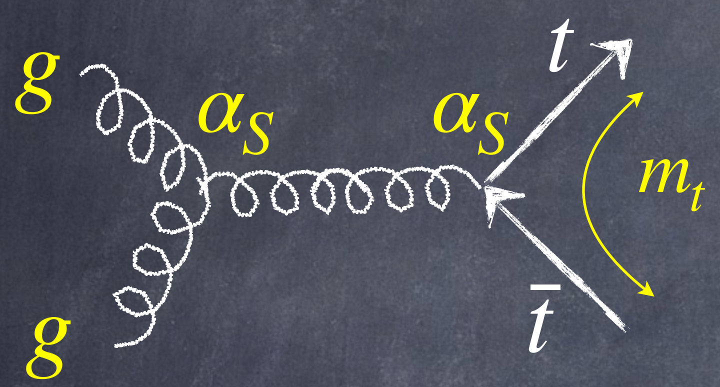
1) fix $g(x)$ AND m_t



✓ $\alpha_S(m_Z)$ can be extracted

Indirect extractions of m_t or $\alpha_S(m_Z)$

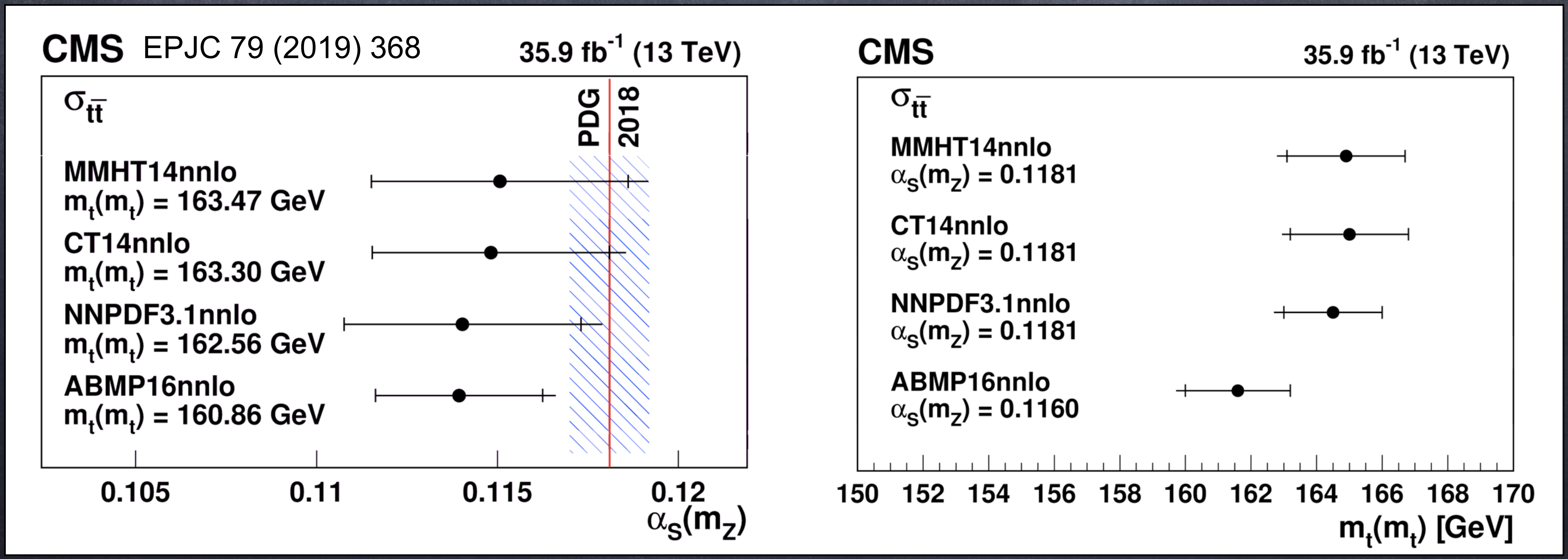
Extraction of m_t or $\alpha_S(m_Z)$ using $t\bar{t}$ production at the LHC at $\sqrt{s}$ = 13 TeV



this time, $\sigma_{t\bar{t}}$ measured independent of m_t^{MC}

(both extracted simultaneously in a multi-dimensional fit to the final state distributions)

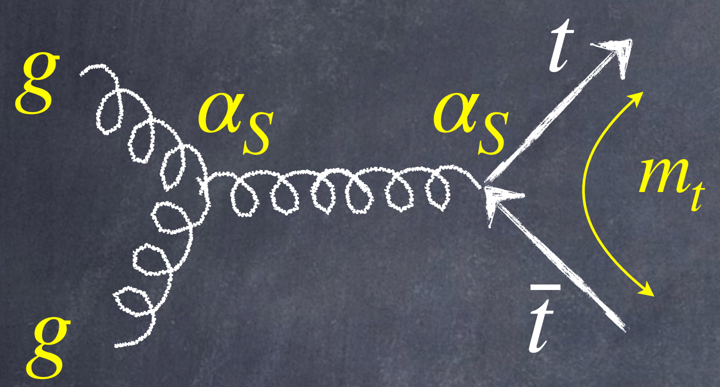
Compare measurement to theory: NNLO pQCD in $\overline{MS}$ renormalisation scheme using different PDFs



CMS EPJC 79 (2019) 368

3-fold correlation in $\sigma_{t\bar{t}}$

Extraction of m_t or $\alpha_S(m_Z)$ using $t\bar{t}$ production at the LHC at $\sqrt{s}$ = 13 TeV

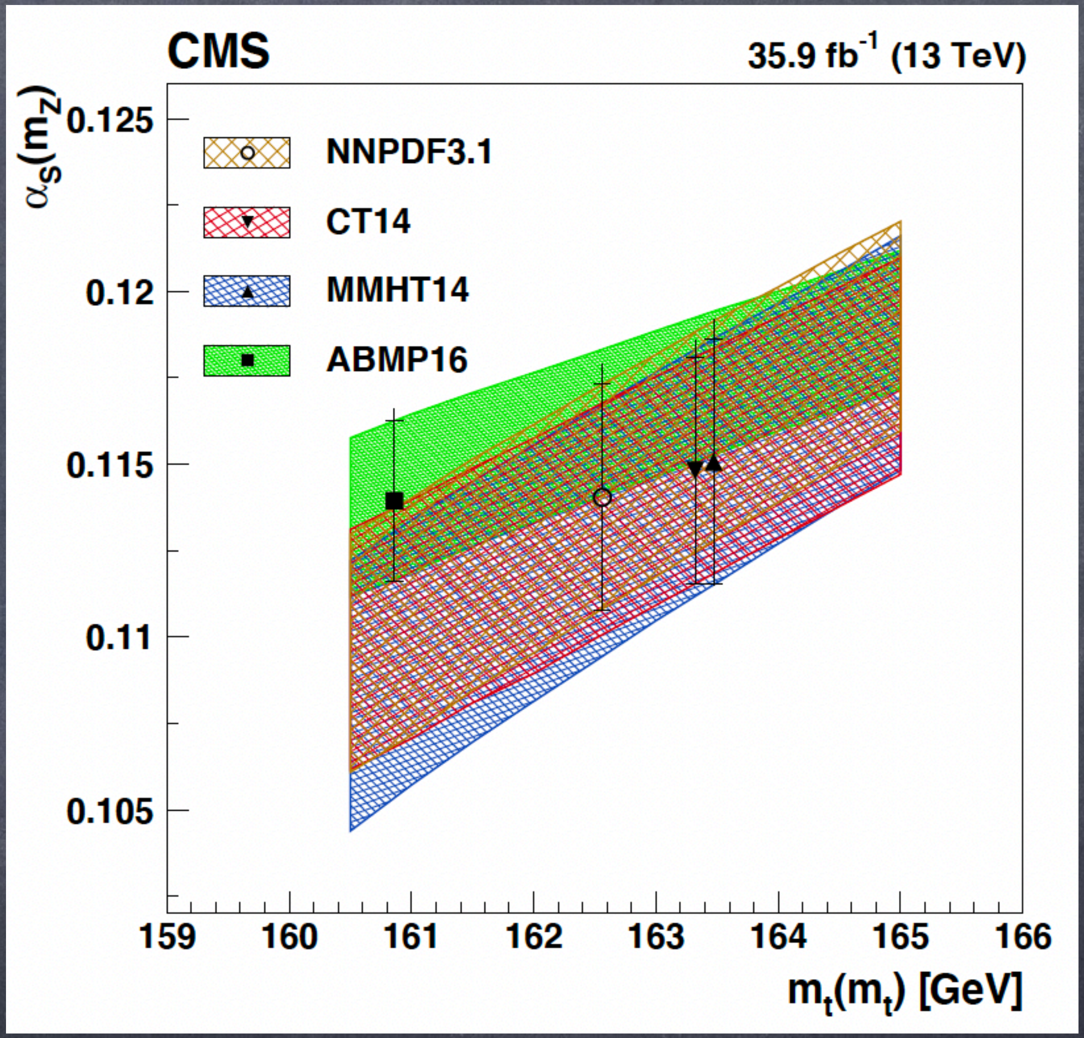


Correlation of $\alpha_S(m_Z)$, m_t and $g(x)$

major problem of m_t

extracted from inclusive

cross section measurement



[CMS EPJC 79 (2019) 368]

Solution: explore differential cross sections,

- use observables less correlated to $\alpha_S(m_Z)$ and PDFs
- mitigate the correlation by simultaneous extraction of $\alpha_S(m_Z)$, m_t and $g(x)$

Less PDF/α_S biased observables in $t\bar{t}$+jet

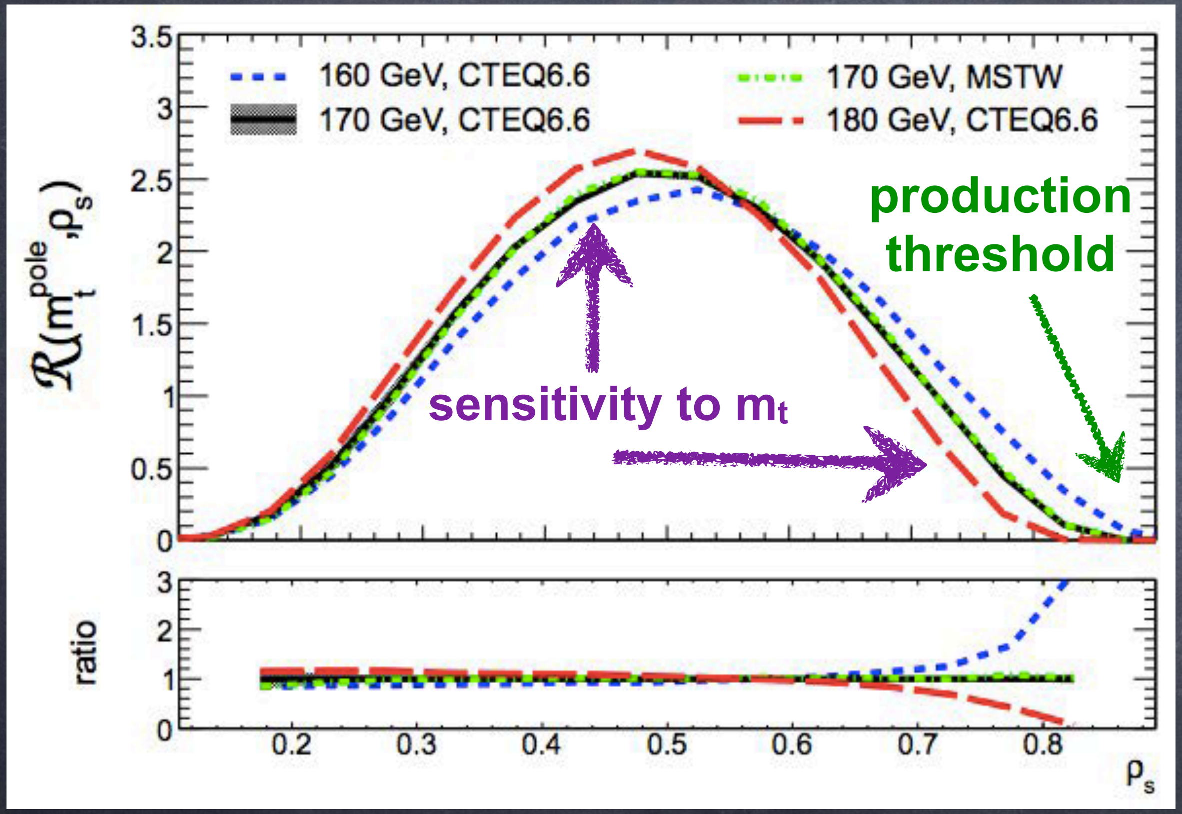
[Alioli et al 1303.6415, arXiv:2202.07975]

