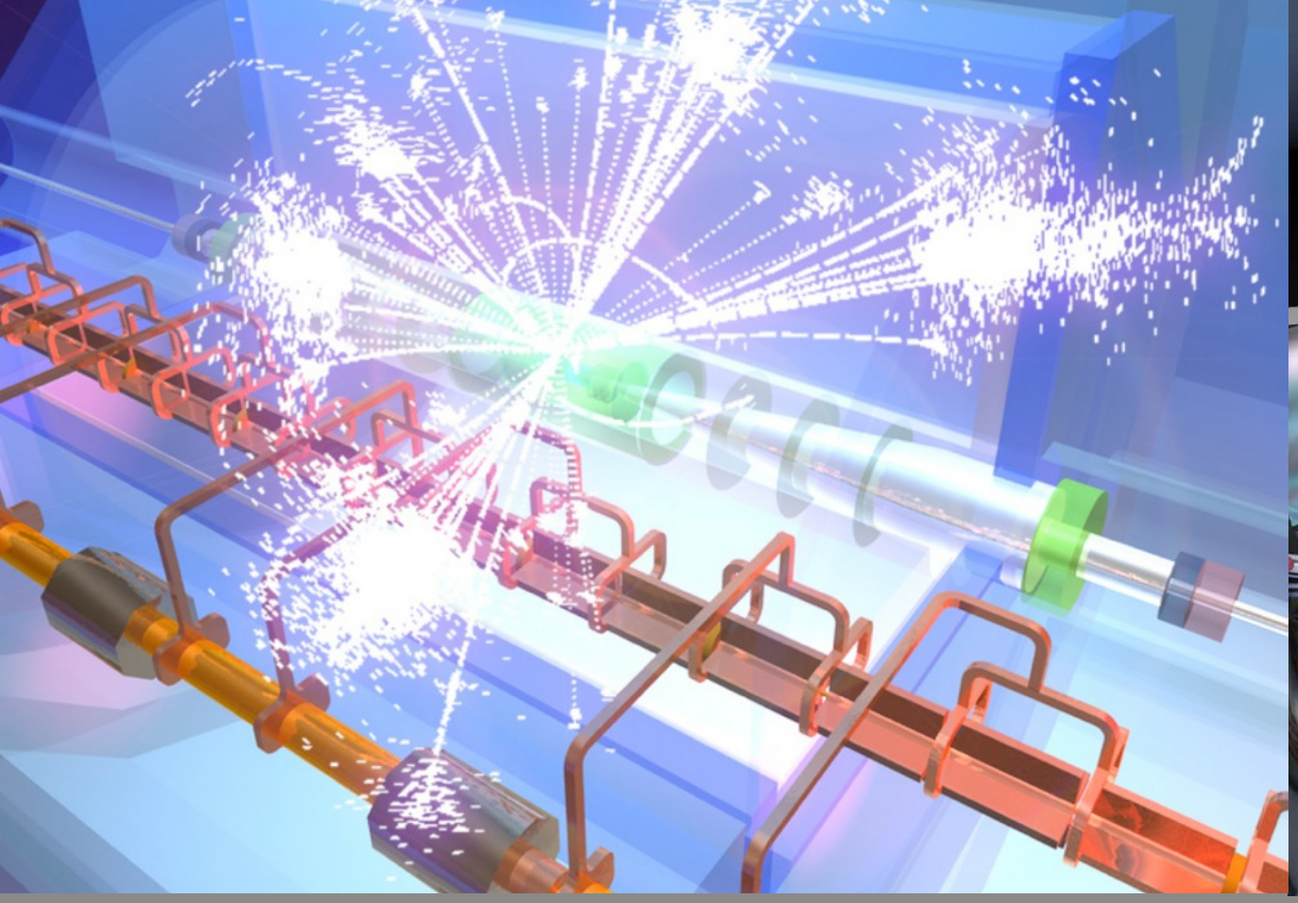
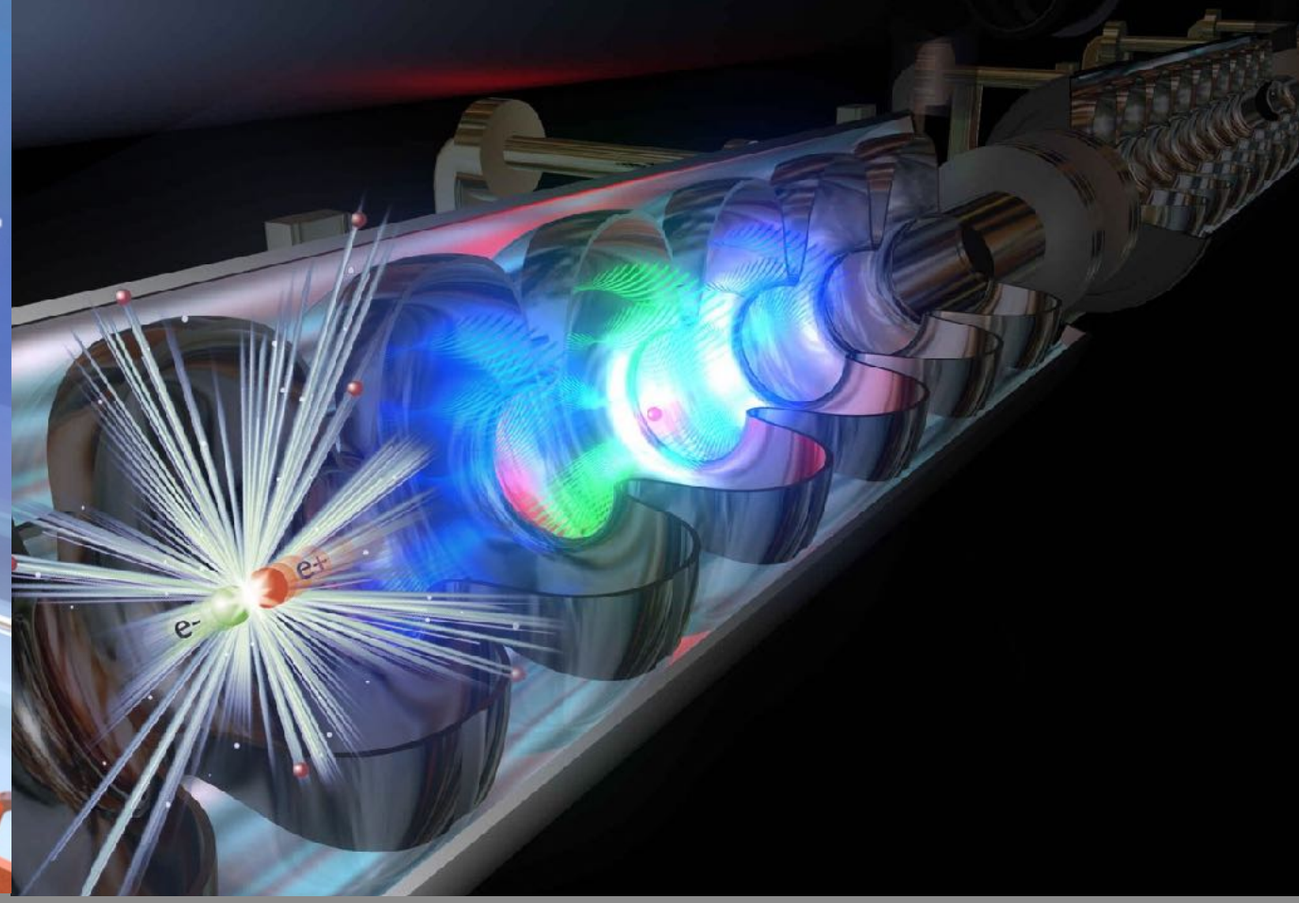
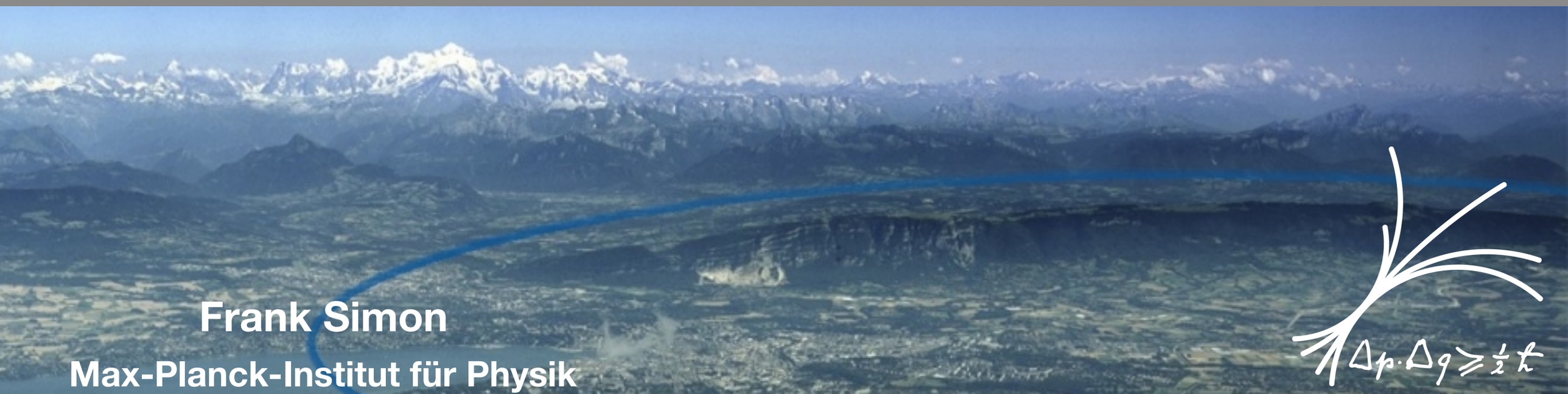




Strong-interaction Physics at Future Energy-Frontier Colliders



Frank Simon

Max-Planck-Institut für Physik

Disclaimer

This talk is not meant to be a comprehensive overview - take it as a collection of a few relevant topics connected to the strong interaction at future energy frontier colliders, and some food for thought

I focus on:

- FCC-hh as a future hadron collider @ 100 TeV (the discussion is also relevant for HE-LHC, correcting for the lower energy)
- e^+e^- colliders - mostly in a generic way, with some examples on machine-specific issues

Outline

- The Physics of Future Colliders

- The role of the Strong Interaction at Future Colliders
  - Opportunities
  - Challenges
  - Potential Improvements

- Conclusions

The Physics Landscape: Two Extremes

Enormous success

- Establishing and testing the Standard Model (and pre-cursors) for 50 years - with ever increasing precision

- A map with unexpected accuracy to guide HEP experiments - all the way to the Higgs discovery in 2012

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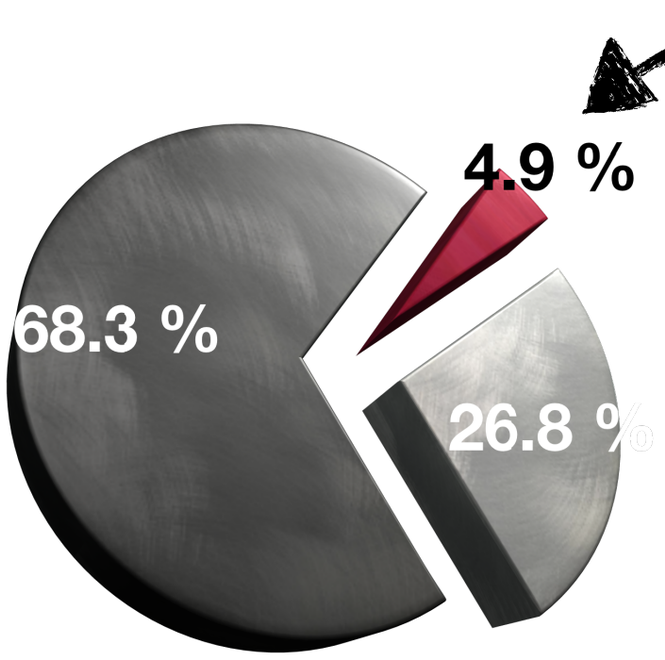
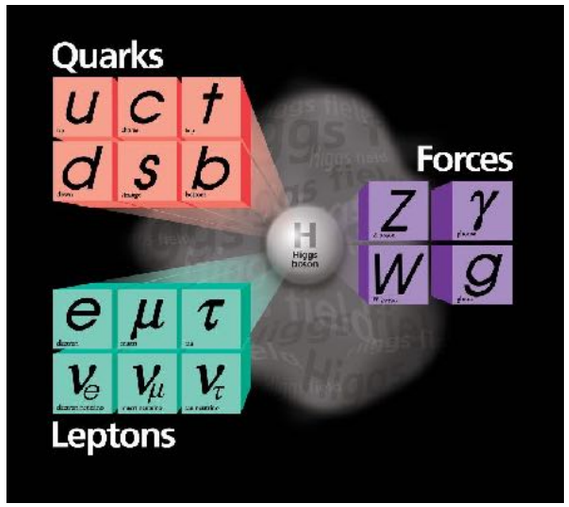
Obvious failure





- 95% of the energy content of the Universe remain unexplained - and a lot of mysteries still surround the 5% we do know:
  - baryon asymmetry
  - origin of EWSB
  - hierarchies
  - ….

The Physics Program at Future Colliders

- The mix of spectacular success of the SM and obvious shortcomings define the key features of the physics program for future experiments at the Energy Frontier

Higgs	**t**op (and ewk precision)	**N**ew Physics
Detailed exploration of this newly discovered sector:	Precision measurements of top quark properties	Direct search for new particles: new states at high mass, more weakly coupled particles that may escape present experiments
Precise, also model-independent measurement of all relevant couplings	Use of top quark observables as a probe for New Physics at high mass scales	Indirect search for new force carriers at high mass scales
direct study of the Higgs potential: Self-coupling	electroweak precision measurements	

The Physics Program at Future Colliders

- This program is mapped onto complementary experimental approaches and facilities:

Highest energy: Direct production of new particles

Highest precision: Detection of new phenomena in deviations from expectations

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Highest energy: Direct production of new particles → LHC, (FCC-hh, HE-LHC…)

Highest precision: Detection of new phenomena in deviations from expectations → Belle II, FCC-ee, …

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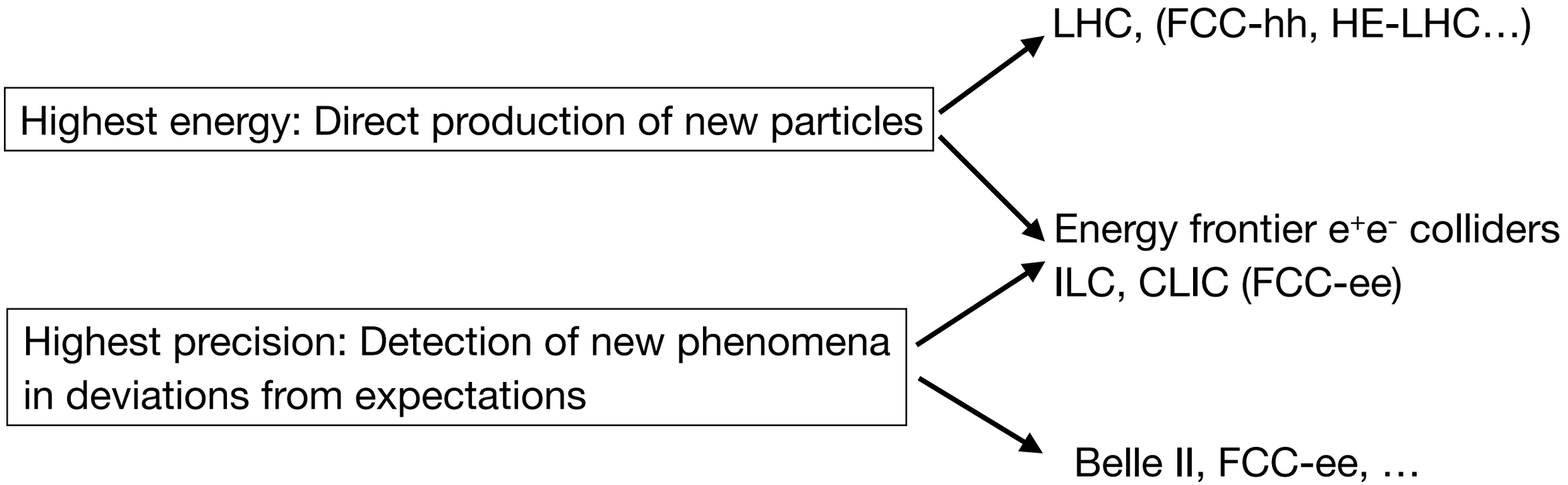

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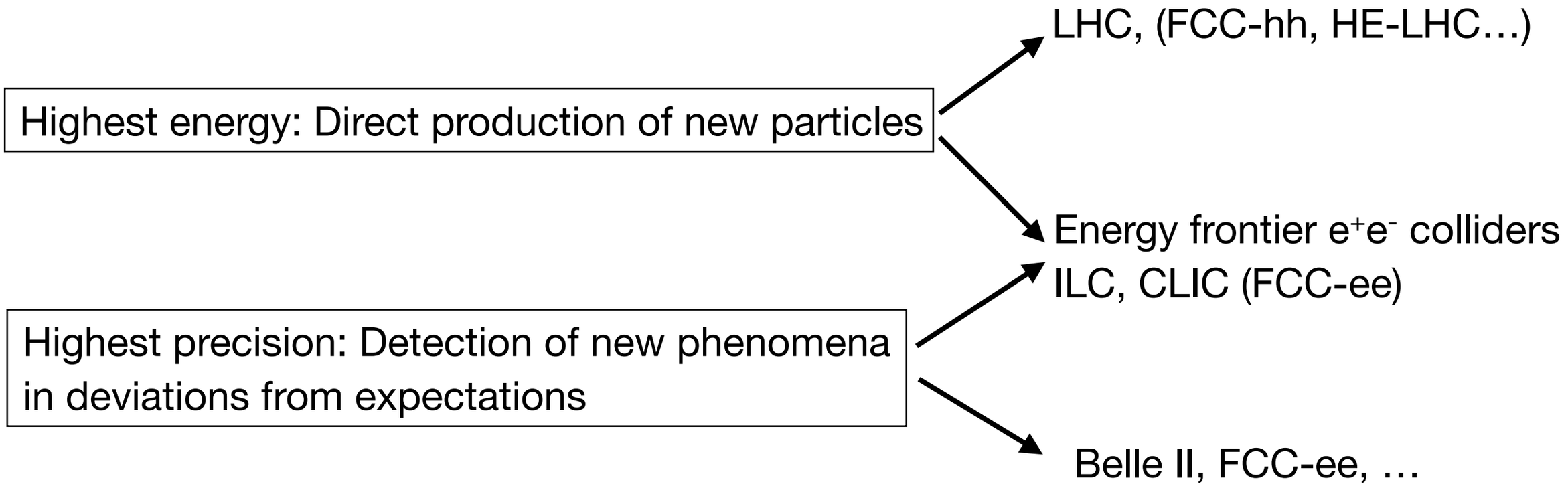
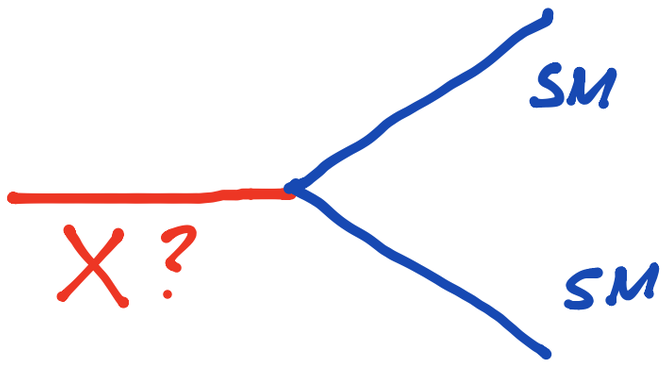


Electroweak phenomena & new particles / sectors dominate the discussion:
This is where the “big questions” are…

Missing Something? QCD is everywhere…

- When discussing the physics potential of future colliders, we discuss this:



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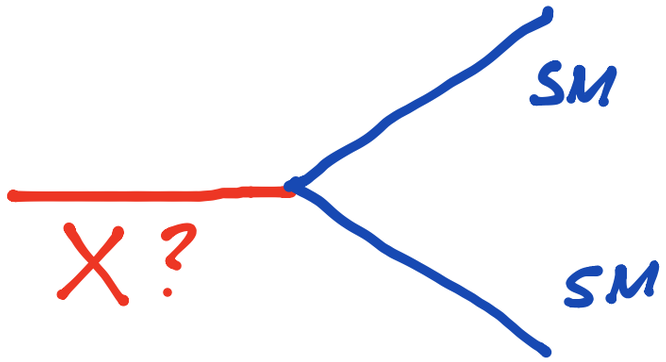

