Theory Summary

Tim M.P. Tait
University of California, Irvine

Top 2014
October 3 2014

Theory Summary

(My Attempt to Paint a Story with Your Beautiful Slides)

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Last Time...

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(Though to be fair, that was graciously corrected once the error was pointed out).

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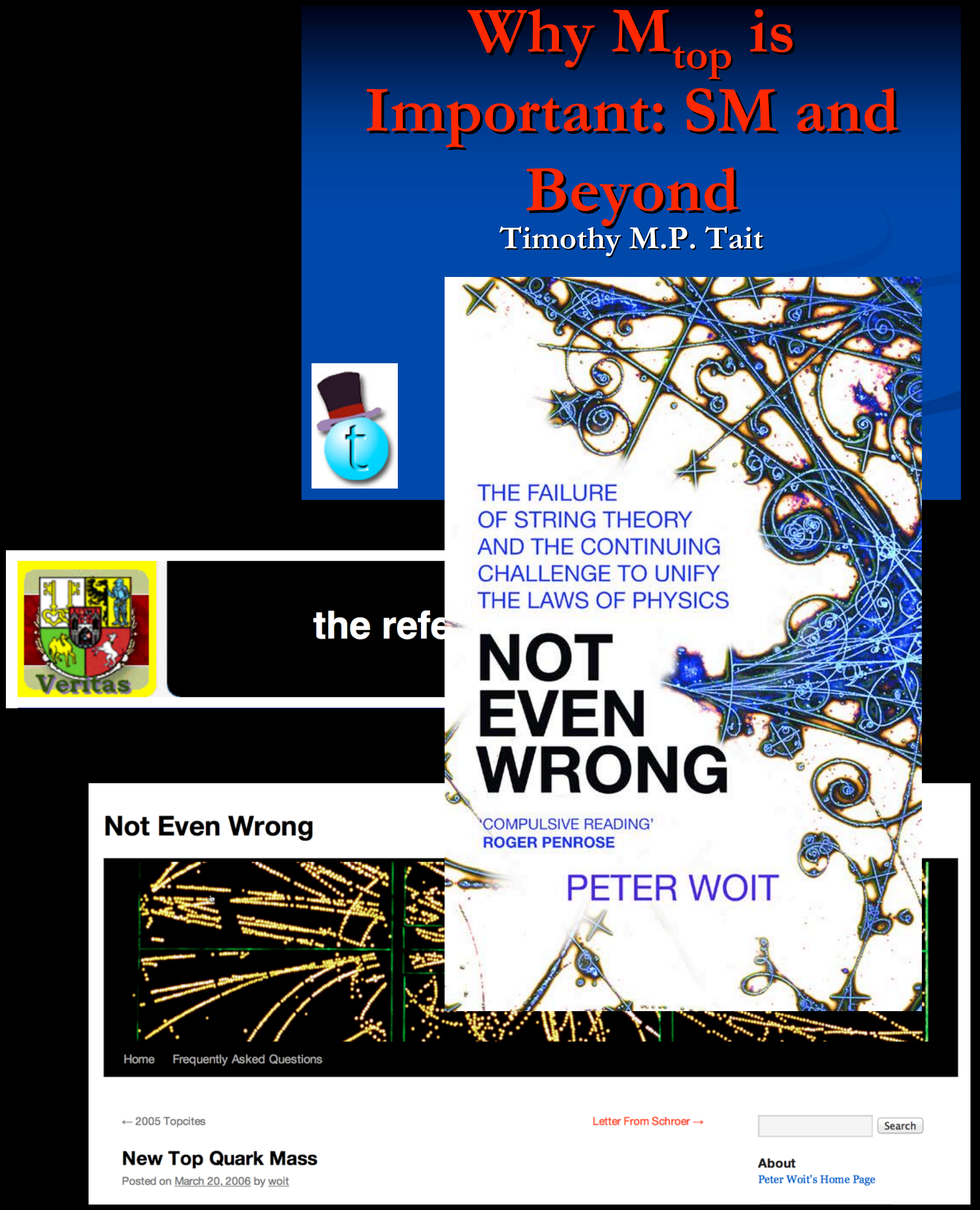
Let's see what happens this time!

It's *very* nice to be here.



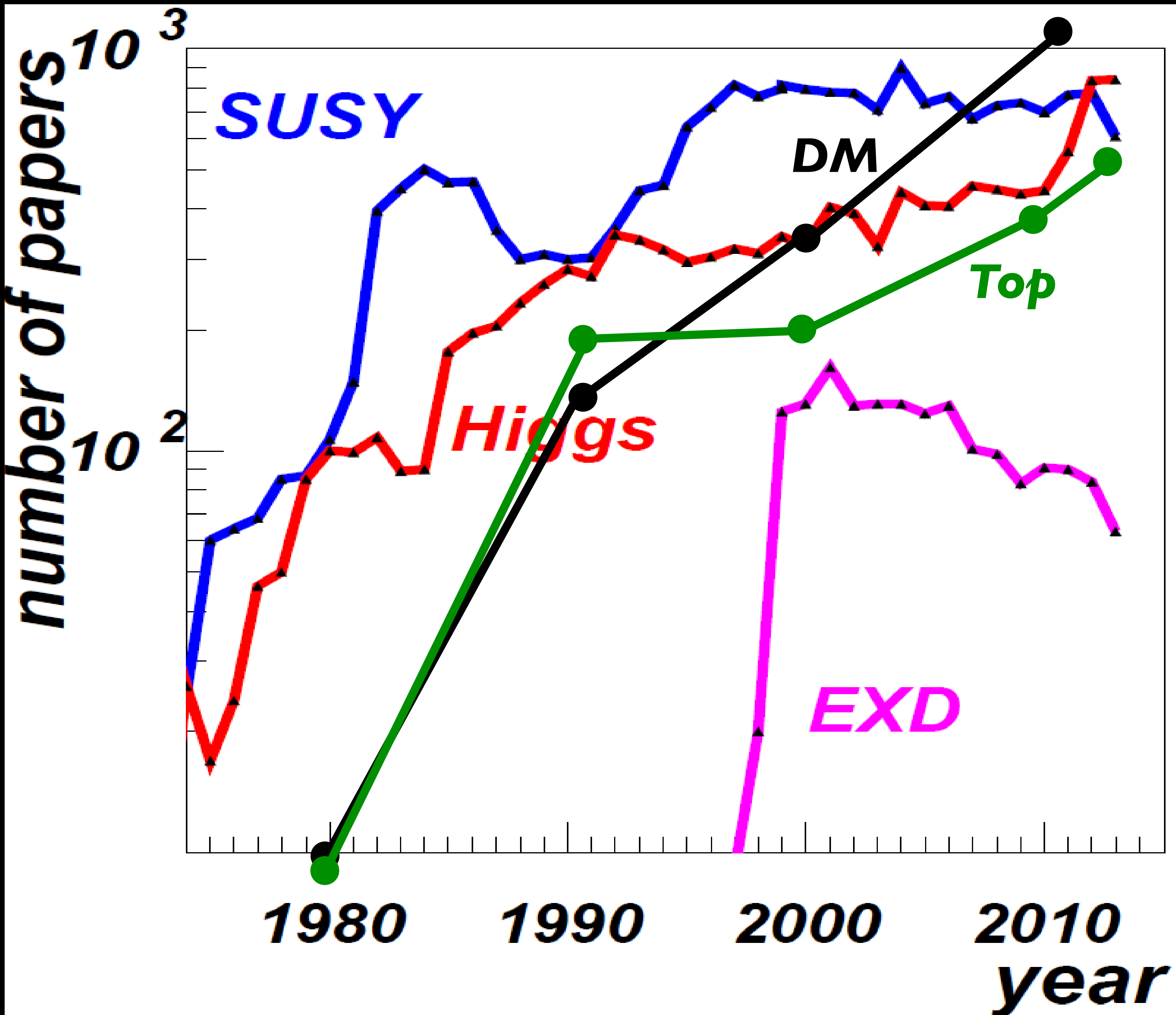
Statistics

~14 talks x ~25 slides = 350 slides

350 slides / 30 minutes ~ 12 slides / minute

Mission Impossible.

Statistics



Credit for idea, SUSY, Higgs + XD Sasha Belyaev

Top data also shown by QH Cao

Top physics is going strong!

Warning:

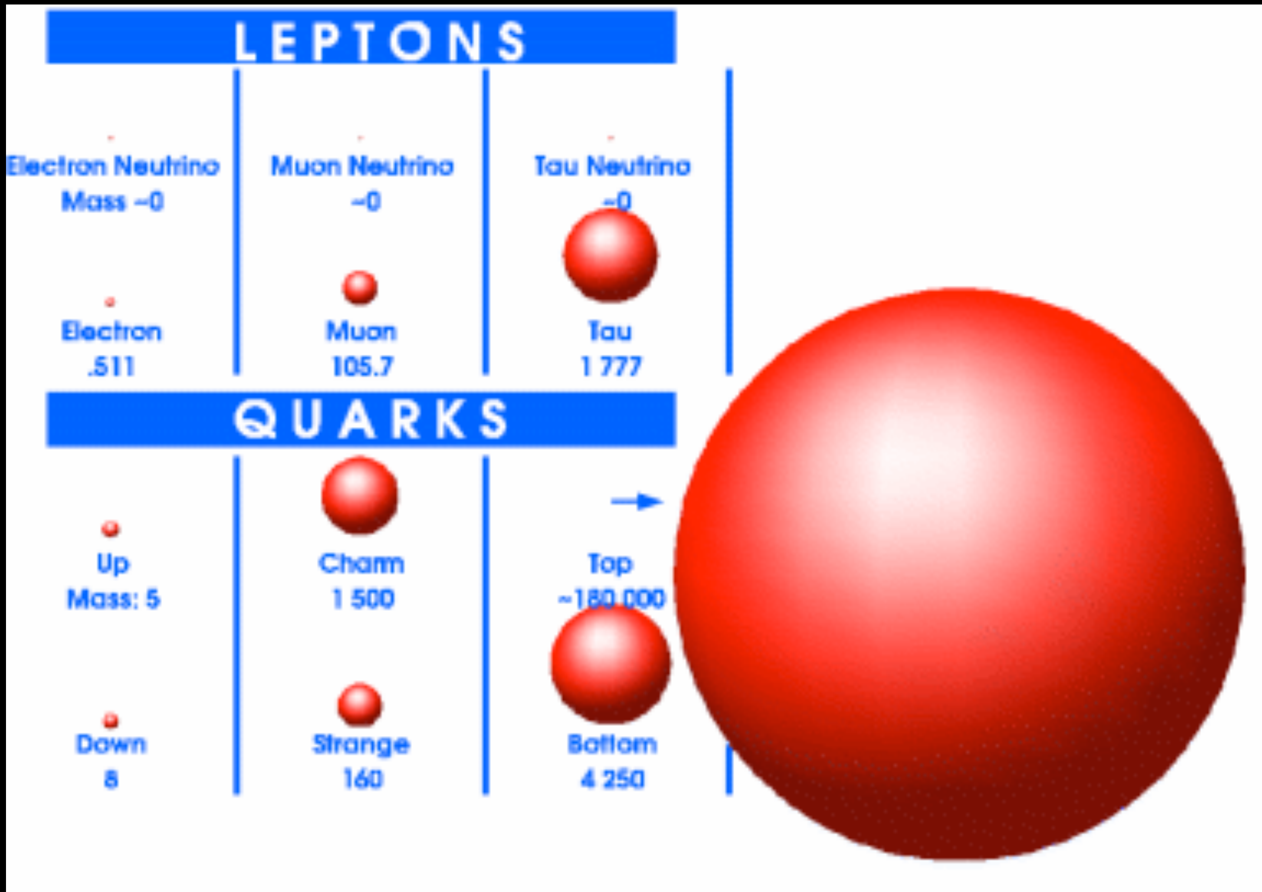
The speakers did an excellent job of providing fair summaries of their topics and referencing the actual work. Here, I am just referencing their talks. Please go to them to find the actual individual references.

Outline

- Inspiration
- Observation
- Characterization
- (More) Observation
- Exploration
- Summary & Outlook

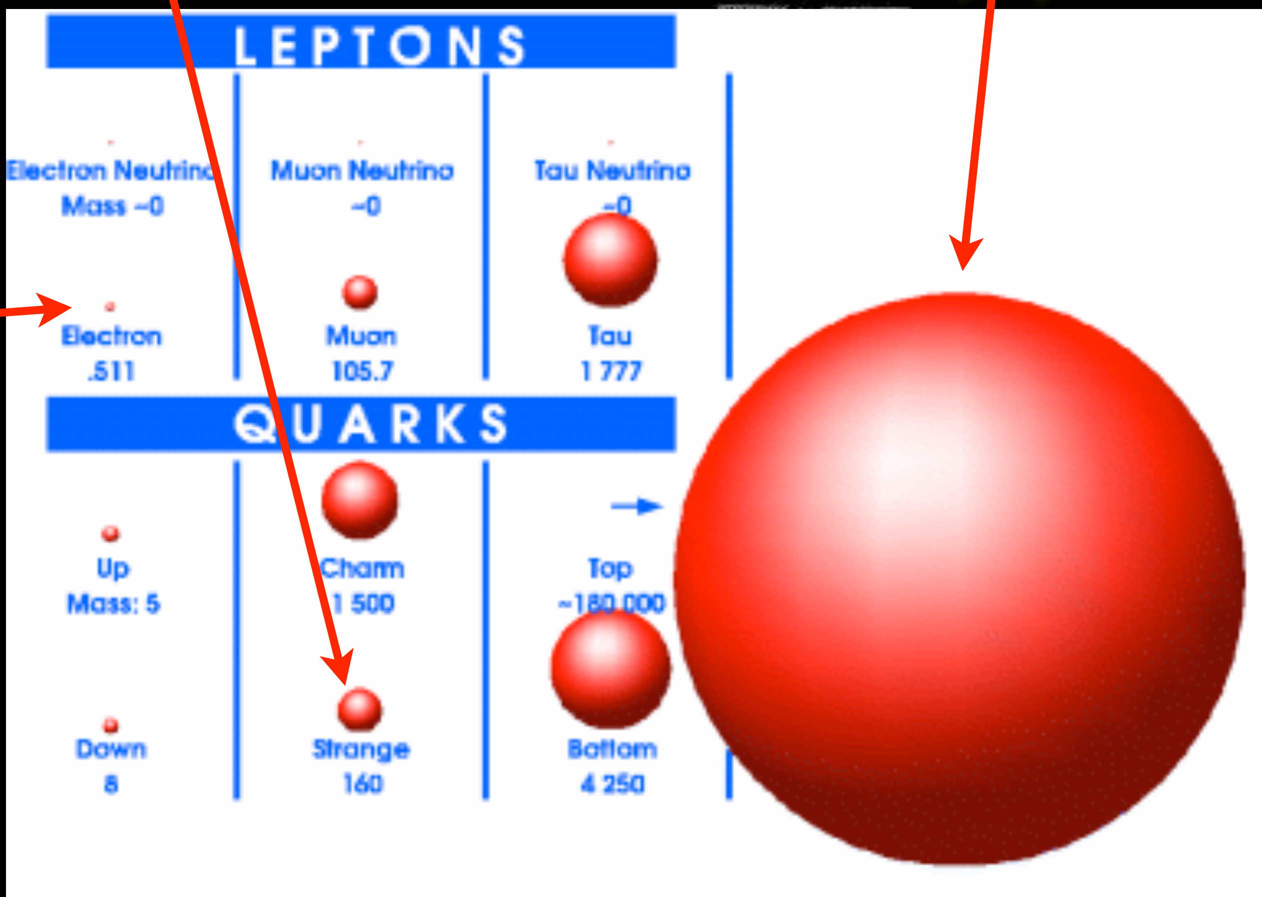
Inspiration

The King of Fermions



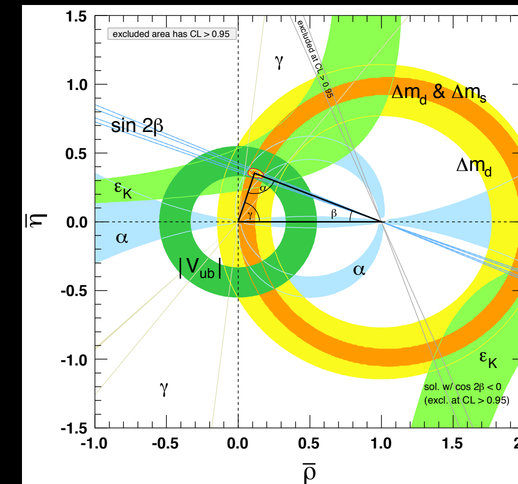
The King of Fermions

I think it is hard not to be inspired when you find something as weird as this.



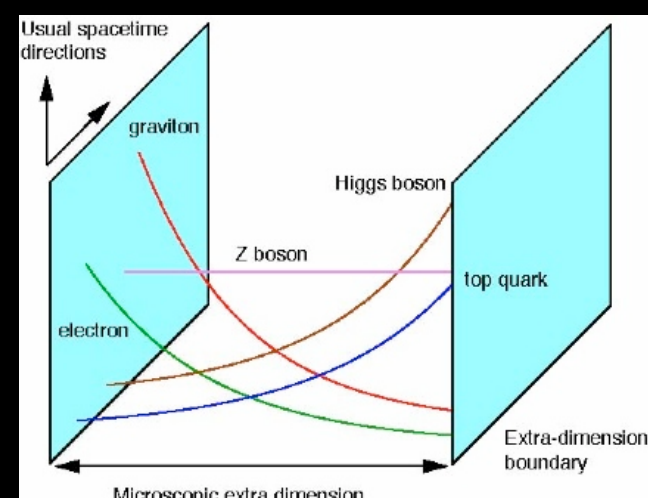
Flavor

- More precisely, the question of flavor is precisely why the top is unusual.
- The masses and mixings of the quarks tell us something fundamental about the Higgs (not W!) couplings.
- This structure seems to beg for some kind of more fundamental explanation.
- Whatever that explanation is, it knows that the top is special.
- We don't know at what scale flavor is selected, but the top may be the key to understanding it.