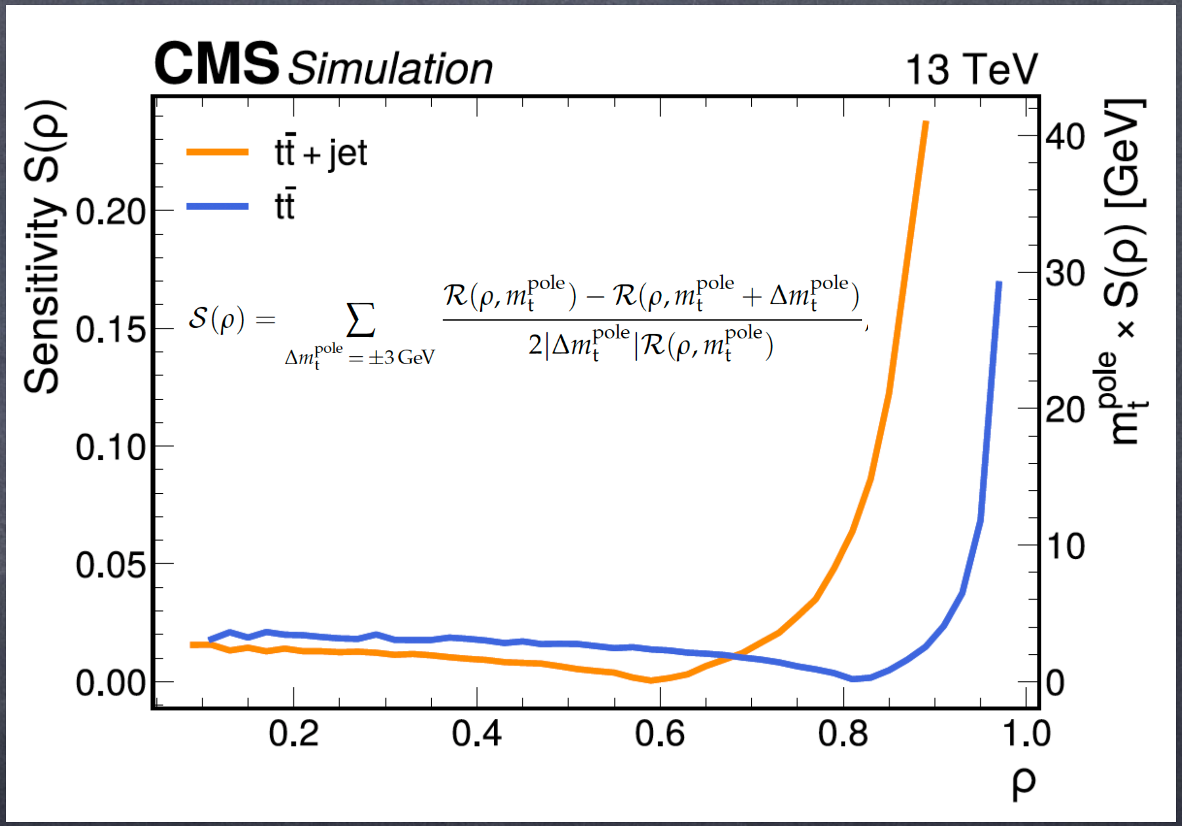
tt+1-jet event topologies, jet with p_T > 30 GeV

Observable: inverse of the system invariant mass (IR-safe)

$$\mathcal{R}(m_t, \rho) = \frac{1}{\sigma_{t\bar{t}+jet}} \frac{d\sigma_{t\bar{t}+jet}}{d\rho}(m_t, \rho)$$

$$\rho = \frac{2m_0}{\sqrt{s_{t\bar{t}+jet}}}, \; m_0 = 170 \text{ GeV}$$





sensitivity also close to threshold, increased wrt $t\bar{t}$ (due to additional gluon radiation)

shape-observable: mitigate PDF + α_S dependence

Less PDF/α_S biased observables in $t\bar{t}$+jet

tt+1-jet event topologies, jet with p_T > 30 GeV

[Alioli et al 1303.6415, arXiv:2202.07975]

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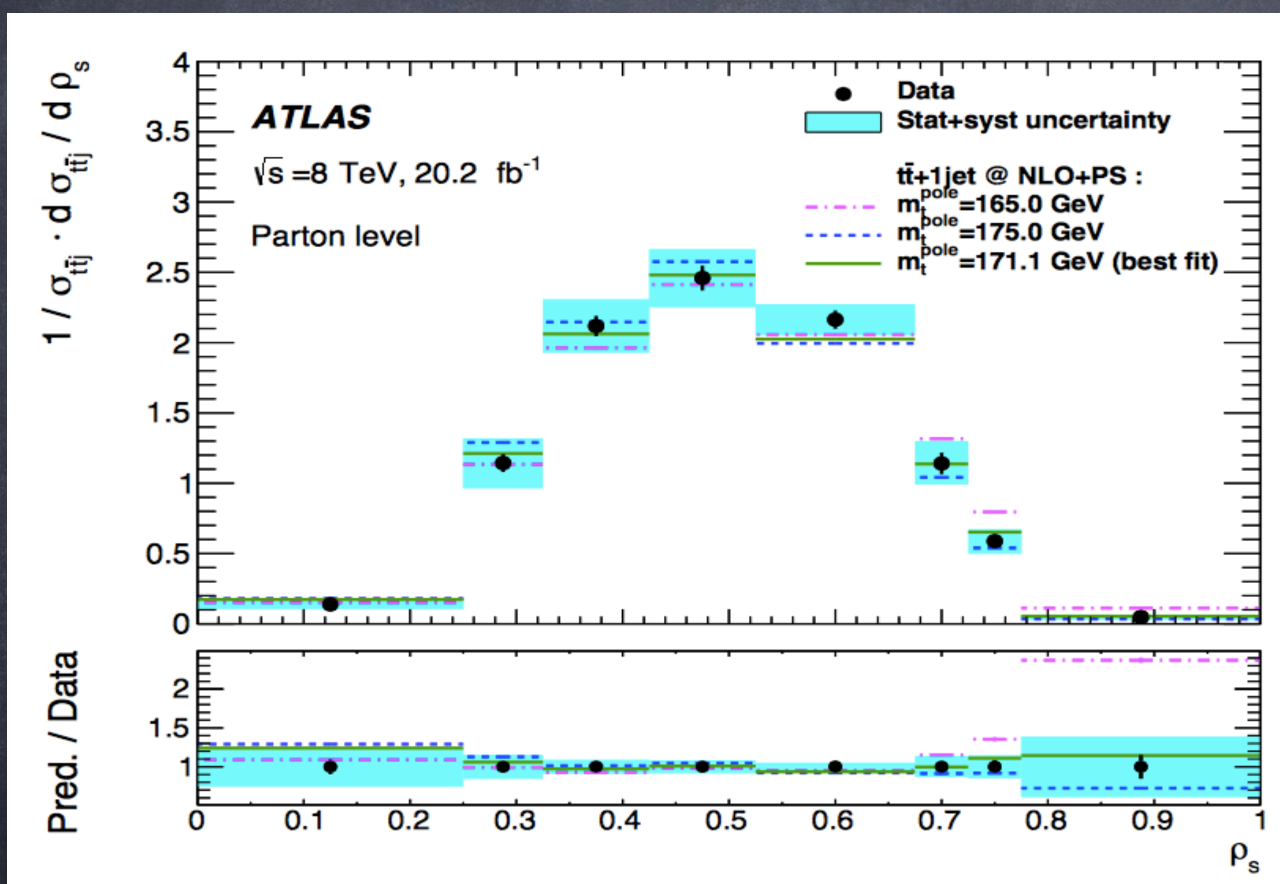
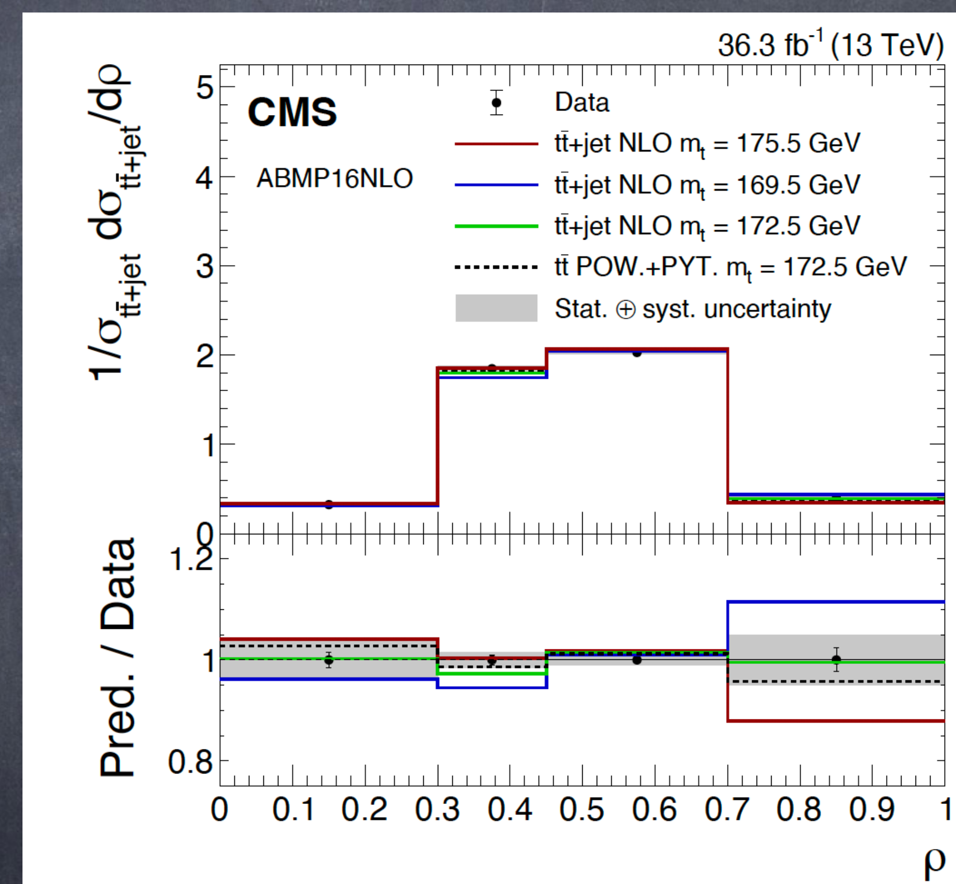
$$\rho = \frac{2m_0}{\sqrt{s_{t\bar{t}+jet}}},\ m_0 = 170\ \text{GeV}$$

[ATLAS,1905.02302]



[CMS 2207.02270]



$$m_t^{pole} = 171.1\ ^{+1.2}_{-1.1}\ \text{GeV}$$

$$m_t^{pole} = 172.93 \pm 1.36\ \text{GeV}$$

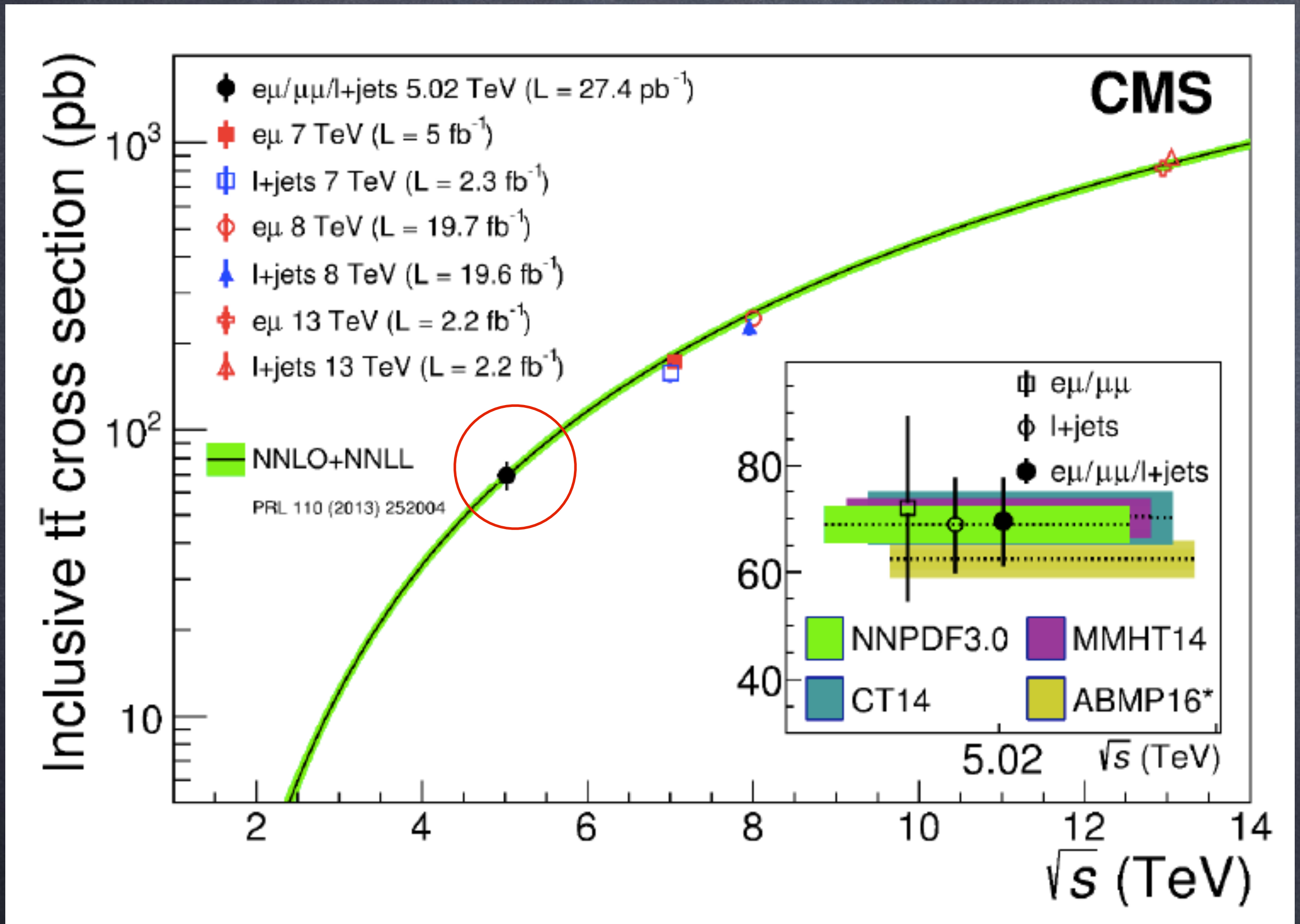
theory NLO, NNLO in work

The top quark and the gluon

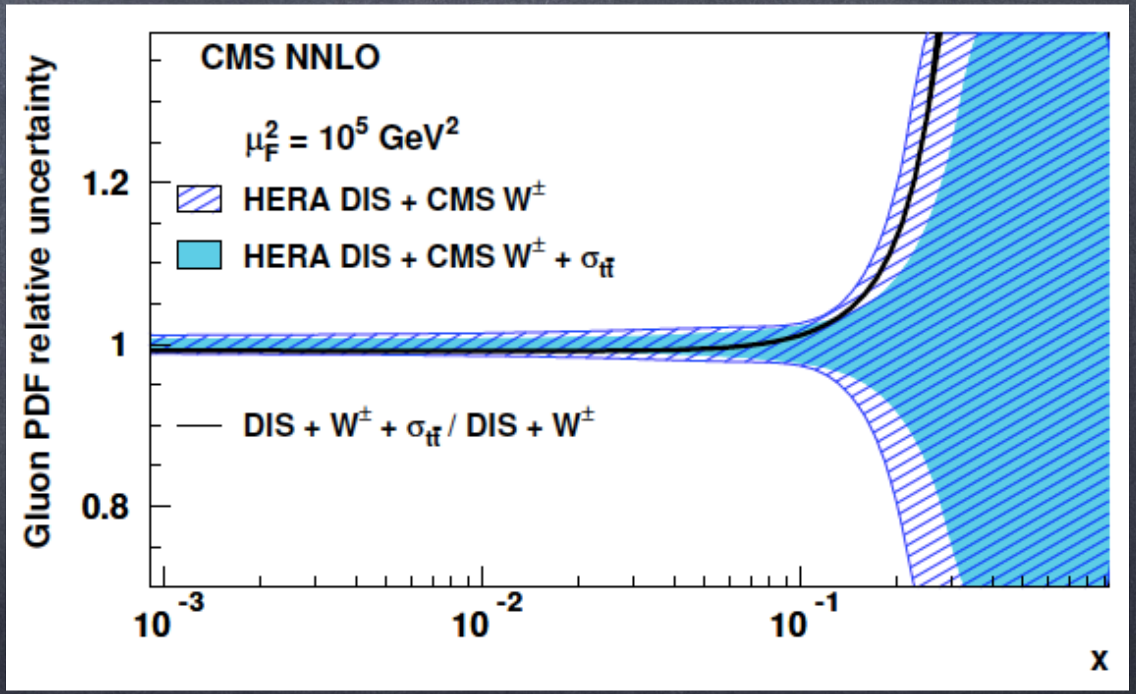
In pp collisions top-quark pair production probes $g(x)$ at high x due to large m_t