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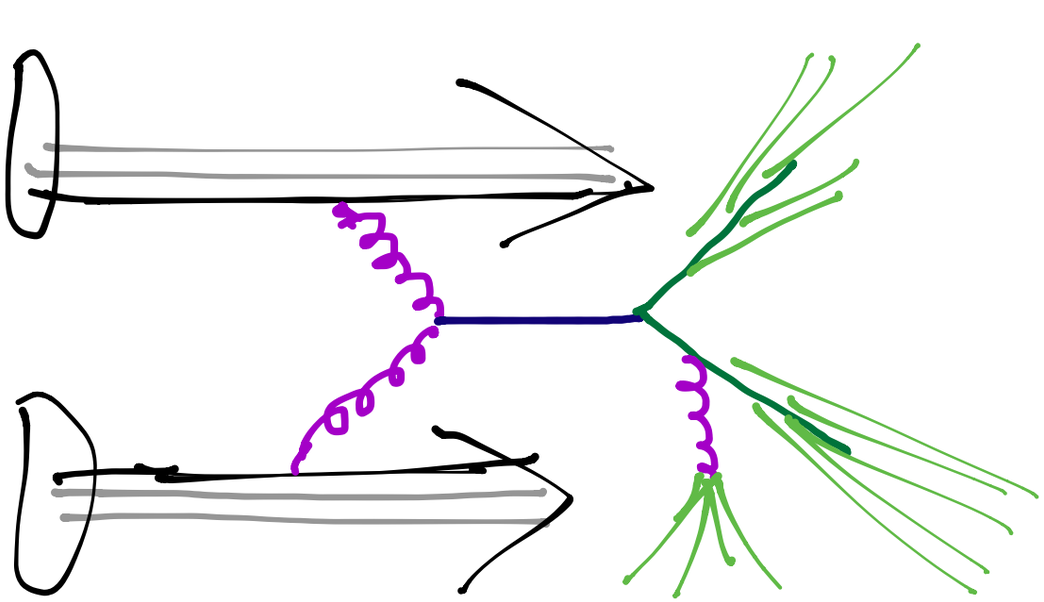

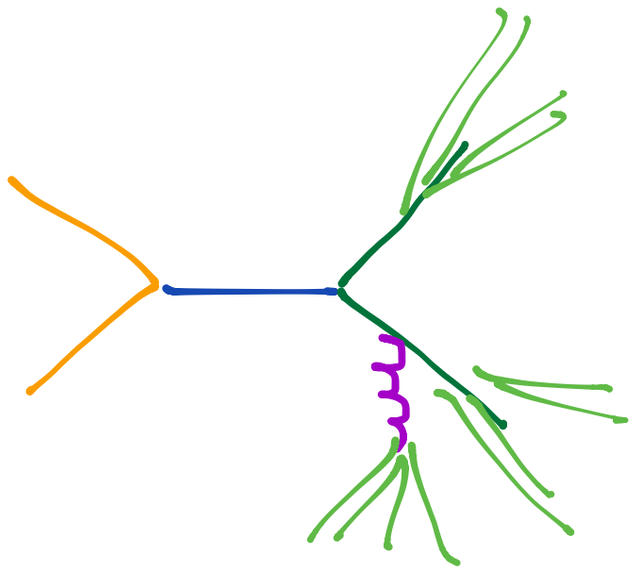

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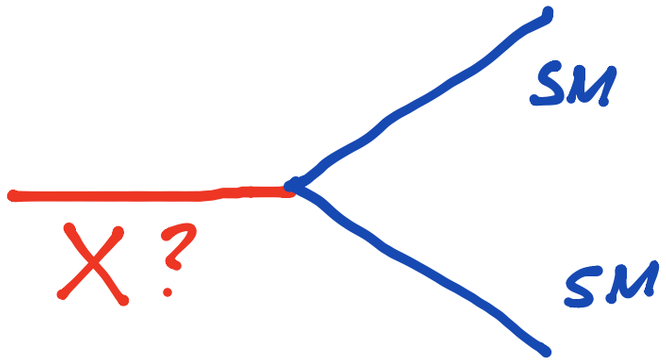

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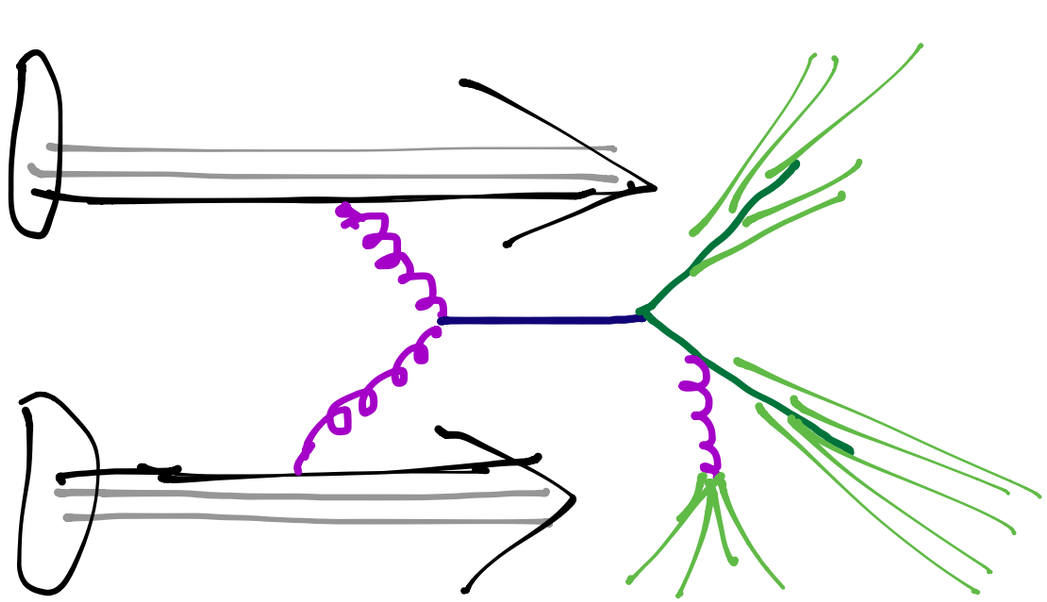

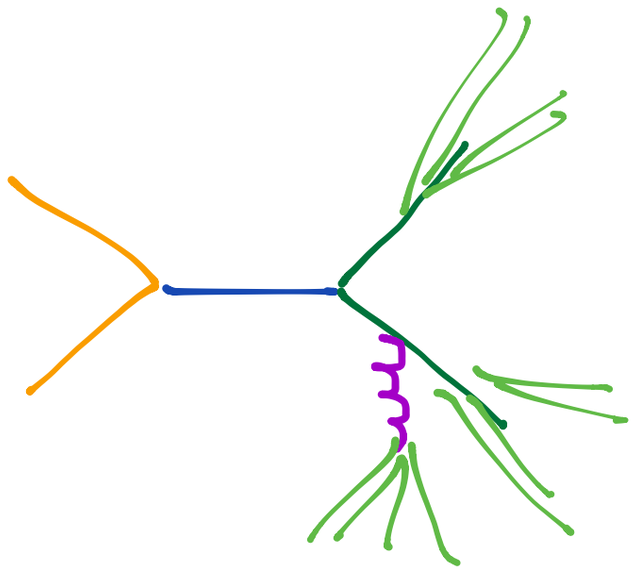

➪ No escaping the strong interaction - even if you avoid it at the ***initial state***, you have to work with it in the ***final state***!

The Three Faces of the Strong Interaction

Enabler

strong production at hadron colliders: large cross sections => high mass reach for new, colored particles

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Source of Uncertainties

uncertainties in the strong domain start to dominate many measurements - limits ultimate precision

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Object of Study

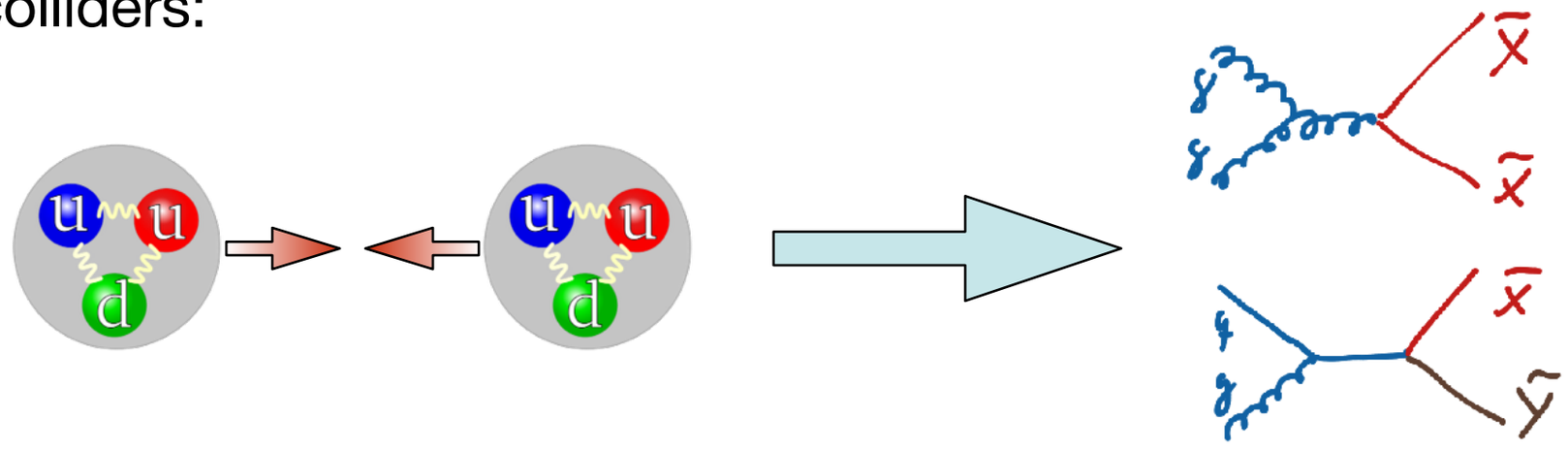
a key ingredient of a future research program: coupling constant, nucleon structure, …

Source of Uncertainties

uncertainties in the strong domain start to dominate many measurements - limits ultimate precision

Enabling Direct Searches at the highest Scales

- The strong interaction is at the heart of the “business model” of high-energy hadron colliders:



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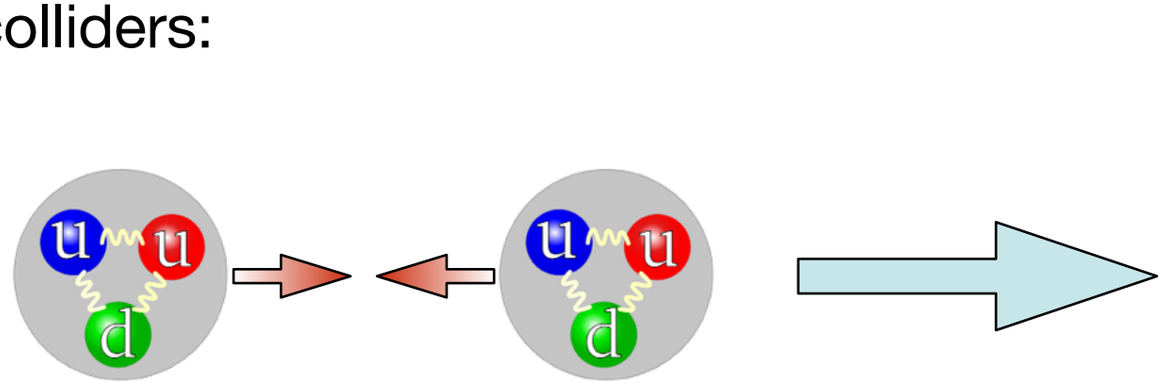
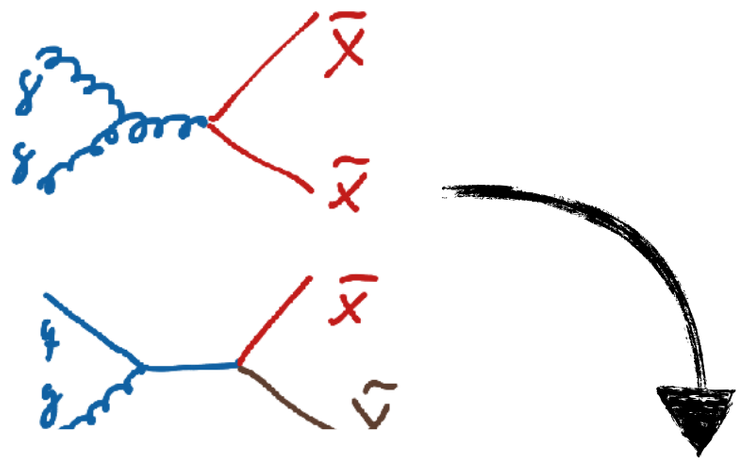
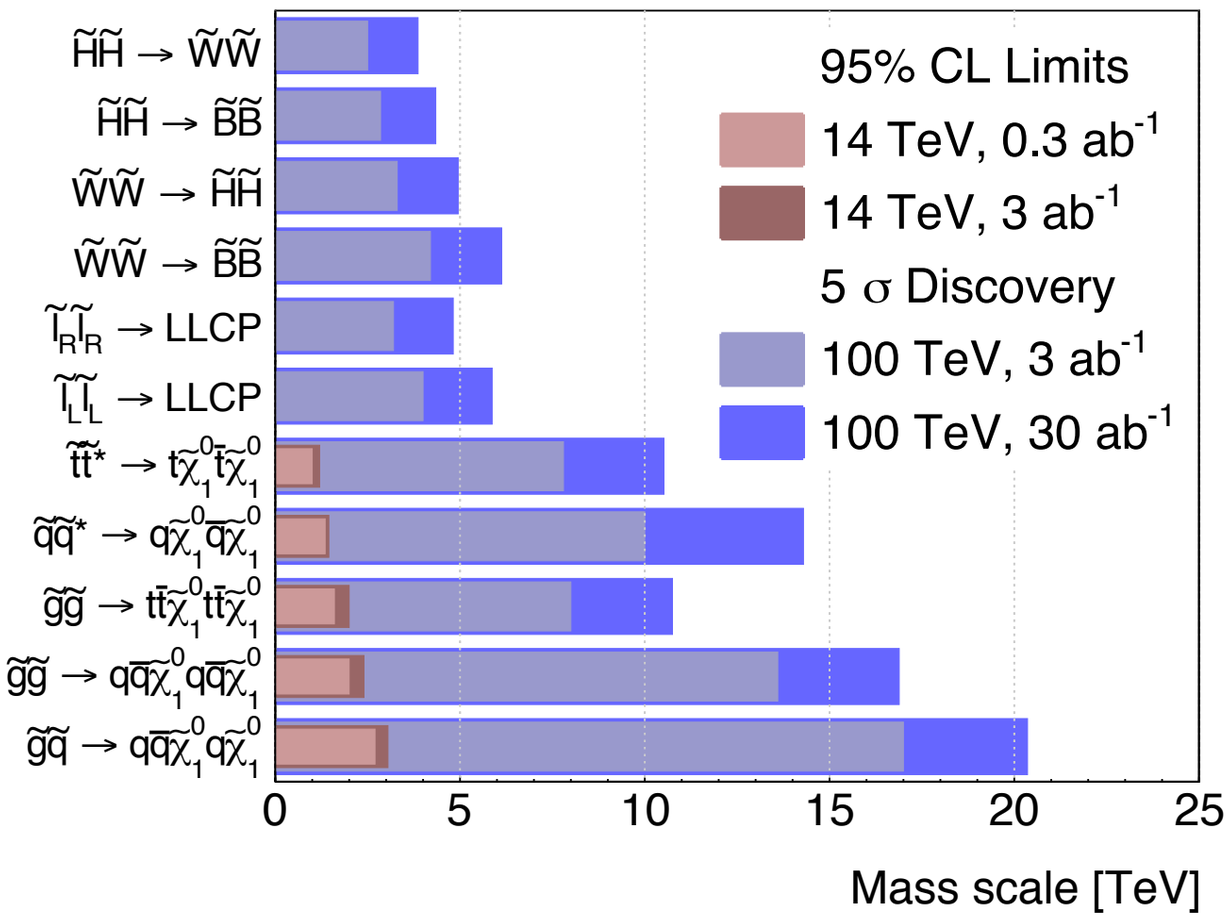






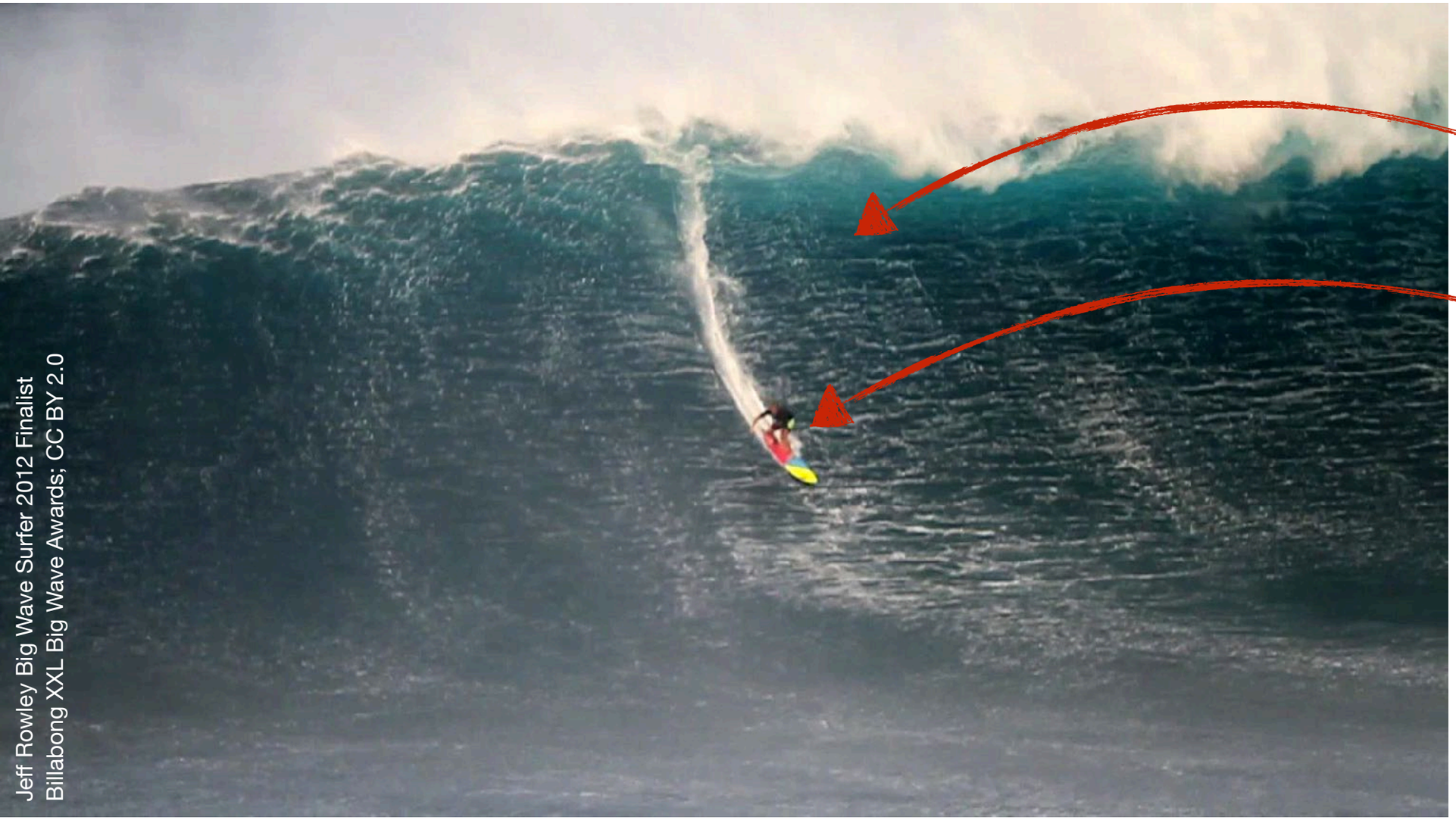
The large cross sections of strong processes will push the discovery reach for colored particles into the **10 TeV region** and beyond for FCChh

Frank Simon (fsimon@mpp.mpg.de)

Riding the Parton Wave

Jeff Rowley Big Wave Surfer 2012 Finalist
Billabong XXL Big Wave Awards; CC BY 2.0