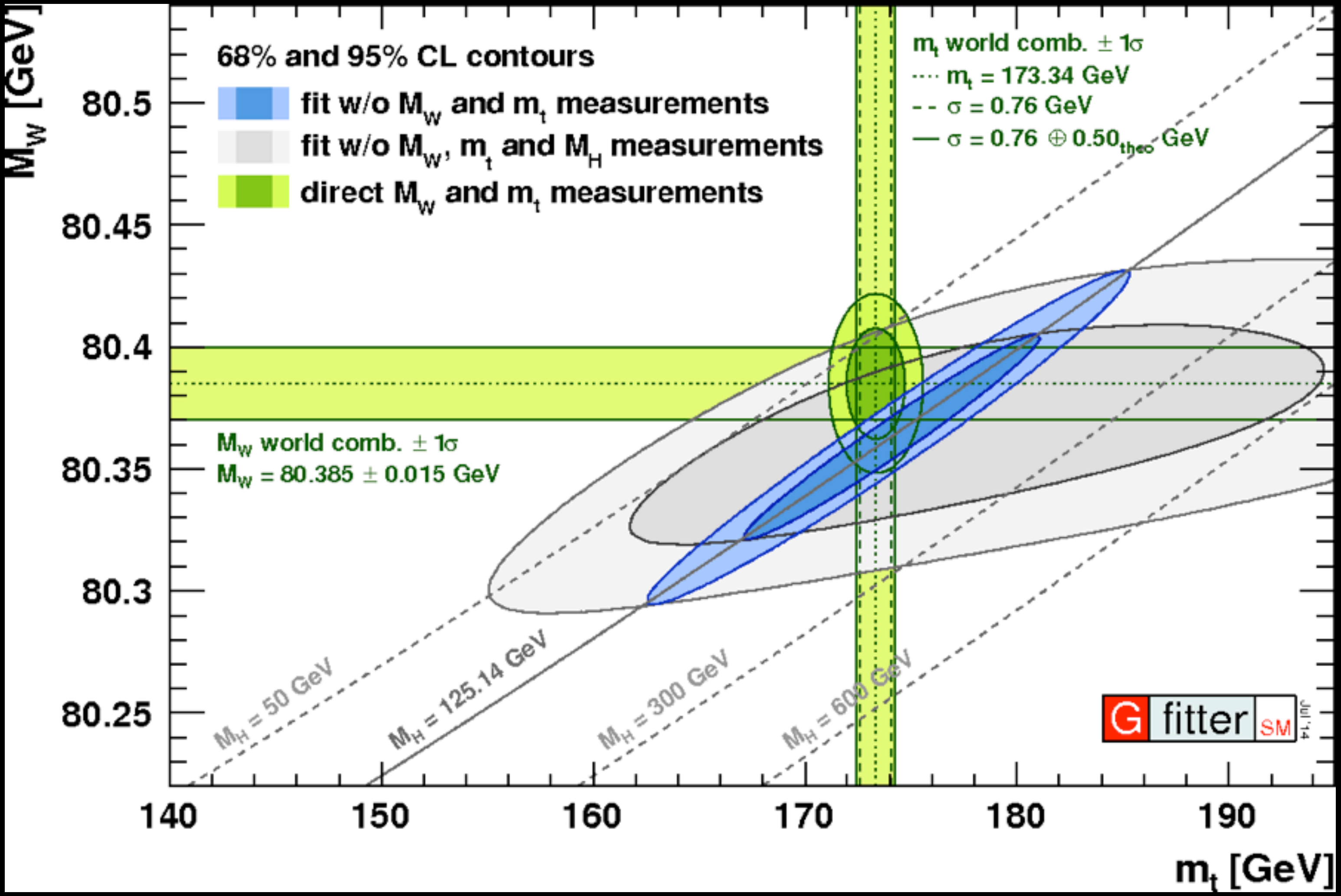
$$\begin{pmatrix} 0.97427 \pm 0.00014 & 0.22536 \pm 0.00061 & 0.00355 \pm 0.00015 \\ 0.22522 \pm 0.00061 & 0.97343 \pm 0.00015 & 0.0414 \pm 0.0012 \\ 0.00886^{+0.00033}_{-0.00032} & 0.0405^{+0.0011}_{-0.0012} & 0.99914 \pm 0.00005 \end{pmatrix}$$

(Assumes Unitarity!)



???

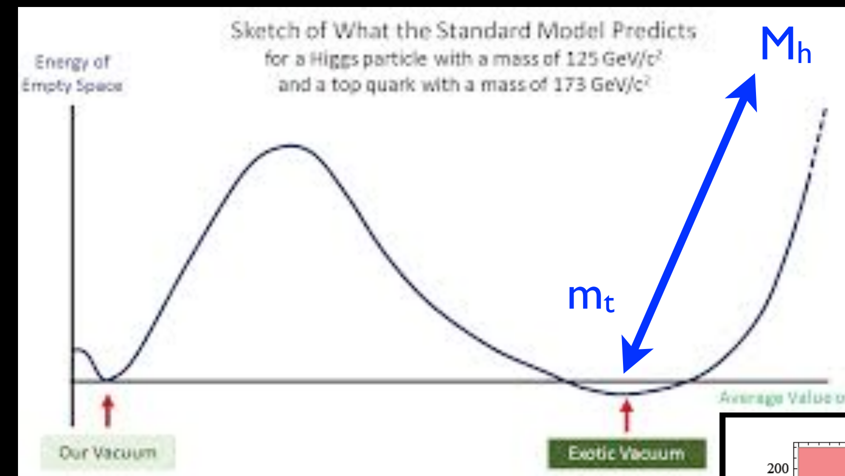
Electroweak Fit



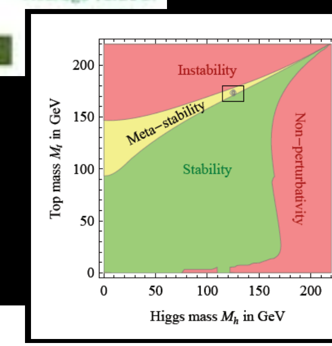
- The top mass is a crucial ingredient into the global fit to the Standard Model.
- The Higgs mass we have been given seems consistent with Mt and MW. This is a huge constraint by itself on many theories of BSM physics.

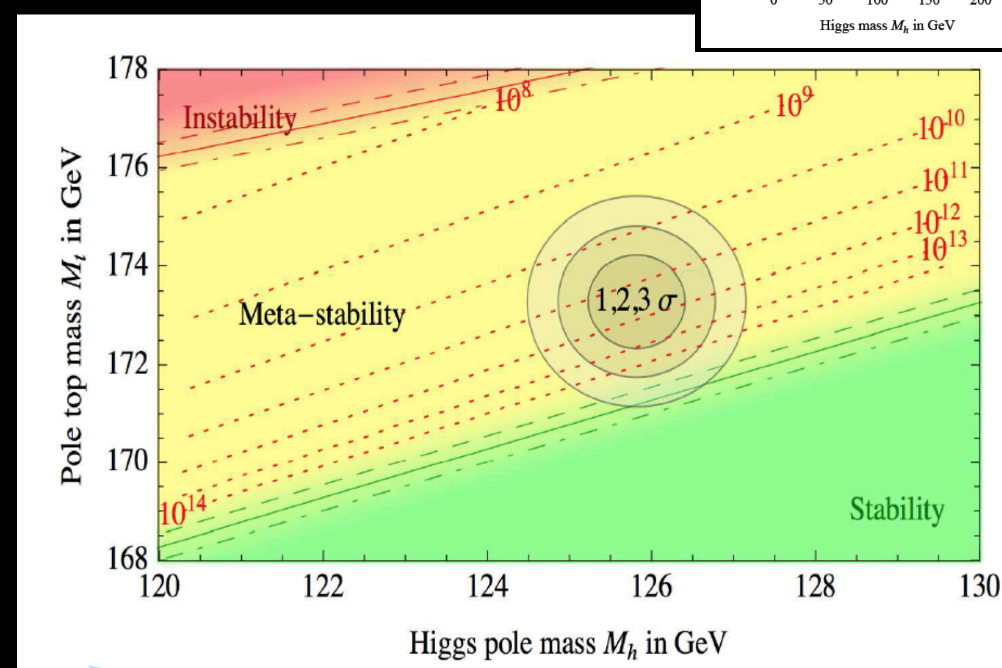
The Fate of the Universe

- Ultimately, the top mass controls the fate of the Universe (in the SM).
- The Higgs potential can be destabilized if the top is too heavy and the Higgs is too light.
- Now that we know the Higgs mass, we can finally ask what this tells us.
- Peversely(?) Nature has chosen a Higgs mass such that we are not entirely sure what this means. It seems that new physics is only *required* at high scales.
- Shifts in the top mass have a large effect on this situation.



Mentioned by Andre, Cedric

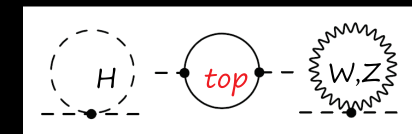




Hierarchy Problem

- The top plays an interesting role in the hierarchy problem.
- Our best theories of quantum gravity include new states at the Planck scale related to the top, such as stringy excitations or Kaluza-Klein modes.
    - These particles inherit the top coupling to the Higgs, and they destabilize the Higgs potential, dragging the weak scale to the Planck scale.
- In other theories, space-time becomes granular or "foamy" at Planck lengths, leading to the same problem.
- Whatever physics protects the electroweak scale from these corrections, it must act particularly on the top sector.

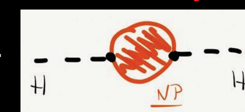
$\delta m_h^2 =$



$\sim -\frac{3Y_{\mathrm{top}}^2}{8\pi^2}\Lambda^2$

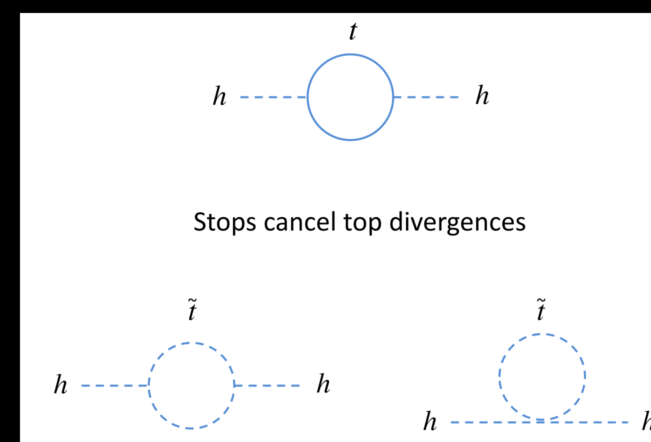
if $\Lambda \gg o(\mathrm{TeV})$ → *Hierarchy problem*

+

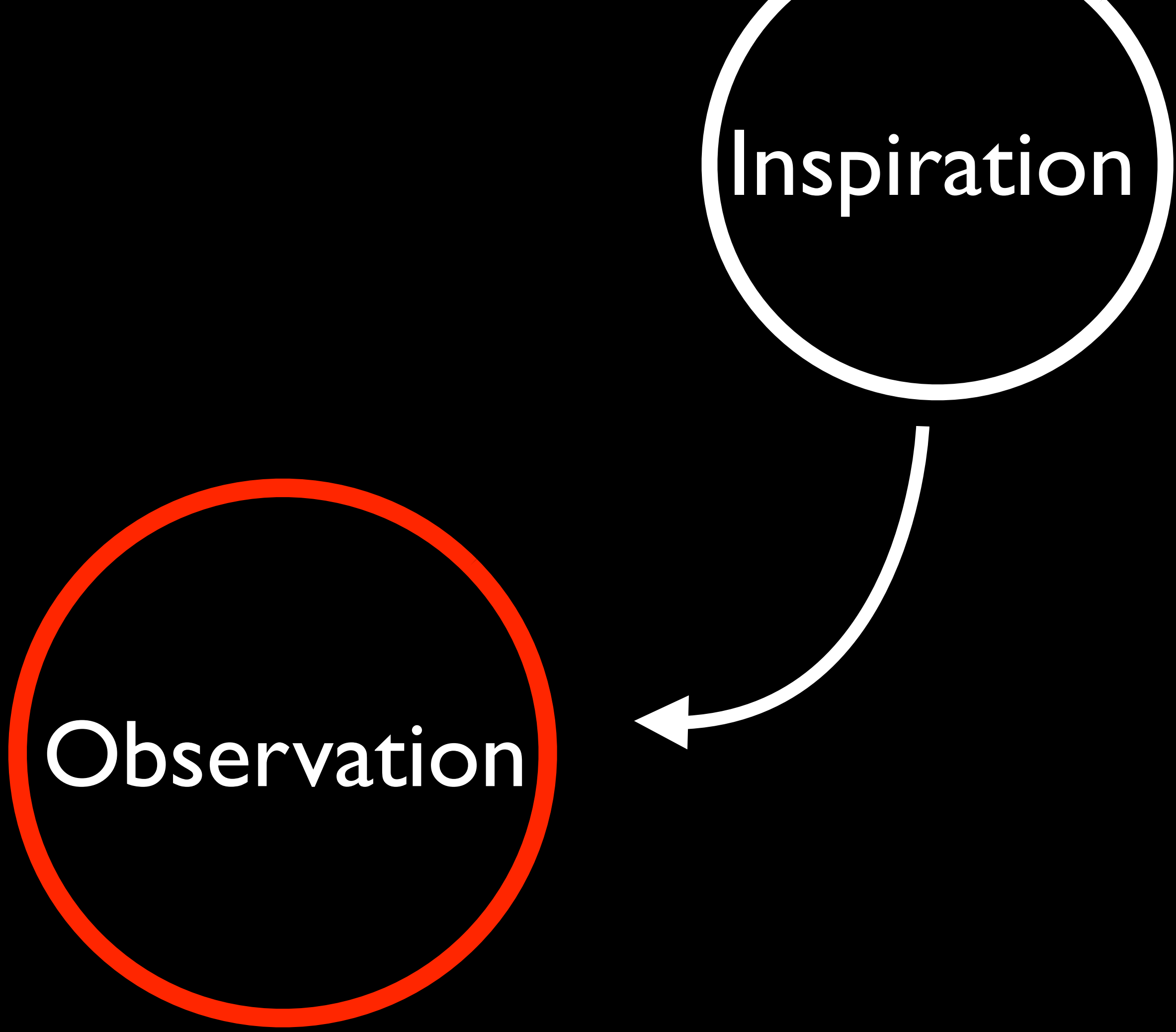


= *log*(Λ) or *finite*

E.g. SUSY:



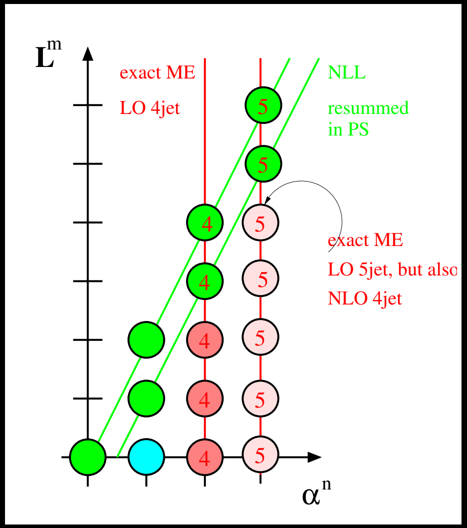
Mentioned by Yevgeny, Cedric



Of course, theorists never really *observe* anything. But experiment requires theory to make the most of its observation. So this section is about how theory plays a role in that process.

The Precision Frontier

- Both Tevatron and LHC have pushed measurements to the point where simple theory no longer has the power to describe the data.
  - Hard processes need NLO or NNLO descriptions, and soft logs need to be resummed (e.g. by the parton shower)
- This is a theme that ran through the entire week.
- Motivated by this, and capitalizing on theoretical advances, theory seems ready to rise the to the challenge.
  - Higher orders are available, and double-counting seems tractable.



Frank Krauss

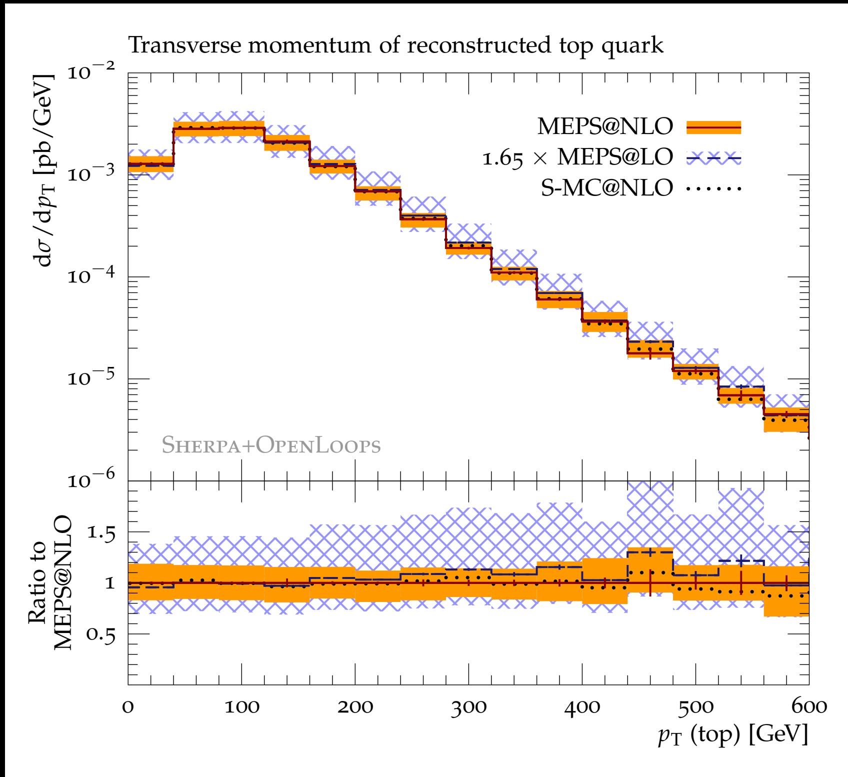
Theoretical Keynote

Multijet-merging at NLO: MEPS@NLO

- basic idea like at LO: towers of MEs with increasing jet multi (but this time at NLO)
- combine them into one sample, remove overlap/double-counting

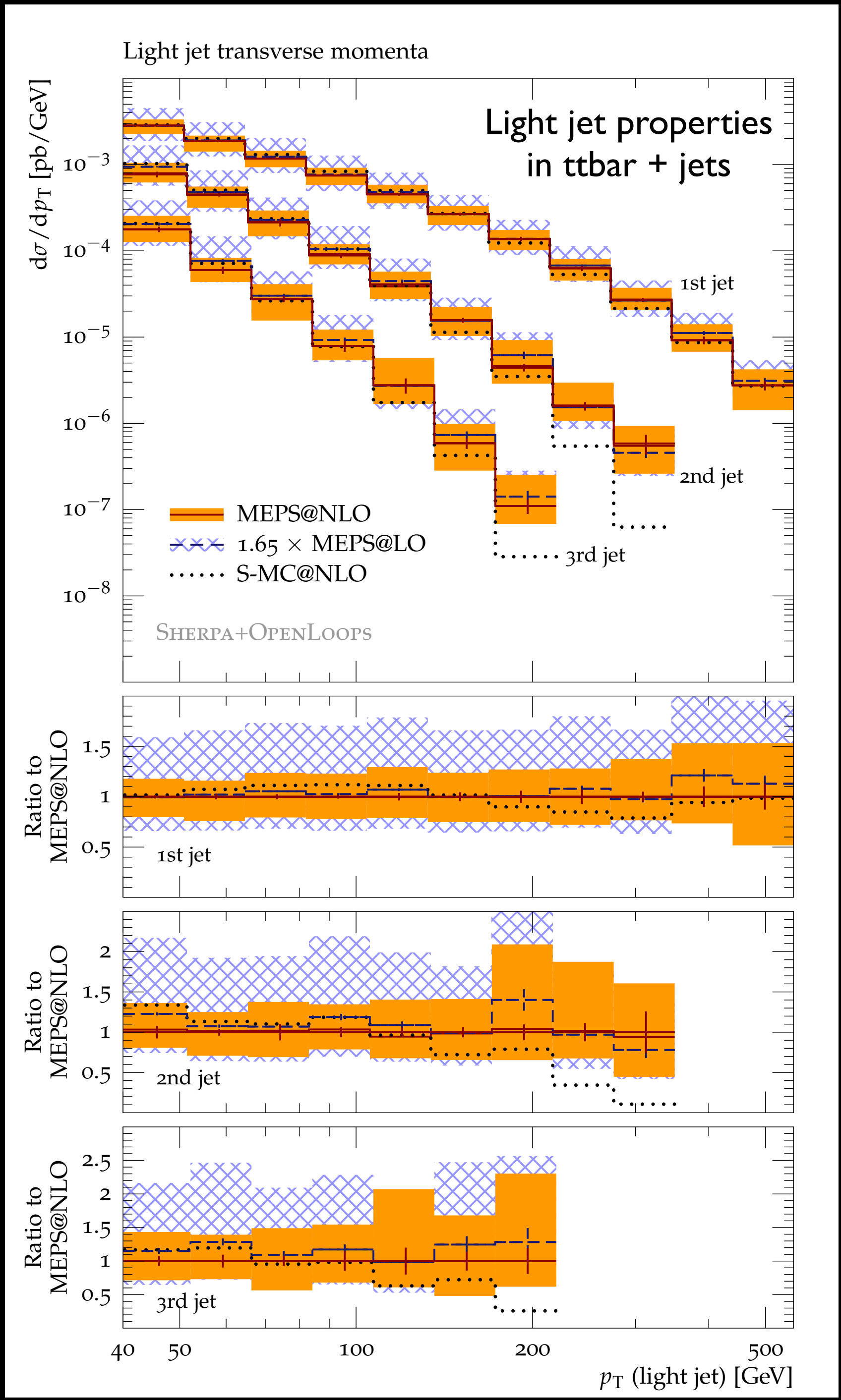
  maintain NLO and LL accuracy of ME and PS