ATLAS and CMS measurements of inclusive $\sigma_{t\bar{t}}$ incorporated in modern PDF sets

Illustration of the impact of a single measurement



1 data point added in the PDF fit to DIS data: reduction of the uncertainty in $g(x)$

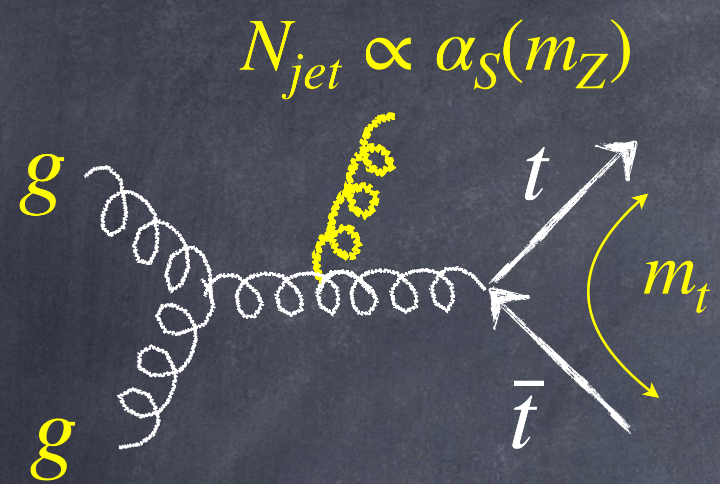


[CMS JHEP 1803 (2018) 115]

Even single (imprecise) measurement has a visible effect on $g(x)$ at high x

Differential cross section measurements have significantly higher impact

Resolving $\alpha_S(m_Z) - m_t - g(x)$ correlation



triple-differential $t\bar{t}$ cross sections as a function of

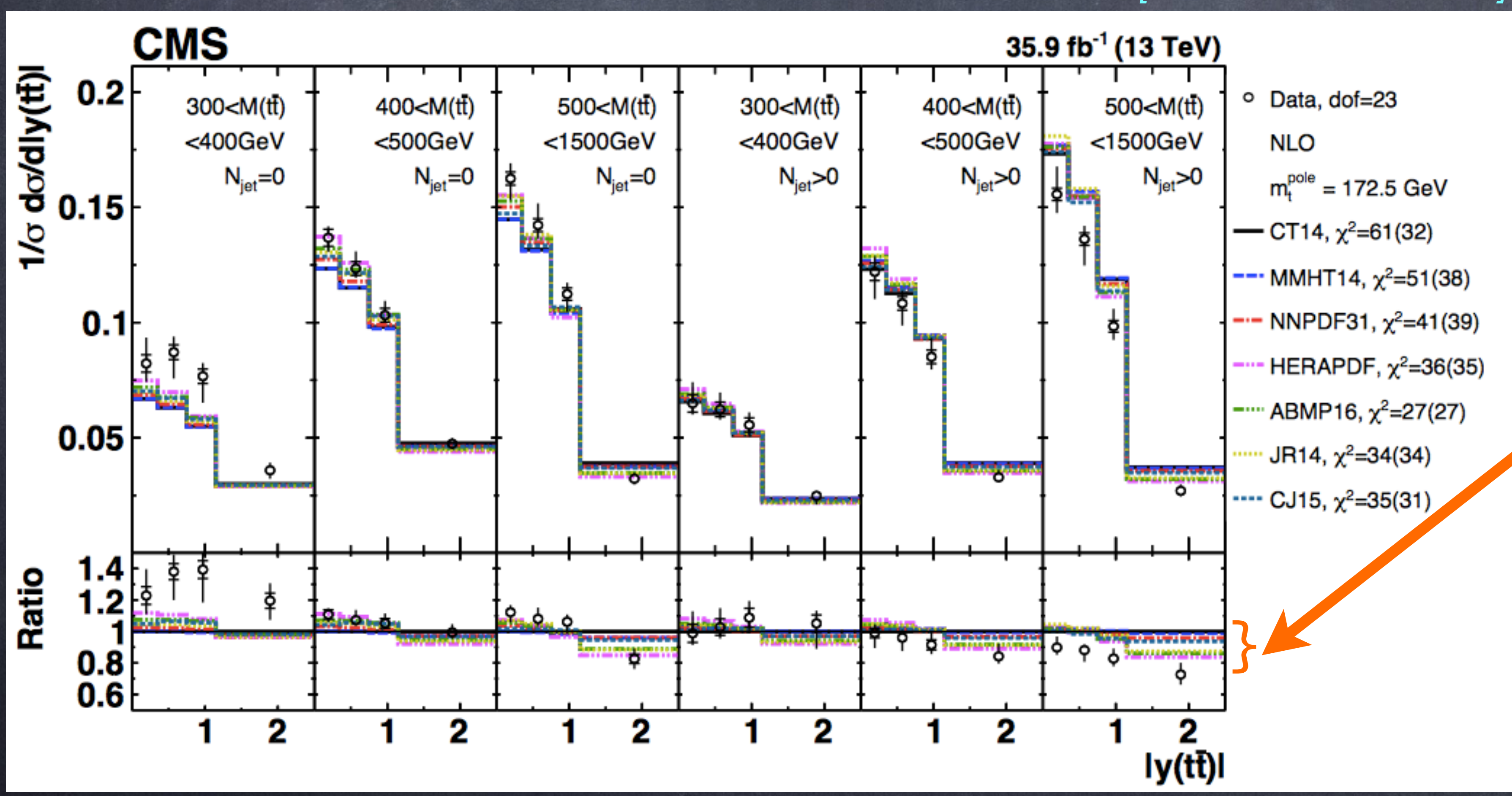
- invariant mass of $t\bar{t}$ pair, $M_{t\bar{t}}$
- rapidity of $t\bar{t}$ pair, $y_{t\bar{t}}$

} *sensitivity to PDFs:* $x_{1,2} = \frac{M_{t\bar{t}}}{\sqrt{s}} e^{\pm y_{t\bar{t}}}$

- number of additional jets: adds sensitivity to $\alpha_S(m_Z)$

- data vs theory* using **different PDFs**

[CMS arXiv:1904.05237]

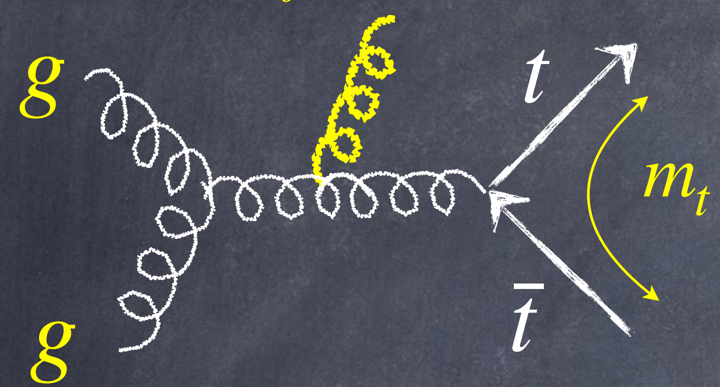


** NLO: MadGraph5_aMC@NLO:*

$\sigma_{t\bar{t}}$ Mangano, Nason, Ridolfi, NPB 373 (1992) 295

$\sigma_{t\bar{t}+jet}$: Dittmaier, Uwer, Weinzierl, PRL 98 (2007) 262002

Resolving $\alpha_S(m_Z) - m_t - g(x)$ correlation



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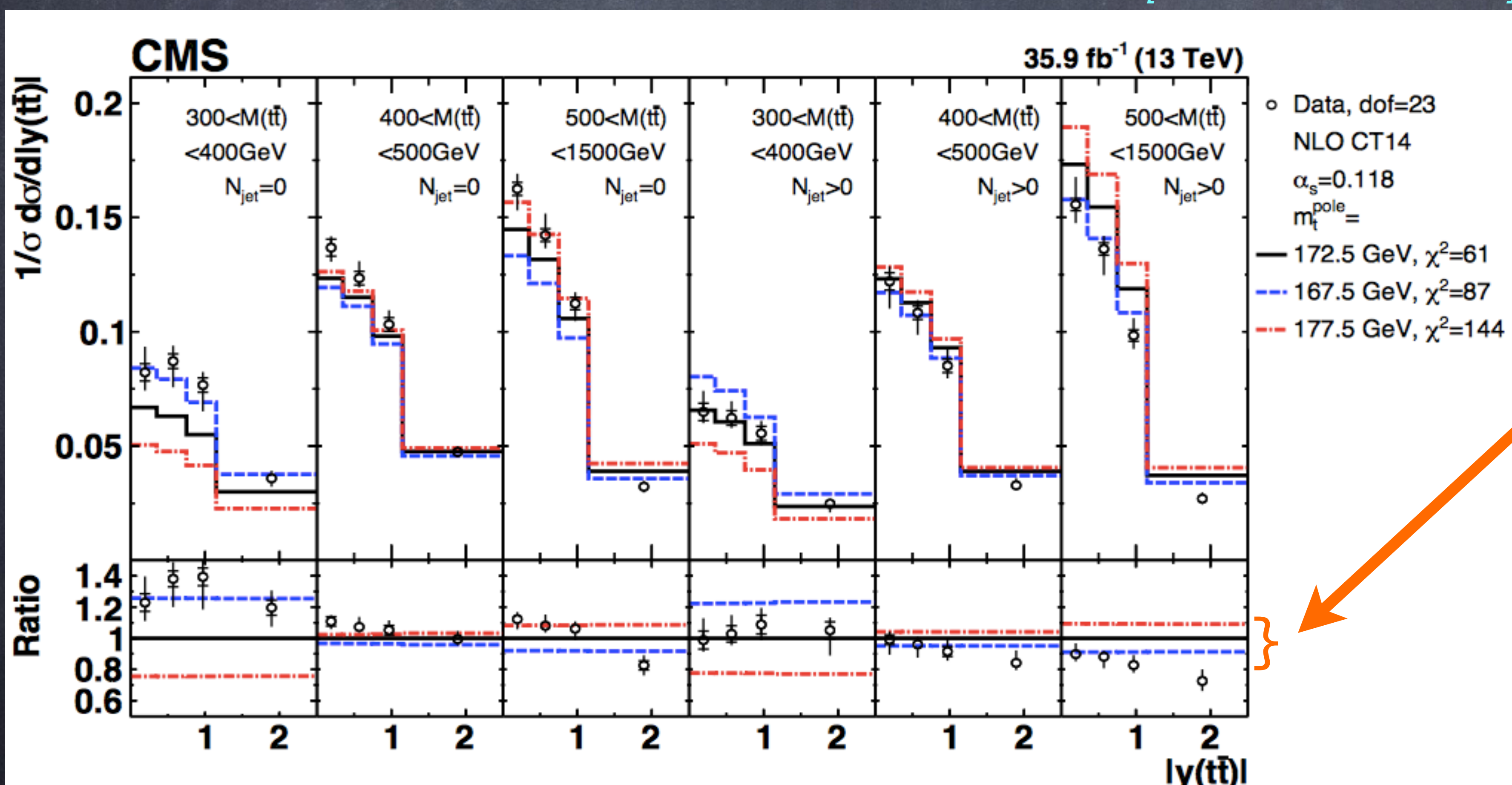
- number of additional jets: adds sensitivity to $\alpha_S(m_Z)$