Riding the Parton Wave



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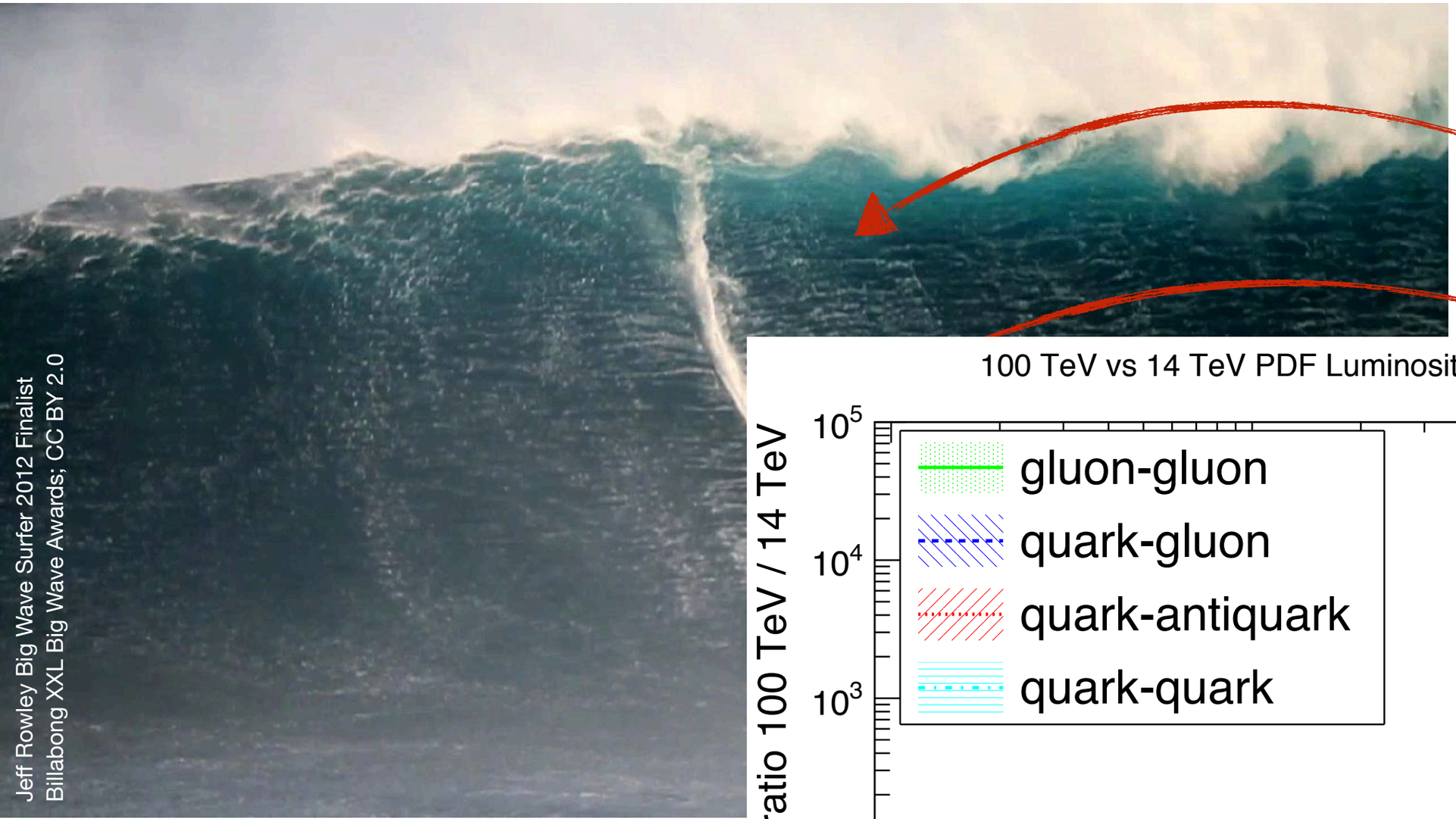

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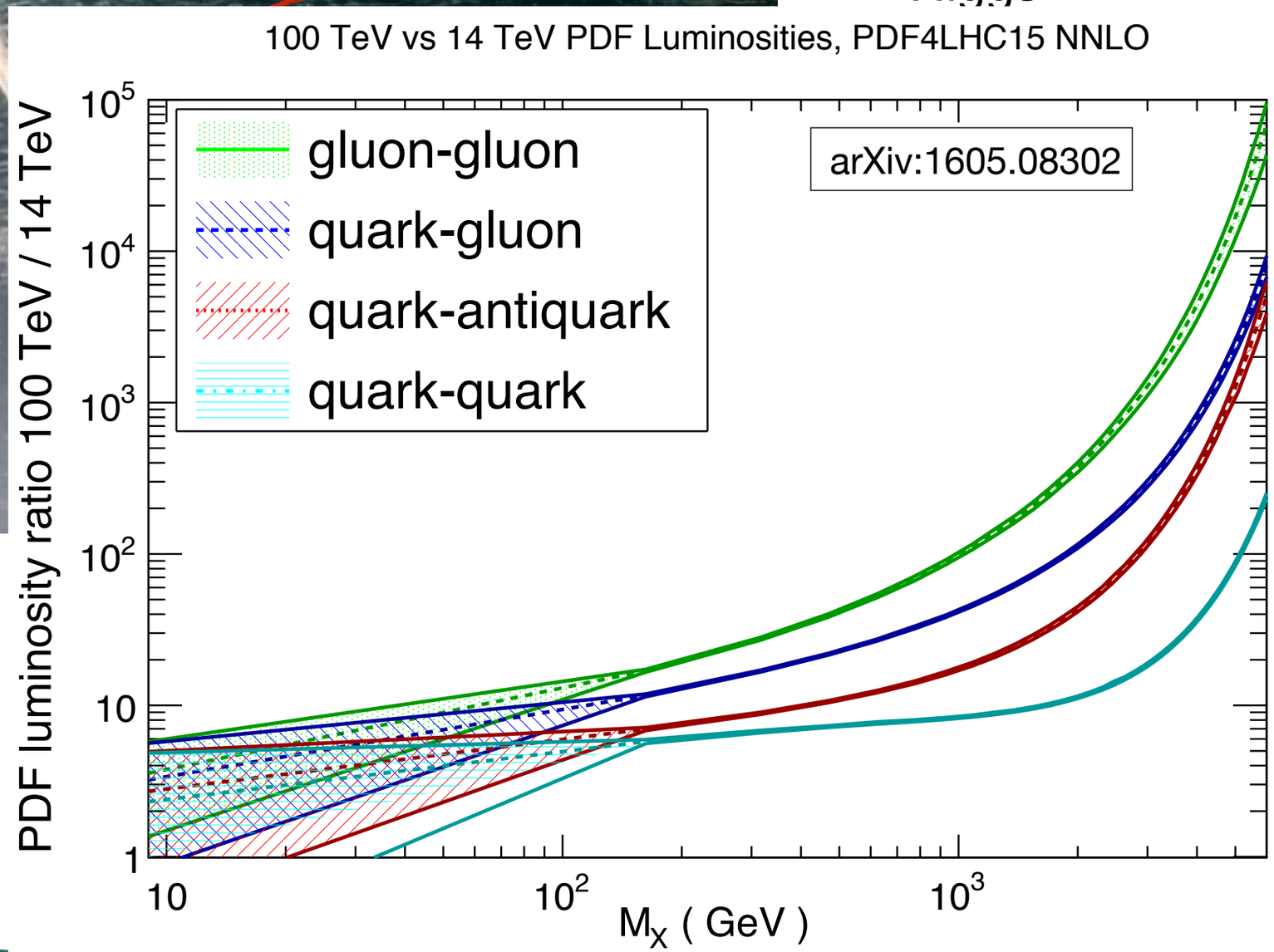
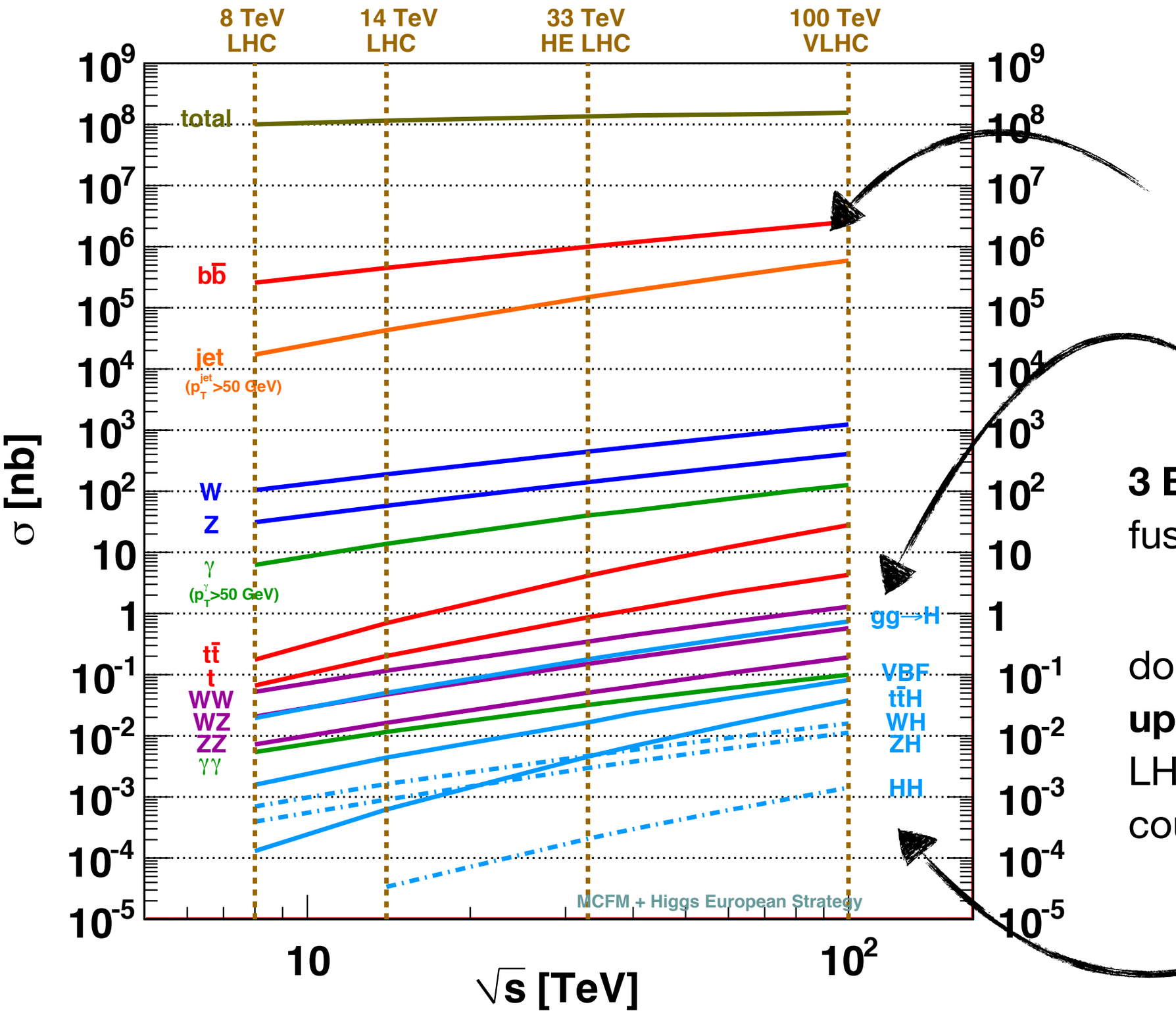


- Strong boosts of particle production rates in higher-energy pp colliders - most dramatic for high masses

Riding the Parton Wave

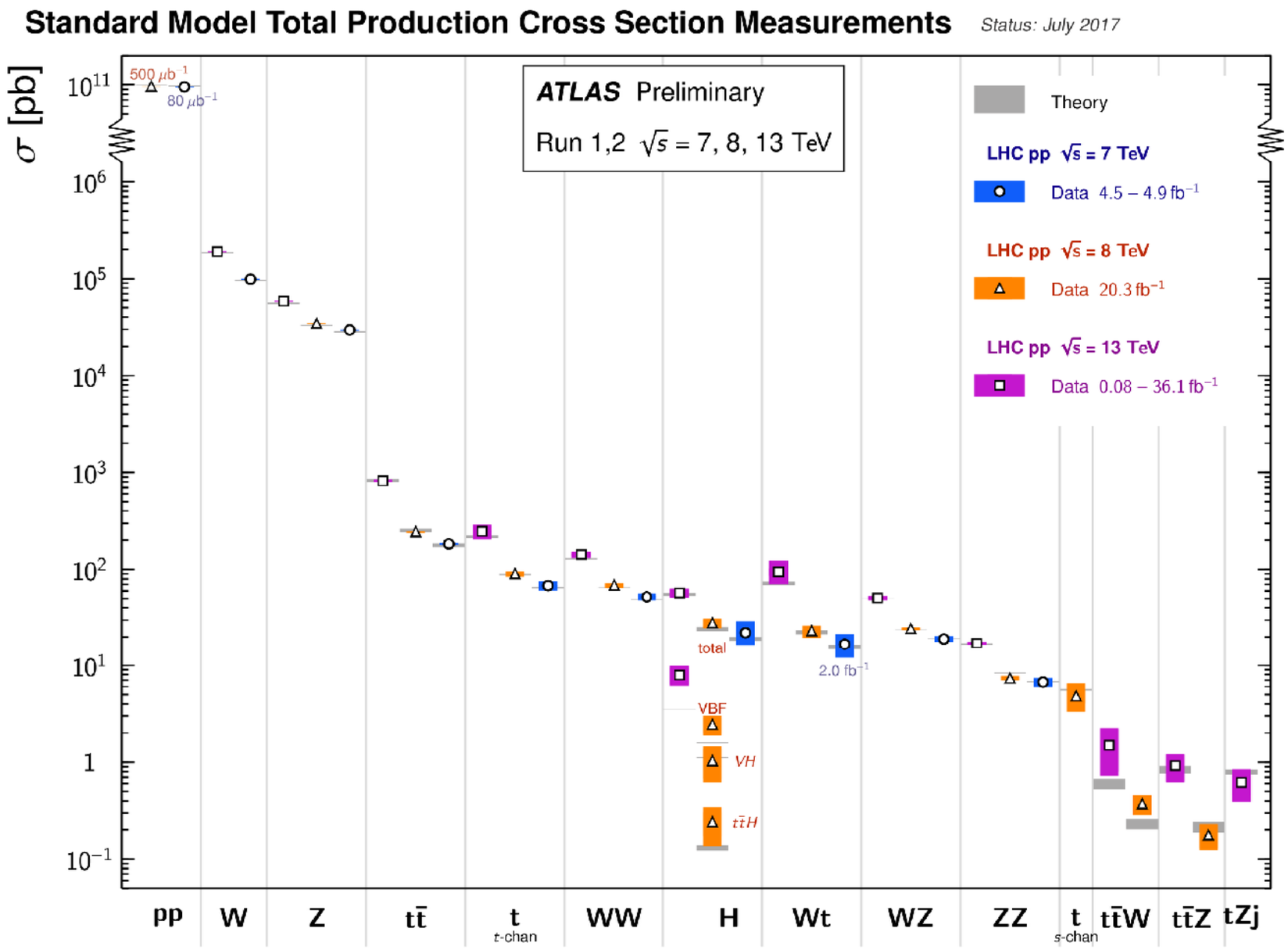


But also: Obscene rates of jets, b quarks, …

3 Billion Higgses in gluon fusion at 100 TeV (3 ab^{-1})

double Higgs production **up by x40** compared to LHC: access to the self-coupling

The Flip Side: Backgrounds, UE, Pileup



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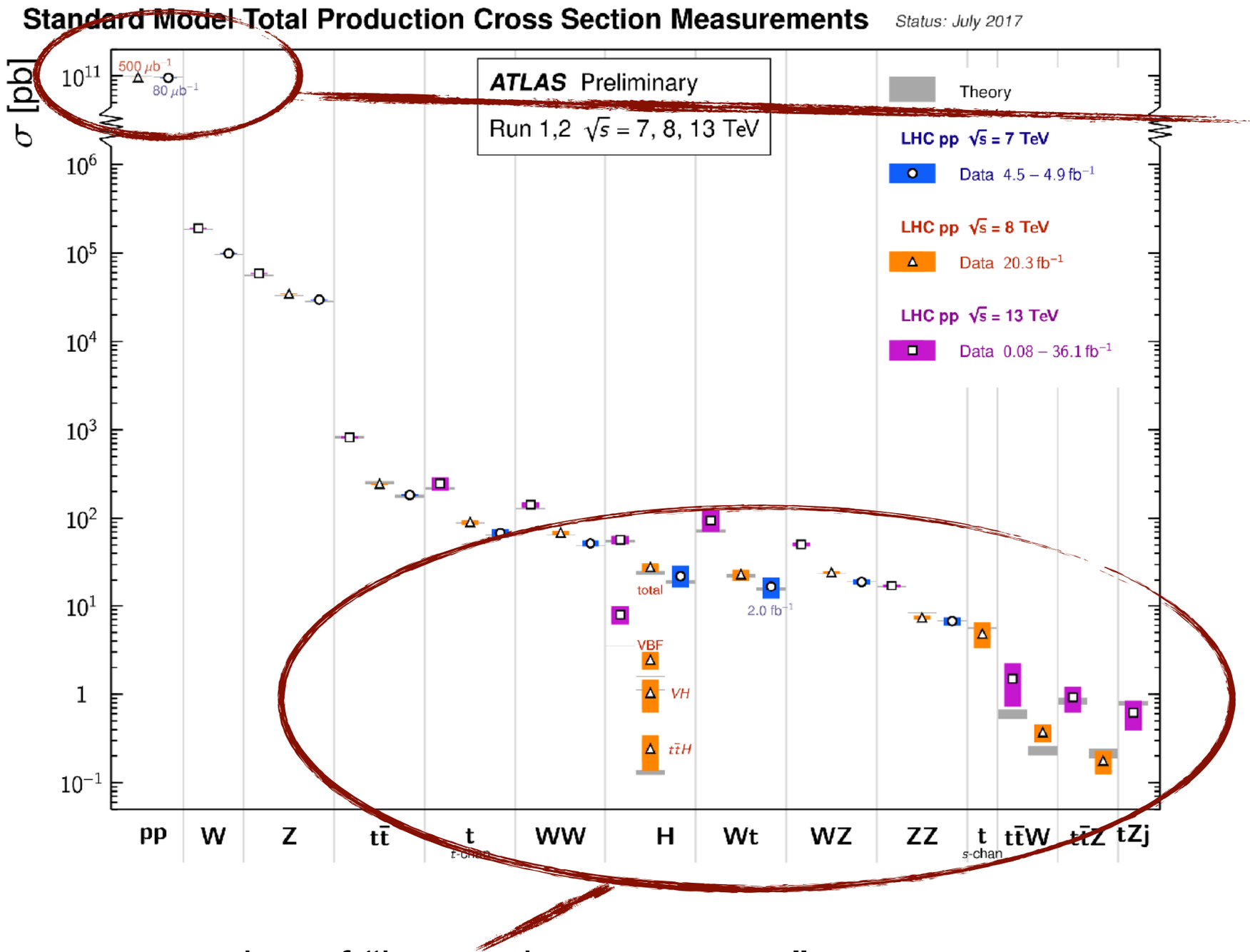
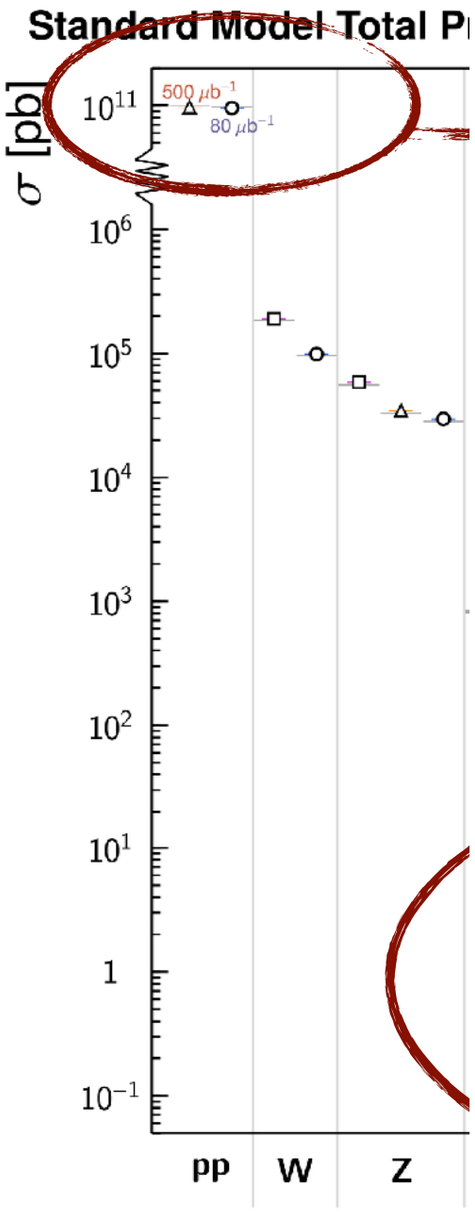


drives pileup, backgrounds

region of “interesting processes”