- this effectively translates into a merging of MC@NLO simulations and can be further supplemented with LO simulations for even higher final state multiplicities



The Precision Frontier

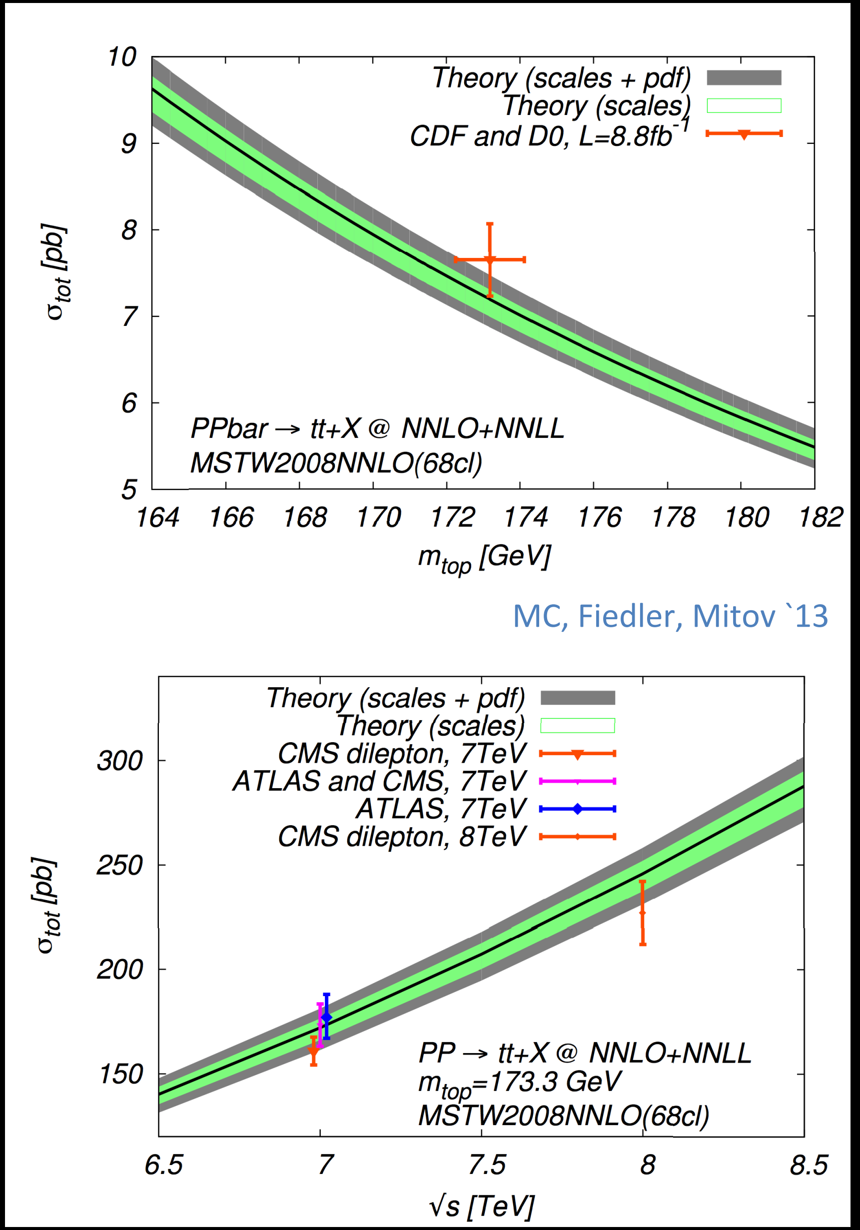
- With higher order improvements comes less dependence on the techniques / Monte Carlo.
    - ...and we saw that for many measurements, MC measuring is a non-negligible part of the systematic budget.
- At the same time, using these codes in complicated analysis is challenging. They are computationally intensive and complicated.
- Still, once modeling dominates the systematics, including the cutting edge codes in analysis is essential to go forward.
- Frank asks for more fiducial cross sections and less correction back to the parton level.



Frank Krauss
Theoretical Keynote

$t\bar{t}$ Production

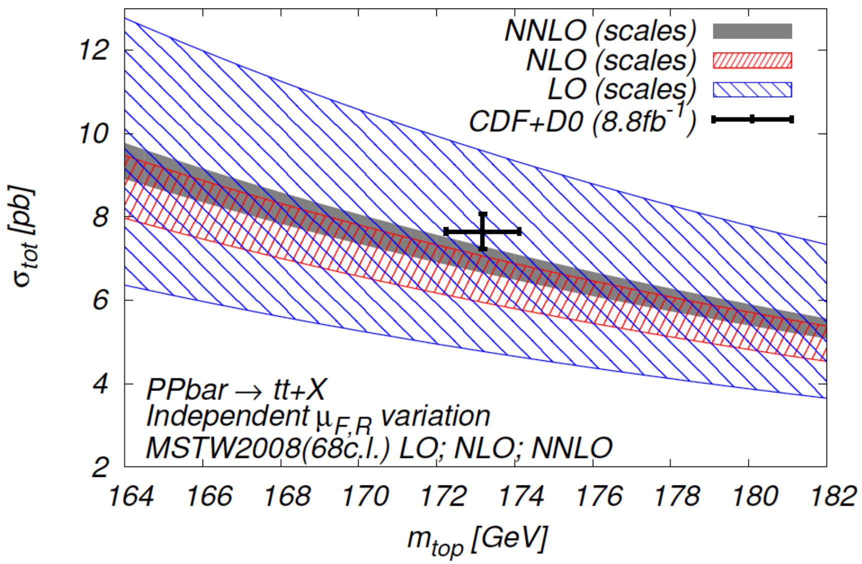
- The inclusive t tbar cross section has been the subject of an intense theoretical campaign.
- Michael Czakon told us about NNLO results which describe the data very well.
- Theory uncertainties on this quantity have reached a few percent.
- It's pretty amazing that a single computation can describe ~2 TeV (ppbar) and ~8 TeV (pp) data so well, given the differences in the important subprocesses of the two colliders.
- Progress on differential quantities advances as well (more about that soon).

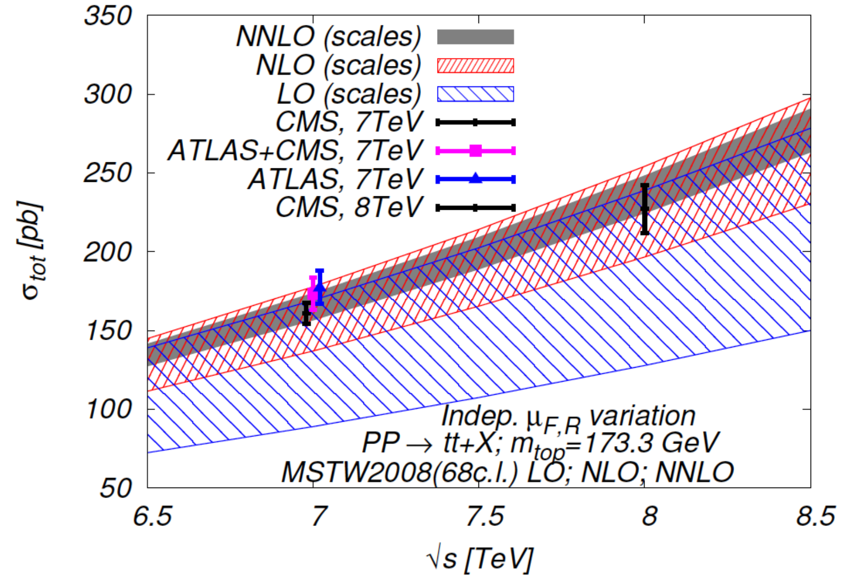


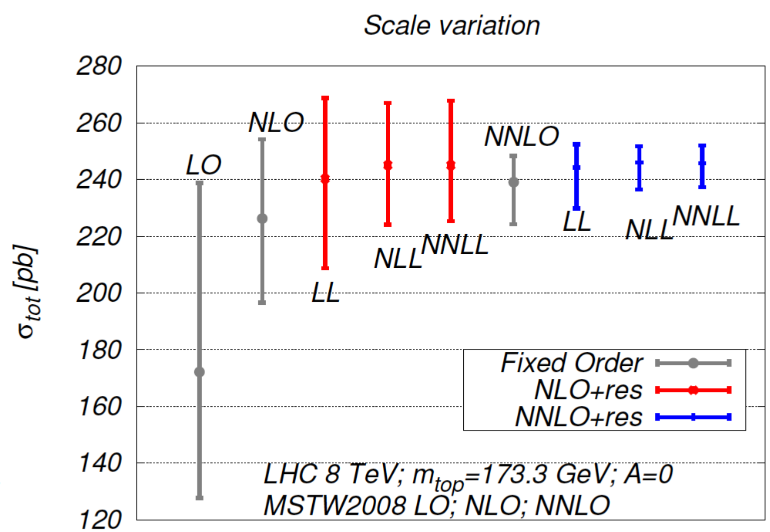
Michael Czakon

T Tbar Production

$t\bar{t}$ Production







Concurrent uncertainties:

Scales	~ 3%
pdf (at 68%cl)	~ 2-3%
α_S (parametric)	~ 1.5%
m_{top} (parametric)	~ 3%

Soft gluon resummation makes a difference:

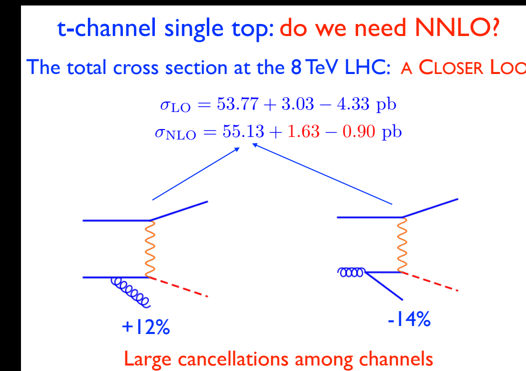
5% -> 3%

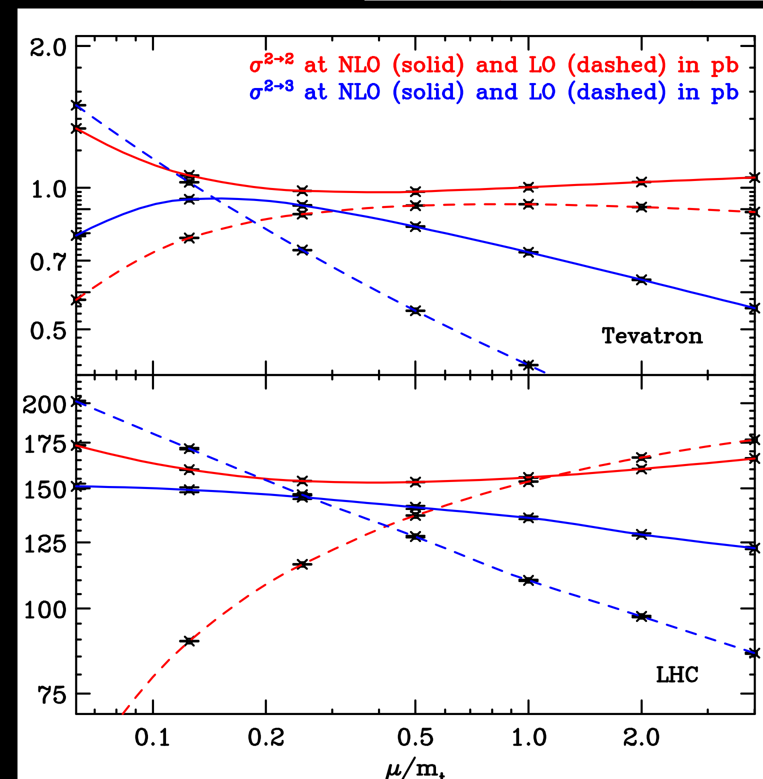
Note the importance of resummation.

Michael Czakon
T Tbar Production

Single Top Production

- Fabrizio Caola told us about the latest effort to bring calculations of the single top t-channel process to NNLO.
- There is an interesting lesson to be had: NLO looks like a tiny correction, but if one looks closer one sees indications that the higher order is necessary.
- This is seemingly due to a large accidental cancellation.
  - It is not the net correction, but the scale variation of its components which characterizes the uncertainties.
  - Another indication is larger scale variation for differential quantities.





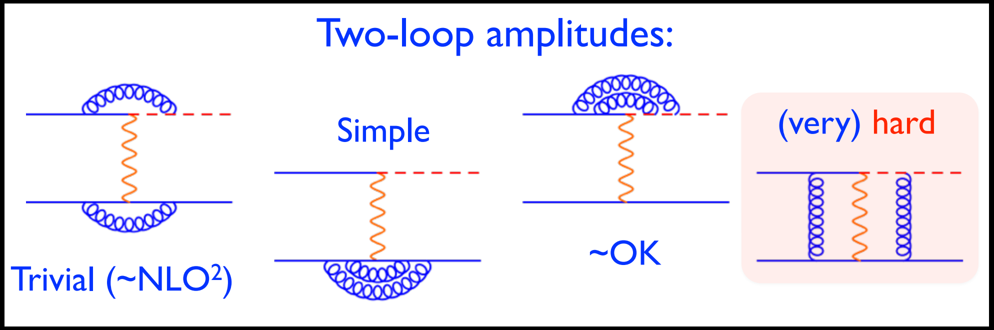
[Campbell et al (2009)]

Fabrizio Caola

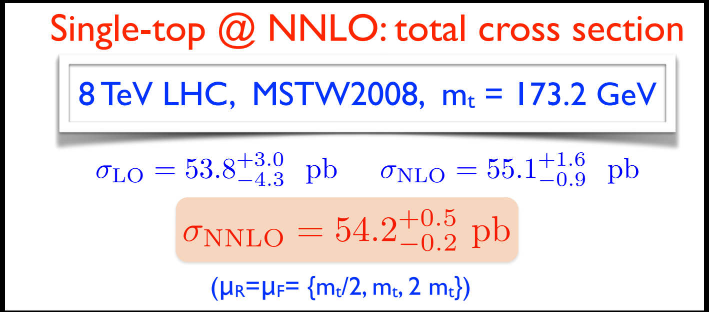
Single Top Production

Single Top Production

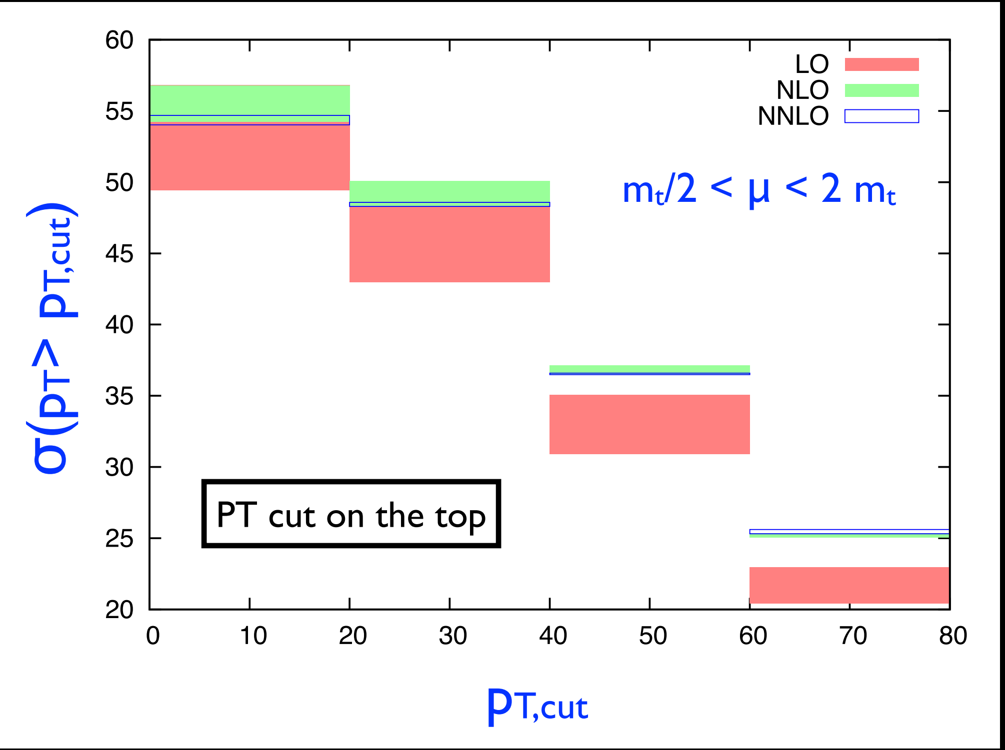
- Fabrizio presented an almost complete NNLO determination of t-channel single top production



- Sure enough, the net NNLO correction to the rate is not suppressed compared to the NLO correction
  - Remember, we do higher orders not to get a different number, but to get a smaller uncertainty!



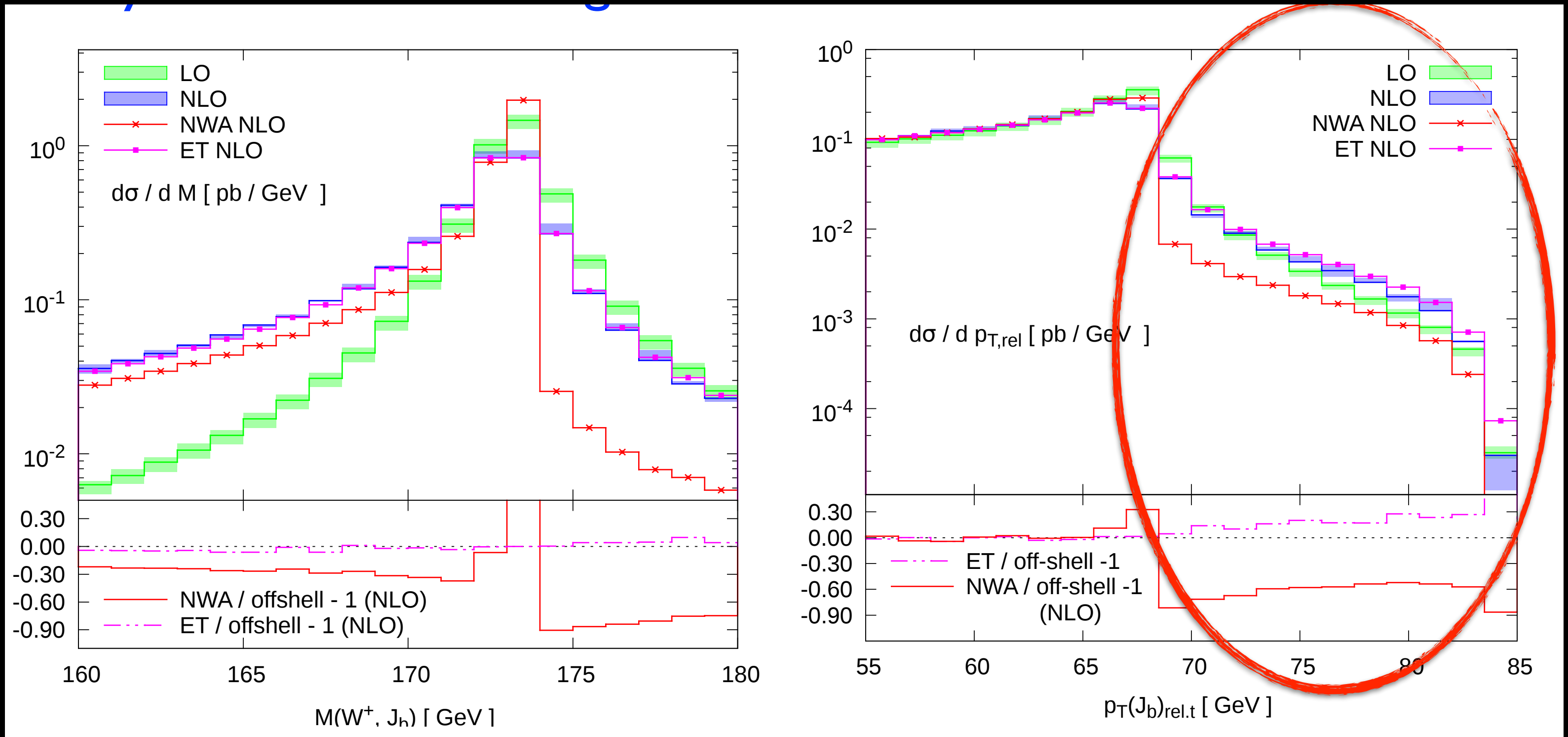
- Differential rates are also described much more accurately, and uncertainties are stable even in differential quantities.