- data vs theory* using **different** m_t^{pole}

[CMS arXiv:1904.05237]



sensitivity to m_t^{pole}

NB: highest sensitivity

@ $t\bar{t}$ production threshold

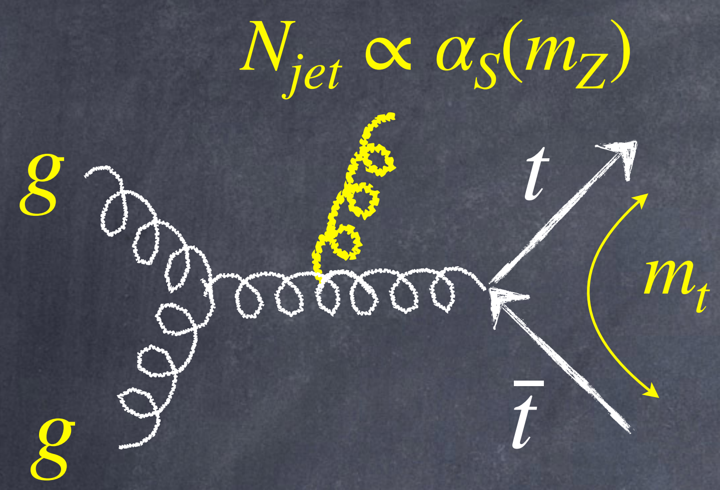
$300 < M_{t\bar{t}} < 400$ GeV

* NLO: MadGraph5_aMC@NLO:

$\sigma_{t\bar{t}}$ Mangano, Nason, Ridolfi, NPB 373 (1992) 295

$\sigma_{t\bar{t}+jet}$: Dittmaier, Uwer, Weinzierl, PRL 98 (2007) 262002

Resolving $\alpha_S(m_Z) - m_t - g(x)$ correlation



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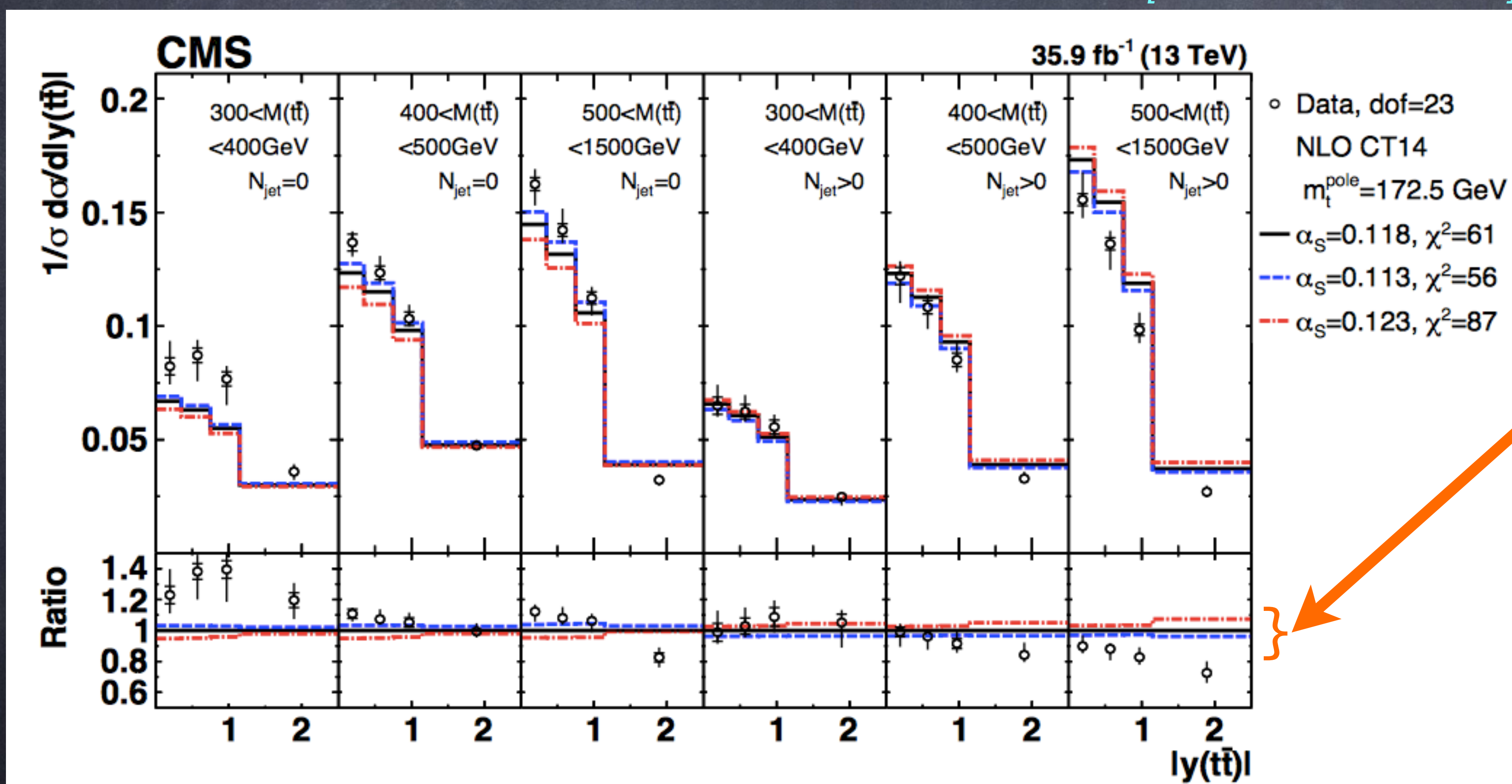
- number of additional jets: adds sensitivity to $\alpha_S(m_Z)$

- data vs theory* using **different $\alpha_S(m_Z)$**

[CMS arXiv:1904.05237]



sensitivity to $\alpha_S(m_Z)$

* NLO: MadGraph5_aMC@NLO:

$\sigma_{t\bar{t}}$ Mangano, Nason, Ridolfi, NPB 373 (1992) 295

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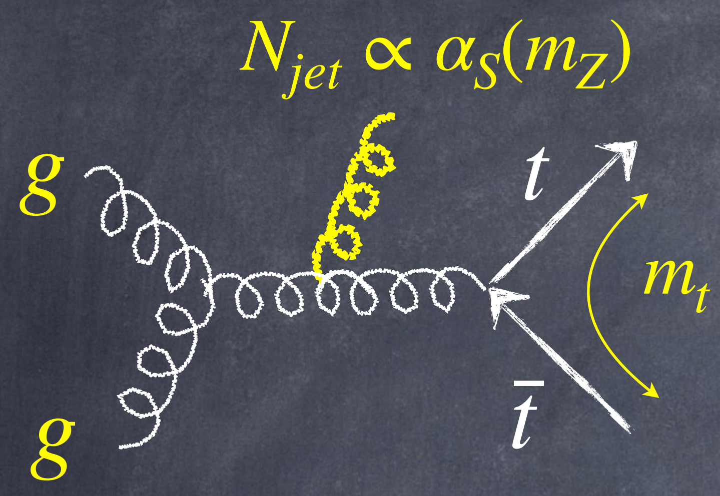
Resolving $\alpha_S(m_Z) - m_t - g(x)$ correlation



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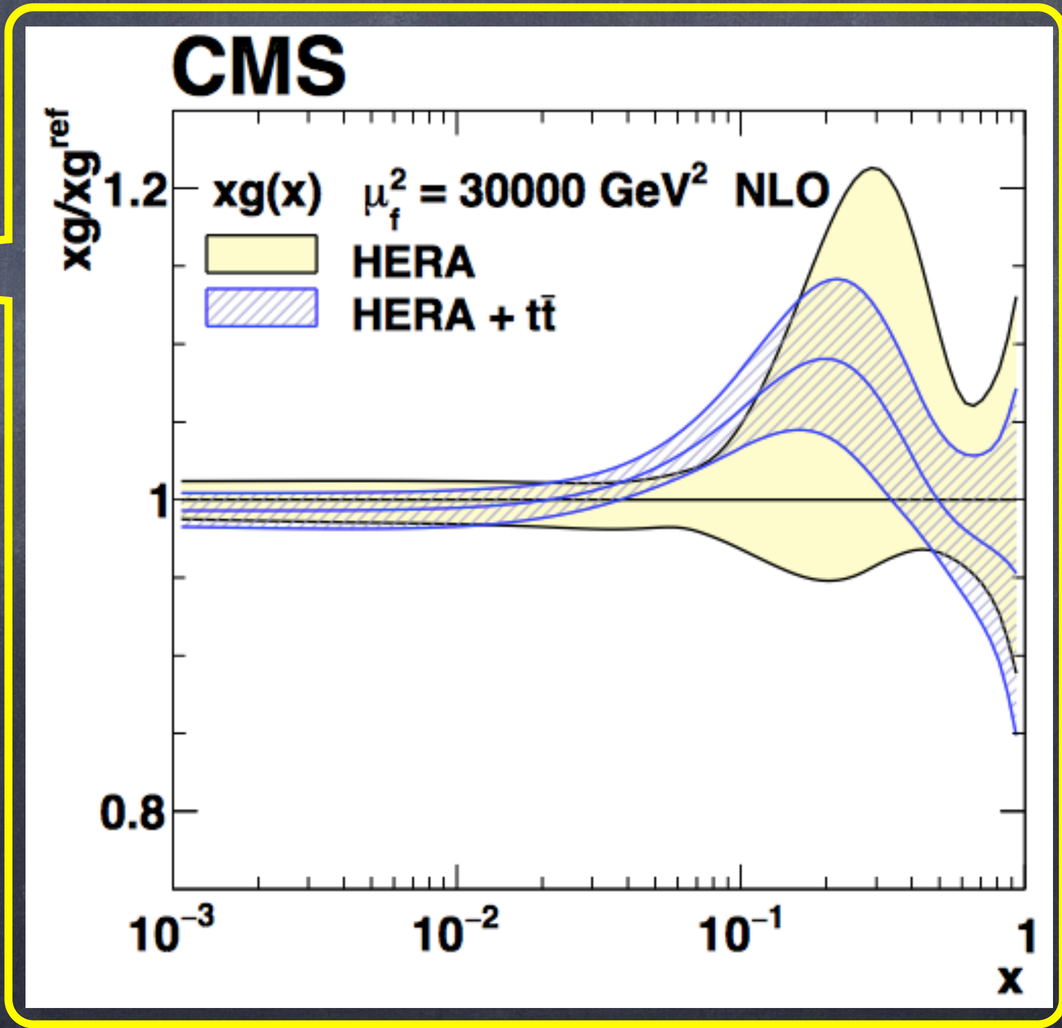
- rapidity of $t\bar{t}$ pair, $y_{t\bar{t}}$
- number of additional jets: adds sensitivity to $\alpha_S(m_Z)$

Idea: extract simultaneously

PDF, $\alpha_S(m_Z)$ and m_t^{pole}

$g(x)$ **gets improved uncertainty**



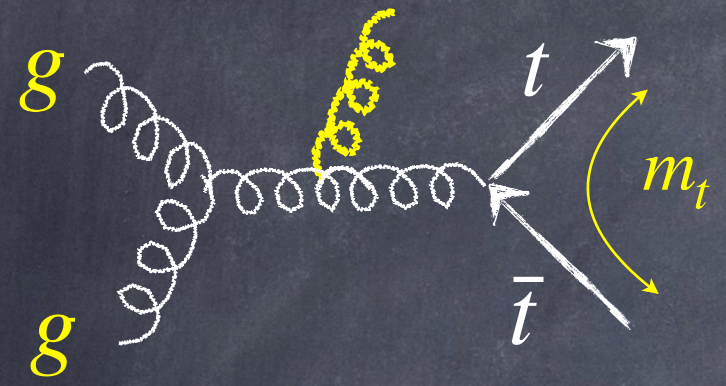
[CMS arXiv:1904.05237]

$m_t^{pole} = 170.5 \pm 0.8$ GeV

$\alpha_S(m_Z) = 0.1135\,^{+0.0021}_{-0.0017}$

Best results, so far ?

$N_{jet} \propto \alpha_S(m_Z)$



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Idea: extract simultaneously

PDF, $\alpha_S(m_Z)$ and m_t^{pole}

Precise results on m_t^{pole} and $\alpha_s(m_Z)$

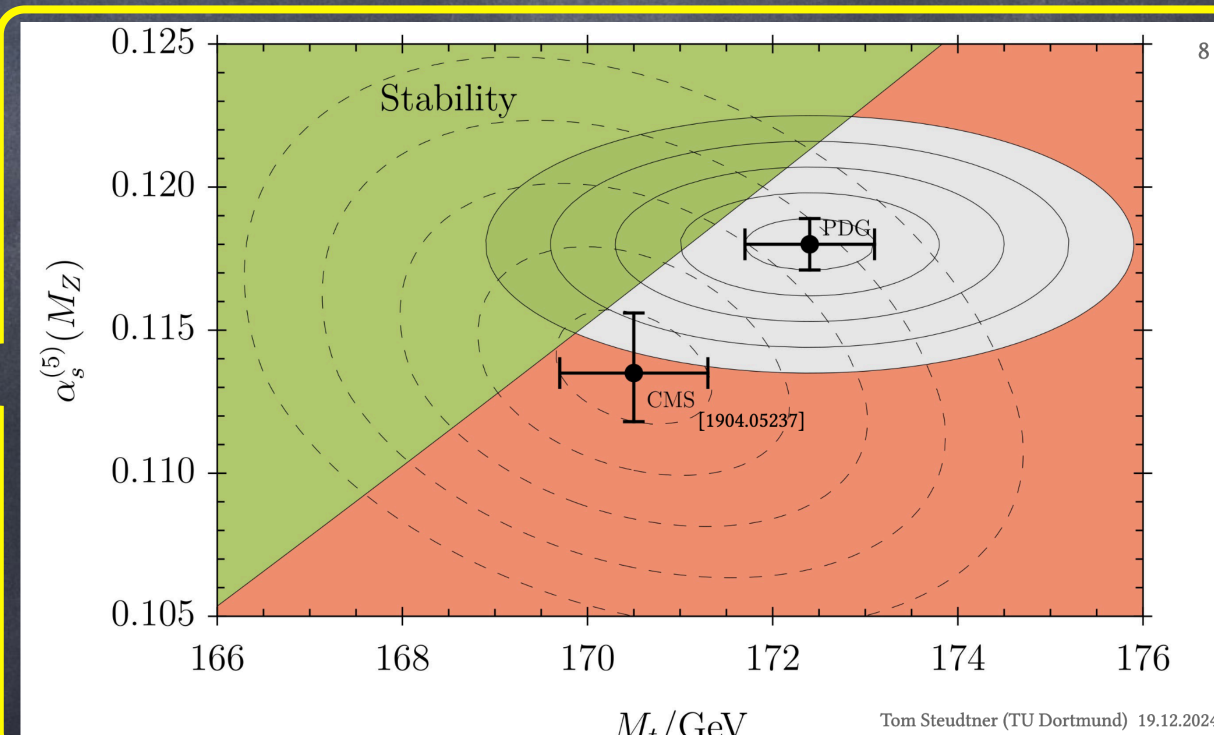
unbiased among each other and from PDFs

$g(x)$ **gets improved uncertainty**

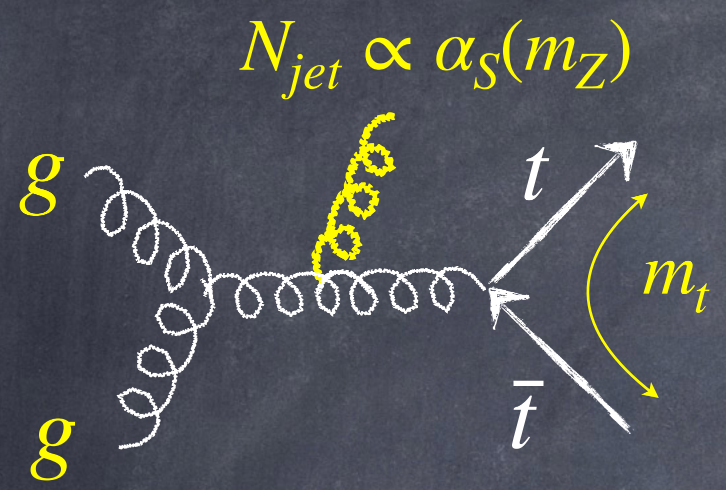
$$m_t^{pole} = 170.5 \pm 0.8 \text{ GeV}$$

$$\alpha_S(m_Z) = 0.1135\,^{+0.0021}_{-0.0017}$$

test SM stability



Other problems …



triple-differential $t\bar{t}$ cross sections as a function of

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- number of additional jets: adds sensitivity to $\alpha_S(m_Z)$