The Flip Side: Backgrounds, UE, Pileup



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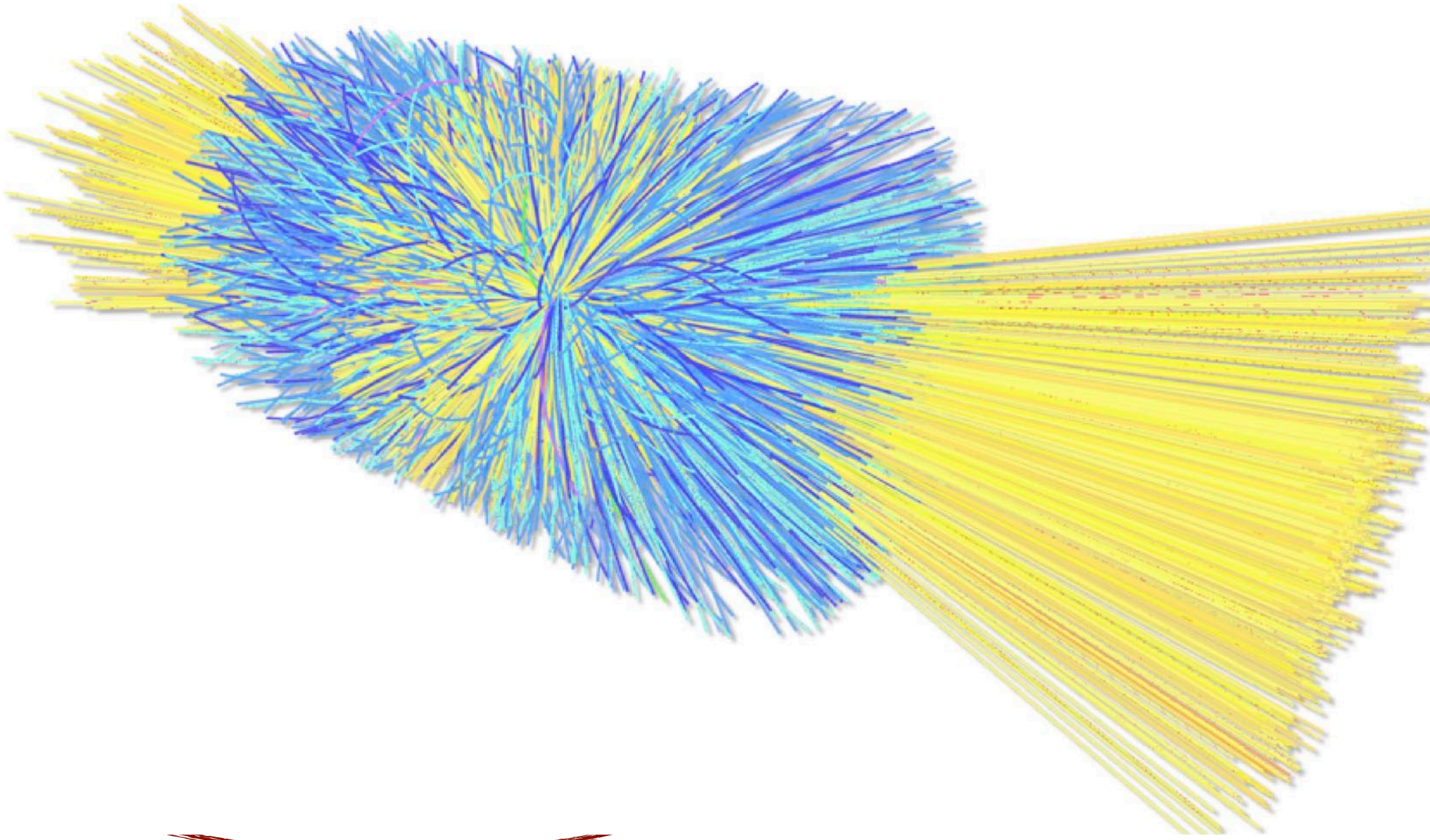
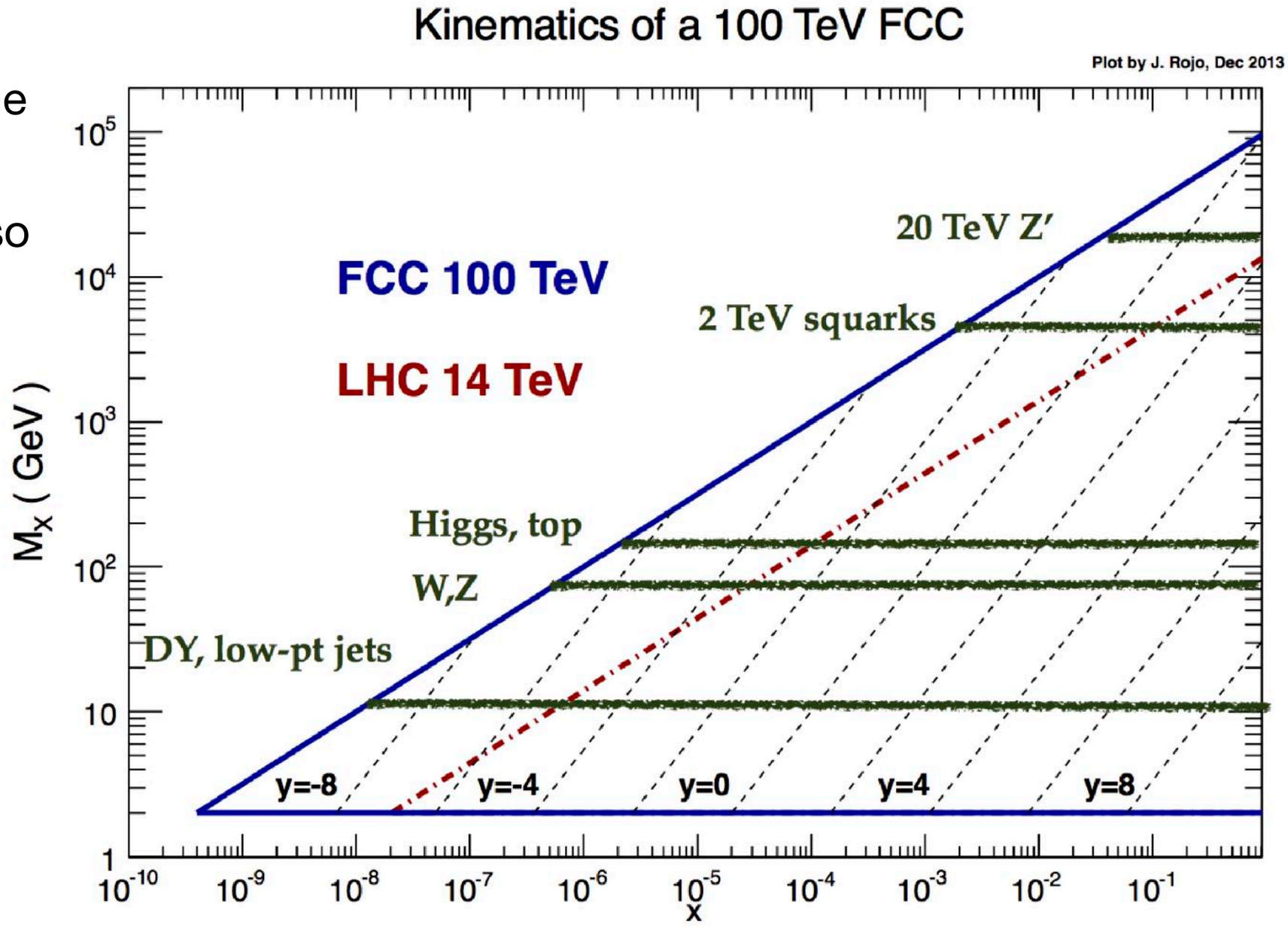


~**200** interactions per BX at HL-LHC, FCC - with increased luminosity it could go up to ~**1000**

Digging Deeper into Problems: PDFs

- A “side-effect” of higher energy collisions: Extreme regions of parton kinematics contribute also to higher-mass objects, such as H (and HH) production



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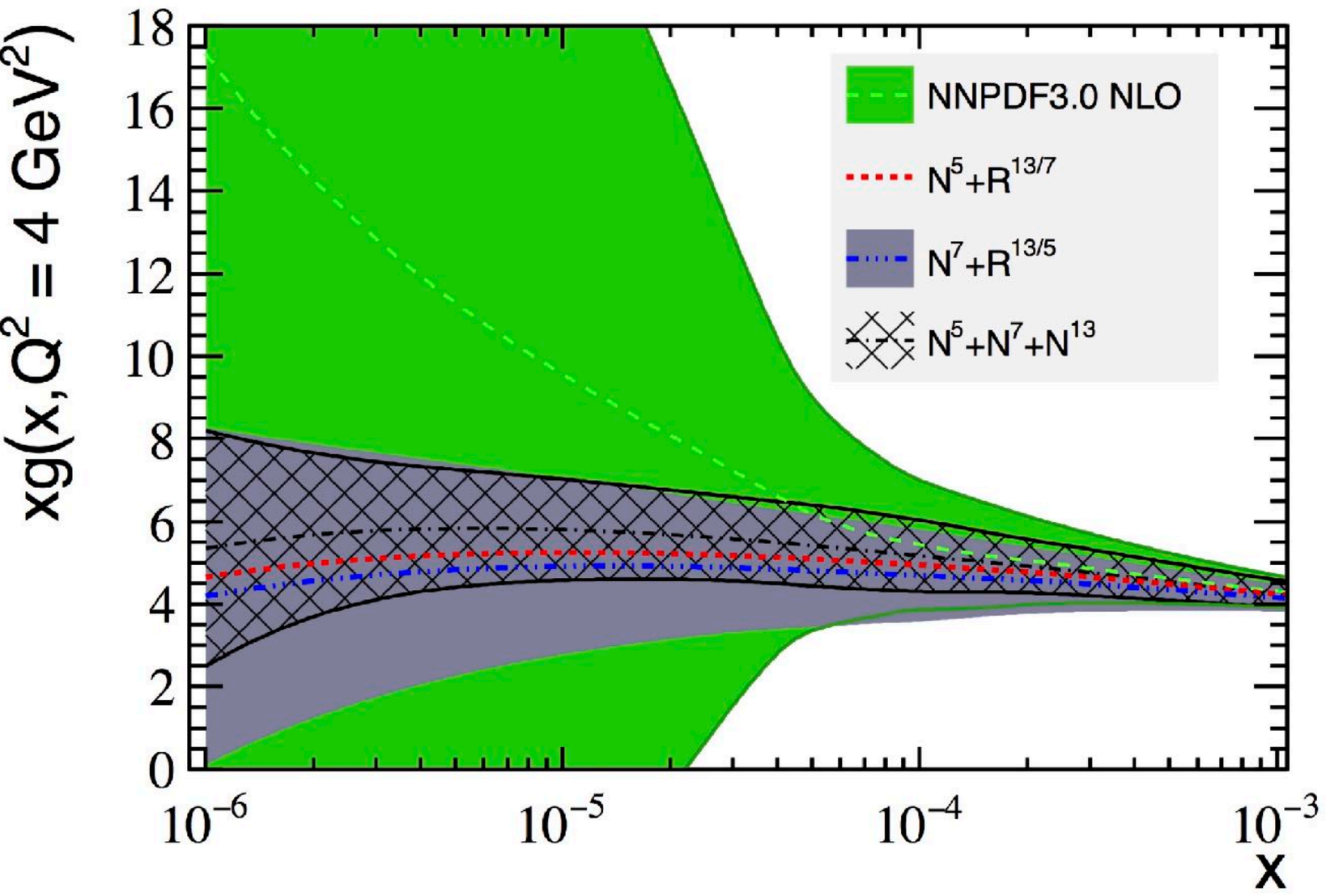

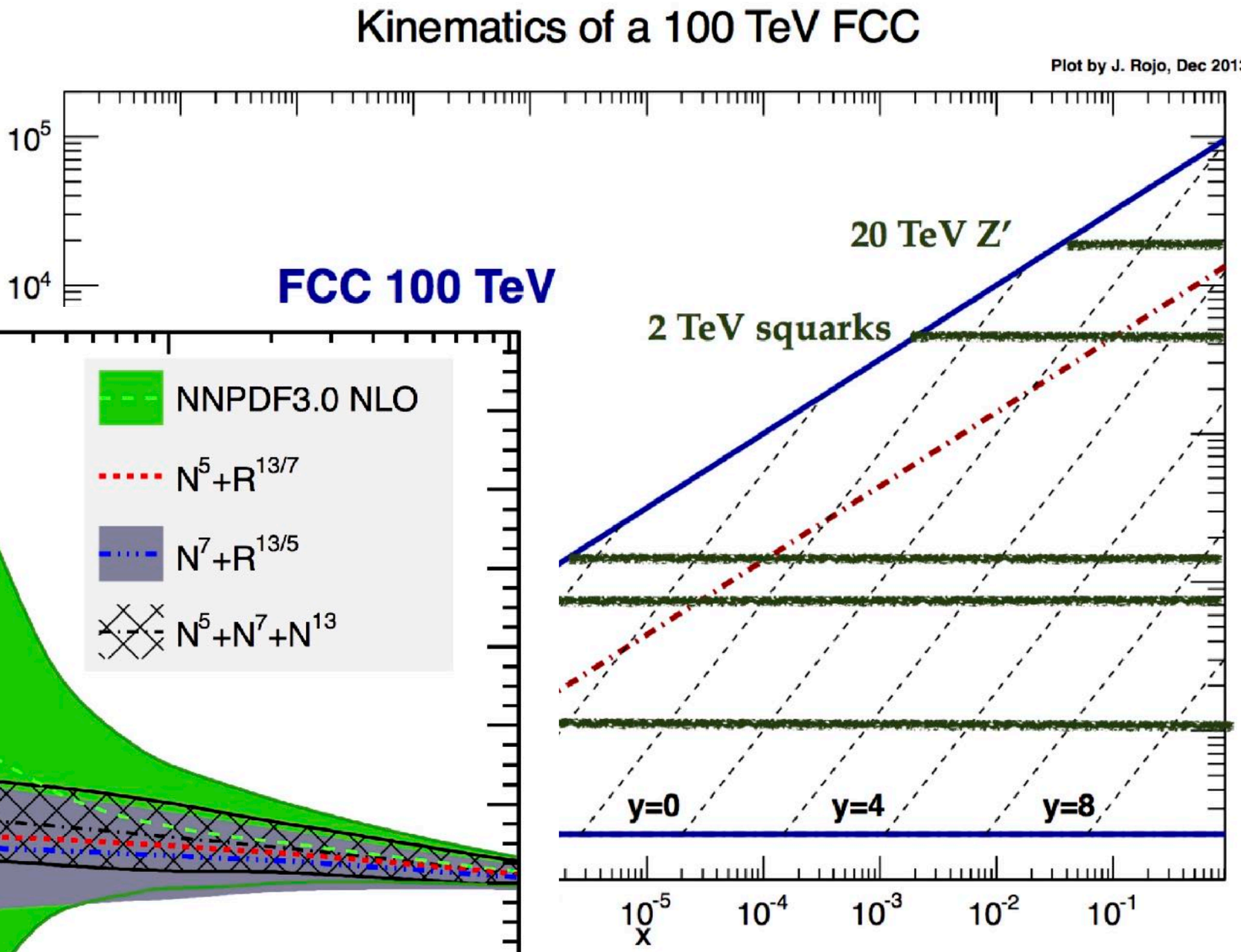

- large uncertainties at low x: results in uncertainties of cross sections

Improving PDFs

- pp collisions at LHC and future machines will improve PDFs in the coming years in the currently poorly constrained regions - in particular at high x
  - But: will suffer from uncertainties

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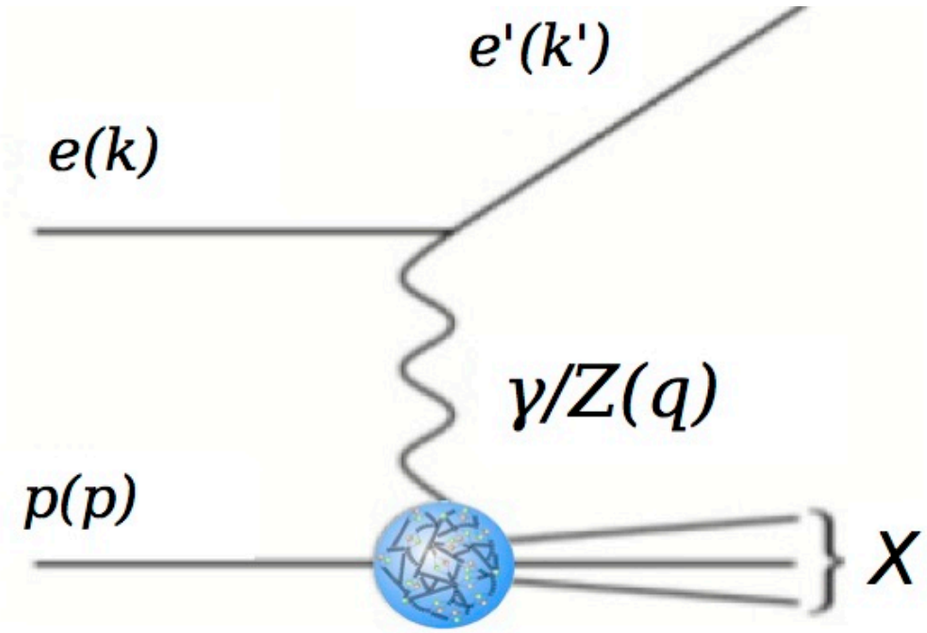
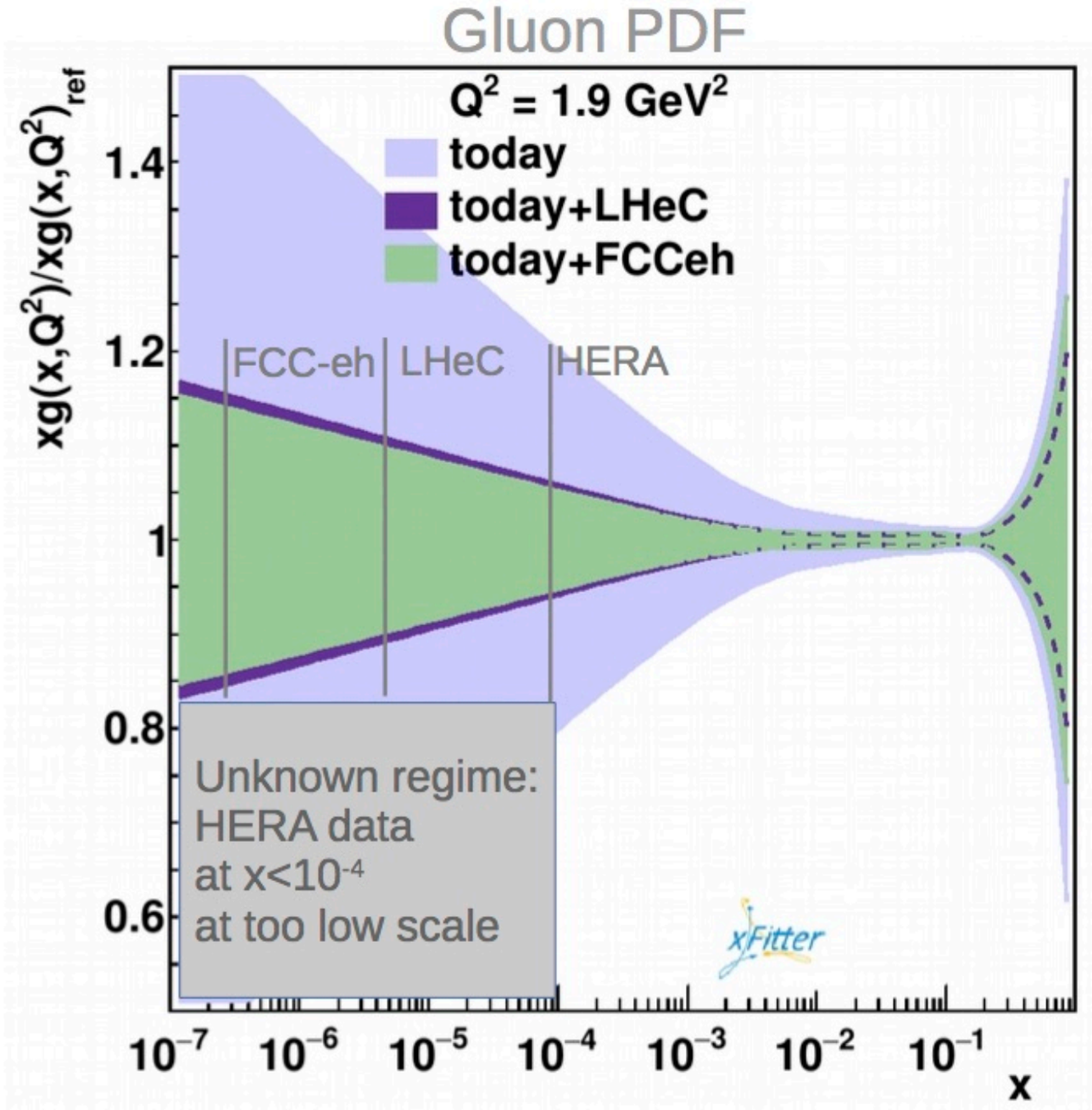
- Larger potential for improvement: eP collisions





All is good in e^+e^-? Not quite…

- No PDF uncertainties, no Underlying Event, no strongly produced backgrounds

  Still: Very high luminosity at $e^{\cdot+}e^-$ colliders required to get appreciable event rates for "interesting" processes - actually even more severe than in hadron colliders

  ⇨ Very strong focusing - strong beamstrahlung: Results in "minijet production" at higher energies - particularly relevant for 500 GeV and above