Fabrizio Caola

Single Top Production

Single Top + NWA



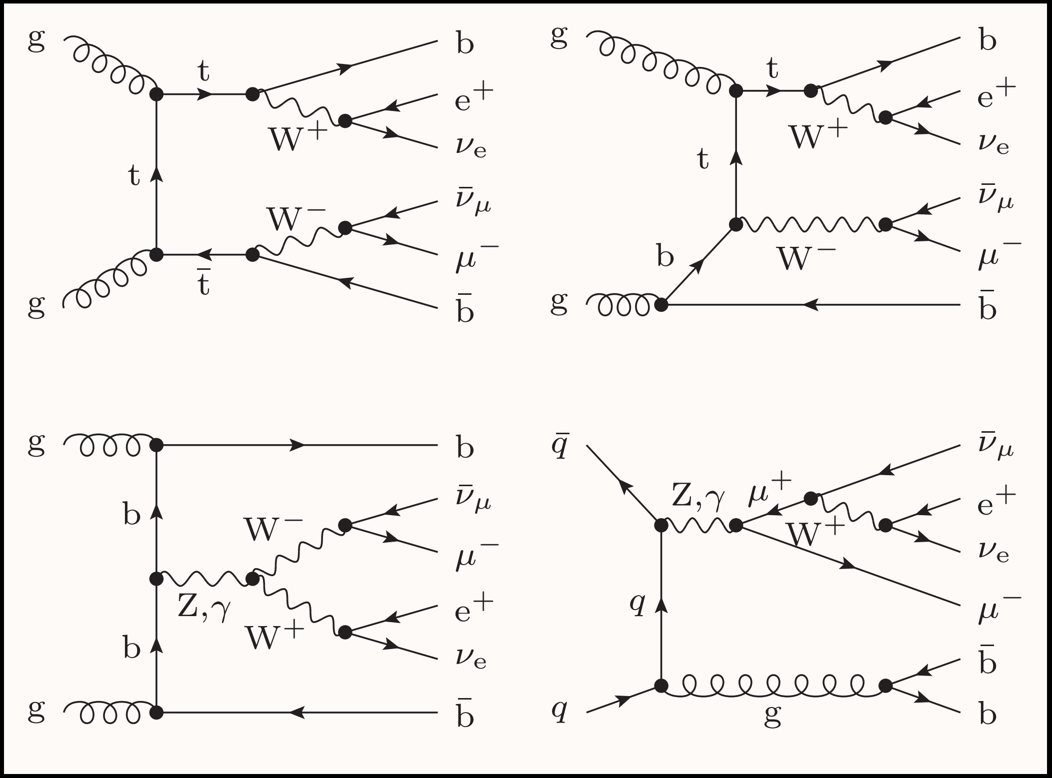
[Papanastasiou, Frederix, Frixione, Hirschi, Maltoni (2013)]

Fabrizio Caola
Single Top Production

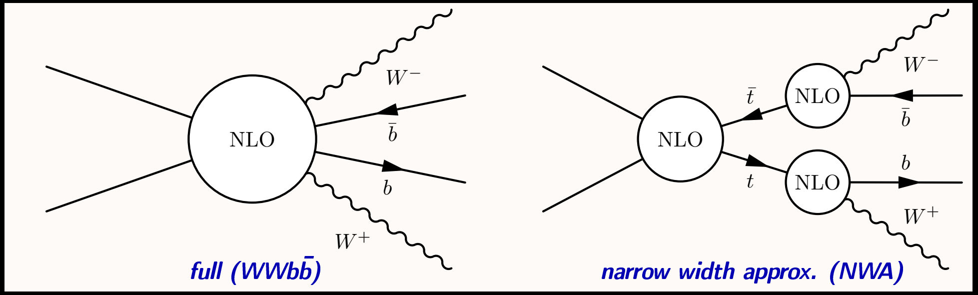
- Many tools treat the top quark as on-shell. As we get to % level measurements, Γ/M ~ 1% effects become important to include.
- The effects are very kinematic-dependent, with regions where it works fine, but also regions where it fails, particularly observables like M_{Wb} and beyond kinematic edges.

Quantum Mechanics

- Quantum mechanics allows us to ask about given initial states and measurable final states.
- The prompt top decay implies that we cannot really think of processes containing top separately from other EW ones.
    - E.g. WWbb vs Wt vs t t
- Resonant regions dominate, but as precision increases, interference cannot be neglected, particularly at higher orders.



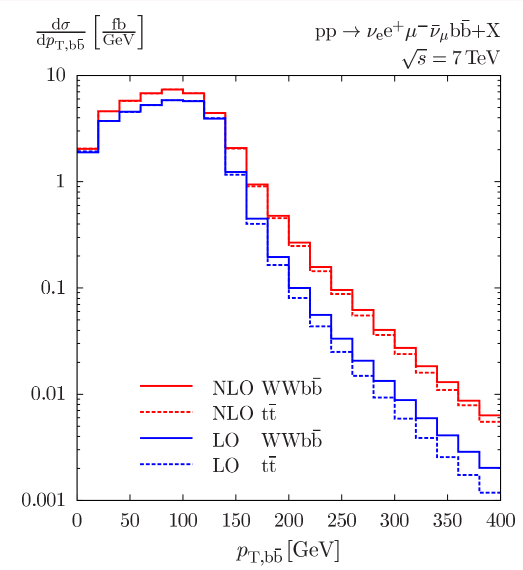
Jan Winter
WbWb at NLO



(Also comments by Frank, Fabrizio)

WbWb @ NLO

- We can see the importance of these effects comparing a full WbWb treatment to one which treats the top quark decay as separated out.
- Distributions show differences, especially when the kinematics pull (at least one of) the tops off-shell.
- But there are also important impact on distributions such as M_{lb}, which impact some of the top mass measurements.



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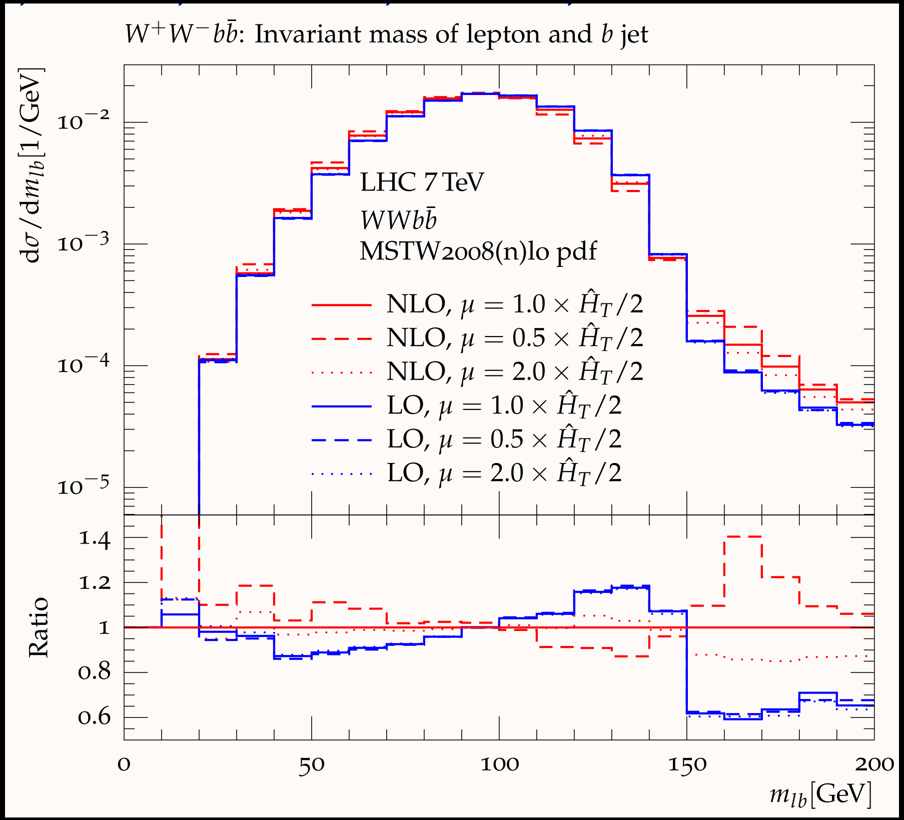
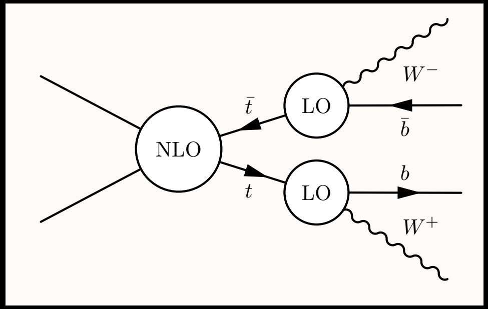
WbWb at NLO



This is Important



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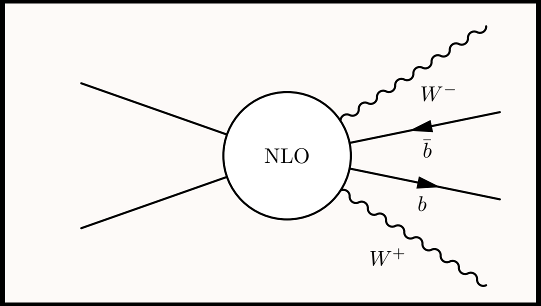
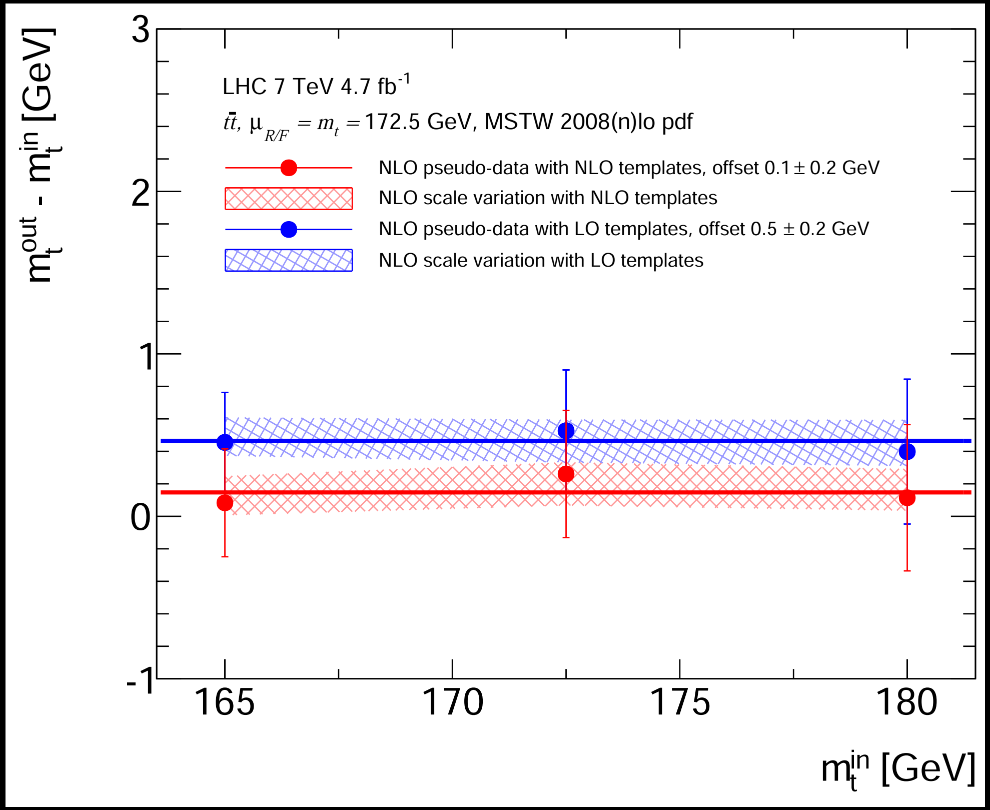
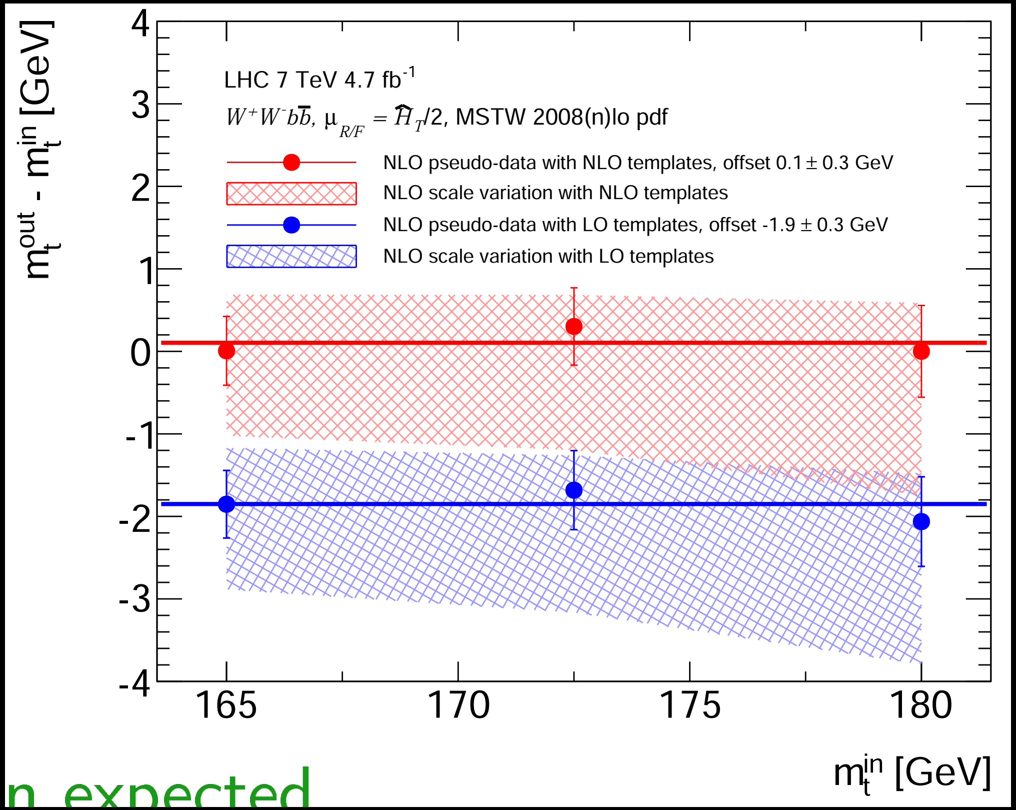
WbWb at NLO



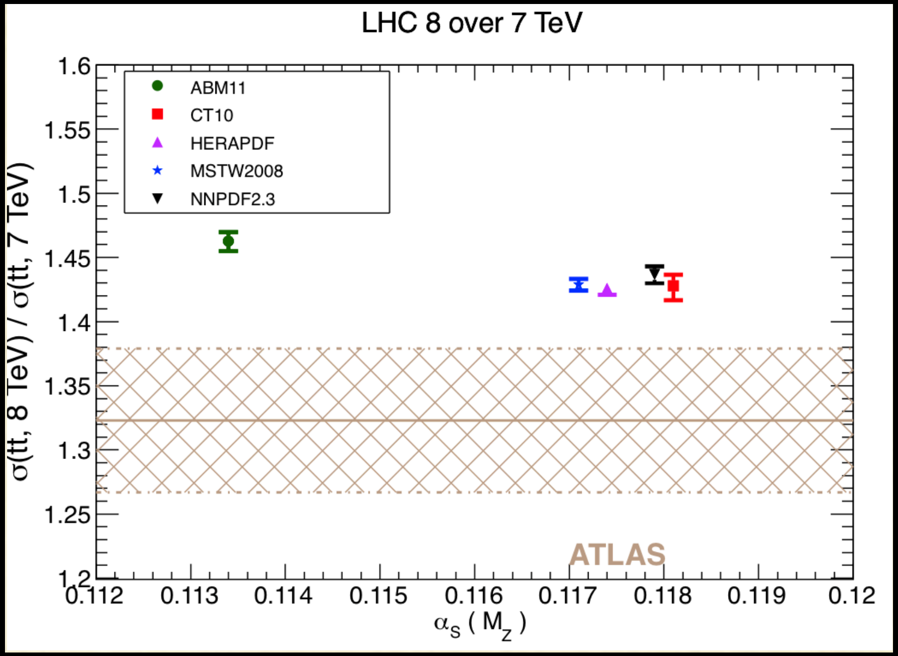




[Heinrich, Maier, Nisius, Schlenk, Winter, arXiv:1312.6659]

Mysteries Remain

- As tools and data improve, we can never stop validating our simulations.
  - This is not just because we need to calibrate them to better accuracy, but because as we go to more advanced observables, we may find flaws in the existing technology or procedures.
  - Our theory tools are sometimes missing physics. Puzzles in secondary quantities is often how we realize this.
- Alex Mitov showed us an example where things do not seem to work quite as we hoped; despite the inclusive measurements of ttbar describing well 7 and 8 TeV data, the ratio seems off by more than the expected uncertainties.