Idea: extract simultaneously

PDF, $\alpha_S(m_Z)$ and m_t^{pole}

$g(x)$ **gets improved uncertainty**

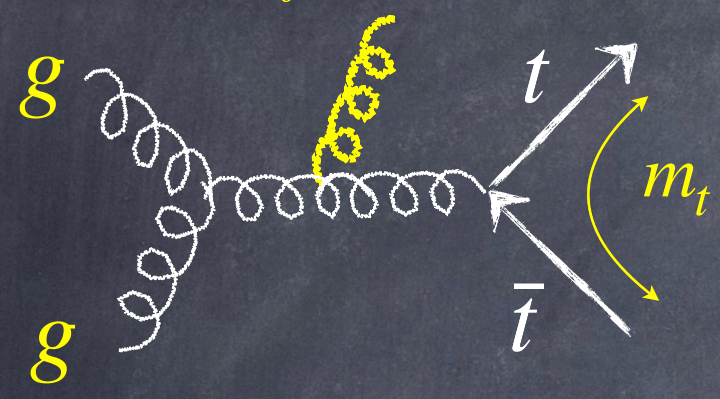
$m_t^{pole} = 170.5 \pm 0.8$ GeV

$\alpha_S(m_Z) = 0.1135\,^{+0.0021}_{-0.0017}$

excellent precision, but sensitivity obtained @ $t\bar{t}$ threshold,
QCD: bound state effects, arising from gluon exchanges in $t\bar{t}$
(toponium discussion, see e.g. special session @ TOPLHC WG Nov. 2024
https://indico.cern.ch/event/1444046/)

Other problems …

$N_{jet} \propto \alpha_S(m_Z)$



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- number of additional jets: adds sensitivity to $\alpha_S(m_Z)$

Idea: extract simultaneously

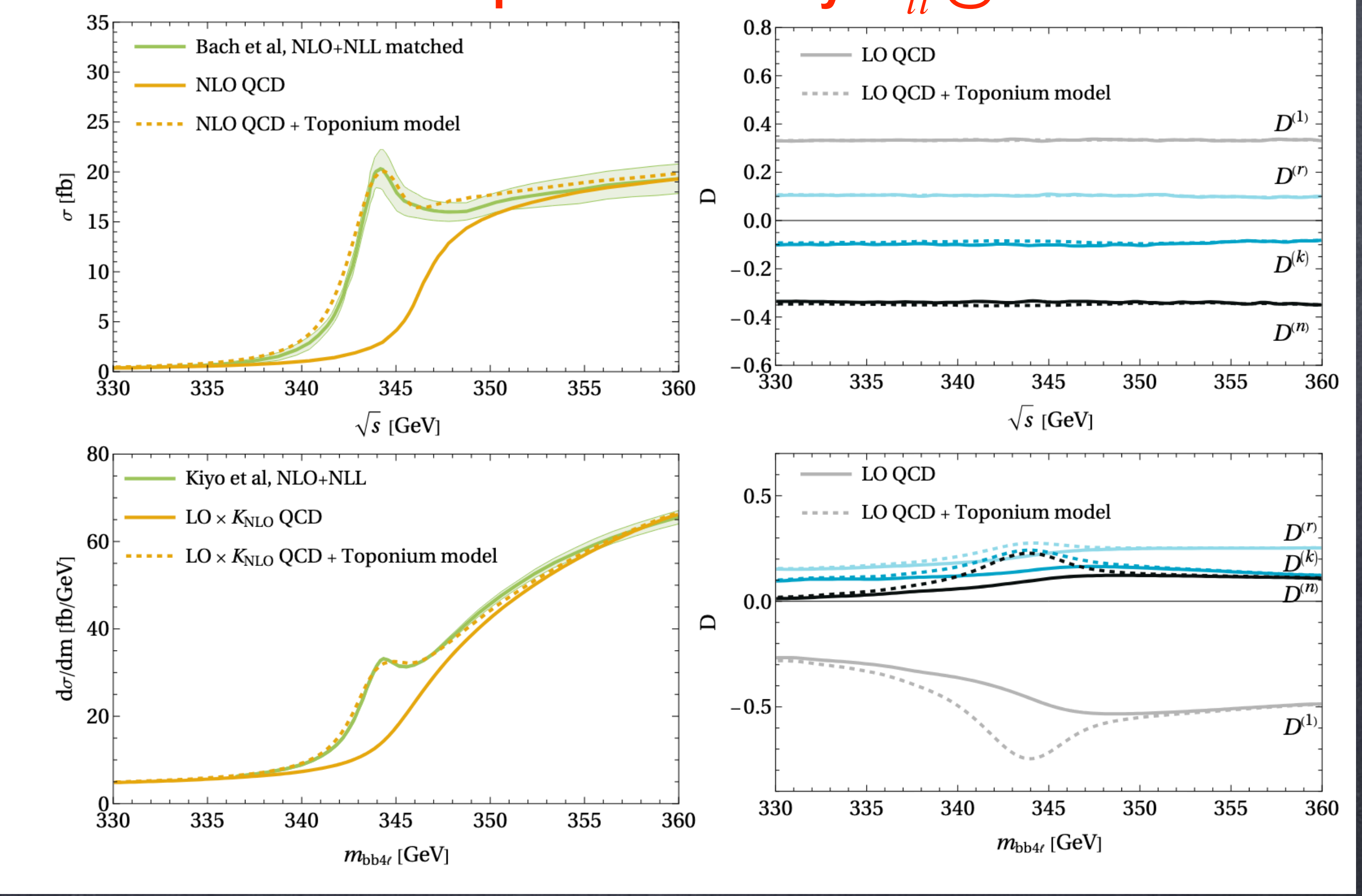
PDF, $\alpha_S(m_Z)$ and m_t^{pole}

$g(x)$ **gets improved uncertainty**

$m_t^{pole} = 170.5 \pm 0.8$ GeV$\pm ?_{toponium}$

$\alpha_S(m_Z) = 0.1135 \,^{+0.0021}_{-0.0017}$

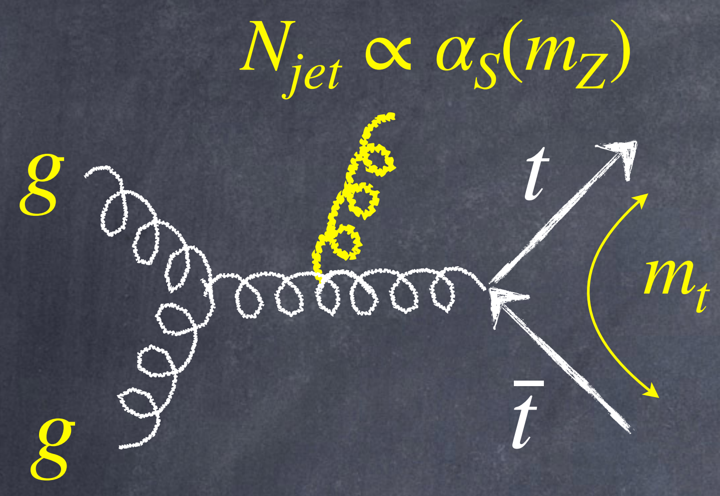
how would 'toponium' modify $M_{t\bar{t}}$ @ threshold?



[Special session @ TOPLHC WG
https://indico.cern.ch/event/1444046/

e.g. Maltoni et al 2404.08049]

Other problems …



triple-differential $t\bar{t}$ cross sections as a function of

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- number of additional jets: adds sensitivity to $\alpha_S(m_Z)$

Idea: extract simultaneously

PDF, $\alpha_S(m_Z)$ and m_t^{pole}

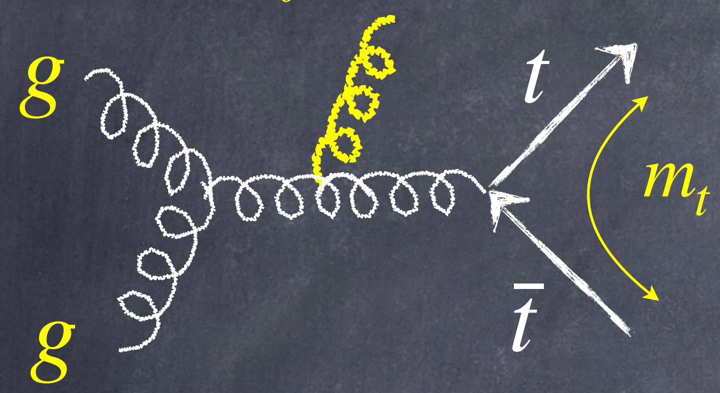
$g(x)$ **gets improved uncertainty**

$m_t^{pole} = 170.5 \pm 0.8$ GeV **: good precision, sensitivity obtained @ $t\bar{t}$ threshold,**
what would be an effect from possible Non-Relativistic contributions?

$\alpha_S(m_Z) = 0.1135\ ^{+0.0021}_{-0.0017}$ **: very precise (in spite of low sensitivity) and very low !**
can be cross-checked with other (m_t - independent) processes?

Other problems …

$N_{jet} \propto \alpha_S(m_Z)$



triple-differential $t\bar{t}$ cross sections as a function of

- invariant mass of $t\bar{t}$ pair, $M_{t\bar{t}}$
- rapidity of $t\bar{t}$ pair, $y_{t\bar{t}}$
- number of addition