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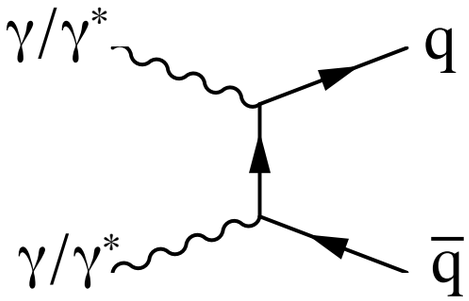
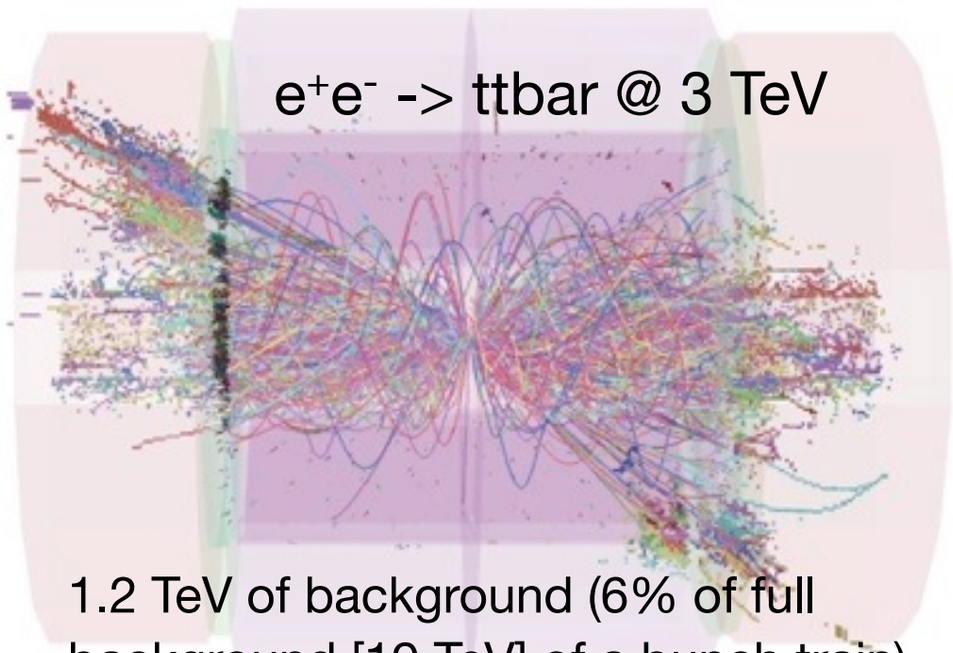
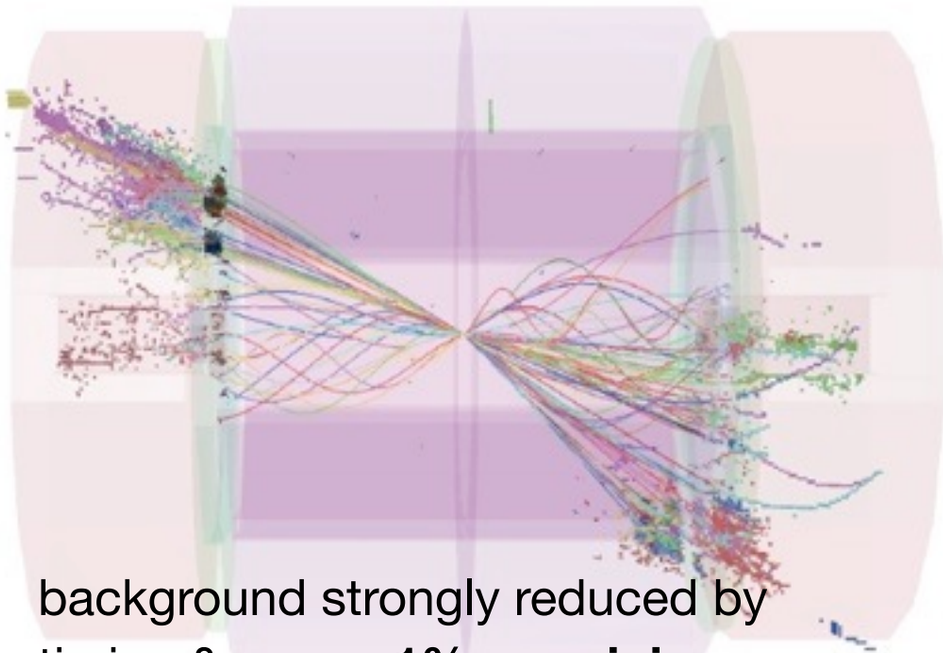


at CLIC: 3.2 interactions /BX, with 2 GHz BX frequency: pileup!



1.2 TeV of background (6% of full background [19 TeV] of a bunch train)



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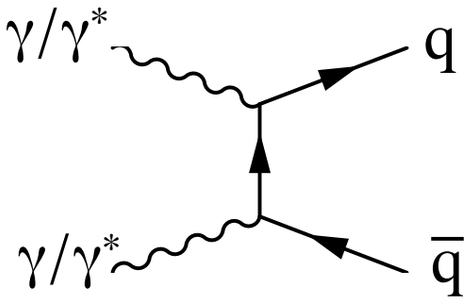

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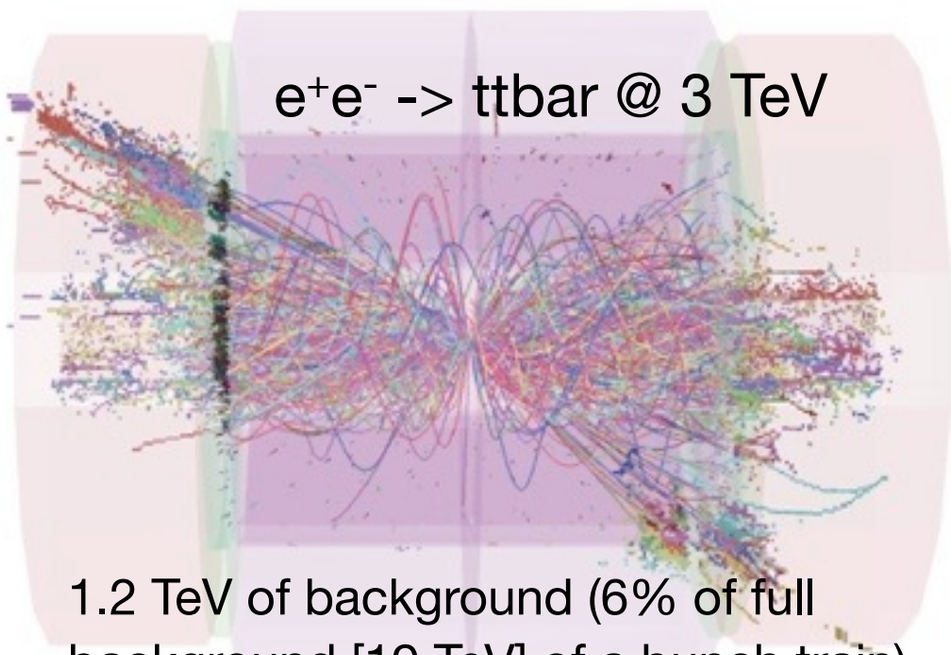

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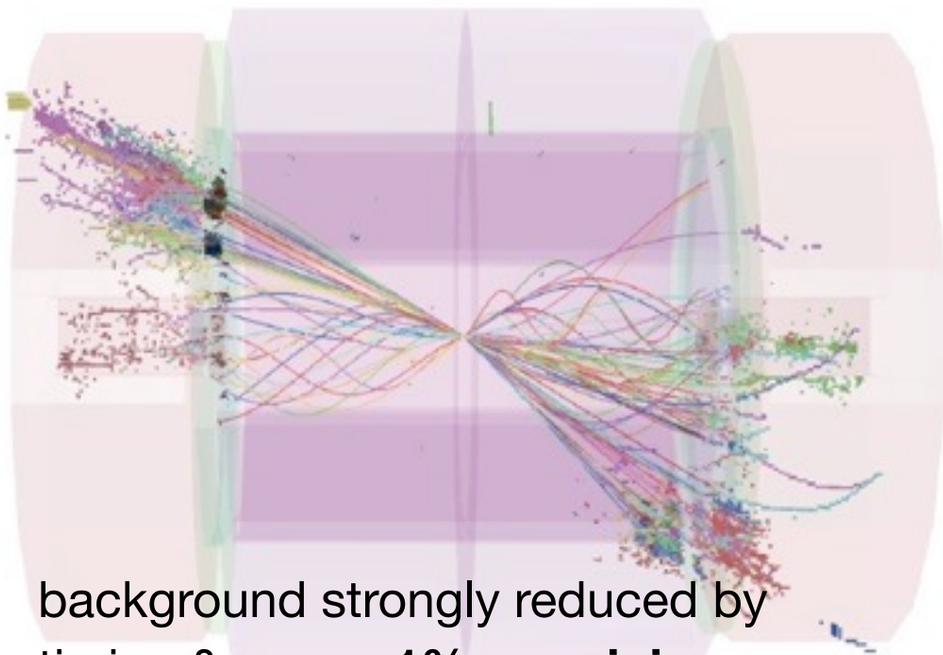

background strongly reduced by timing & reco ~ **1% remaining**

Details of impact depend on accelerator time structure and bunch by bunch luminosity

Imposes requirements on detectors and on jet finding

Rethinking Jet Reconstruction in e^+e^-

- The strong interaction comes in all final states involving colored particles:
  Jets - a whole field on its own
  - Here: A brief look at developments originally motivated by CLIC conditions

Classical e^+e^- jet finders not suitable for CLIC conditions: susceptible to machine-induced backgrounds

- also: events get more asymmetric (boost along beam axis) due to beamstrahlung

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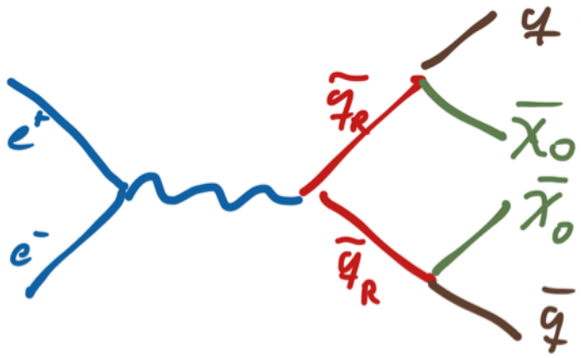
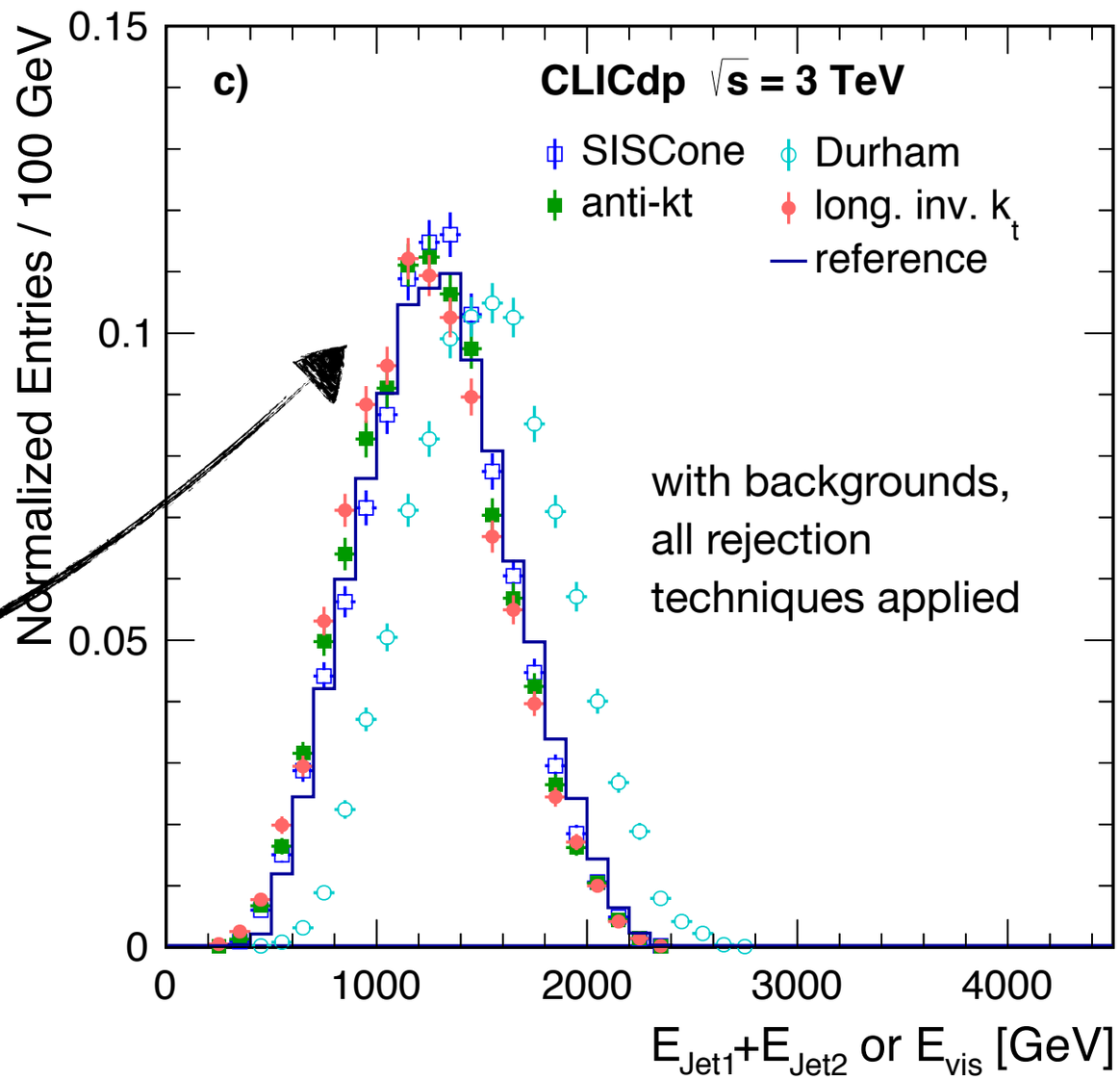
A test case for the CLIC CDR:
TeV - scale squark production

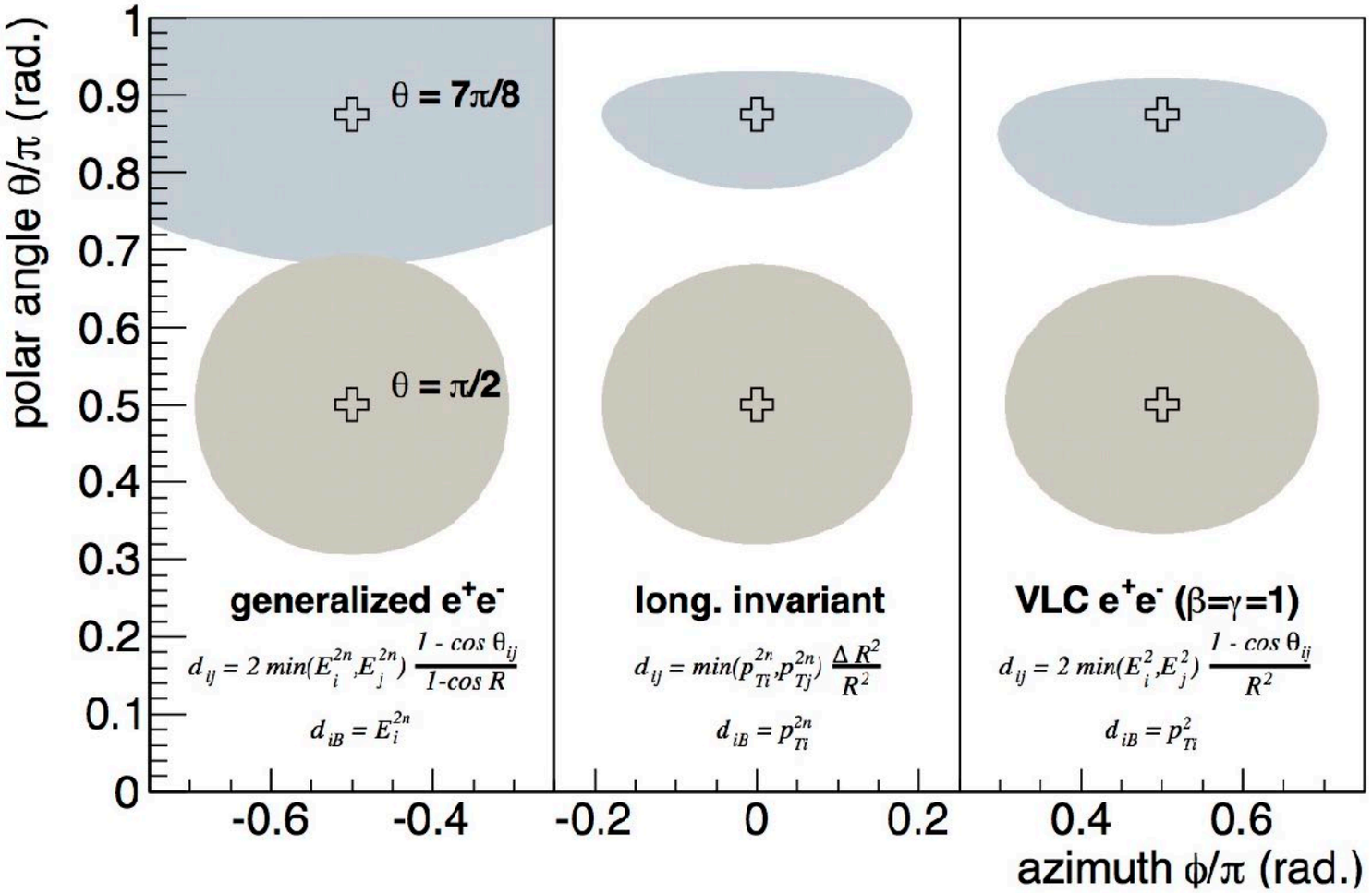




Rethinking Jet Reconstruction in e^+e^-

- Going beyond the longitudinally invariant k_t algorithm: VLC
  - maintains the positive features of the Durham algorithm of a two-particle distance definition given by energy, polar angle rather than p_t, rapidity, but is robust against beam-induced background

$$d_{ij} = min(E_i^{2\beta}, E_j^{2\beta})(1 - \cos\theta_{ij})/R^2$$



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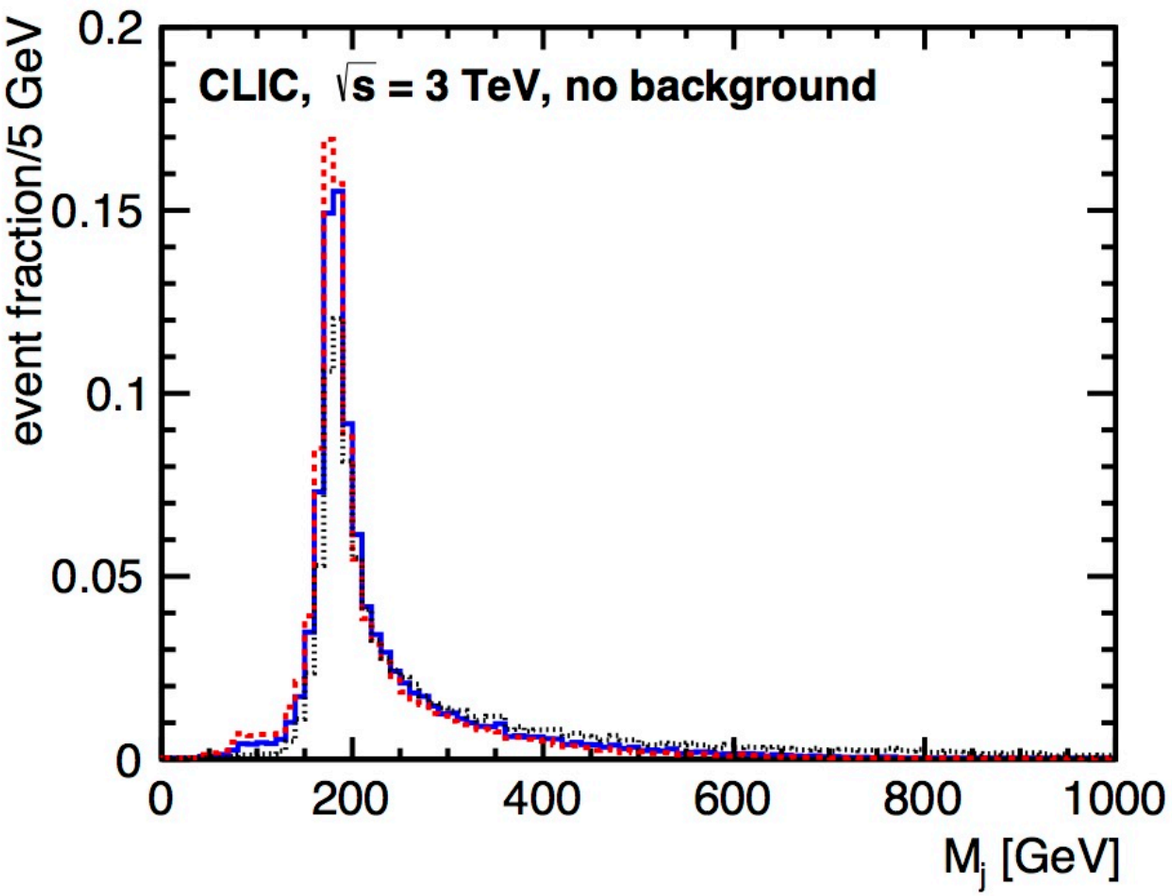
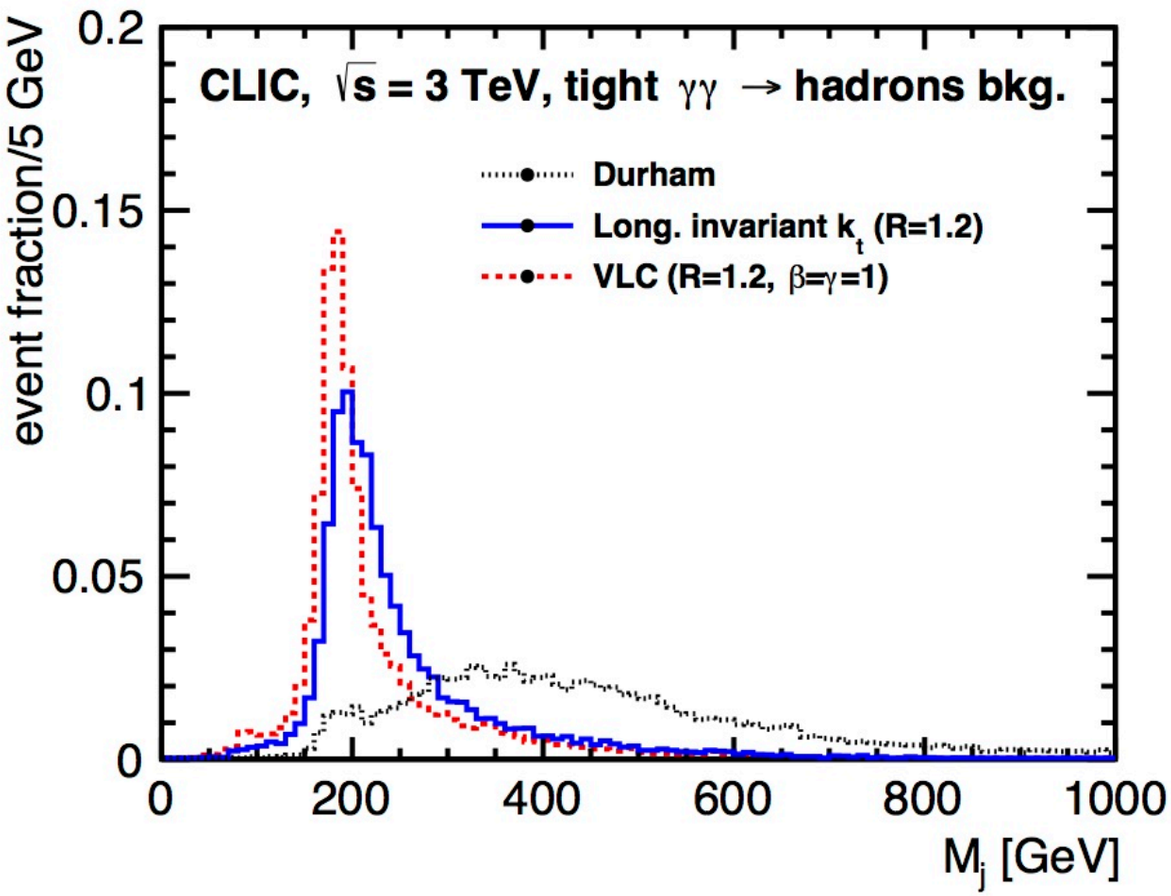
Rethinking Jet Reconstruction in e^+e^-