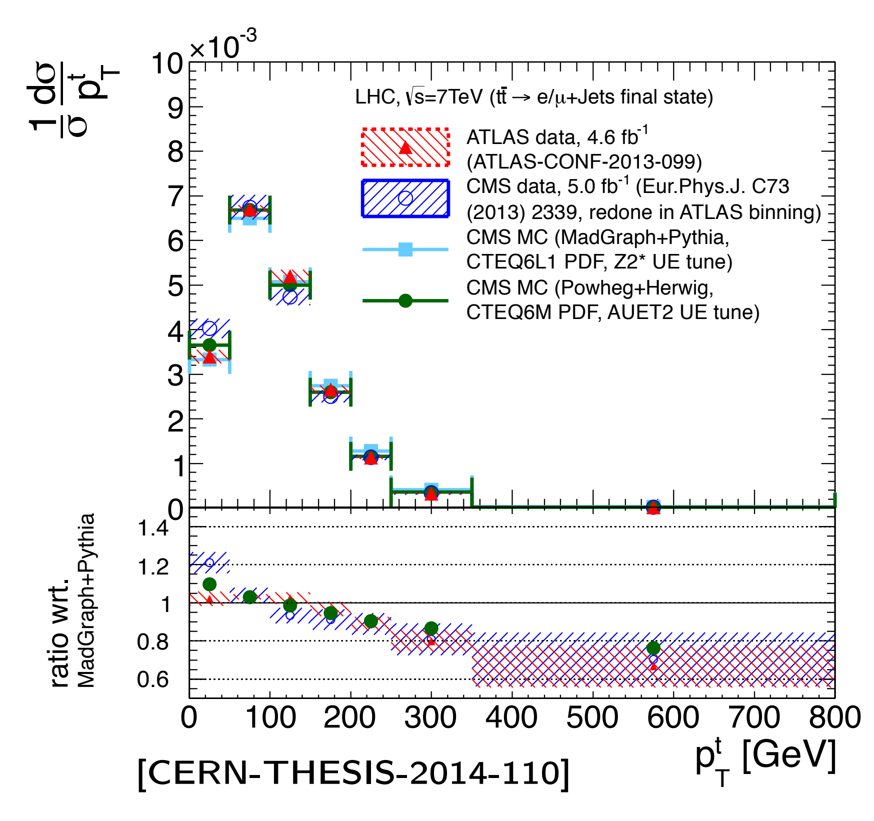


Alex Mitov

MC Workshop Summary

Mysteries Remain

- Another quantity that was discussed several times at the workshop by many speakers was the PT distribution of the top quark in top pair production.
- Here, we seem to see a systematic shift between tools and data at the highest PTs.
- Is this a sign that at the highest PTs, we think about this process in a fundamentally flawed way?
  - Is this "jets + ttbar" instead of "ttbar + jets"?
- Obviously this is something that needs to be understood as we go to higher energy and luminosity.



Markus Seidel
Theory Systematics

Systematics

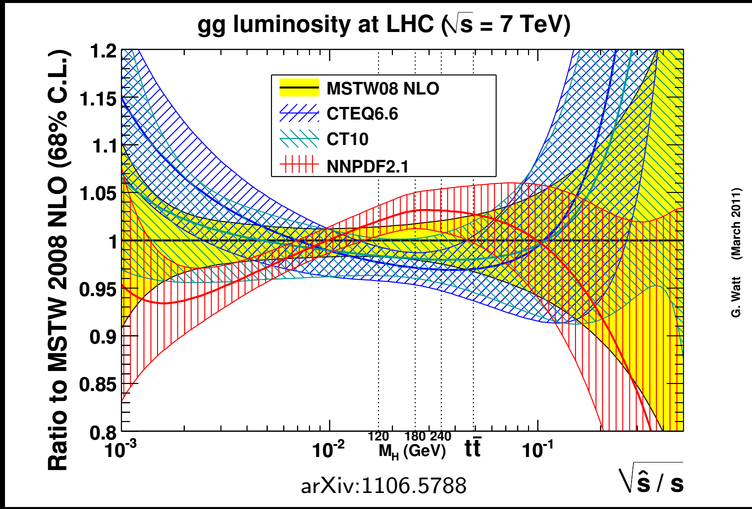
Markus Seidel

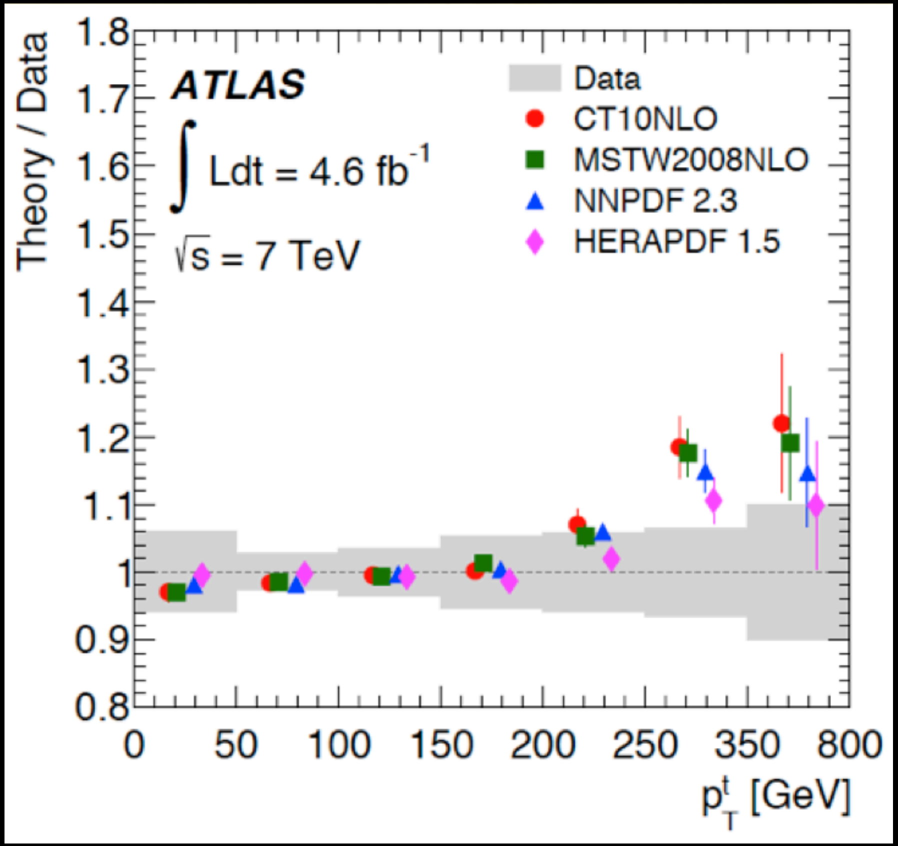
Theory Systematics

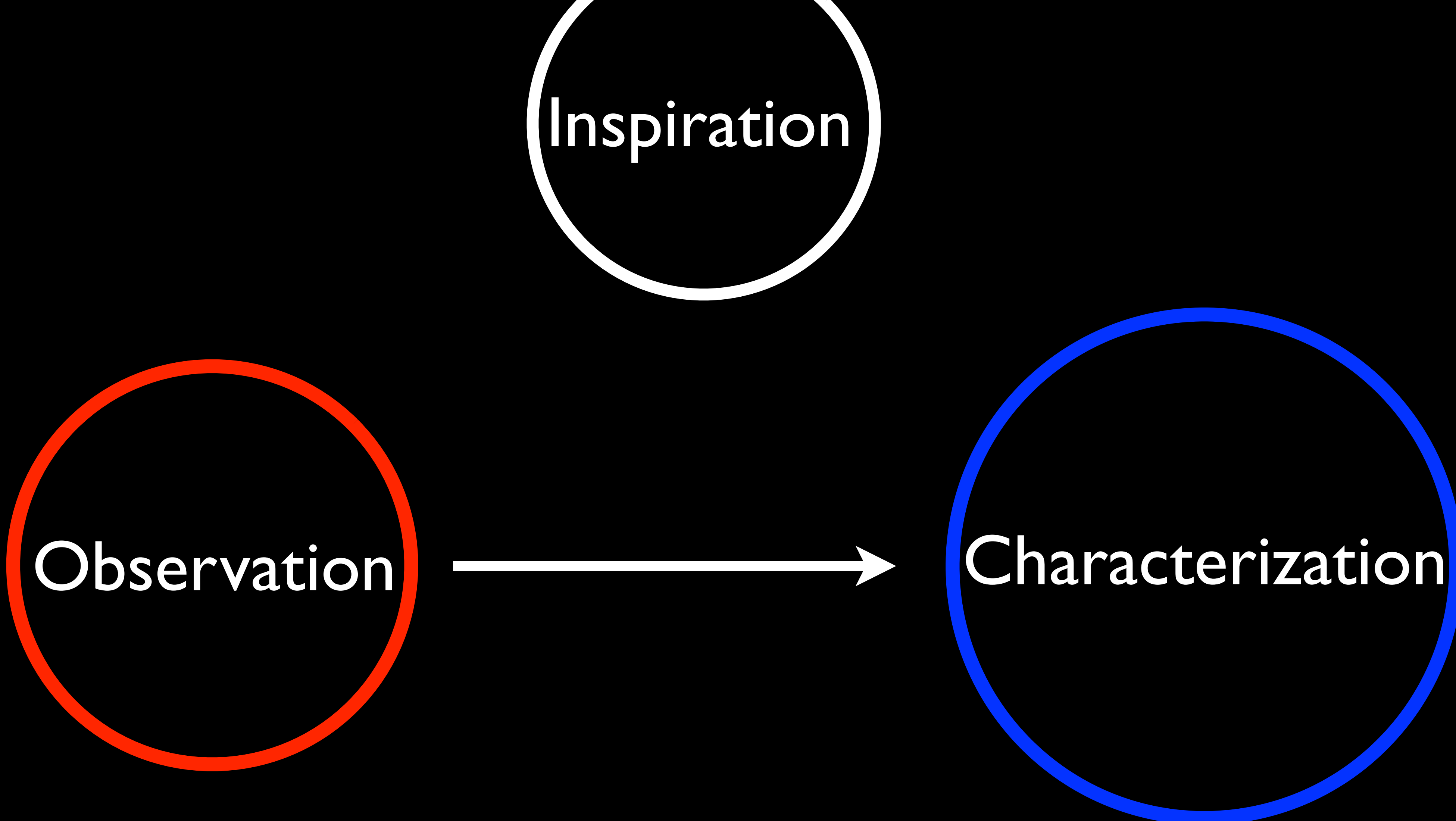
- The theory systematics are not just a source of mystery, but also an opportunity.
- Top provides a place where precision measurements can improve inputs, which may have implications beyond top physics itself.
- For example, top observables may ultimately help improve the PDF fits to the gluon density at large(ish) x.
- This could be very helpful, e.g. in precision Higgs physics.

Alex Mitov

MC Workshop Summary







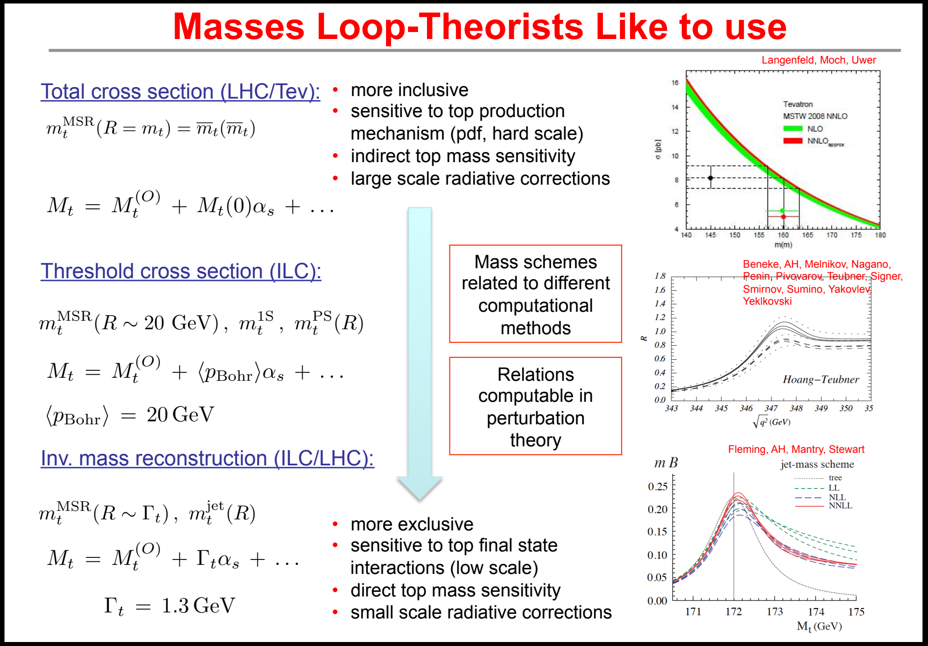
Once basic observations are under control, we want to characterize what these imply for fundamental properties.

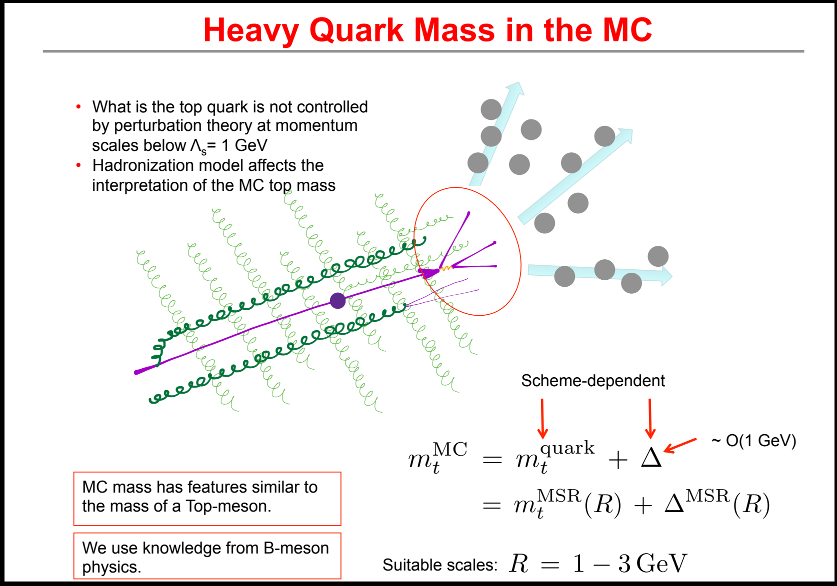
What is Mt?

- The top mass, like any parameter in the Lagrangian, must be connected to observables through calculation.
- In the perturbative regime, this is a problem we can solve in perturbation theory.
- Monte Carlo involves low energy scales (hadronization), this introduces an uncertainty in matching what the MC means by Mt compared to any other definition.
- Since this part is modeled, and not under control, there are uncertainties of order GeV associated with it.
- Precision versus accuracy.

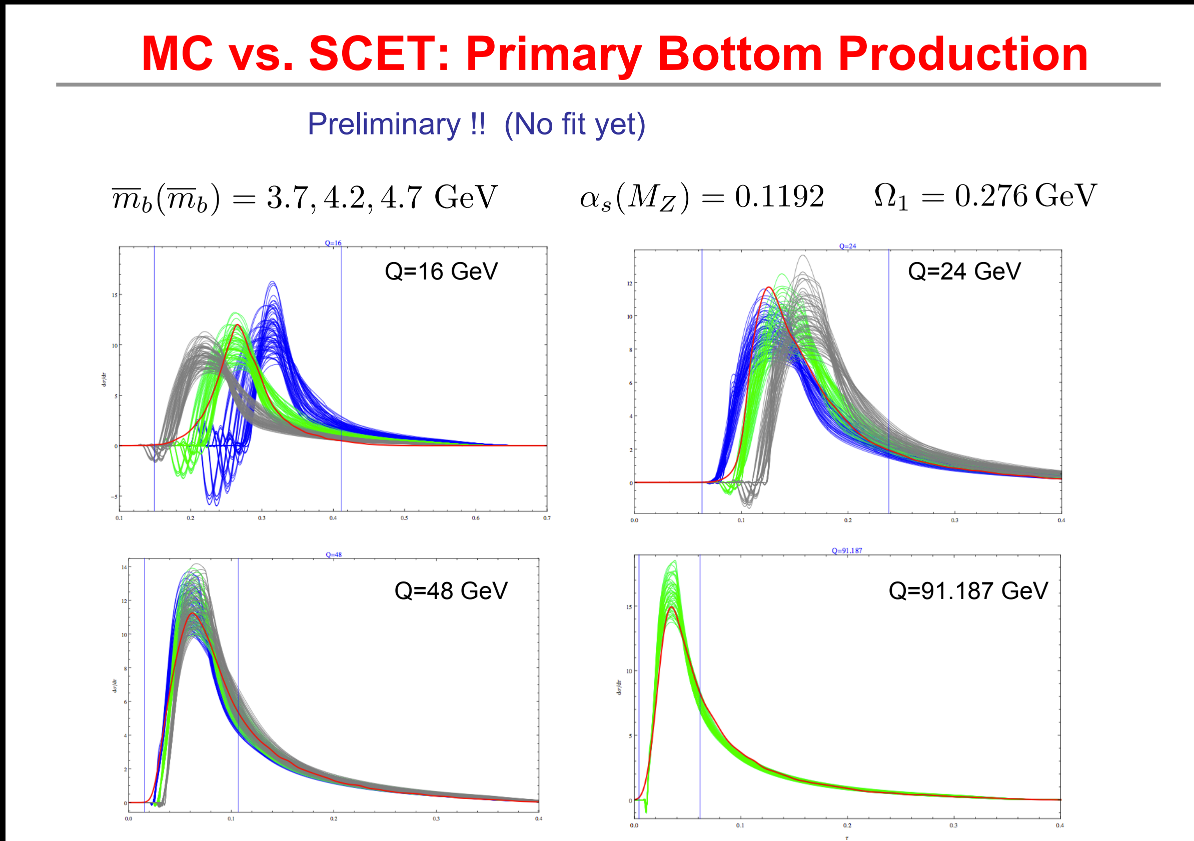
Andre Hoang

Top Mass Interpretation





What is Mt?



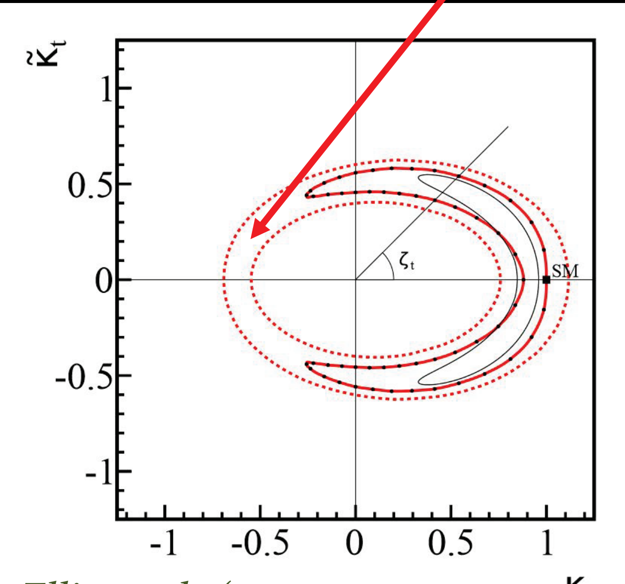
Andre Hoang

Top Mass Interpretation

- Andre proposes to determine the meaning of the mass inside a Monte Carlo program.
- To begin with, he examines the bottom mass in e+e- collisions, as an easier but obviously related problem.
- He performs his own computation of the kinematics of the process using SCET, and compares with MC to see where they match.

Top Yukawa Coupling

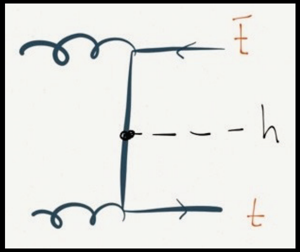
- The top Yukawa coupling is a fundamental quantity that has great importance in both the SM and theories going beyond it.
- Nominally the inclusive Higgs production tests its value, but this is degenerate with other quantities such as an intrinsic coupling mediated by new heavy particles.
- There is plenty of room for surprises, and the obvious way to access this coupling directly is to access direct probes such as ttbar+H or single top + H.