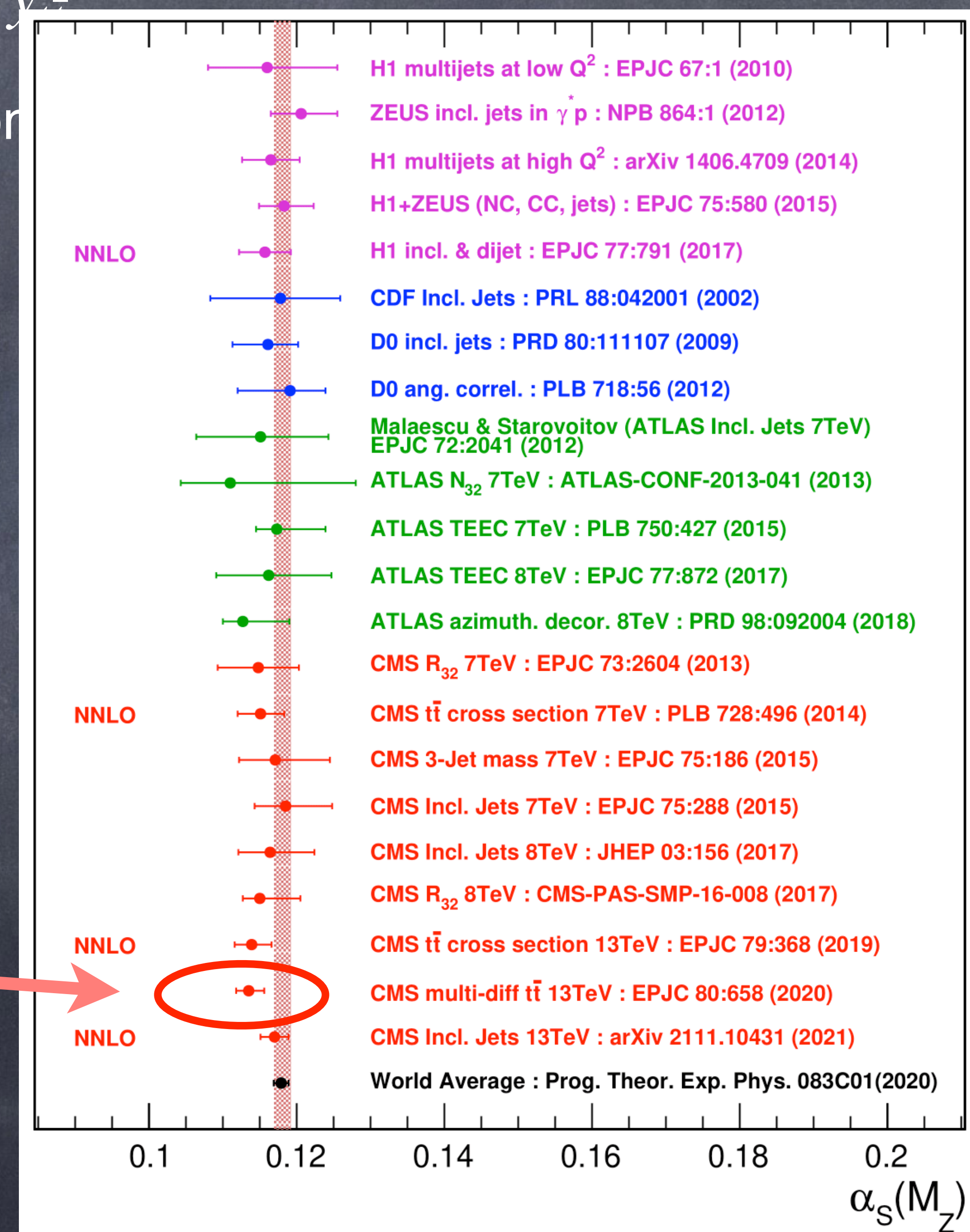
Idea: extract simultaneously

PDF, $\alpha_S(m_Z)$ and m_t^{pole}

$g(x)$ gets improved uncertainty

$m_t^{pole} = 170.5 \pm 0.8$ GeV

$\alpha_S(m_Z) = 0.1135\ ^{+0.0021}_{-0.0017}$

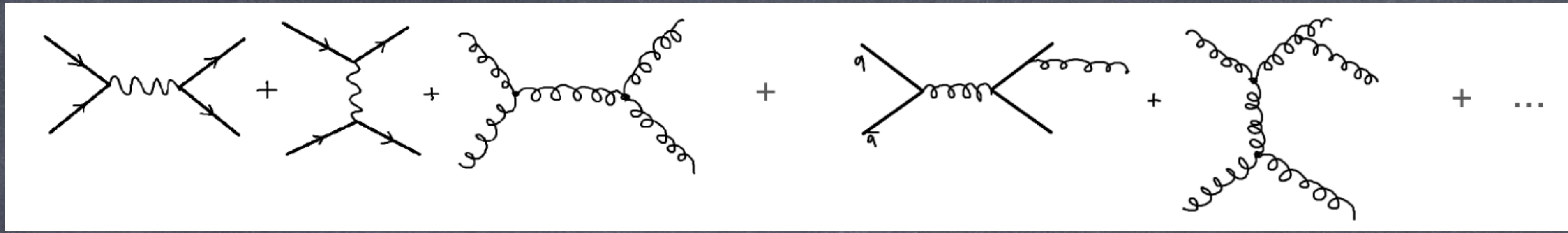


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

PDF-unbiased $\alpha_S(M_Z)$ from other processes

inclusive jet production

$pp \rightarrow jet + X$



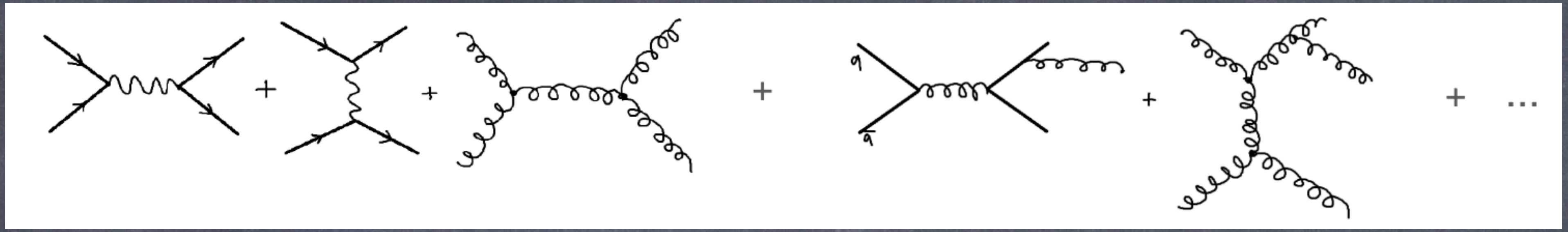
PDF in every line, α_S at every corner: ideal process to extract $\alpha_S(m_Z)$ and PDFs

earlier results based on NLO QCD, limited by missing higher-order (MHO) corrections

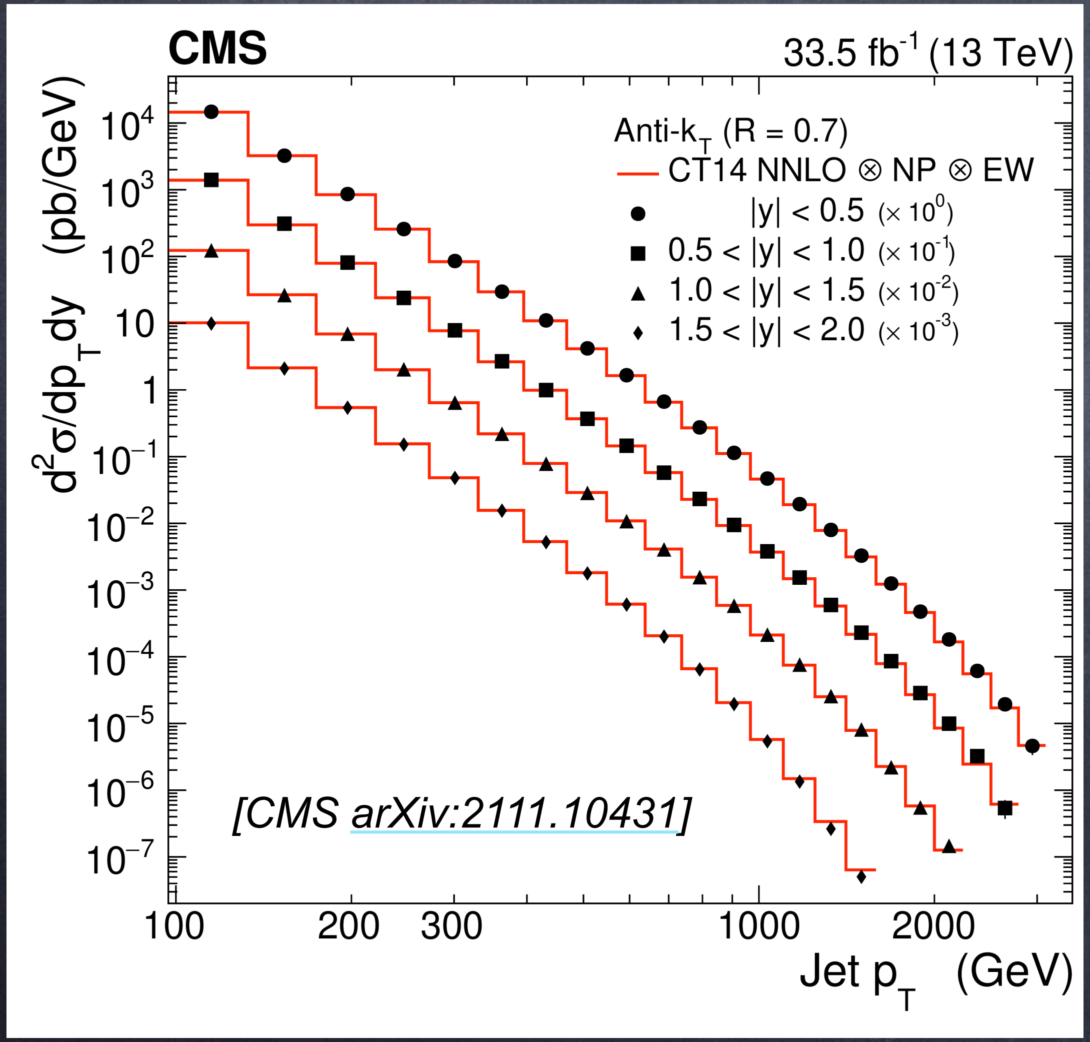
PDF-unbiased $\alpha_S(M_Z)$ from other processes

inclusive jet production

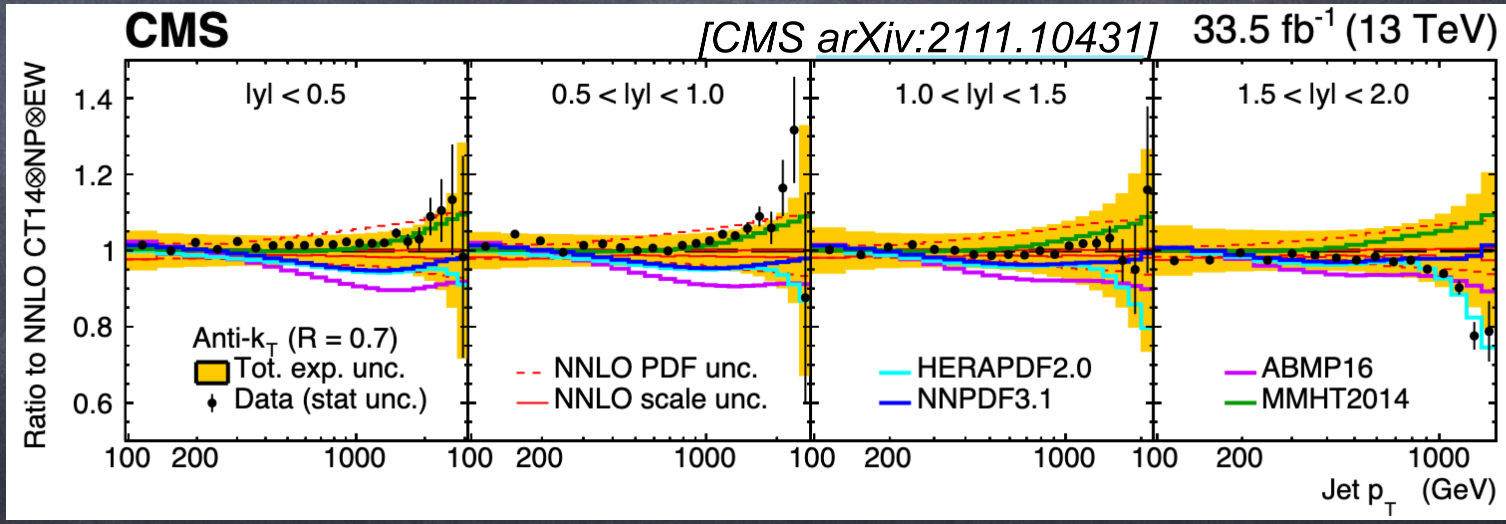
$pp \to jet + X$



Recent result vs NNLO:



NNLO: e.g. [Currie, Glover, Pires, PRL118 (2017) 072002]
[Currie et al. , JHEP 10 (2018) 155]
[T. Gehrmann et al.,PoS RADCOR2017 (2018) 074]
NLOJet++ [Z. Nagy PRL 88 (2002) 122003, PRD 68 (2003) 094002]
fastNLO [D. Britzger, K. Rabbertz, F. Stober, M. Wobisch, arXiv:1208.3641]
+ ApplFast collaboration etc..

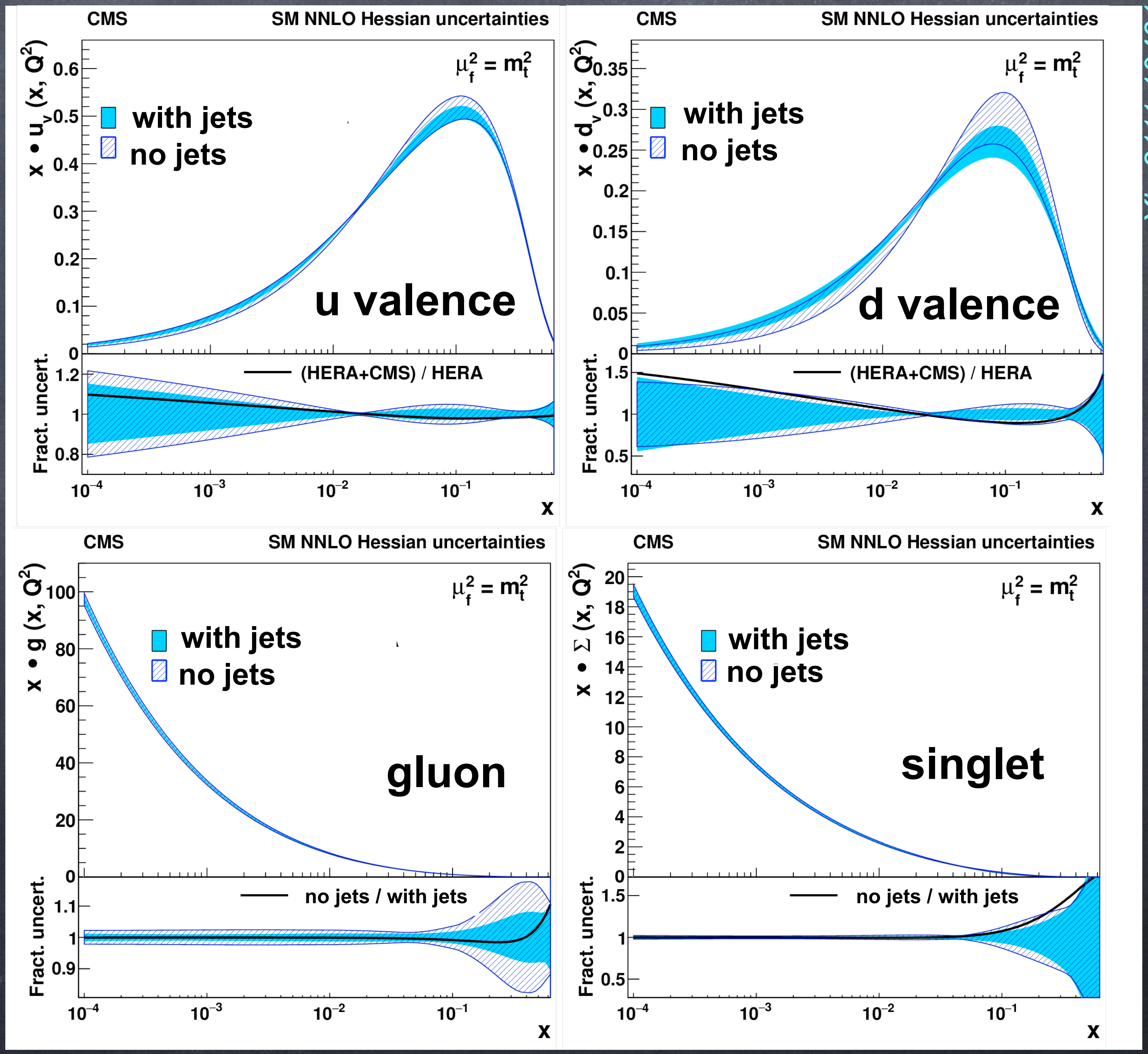


MHO corrections not a limiting factor any more, PDF dominant uncertainty

PDF-unbiased $\alpha_S(M_Z)$ from incl. jets

- **QCD fit at NNLO:** basis data - ep inclusive DIS cross sections (HERA) *[arXiv:1506.06042]* + CMS inclusive jets at 13 TeV *[arXiv:2111.10431]*