- Going beyond the longitudinally invariant k_t algorithm: VLC
  - maintains the positive features of the Durham algorithm of a two-particle distance definition given by energy, polar angle rather than p_t, rapidity, but is robust against beam-induced background

$$d_{ij} = min(E_i^{2\beta}, E_j^{2\beta})(1 - \cos\theta_{ij})/R^2$$

ttbar, all hadronic decay





Strong Interaction Uncertainties: Higgs in e^+e^-

- Imperfect knowledge of the strong interaction still leads to systematic uncertainties - which can even dominate selected precision measurements

  One example: Precision Higgs studies at Linear Colliders

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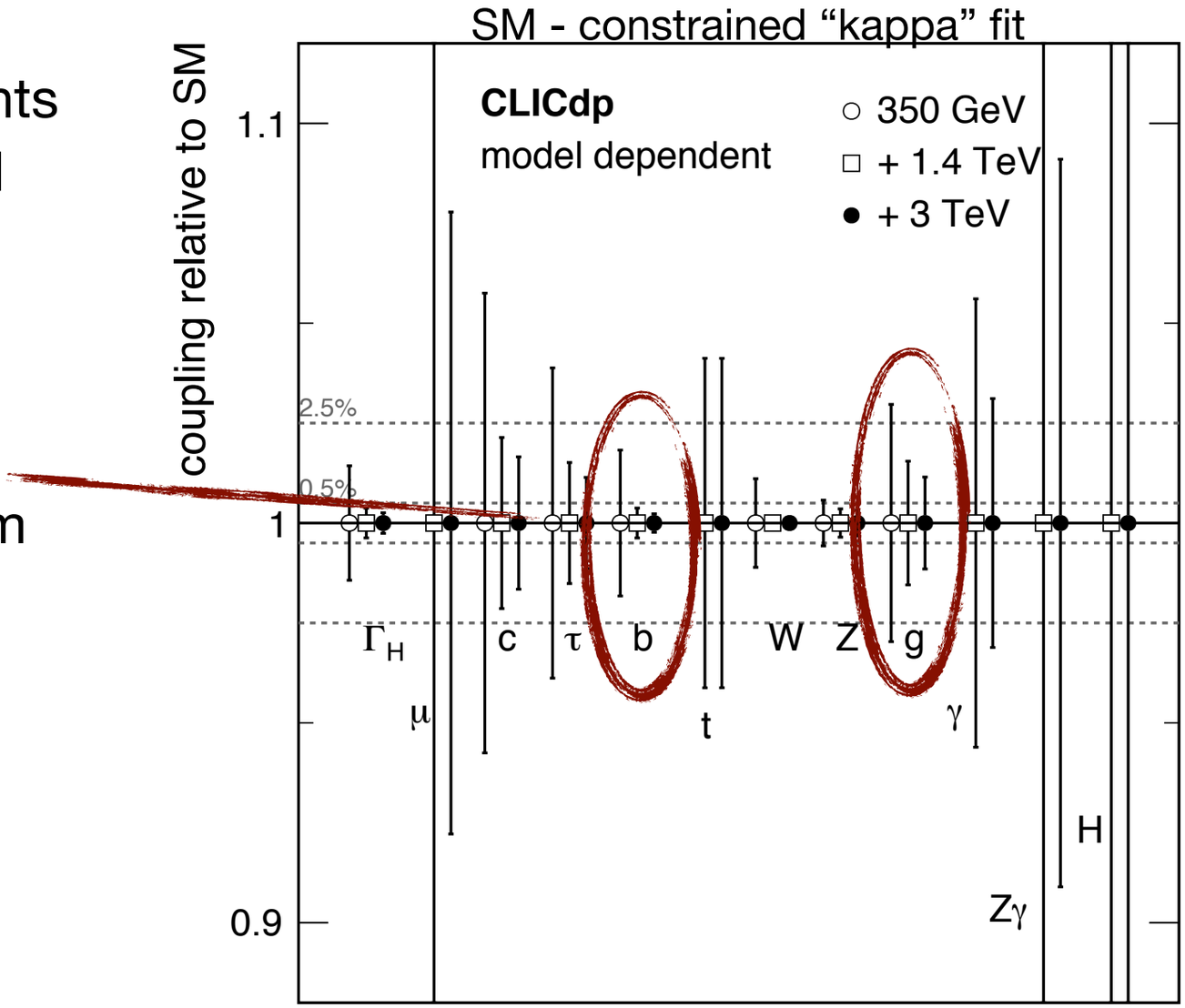
Expect highly precise measurements of Higgs couplings - going beyond theoretical uncertainties of these couplings

a 2.3 ‰ measurement of κ_{bb},
1.2% of κ_{gg} in the full CLIC program



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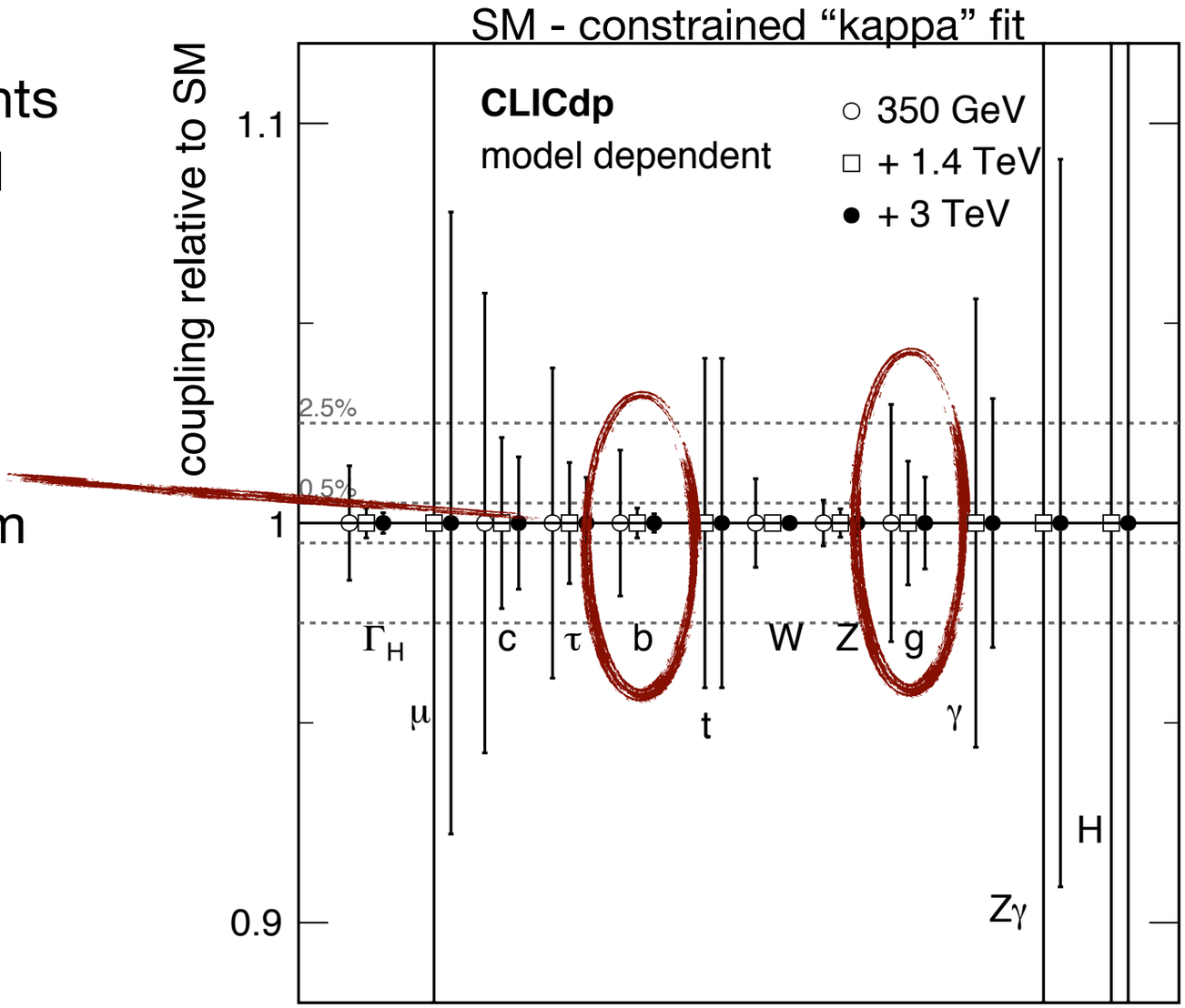
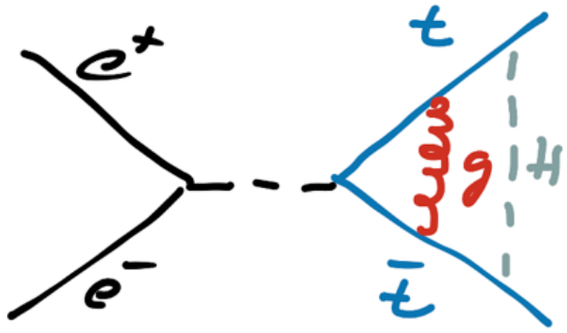
With current uncertainties:

- 1.4% κ_{bb}, includes a 0.8% uncertainty of BR from α_s alone
- 3.9% κ_{gg}, includes a 3.6% uncertainty of BR from α_s alone

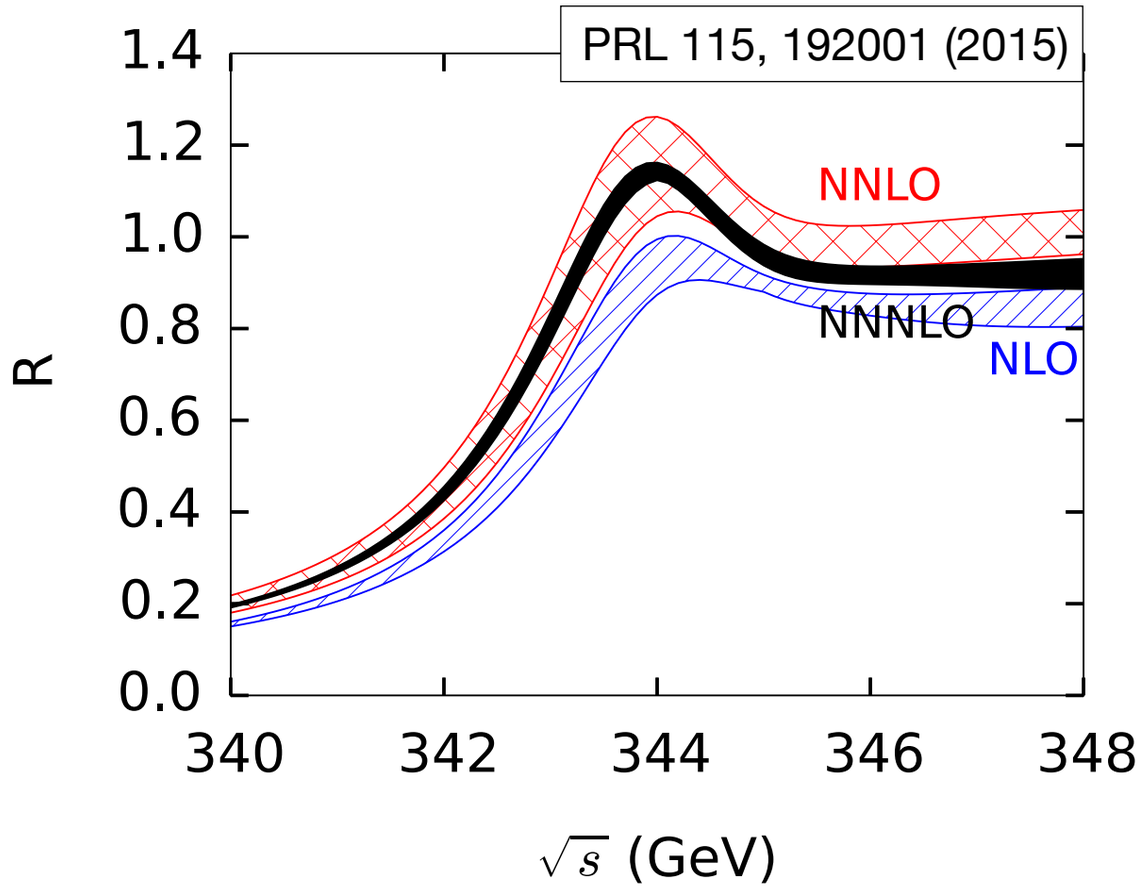


The Top Quark Mass in a Threshold Scan

- In principle an electroweak measurement - but with tops you cannot escape QCD



Precisely calculated cross section: NNNLO QCD now available



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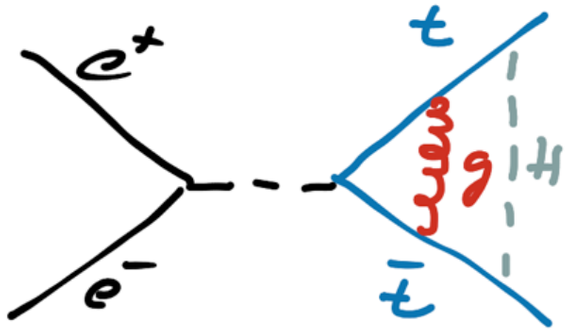

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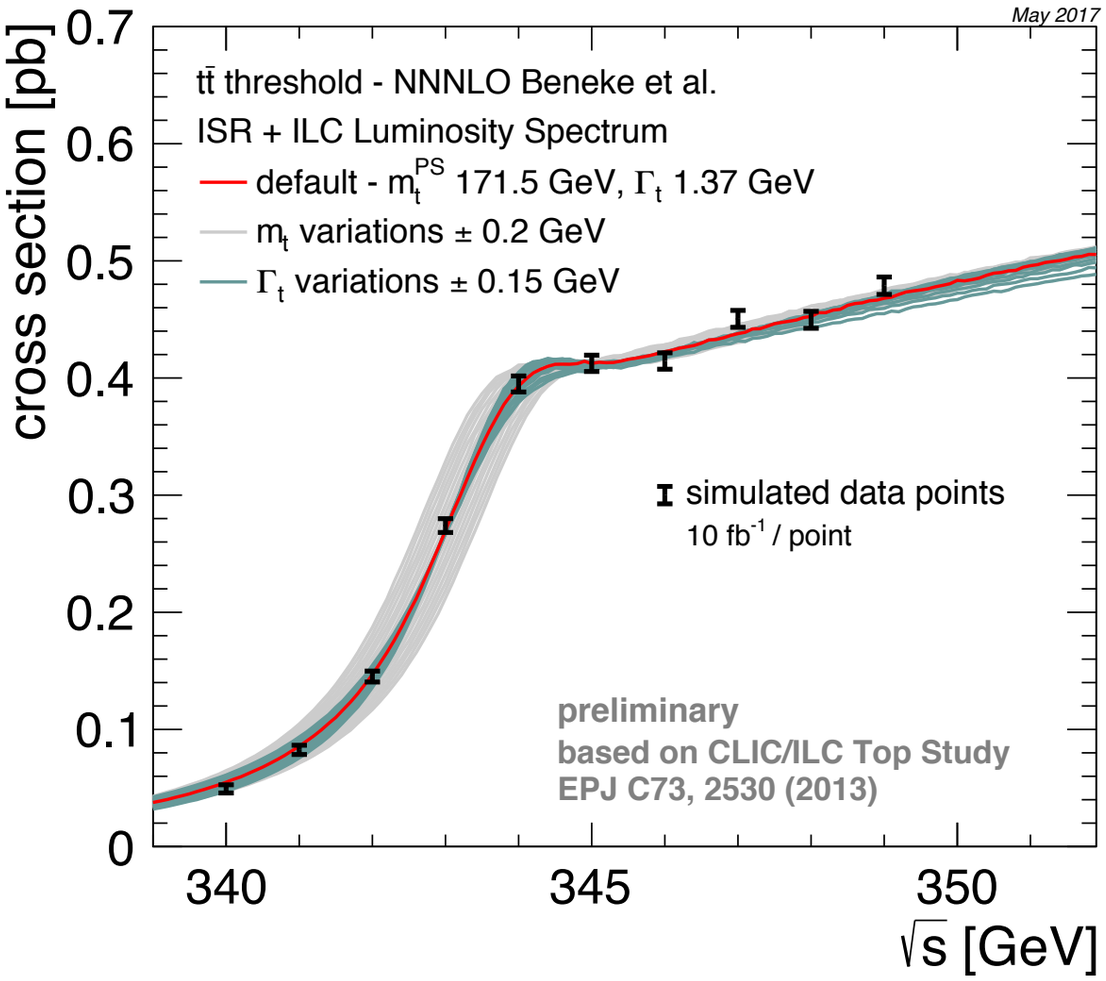
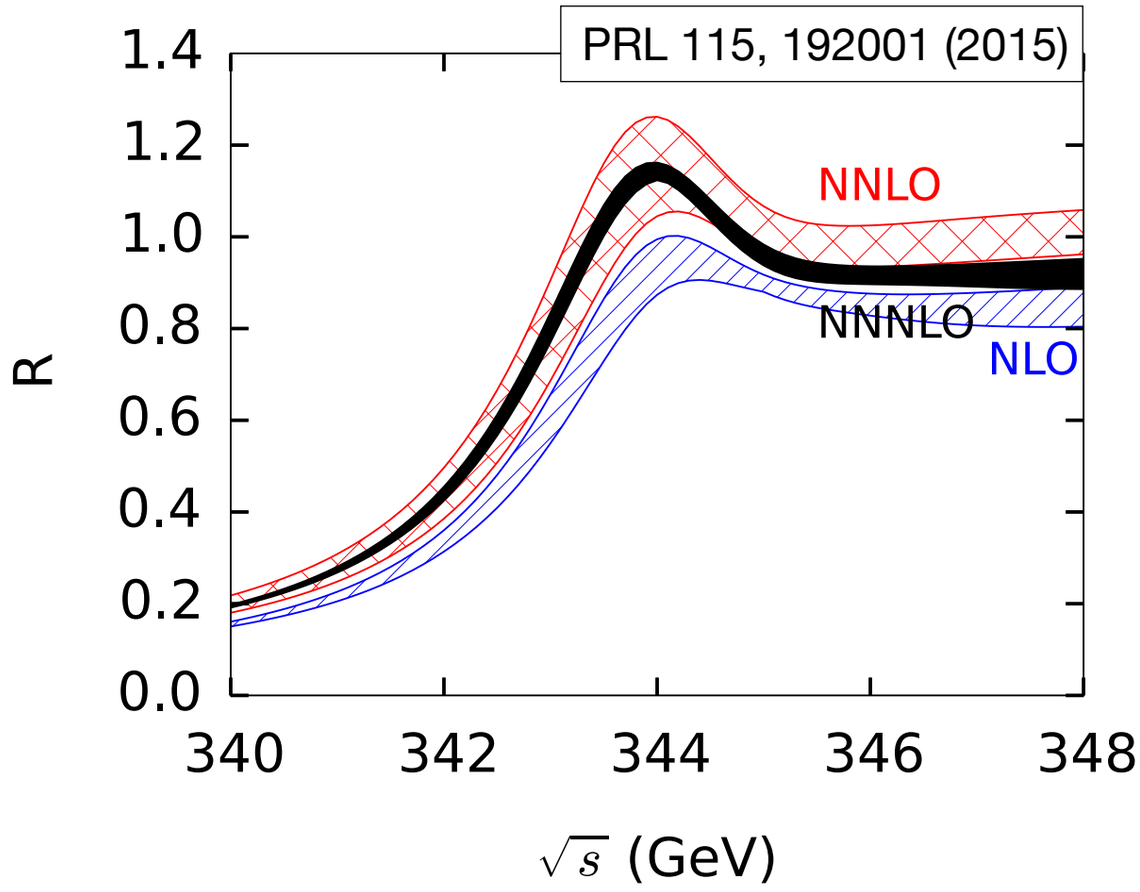
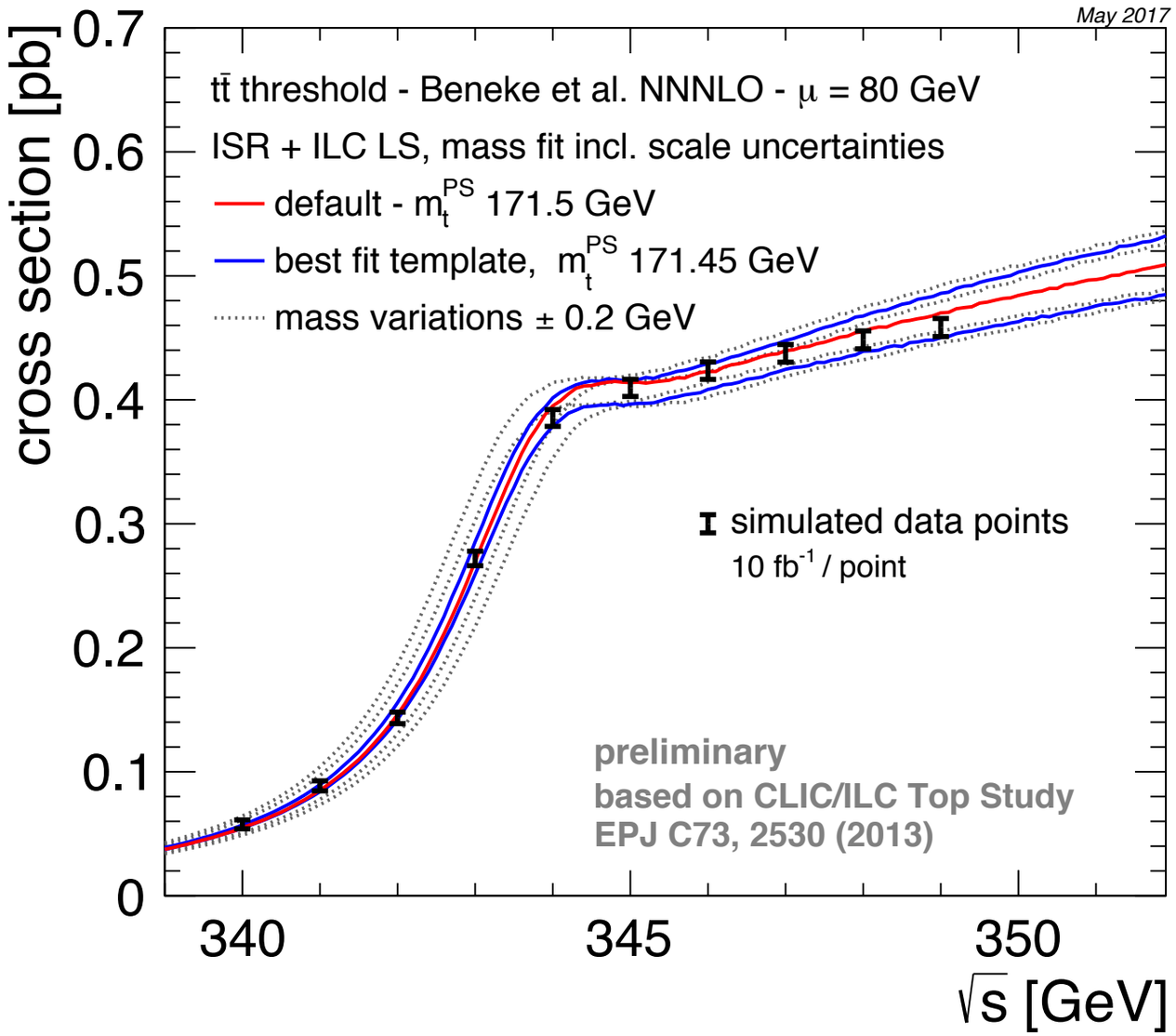