Ellis et al., '14

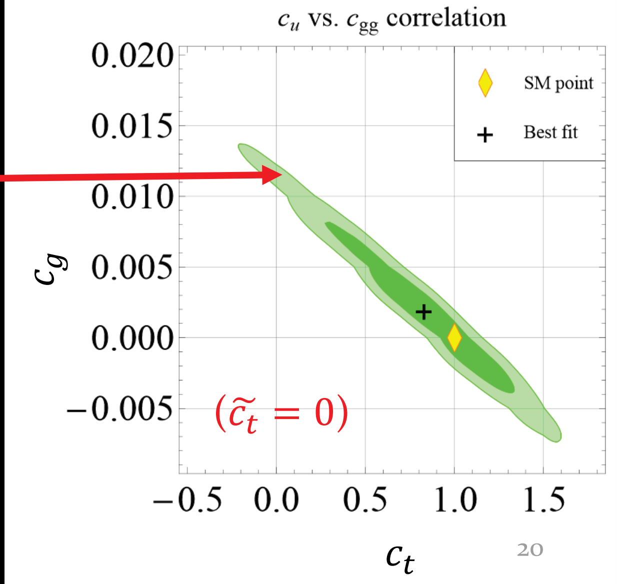
Brod-Haisch-Zupan, '13

NB: Our determination of the Higgs as a "CP even scalar" in no way prevents the pseudo-scalar coupling of this type.



Falkowski et al. '12

latest results from Belúsca-Maïto RPP2014



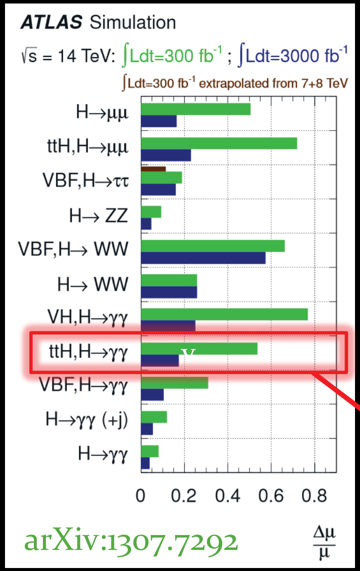
Cedric Delaunay

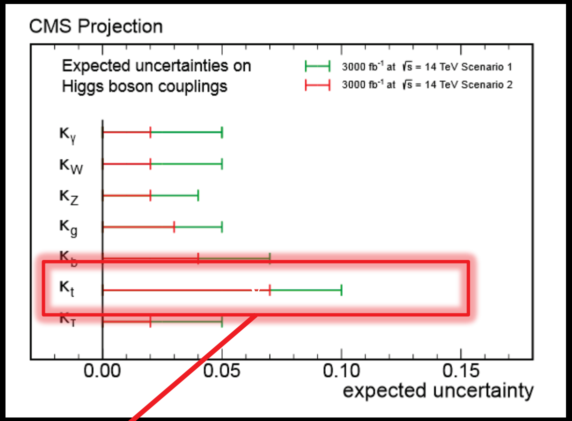
ttH Theory

Top Yukawa Coupling

- The prospects for ttH are excellent. O(10%) measurements are eventually possible.
- There are also prospects for the inclusive Higgs channel in the very boosted regime. This resolves the top quark loop. Once it no longer looks point-like, it can be kinematically distinguished from contributions by heavier colored particles such as top partners.

$(\sigma_h^{14\text{TeV}} \approx 2.6 \times \sigma_h^{8\text{TeV}})$





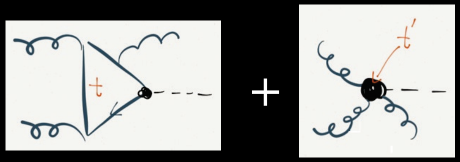
$\Delta c_t/c_t \approx 10\%$ by ~2030

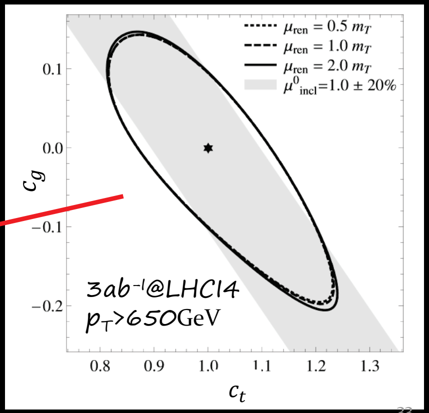
(ILC: ~5%)

Very boosted Higgs production:

Grojean-Salvioni-Schlaffer-Weiler '13
see also Banfi-Martin-Sanz '13

requiring $p_T^{\text{Higgs}} > m_{\text{top}}$ resolves the top loop and lift up the degeneracy w/ partners





$\Delta c_t/c_t \approx 20\%$

same ballpark as tt+h channel

Cedric Delaunay
ttH Theory

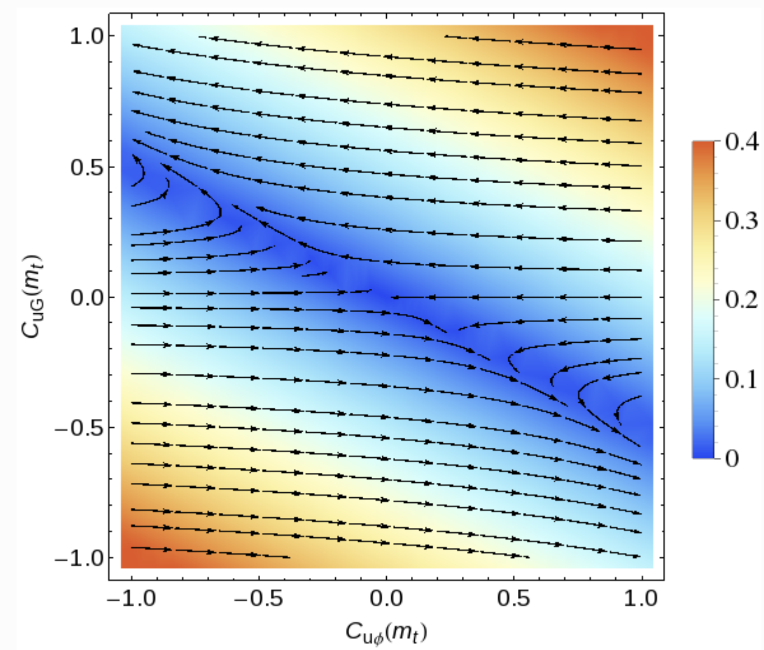
Effective Lagrangians

- Effective Lagrangians are powerful ways to capture new physics effects when the particles that mediate them are heavy, above the energies we probe.
- In a top decay, that energy is the top mass. In a production process, it is usually larger.
- Cen wrote down several complete sets of "dimension six" operators that were both flavor-violating and flavor conserving.
- He demonstrated that at higher order, the operators bleed into one another, and mix.

Operators

$$O_{uG}^{(13)} = y_t g_s (\bar{q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}$$
$$O_{uW}^{(13)} = y_t g_W (\bar{q}\sigma^{\mu\nu} \tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$
$$O_{uB}^{(13)} = y_t g_Y (\bar{q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$
$$O_{u\varphi}^{(13)} = -y_t^3 (\varphi^\dagger \varphi)(\bar{q}t)\tilde{\varphi}$$

Mixing between color-dipole and Yukawa



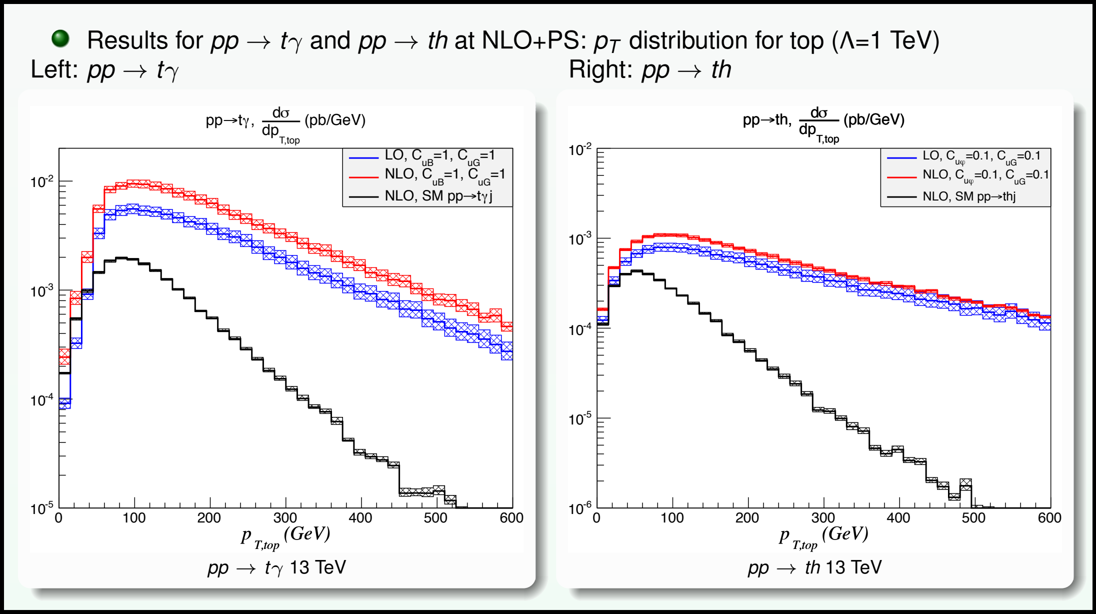
Scale corresponds to the change from m_t to 2 TeV.

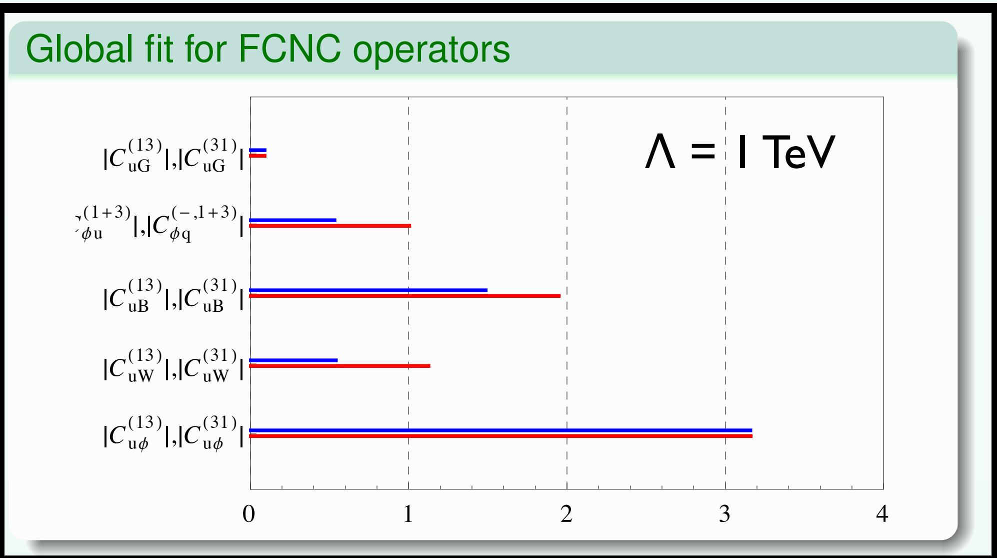
Cen Zhang

New Physics in Top Couplings

Effective Lagrangians

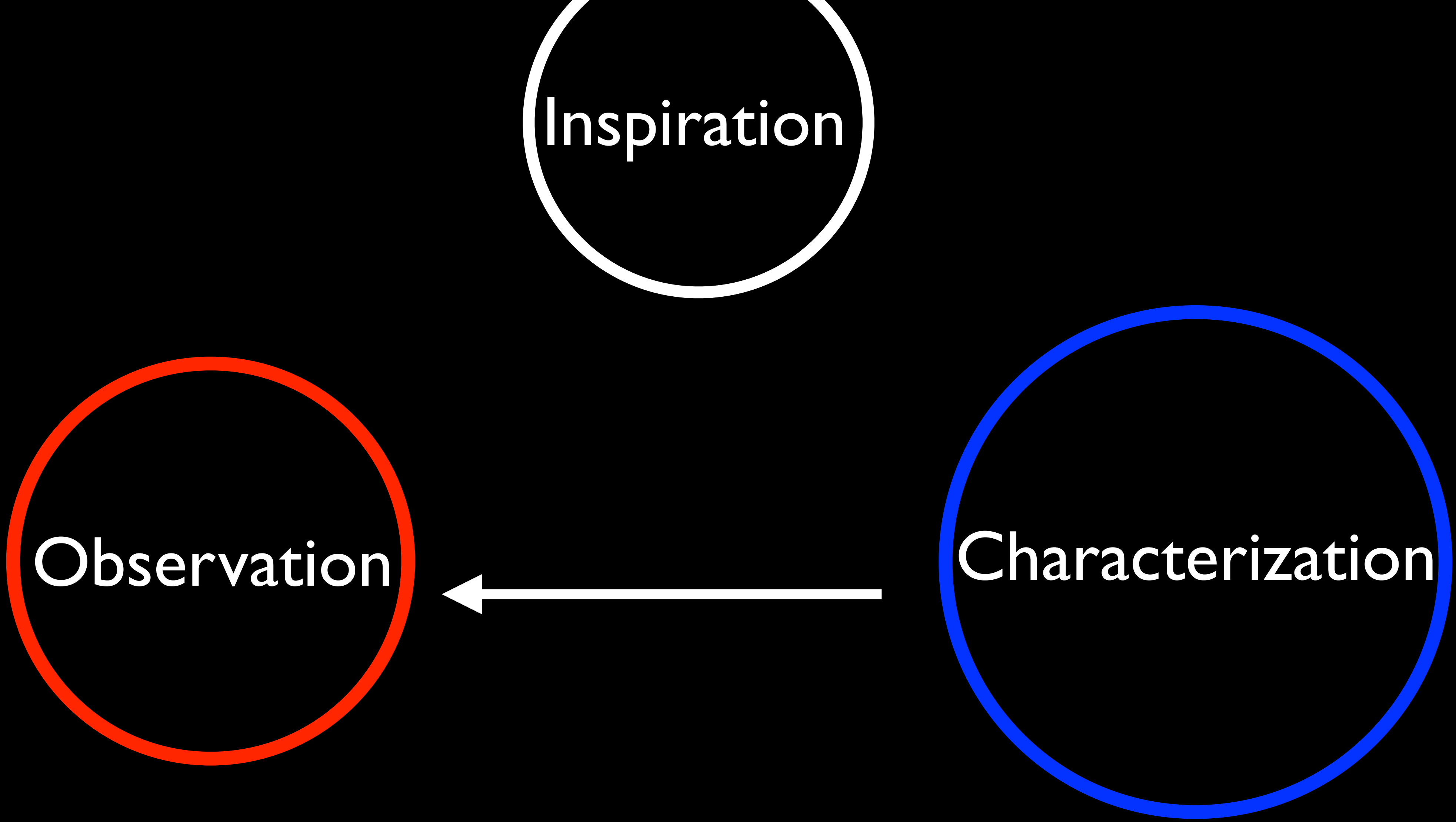
- Work makes predictions for new physics processes based on these observables including QCD corrections.
- To be general, a complete set of dimension six operators consistent with symmetries should be considered.
- A set of operators constrains linear combinations of the new physics coefficients.
- Any ultraviolet theory will predict patterns in these coefficients, and one starts to see how to map a discovery onto UV theories based on which ones are observed.





Cen Zhang

New Physics in Top Couplings



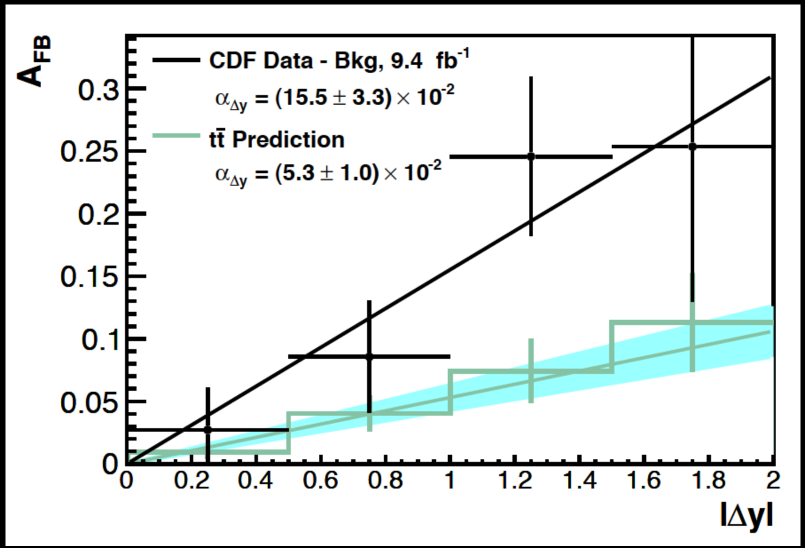
Once we know what we would like to measure, it suggests new ways to extract interesting information.

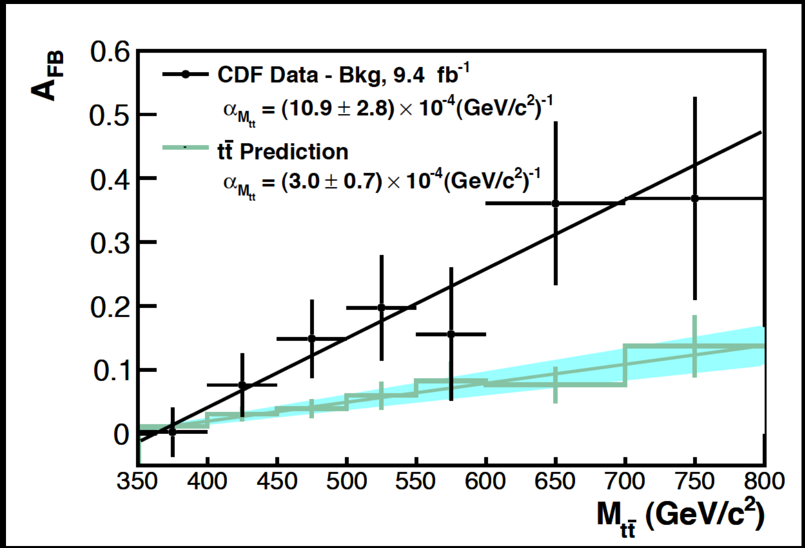
FB Asymmetry

- One that has attracted a lot of attention in the recent years is the forward-backward asymmetry of the top quark at the Tevatron.

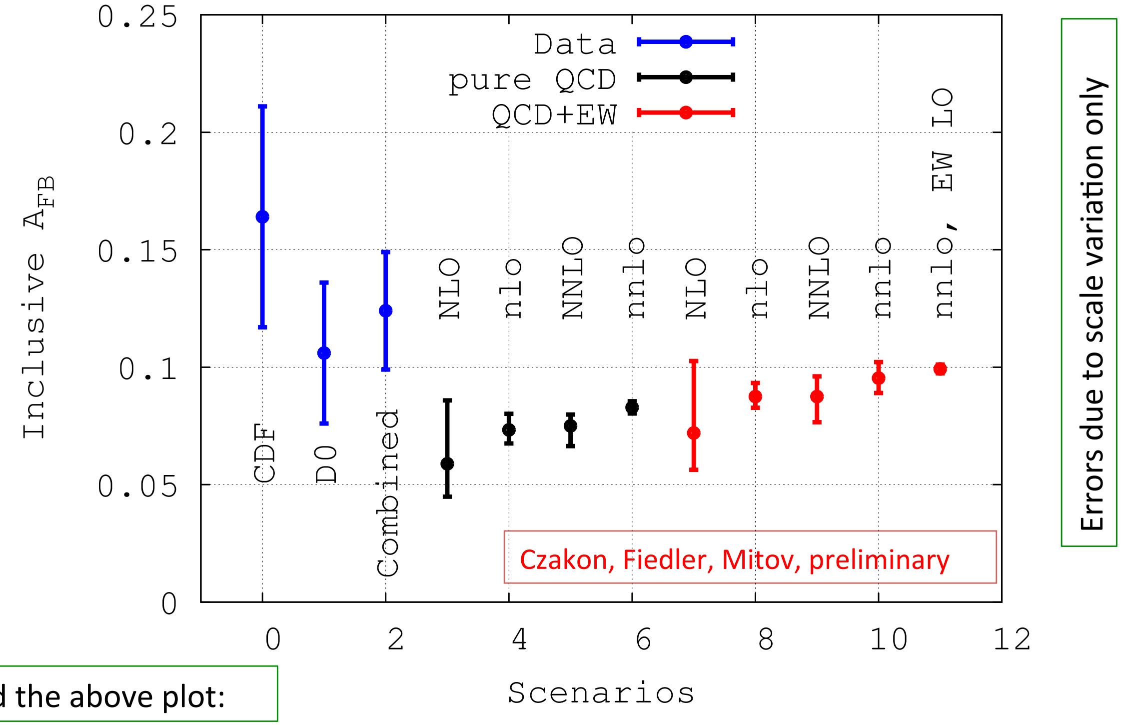
$$A_{\mathrm{FB}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

- This measurement, like the related charge asymmetry at the LHC, is a subtle probe of new physics that might otherwise hide.