PDF fit together with $\alpha_S(m_Z)$



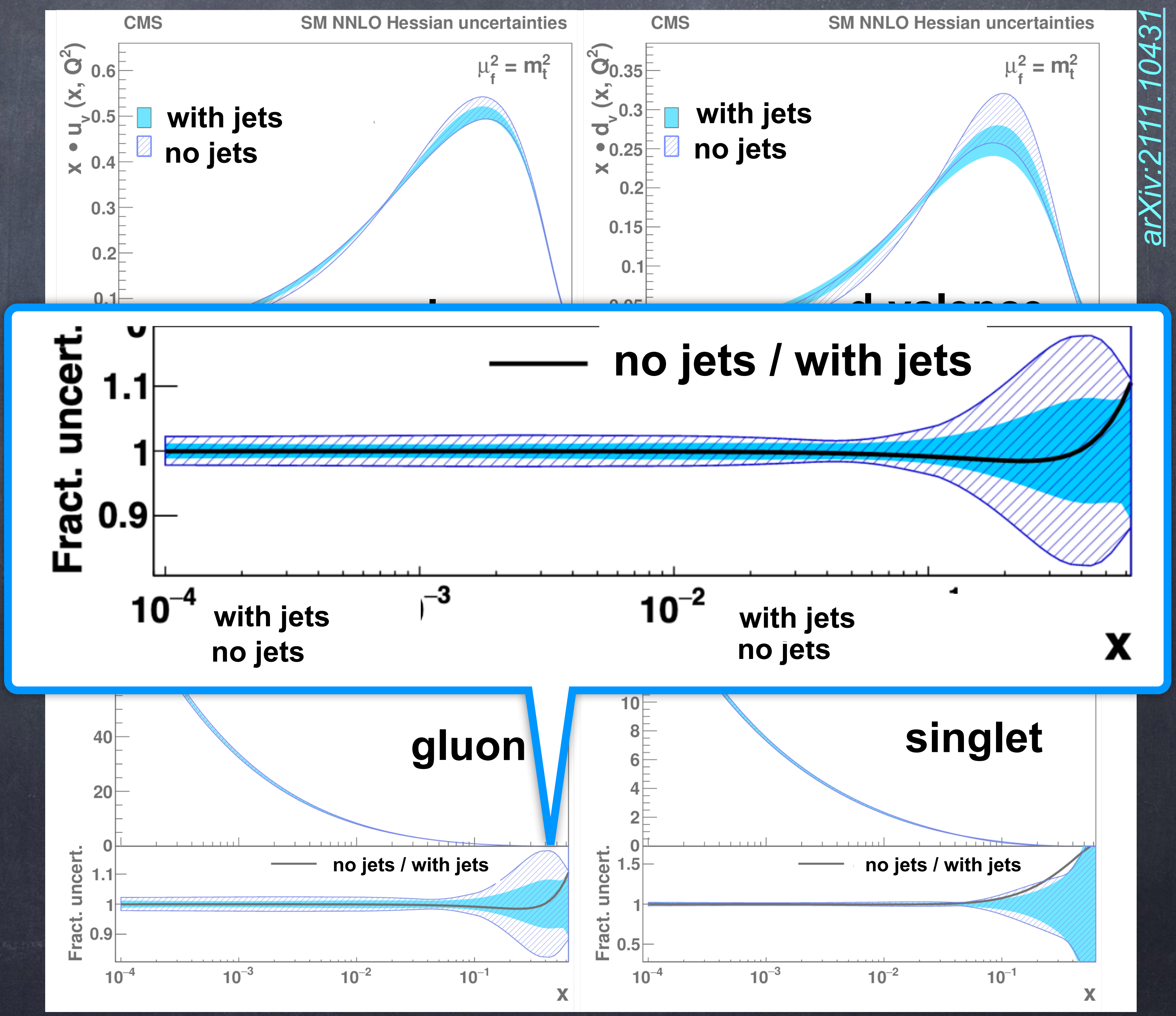
arXiv:2111.10431

PDF-unbiased $\alpha_S(M_Z)$ from incl. jets

- **QCD fit at NNLO:** basis data - *ep* inclusive DIS cross sections (HERA) *[arXiv:1506.06042]*
  + CMS inclusive jets at 13 TeV *[arXiv:2111.10431]*

PDF fit together with $\alpha_S(m_Z)$

addition of jet cross sections improves precision of the gluon at high x !

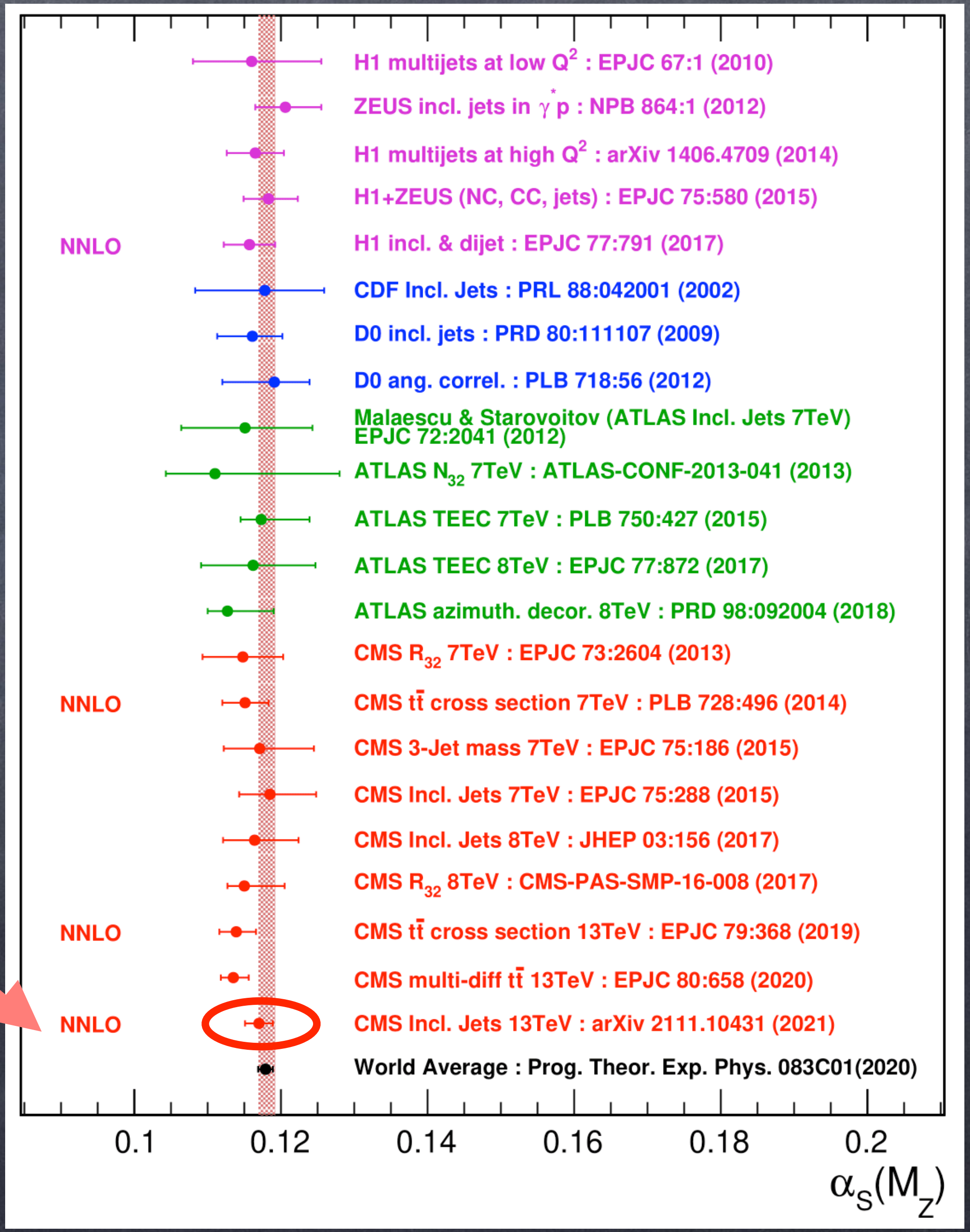


PDF-unbiased $\alpha_S(M_Z)$ from incl. jets

- **QCD fit at NNLO:** basis data - ep inclusive DIS cross sections (HERA) *[arXiv:1506.06042]*
  + CMS inclusive jets at 13 TeV *[arXiv:2111.10431]*

PDF fit together with $\alpha_S(m_Z)$

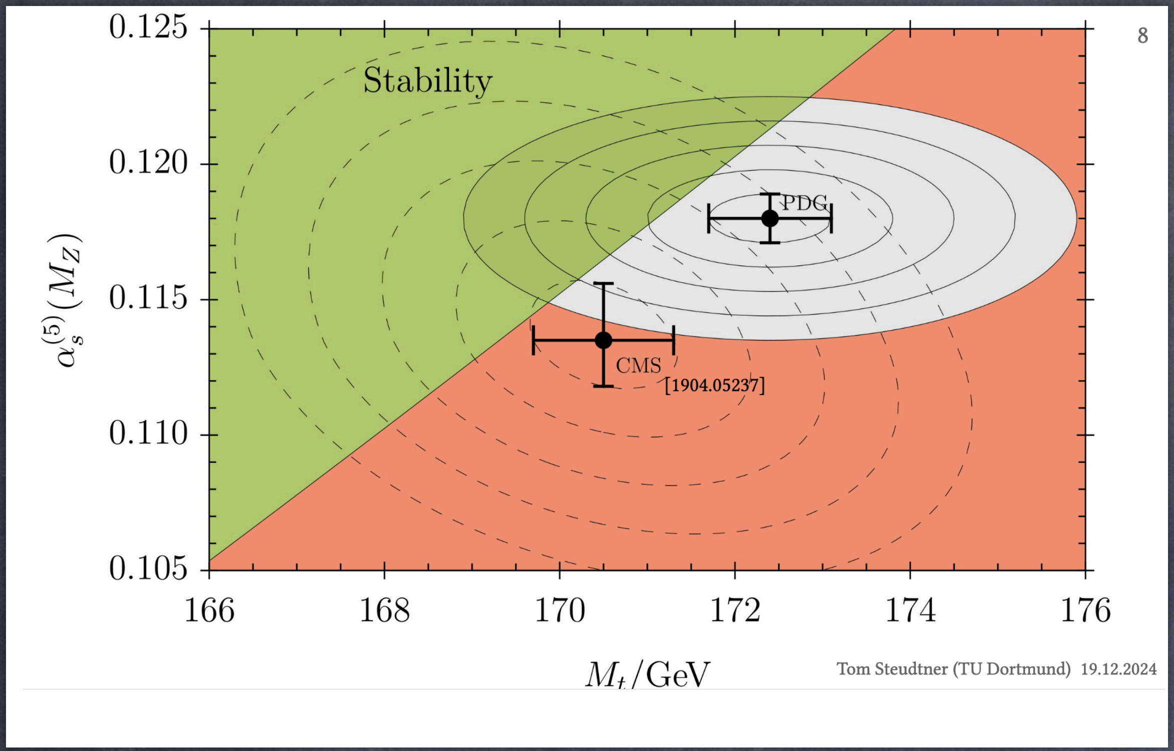
$\alpha_S(m_Z) = 0.1166 \pm 0.0017$ **(NNLO)**

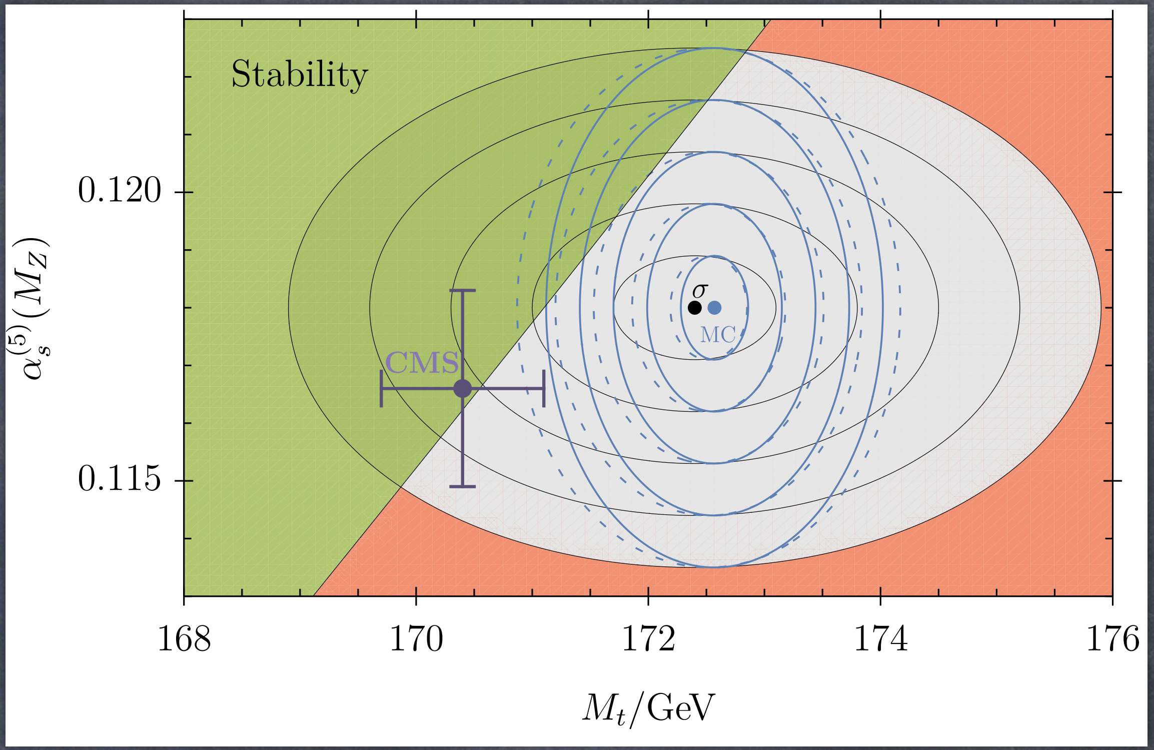


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

Should we use better value for $\alpha_S(m_Z)$?