Excellent sensitivity to the top quark mass (and in principle also to other parameters, such as the width):
For a 10 point scan with a total of 100 fb^{-1}:
Statistical uncertainties ~ **18 MeV**

The Top Quark Mass in a Threshold Scan

- Once you add remaining QCD scale uncertainty the picture changes a bit



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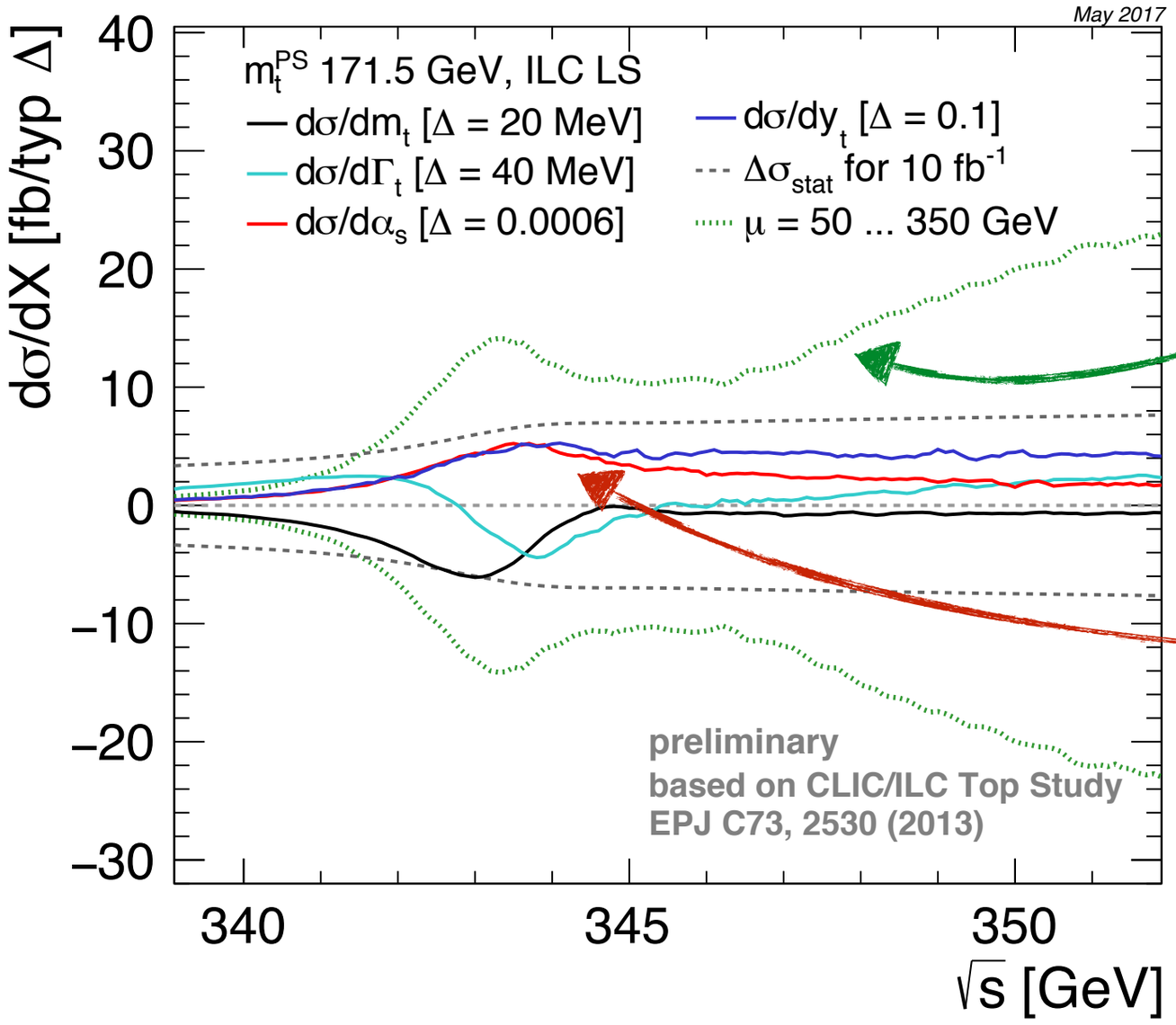

- … and on top of that there is also α_s

scale uncertainties @ NNNLO:
a **40 MeV** systematic on the mass

parametric uncertainties from α_s:
27 MeV / 0.001 uncertainty in α_s
32 MeV with present WA

Uncertainties related to the strong interaction are leading uncertainties on the top mass measurement at e^+e^- colliders

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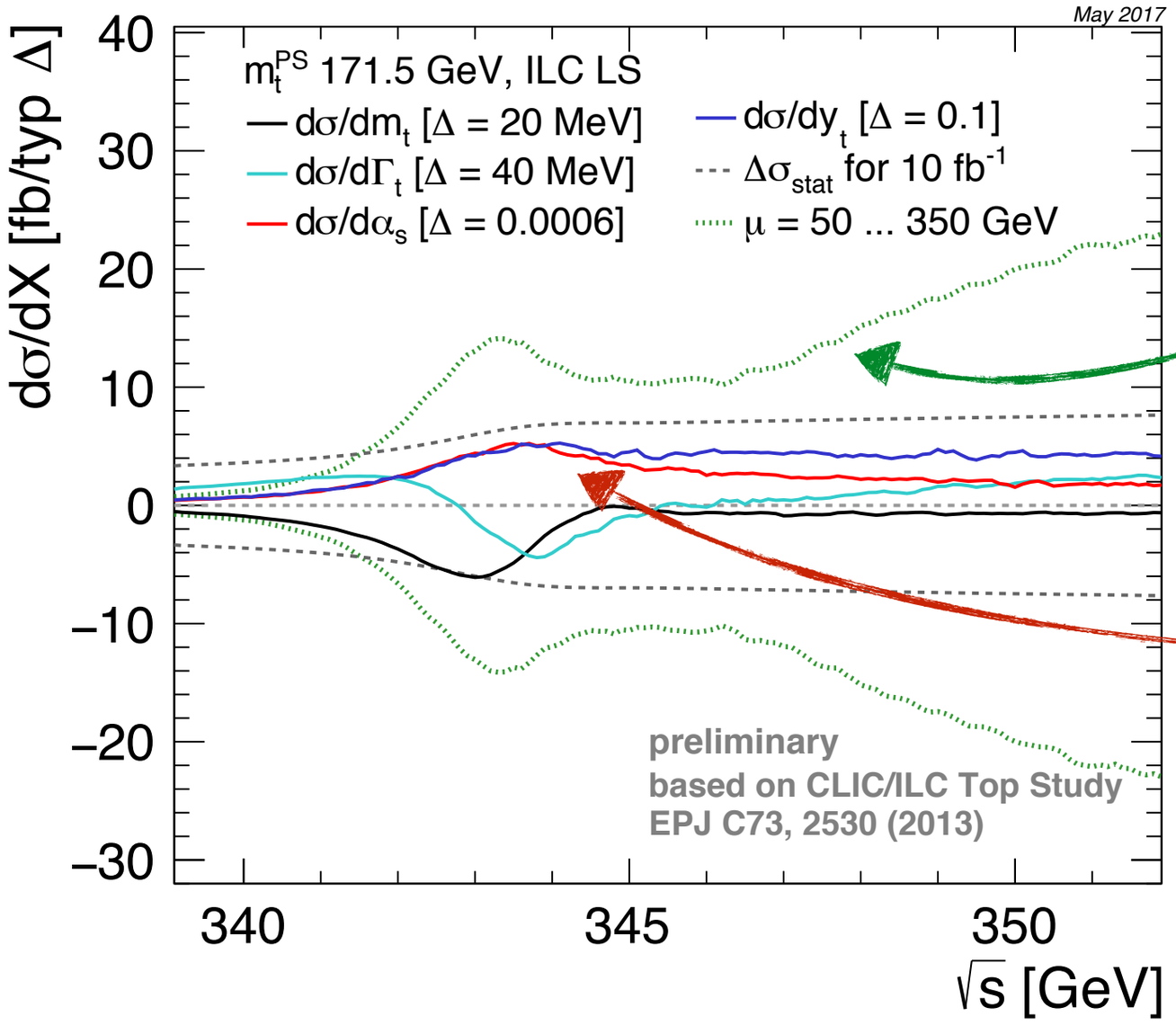

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… but even with with present-day uncertainties this would be a very precise measurement!

The Top Quark Mass in a Threshold Scan

- Ultimately the primary interest is in the MSbar mass: Requires an additional conversion
- This conversion is now known at N^{4}LO in QCD

P. Marquard *et al.* PRL 114, 142002 (2015)

$$\frac{m_t(m_t)}{\text{GeV}} = 163.643 \pm 0.023 + 0.074\Delta_{\alpha_s} - 0.095\Delta^{\text{PS}}_{m_t},$$

=> **74 MeV** / 10^{-3} in α_s

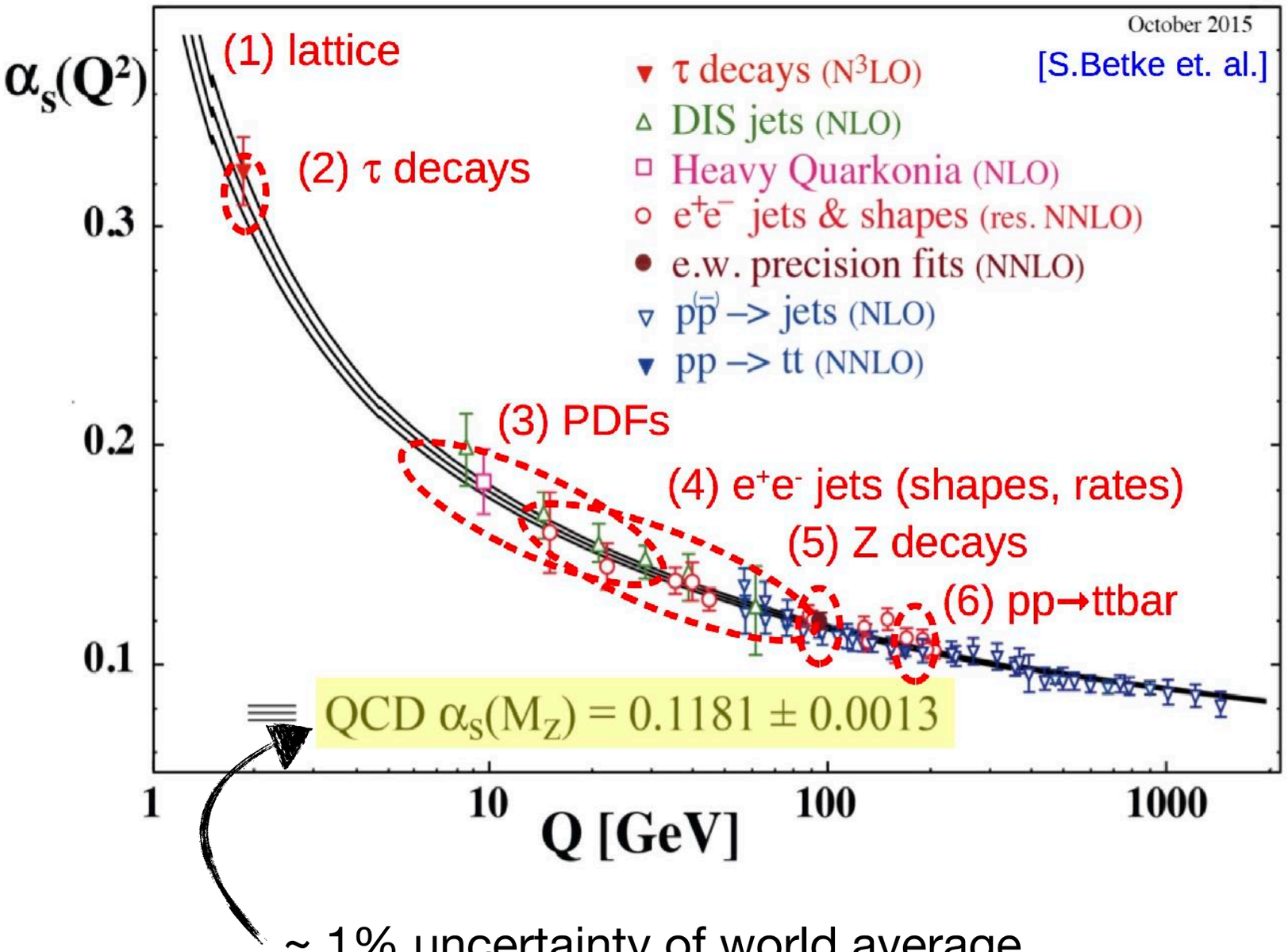
with $\Delta\alpha_s$ in units of 10^{-3} changes relative to default $\alpha_s(m_Z)$

NB: Sign opposite to the uncertainty when extracting the top quark mass in the PS scheme: Resulting total combined uncertainty of~ 50 MeV / 10^{-3} in α_s

⇨ **~ 60 MeV** with current WA

Strong Coupling: Potential for Improvement?