Differential $t\bar{t}$ @ NNLO



- *NLO, NNLO* : exact numerator and denominator (see previous slide)
- *nlo, nnlo* : expanded in powers of a_s

Michael Czakon

T Tbar Production

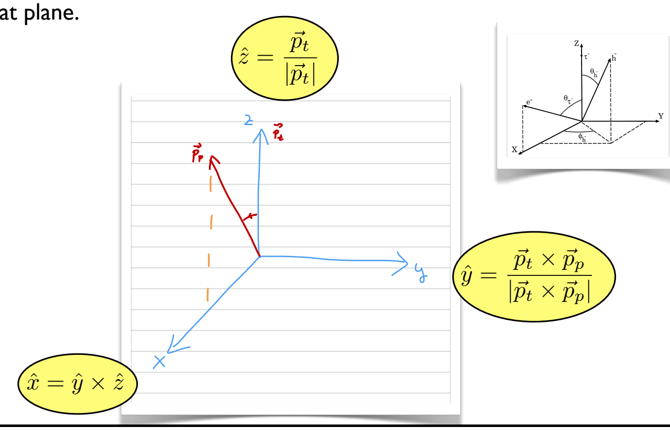
- The observable is only non-zero at NLO (in the inclusive calculation).
- The new NNLO computations, together with further combined measurements from the Tevatron, are essentially compatible.
- Not good news for new physics, but very good news in terms of our understanding of top!

Top Polarization

- The electroweak decay provides an opportunity: (in the SM), top quarks "analyze their own polarization information".
- Three observables are related to the expectation of the top spin along three axes.
- At the Tevatron, this is relatively easy to do, because the asymmetric beams provide a natural axis to decompose the information.

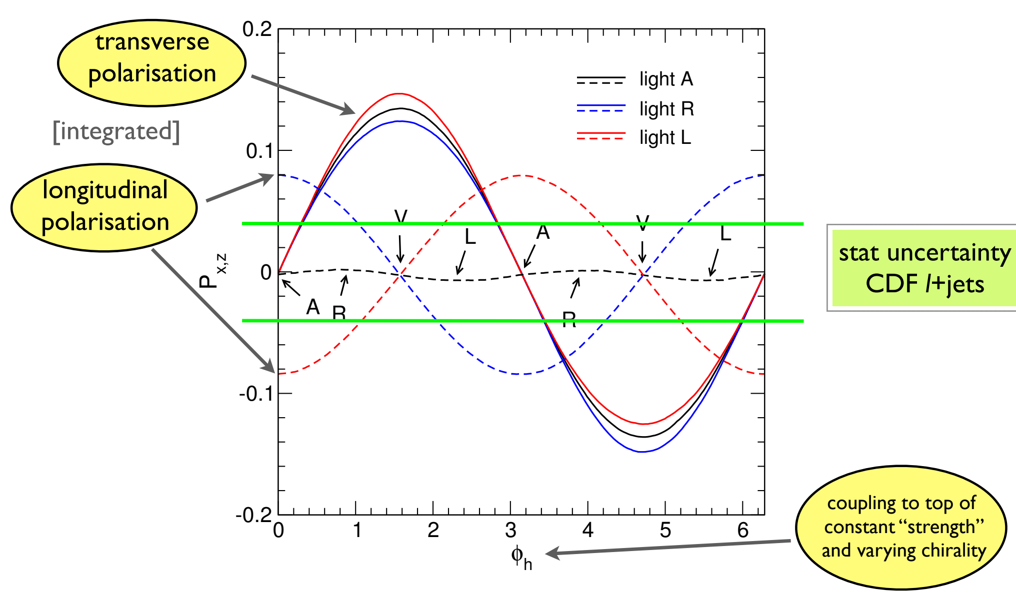
Top pair production at Tevatron

The *x* direction can be taken in the plane spanned by the top quark momentum and the proton, in CM frame. The *y* direction is perpendicular to that plane.



The transverse and normal polarisations provide independent probes for new physics.

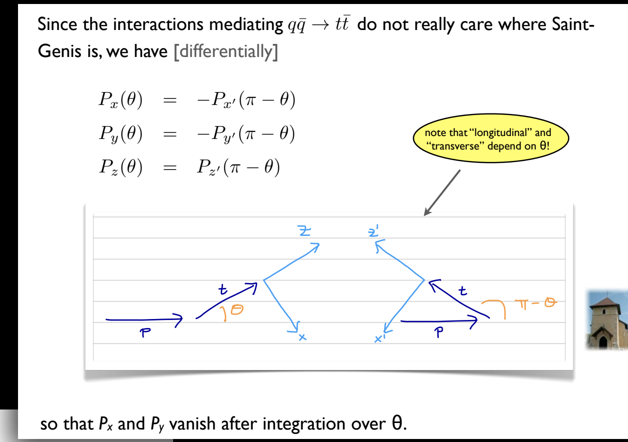
Example: P_x and P_z for new colour octet M = 250 GeV with *reasonable* couplings to generate a FB asymmetry at Tevatron. JAAS '14

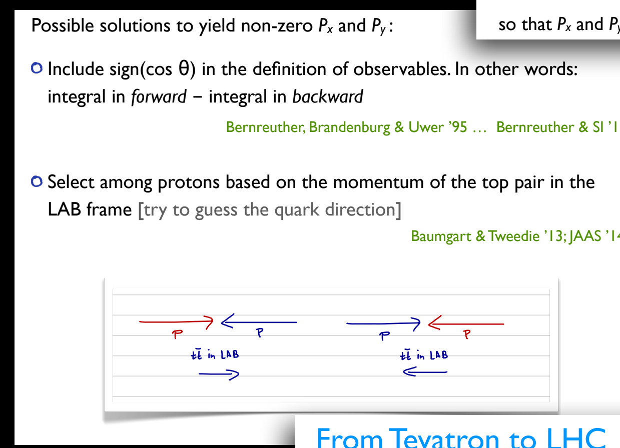


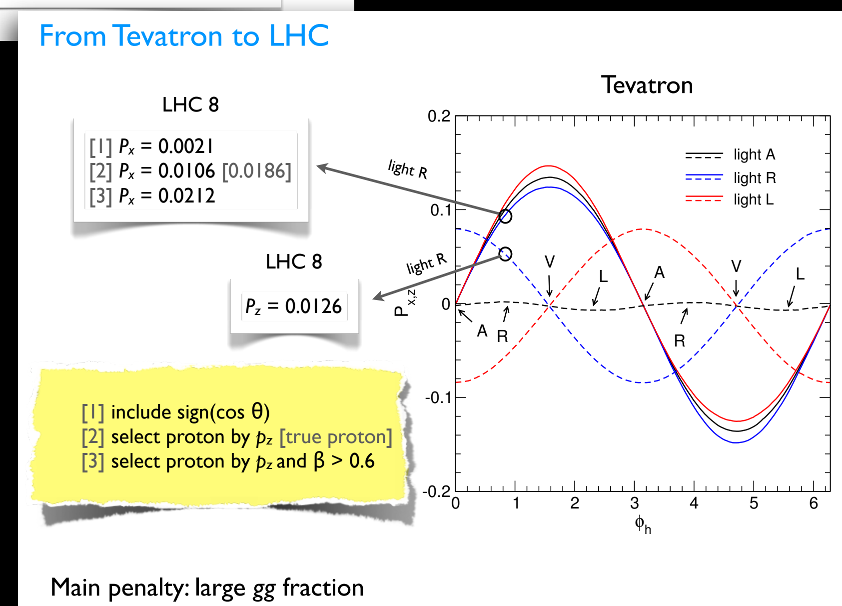
JA Aguilar Saavedra
Top Properties

Top Polarization

- At the LHC, this handle does not exist, but that doesn't ruin the opportunity.
- Carefully chosen observables can improve the purity of the qqbar initial state and correlate with the direction of quark vs anti-quark.
- These are very interesting tools to look for new physics, measure properties and further refine future discoveries in other observables.







JA Aguilar Saavedra

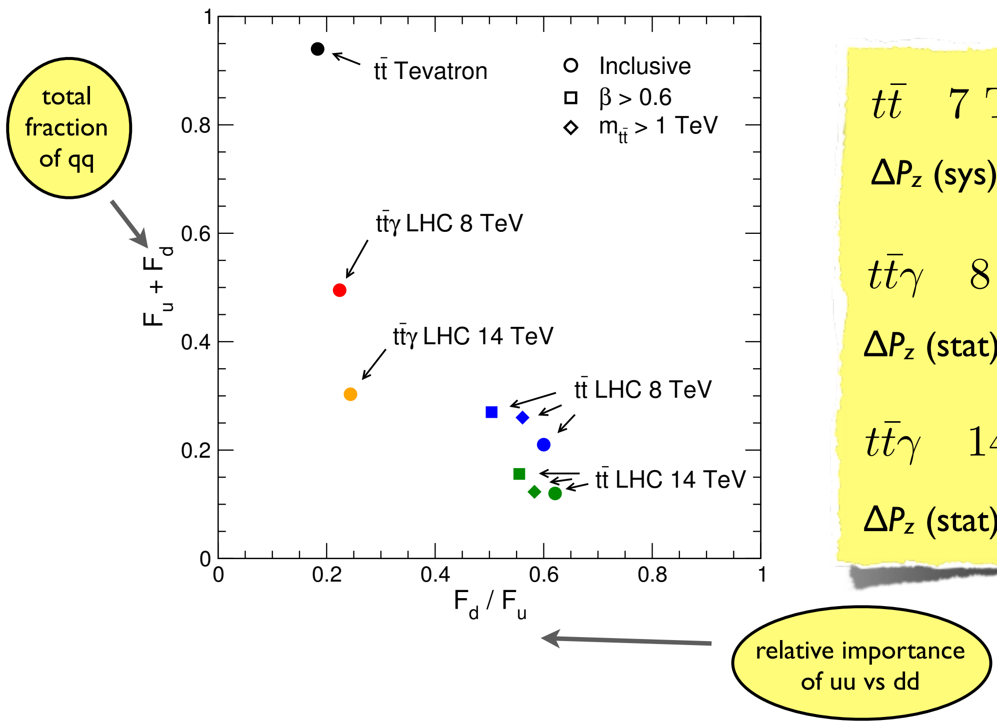
Top Properties

A Different Process?

Photon handle for polarisation?

Already proposed for charge asymmetry A_C

JAAS et al. '14



$t\bar{t}$ 7 TeV

ΔP_z (sys) = 0.037

$t\bar{t}\gamma$ 8 TeV

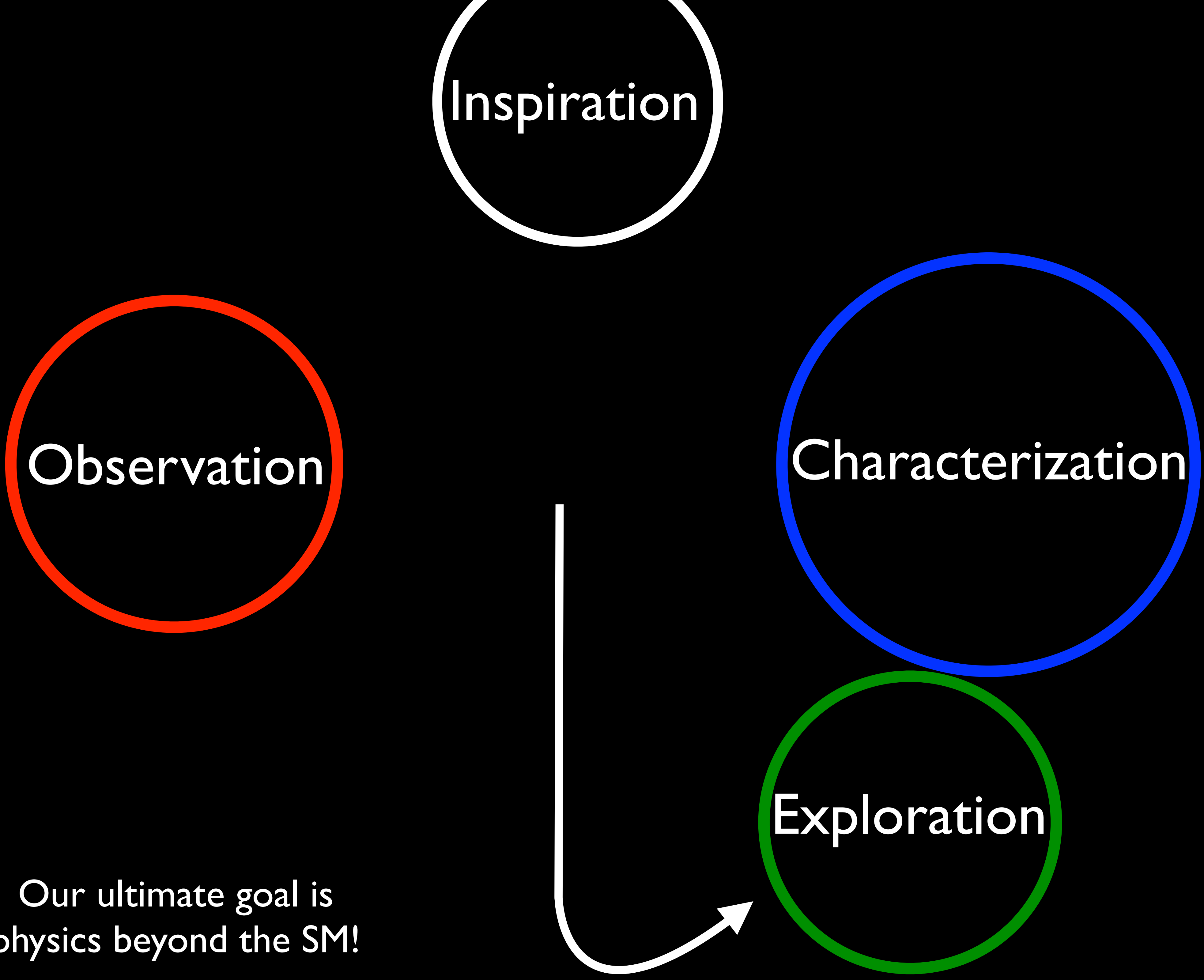
ΔP_z (stat) = 0.09 same sensitivity

$t\bar{t}\gamma$ 14 TeV 100 fb^{-1}

ΔP_z (stat) = 0.02 1.5 × sensitivity

JA Aguilar Saavedra
Top Properties

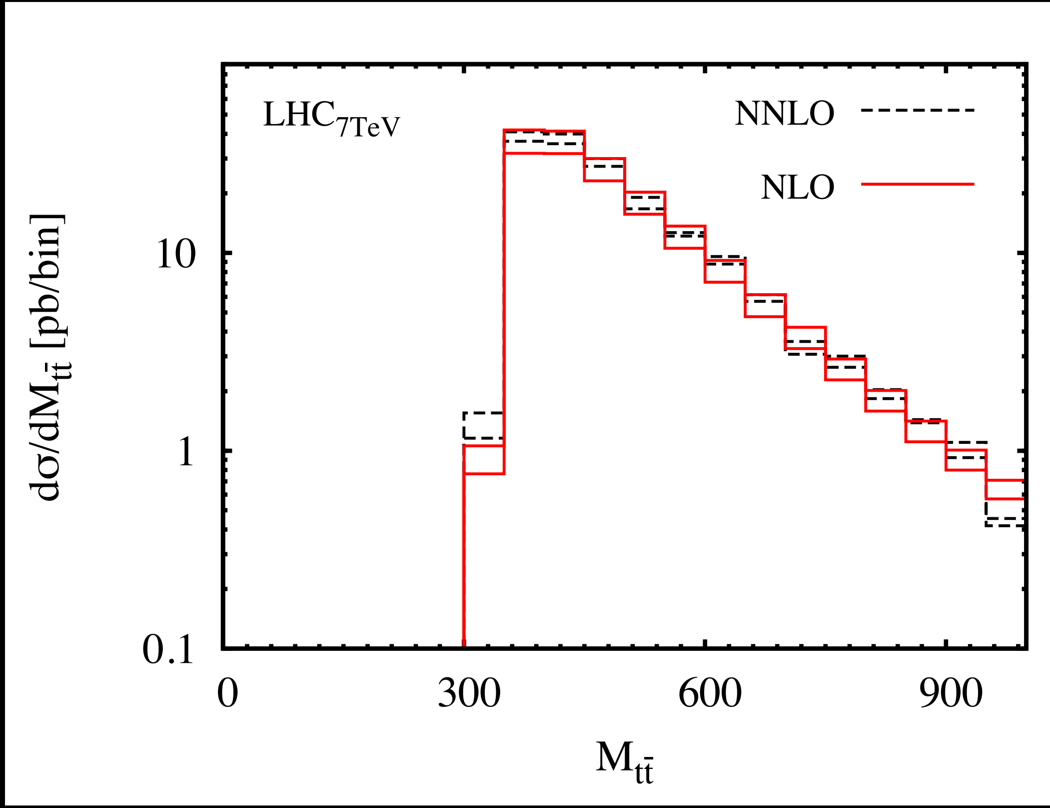
- A process with extra ISR, such as ttbar + photon, could enhance the contribution from the qqbar initial state, and improve the prospects.



Our ultimate goal is physics beyond the SM!

Extreme $t\bar{t}$

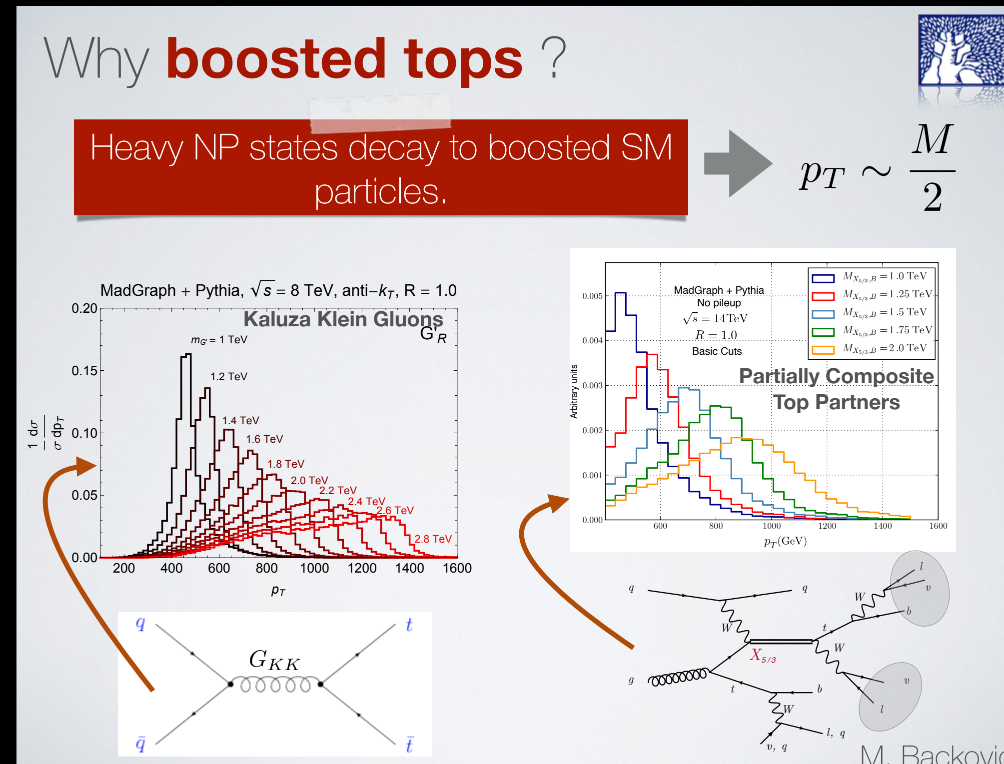
- An obvious place to explore is top quarks under "extreme conditions".
- For example, at large invariant mass, top quarks may reveal new particles that like to decay into them as resonances.
- Obviously, a starting point is to have tools we can trust to predict these extreme kinematics.
    - Do our existing tools work, ready to be extrapolated, or do we need further refinements?