Thanks Tom !





$\alpha_S(m_Z) = 0.1135\,^{+0.0021}_{-0.0017}$ **(NLO)**

$m_t^{pole} = 170.5 \pm 0.8$ GeV **(NLO)**

[from CMS arXiv:1904.05237]

$\alpha_S(m_Z) = 0.1166 \pm 0.0017$ **(NNLO)**

[CMS arXiv:2111.10431]

$m_t^{pole} = 170.5 \pm 0.8$ GeV **(NLO)**

[from CMS arXiv:1904.05237]

Get more into stability region…
… but not very consistent
(some correlations might be not considered)

Fit jets and $t\bar{t}$ 3-d cross sections together

- **Full QCD fit at NLO:** basis data - ep inclusive DIS cross sections (HERA) *[arXiv:1506.06042]*

  + CMS inclusive jets at 13 TeV *[arXiv:2111.10431]*: **sensitivity to PDF and α_S**

  + CMS 3-D $t\bar{t}$ cross sections *[arXiv:1904.05237]*: m_t **+ additional sensitivity to α_S**

- **PDF errors larger than NNLO**

- $\alpha_S(m_Z) = 0.1188 \pm 0.0026$

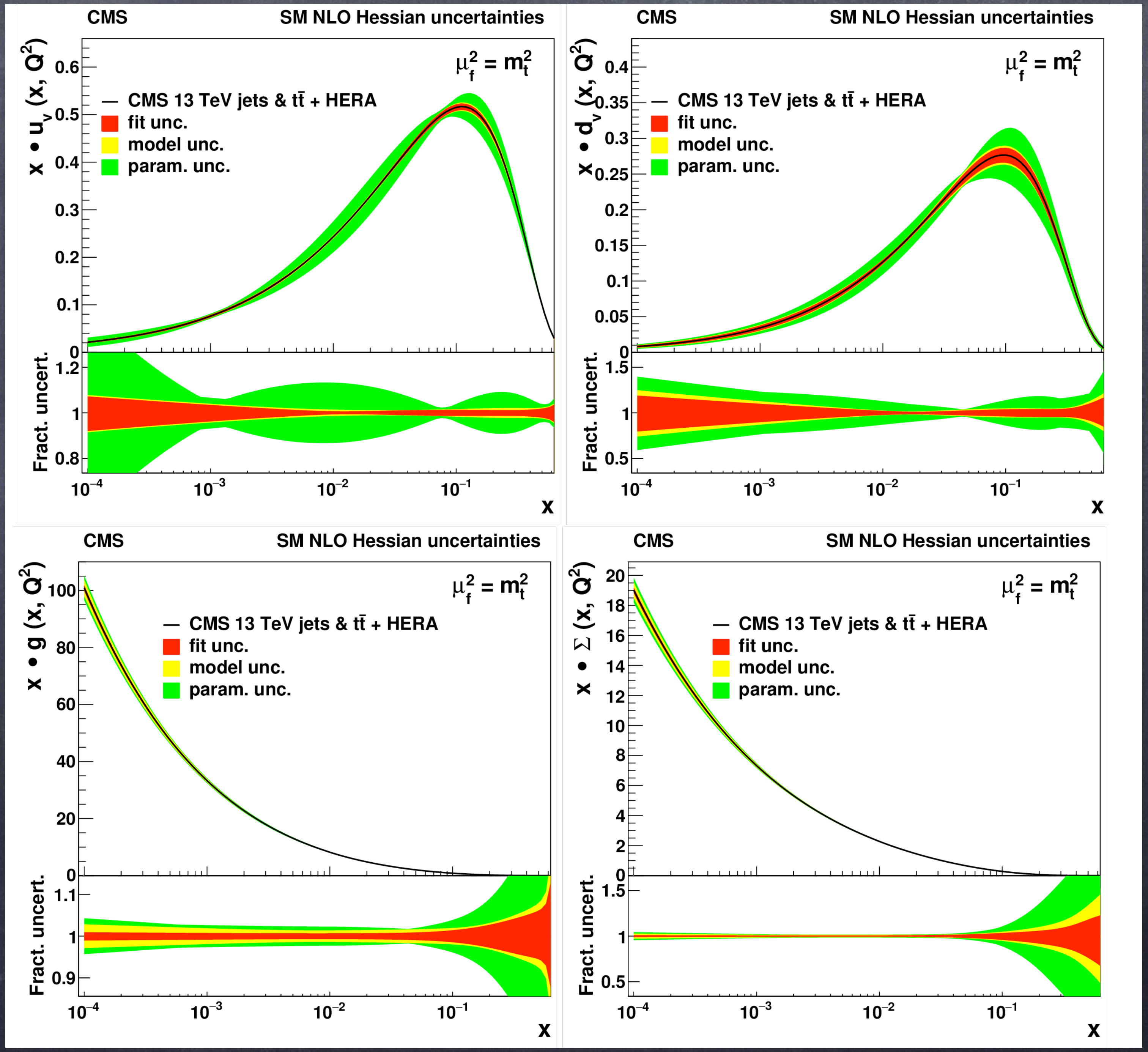
$0.0017_{fit} \pm 0.0025_{scale} \pm 0.0004_{mod} + 0.0001_{param}$

consistent with world average

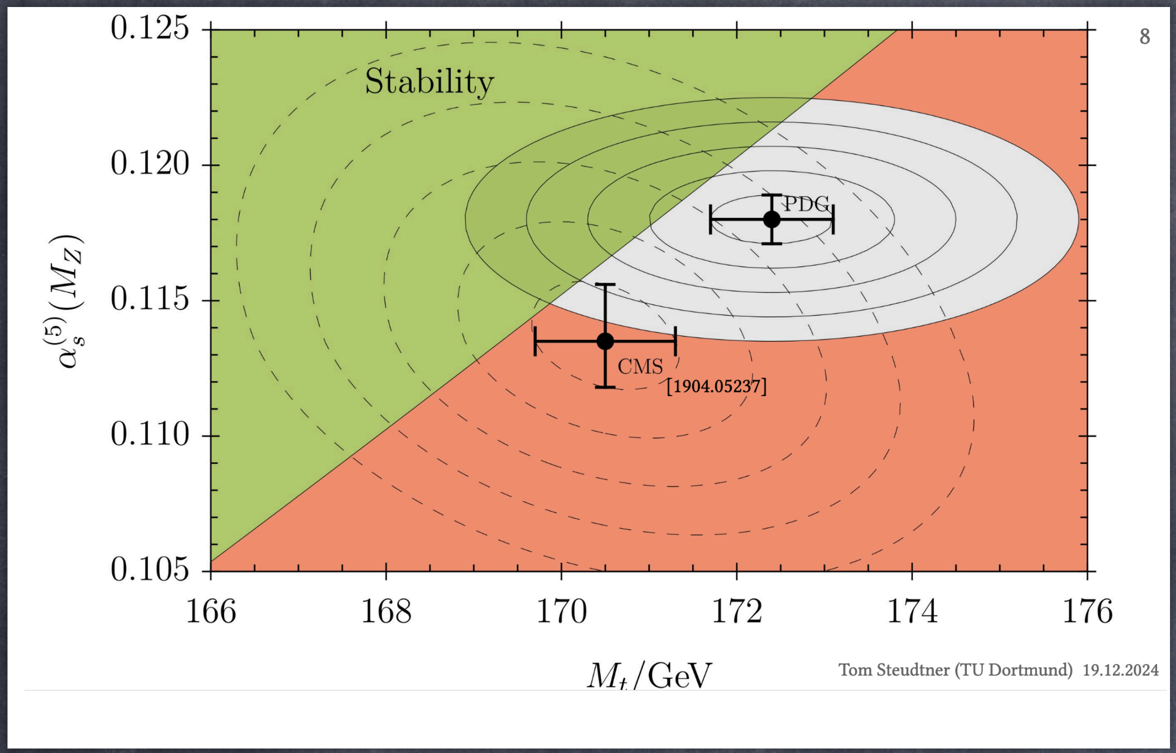
$m_t^{pole} = 170.4 \pm 0.7$ **GeV**

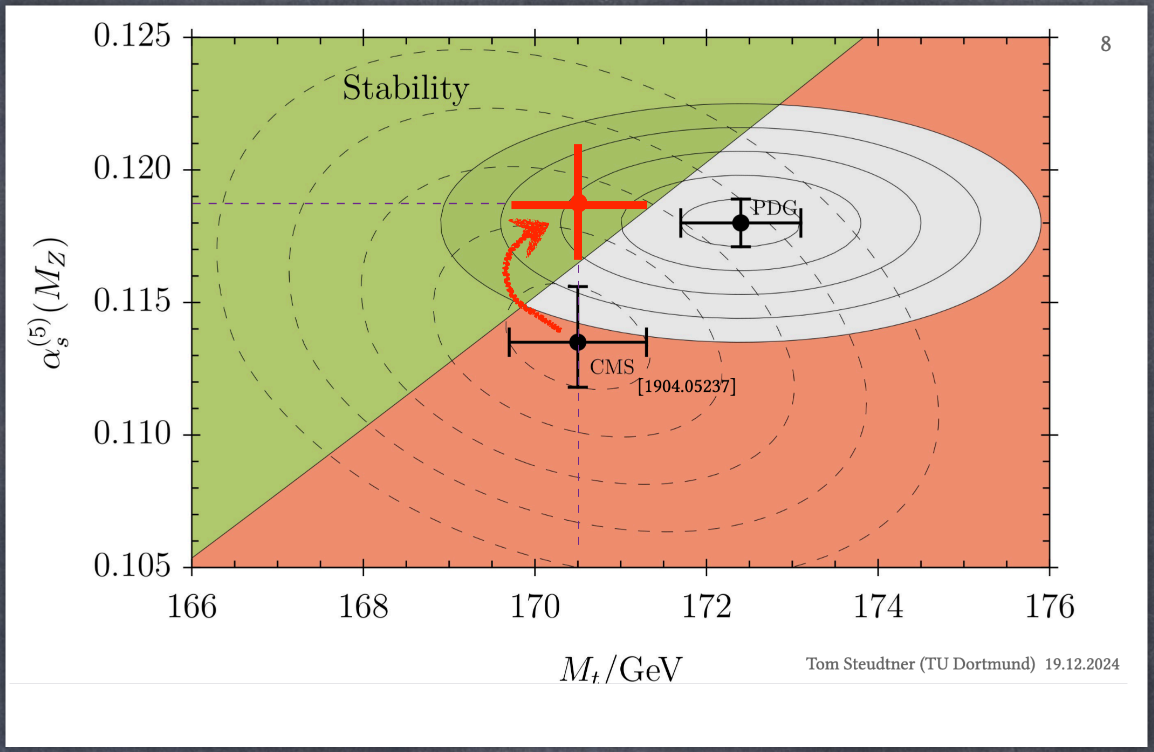
$0.6_{fit} \pm 0.1_{scale} \pm 0.1_{mod} \pm 0.1_{param}$

consistent with *[arXiv:1904.05237]*



Using consistent m_t^{pole} and $\alpha_S(m_Z)$





$\alpha_S(m_Z) = 0.1135\ ^{+0.0021}_{-0.0017}$ **(NLO)**

$m_t^{pole} = 170.5 \pm 0.8$ **GeV (NLO)**

[from CMS arXiv:1904.05237]

$\alpha_S(m_Z) = 0.1188 \pm 0.0026$ **(NLO)**

$m_t^{pole} = 170.4 \pm 0.7$ **GeV (NLO)**

[CMS arXiv:2111.10431]

Get even deeper into stability region…

What's next?

- **Simultaneous extraction of PDF, $\alpha_S(m_Z)$ and m_t $(m_t^{pole}, m_t(m_t), m_t^{MSR})$ seems the way to go**

- **Differential NNLO for $t\bar{t}$ are meanwhile available (also as PDF interpolation grids)**

- **Less PDF+α_S - dependent observables for m_t extraction under investigation** *[ATLAS 1905.02302 CMS 2207.02270]*

- **Most sensitivity to m_t still from the threshold: theory work on $M_{t\bar{t}}$ ongoing**

e.g. Moch et al DESY 24-207 (in preparation)

need to bring all these peaces together…

What if there would be new physics?

Jet transverse momenta and $M_{t\bar{t}}$ would be affected by new operators (mostly dimension 6)

- Simultaneous extraction of PDF+$\alpha_S(m_Z)$ and EFT couplings already in place

[CMS arXiv:2111.10431]

- Framework for simultaneous extraction of PDF+$\alpha_S(m_Z)$+m_t and EFT couplings in place

Shen, Lipka, et al arXiv:2407.16061

need to bring also these peaces together…