- A key ingredient to reduce the systematic limitations imposed by the strong interaction: Improved measurement of the strong coupling constant



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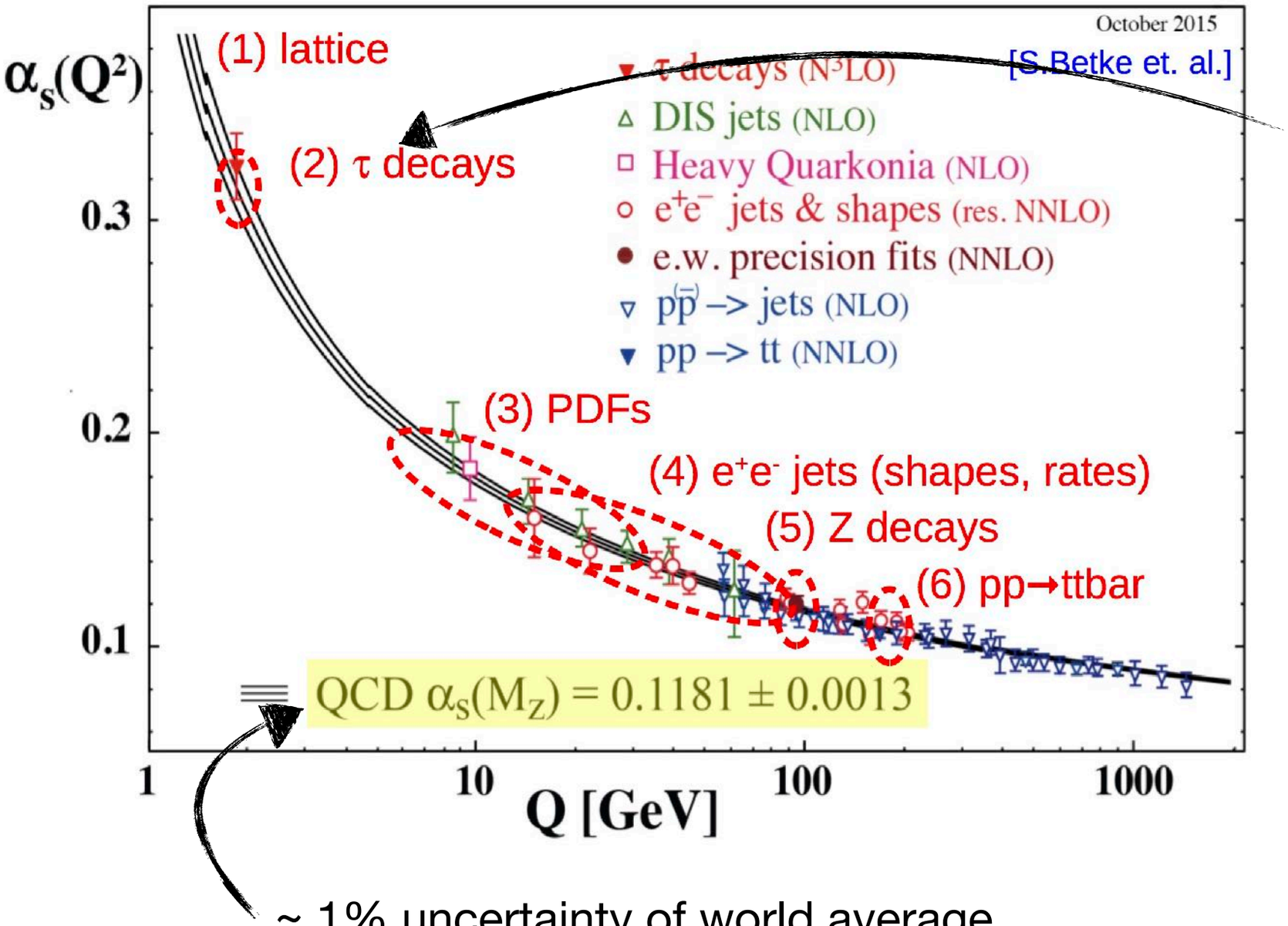

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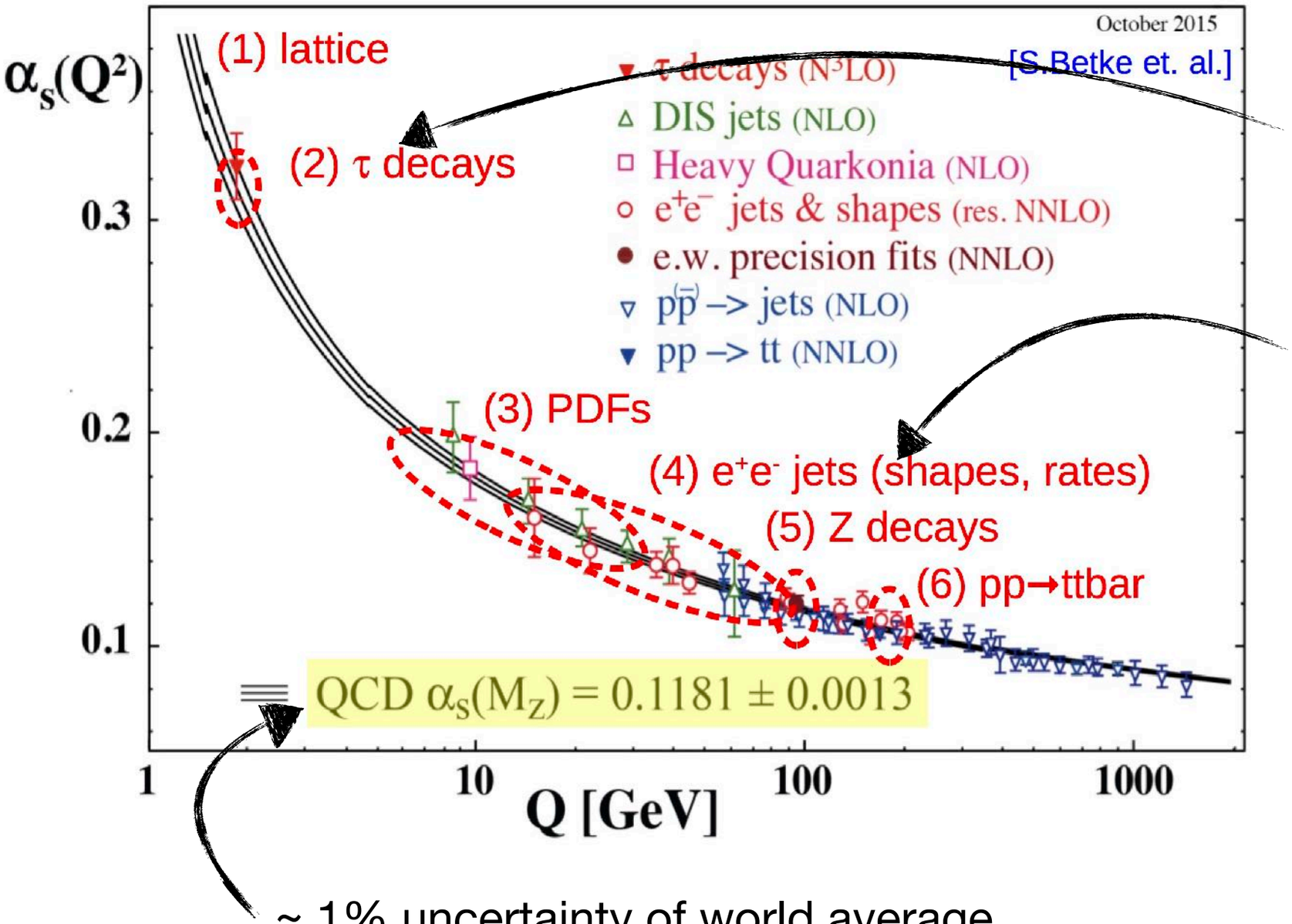

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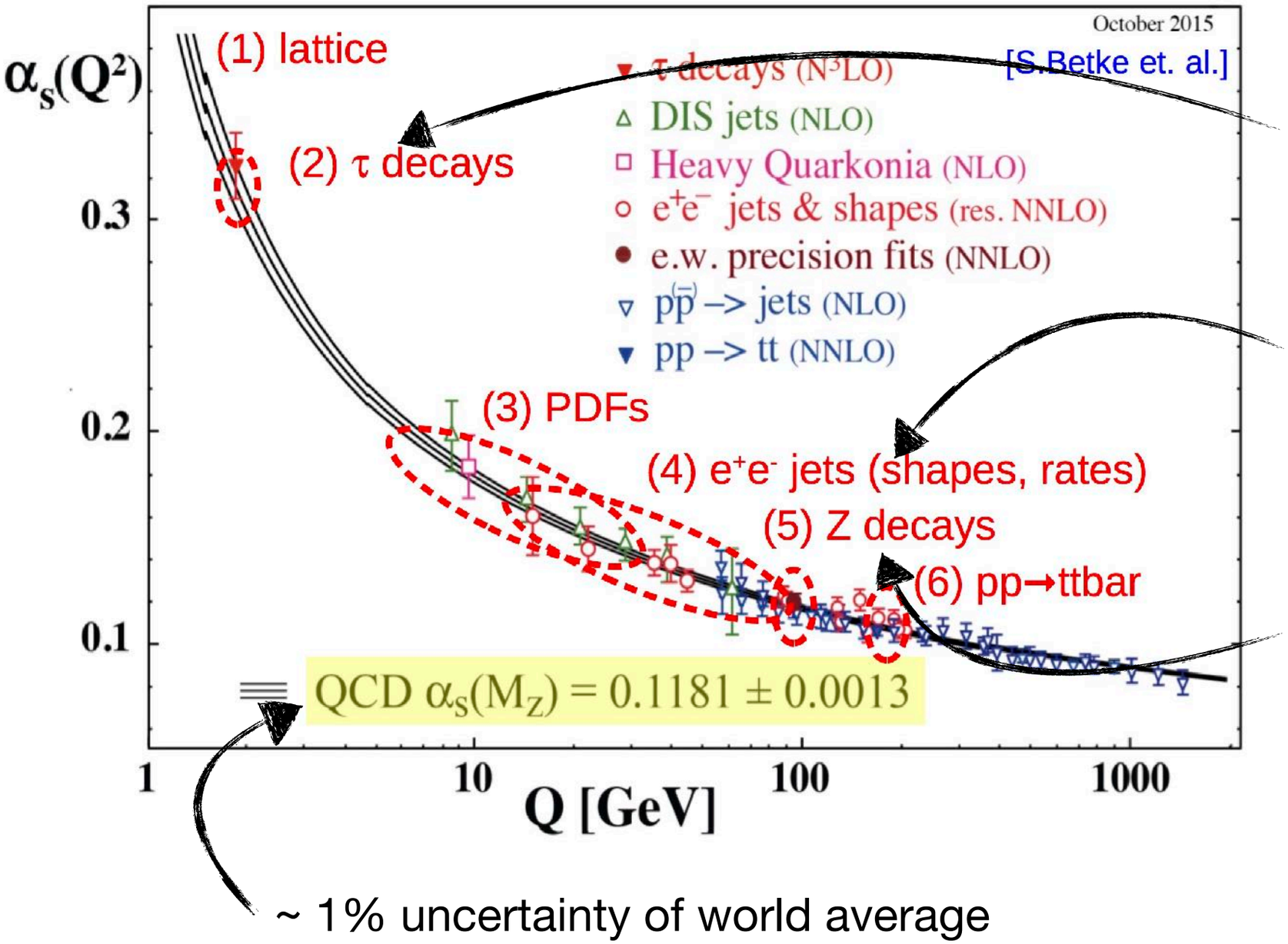

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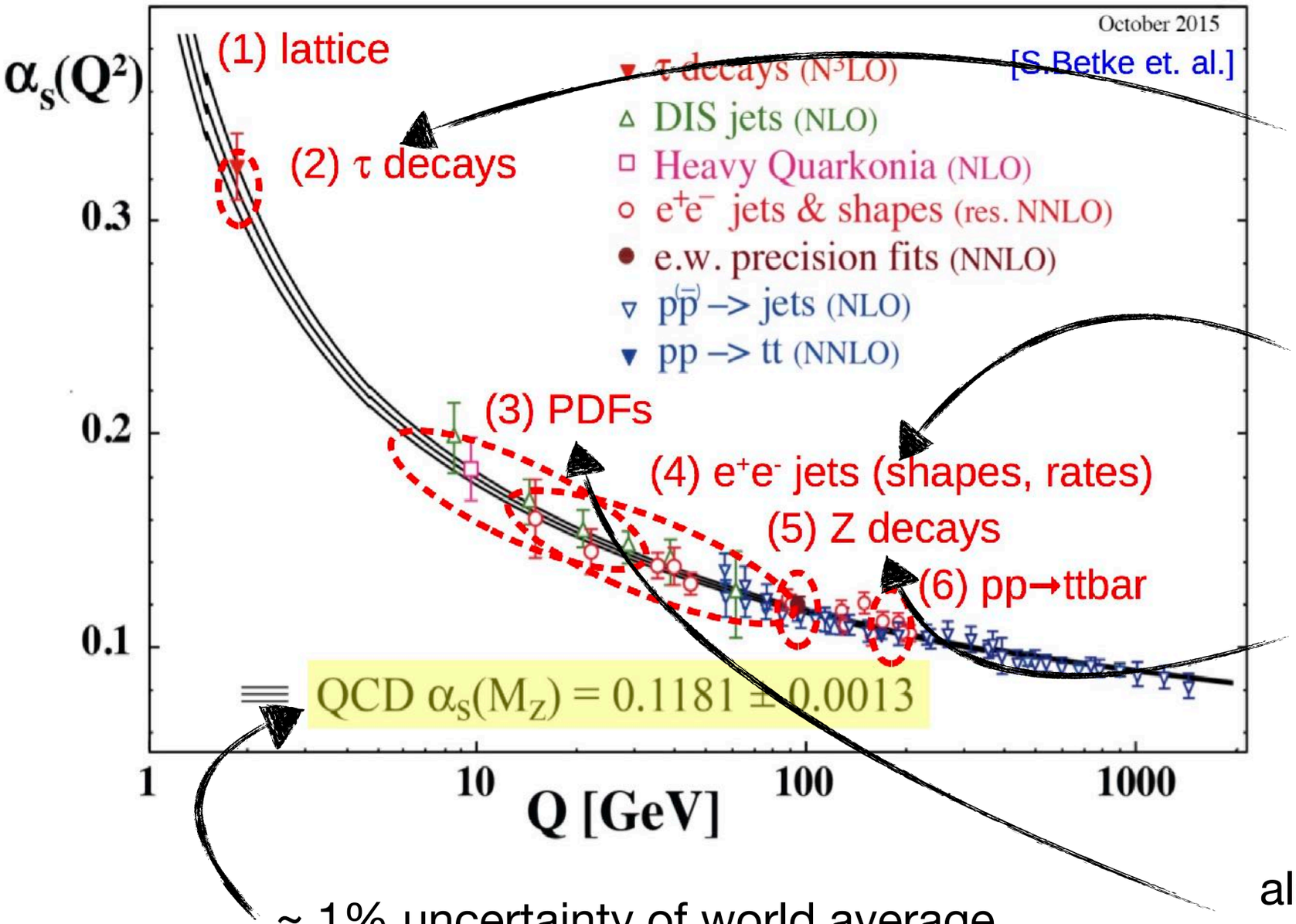

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also: PDFs in potential future eP colliders

The Strong Coupling: Where Can We Go?

- In general: for most classes of measurements the issue is not just data alone
  - theory uncertainties: Requires additional orders - should be available on the time scale of future machines (*O* decade(s))
  - conceptual issues / limitations, such as hadronisation treatment for event shapes / rates, PDFs for DIS, top threshold effects for hadron collider measurements, …

➪ Pushing single measurements below 1% precision is tough!

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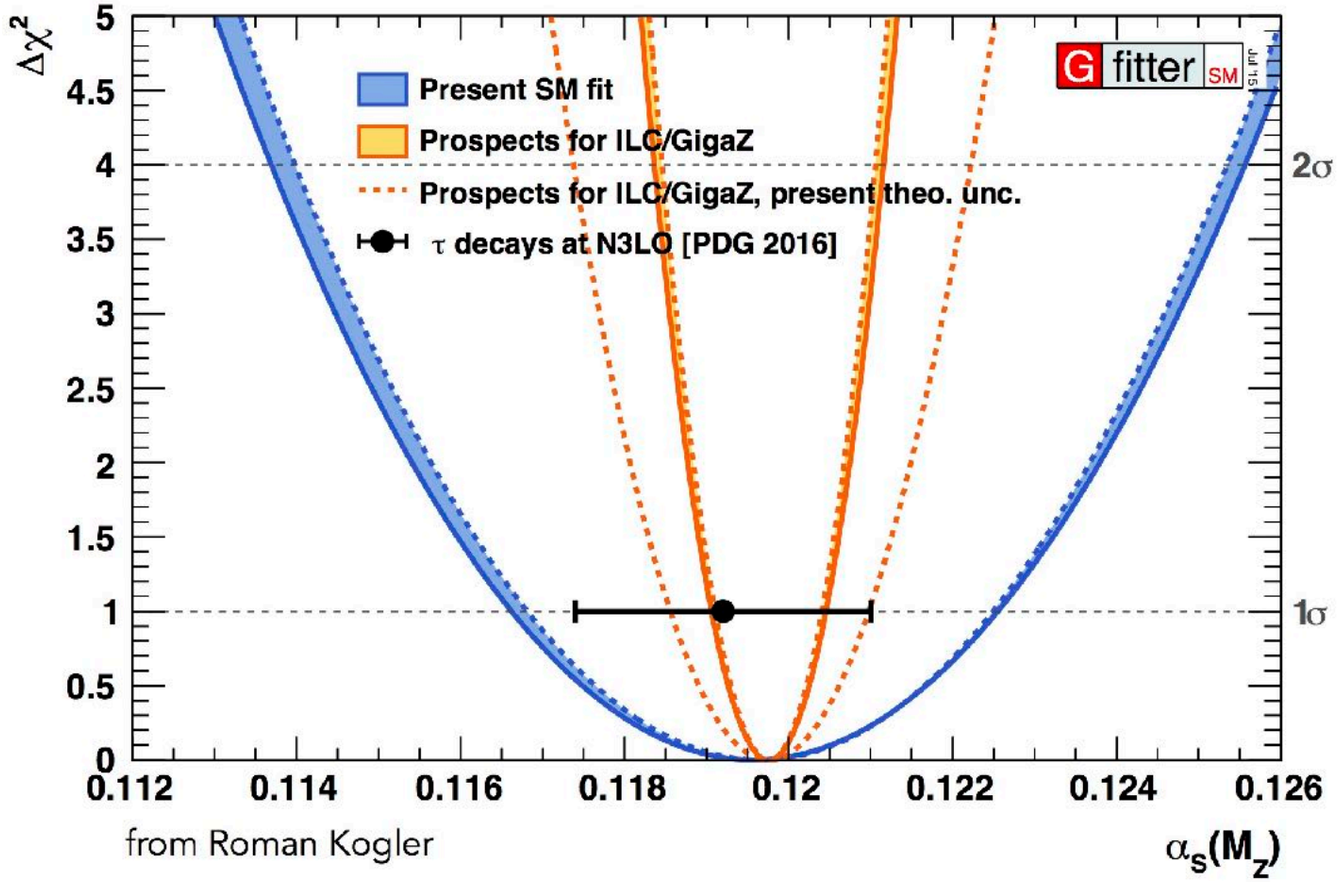

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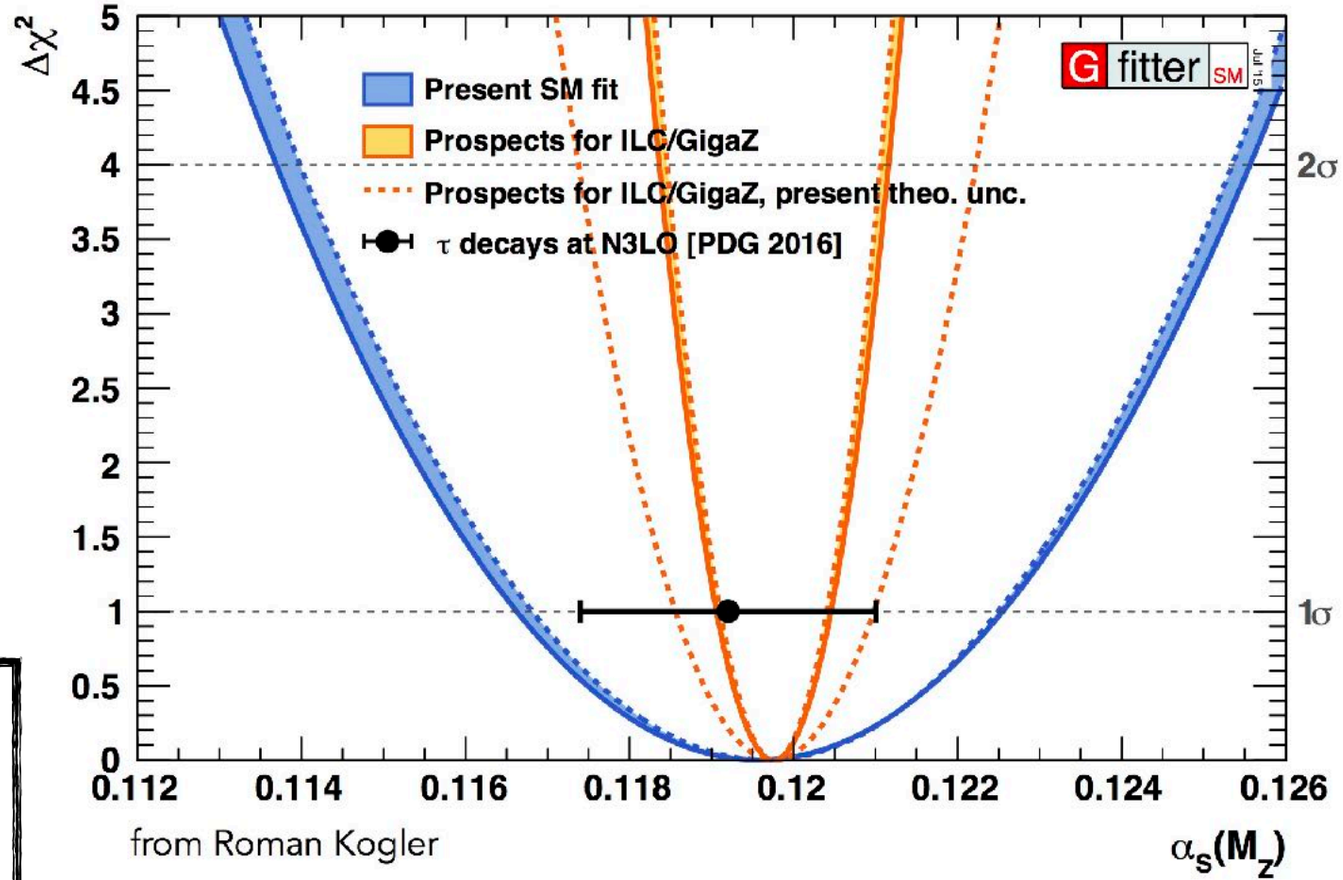
FCCee: ~ 0.3%

combined with other measurements, incl lattice: Takes us in the direction of 1‰ - but: watch out for inconsistencies!



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Conclusions

- The physics case of future colliders is built around “electroweak” phenomena

- The strong interaction deserves more attention - and studies are beginning:
  - At the heart of production at high-energy pp colliders: Substantial uncertainties from current level of PDF uncertainties
  - A crucial source of parametric uncertainties for precision measurements at e^+e^- colliders - limits achievable precision for electroweak observables

- New measurements will improve our understanding:
  - Better measurements of α_s - potentially down to the few permille level
    - Would essentially eliminate α_s uncertainties from Higgs analyses
    - Would reduce corresponding uncertainties in top mass studies (including conversion to MSbar mass) to a few MeV
  - Improved PDFs - from pp data, and possible a new eP collider

Conclusions

- There is (almost) no physics at future colliders without strong interaction - irrespective of the type of collider (hadrons, leptons)

- Over the coming decade(s), expect
  - Advances in theory
  - New measurements

- Over the next two years, expect
  - An even better understanding of and more publicity about the role of the strong interaction at future colliders

- During this week: In-depth discussions of various aspects of strong interaction physics!