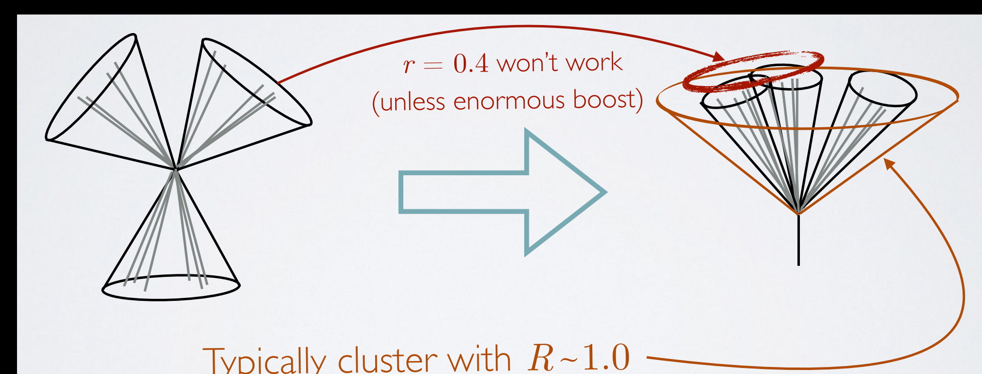


Michael Czakon
T Tbar Production

Boosted Tops

- If new physics is heavy, decays could produce top quarks with very large energies.
- Such boosted tops decay have collimated decay products, which may not appear as distinct objects to standard analysis.
- Boosted techniques try to reconstruct the results of boosted tops (objects), and then detect the signs that they really contain multiple hard decay products corresponding to the bottom and W.

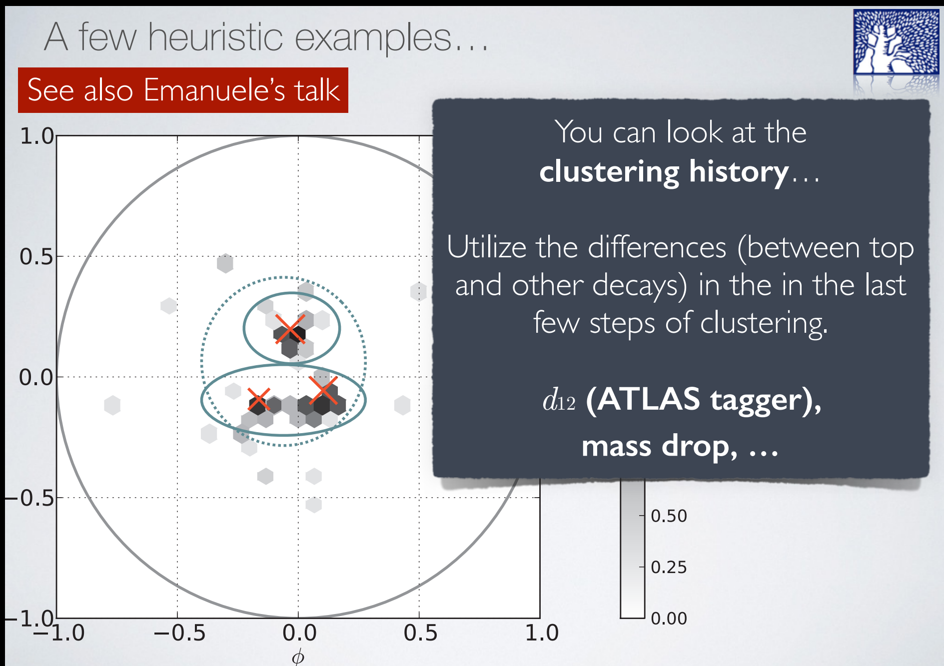


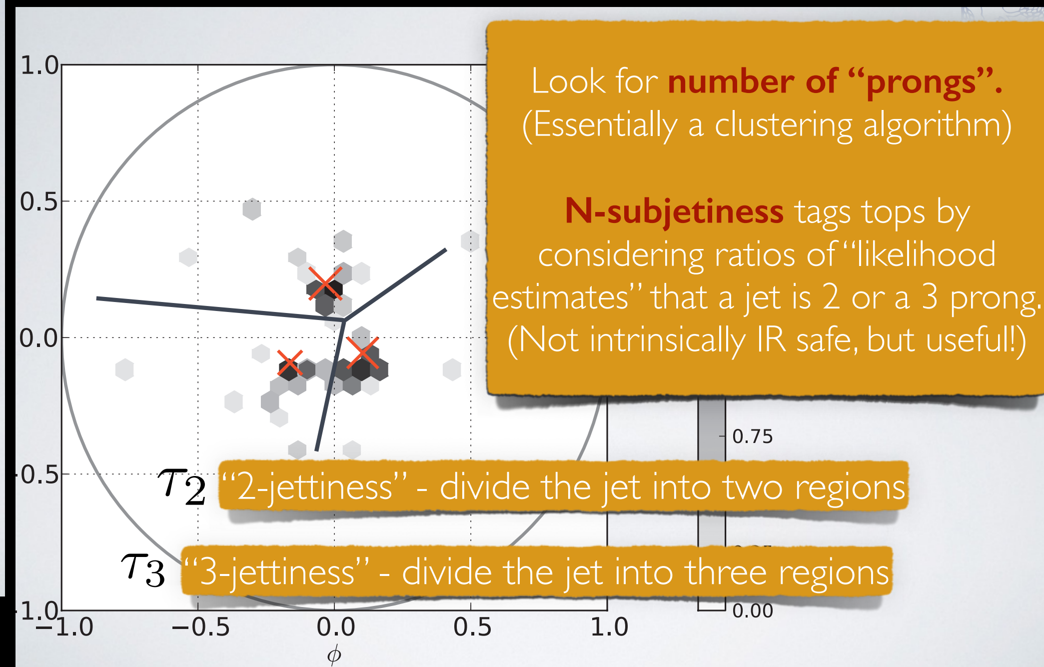


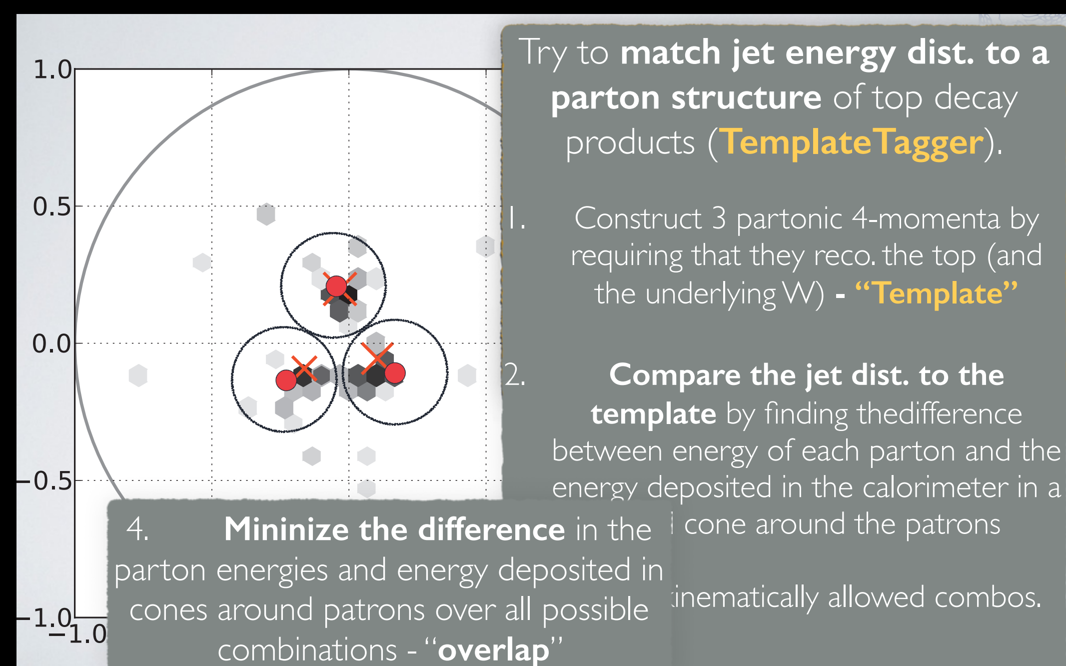
Mihailo Backovic

Boosted Top Theory

Boosted Strategies







- There are many strategies, and work is ongoing to understand how they all fit together.
- Mihailo also discussed sensitivity to pile-up, etc.

Mihailo Backovic

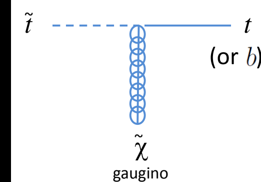
Boosted Top Theory

Top in SUSY Decays

- Due to the stop's role in determining which SUSY theories are natural, many SUSY theories produce particles which like to decay into top quarks.
- Many signatures are possible, some involving missing transverse momentum (if R-parity is conserved) or not (if not).
- We like theories with R-parity because of dark matter, but this could be a red herring and R-parity has nothing to do with SUSY's answer to the hierarchy problem.

SUSY gives tops in return

SUSY counterpart of gauge interaction



Example with stop pair production

$pp \to \tilde{t}\tilde{t}^*, \quad \tilde{t} \to t\tilde{\chi}^0, \quad \tilde{\chi}^0$ stable

overall: $pp \to t\bar{t} + \text{invisible}$

Example with gluino pair production

$pp \to \tilde{g}\tilde{g}, \quad \tilde{g} \to \tilde{t}\bar{t}, \quad \tilde{t} \to jj$ via RPV

overall: $pp \to t\bar{t} + \text{jets} \quad (\text{or: } tt + \text{jets})$

Example without real tops

$pp \to \tilde{t}\tilde{t}^*, \quad \tilde{t} \to b\tilde{\chi}^+, \quad \tilde{\chi}^+ \to \tau^+ jj$ via RPV

overall: $pp \to (b\tau^+ jj)\,(\bar{b}\tau^- jj)$

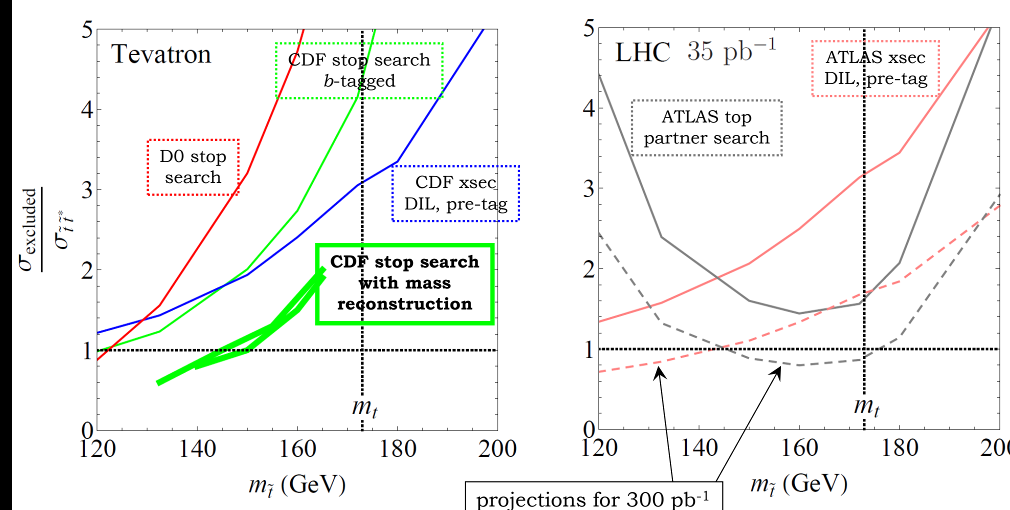
Different $t\bar{t}$ channels are affected differently!

Example: decay to massless gravitino (gauge mediation)

$pp \to \tilde{t}\tilde{t}^*, \quad \tilde{t} \to W^+ b\tilde{G}, \quad \tilde{G}$ stable

overall: $pp \to W^+ b W^- \bar{b} + \text{invisible}$

YK and Shih
JHEP 08 (2011) 049



Yevgeny Kats
Top and SUSY

Degenerate Stops

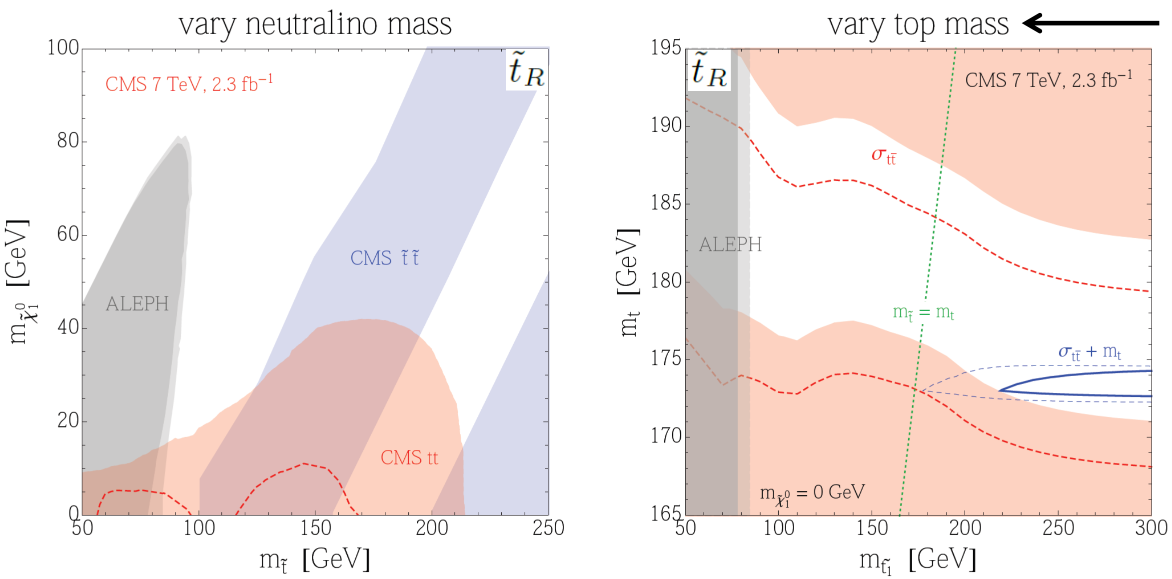
Most recent updates

Using NNLO + NNLL theory cross section

Czakon, Fiedler, Mitov, PRL 110, 252004 (2013)

and CMS dilepton channel (2.3/fb at 7 TeV)

CMS Collaboration, JHEP 1211, 067 (2012)



In case top mass measurement is affected by stop contamination...

Czakon, Mitov, Papucci, Ruderman, Weiler, arXiv:1407.1043

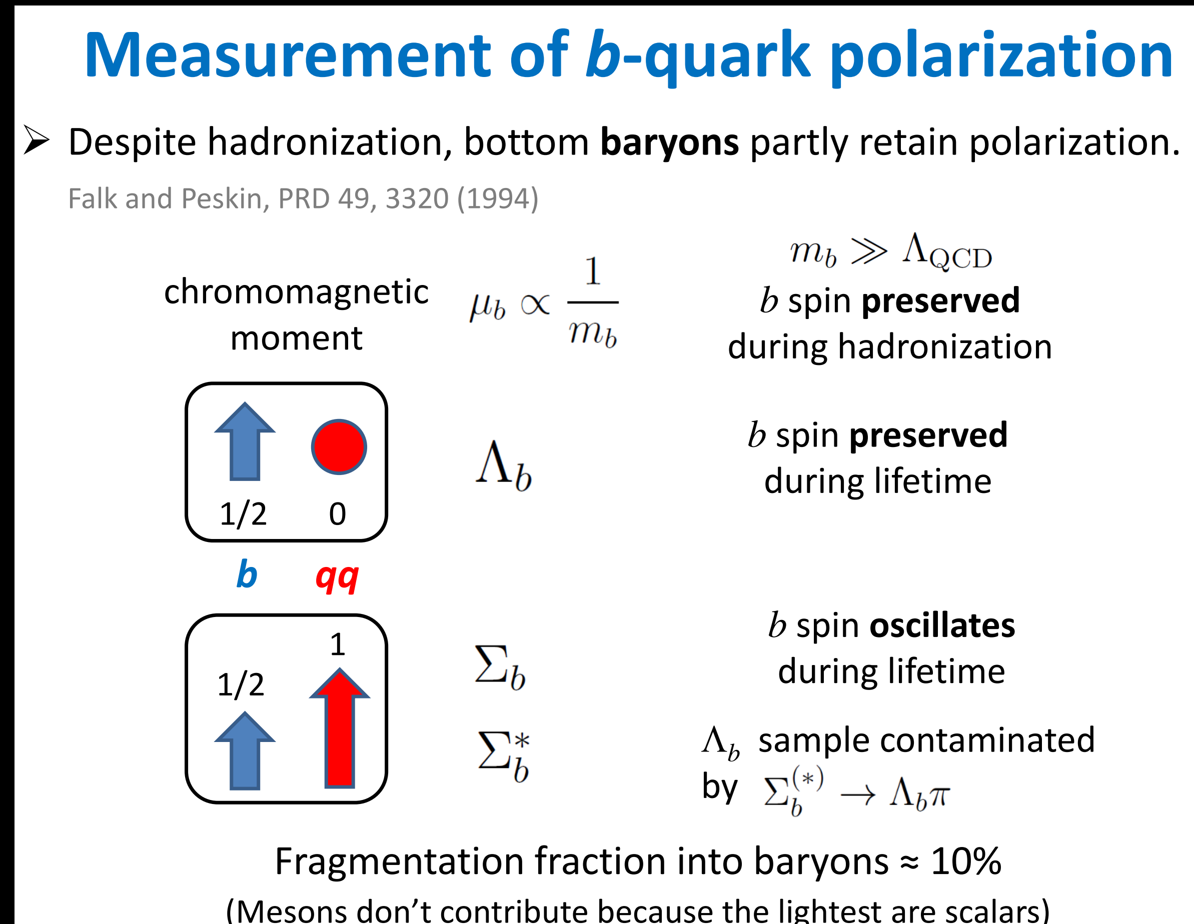
Yevgeny Kats

Top and SUSY

- A recent study attempts to use the top cross section measurement to put a bound on stops.
- Given the complicated way the cross section is extracted, there may be corrections to the theorist-derived results; it would be great for the experiments to do this themselves.

Top as a Tool

- Yevgeny also told us about a very interesting idea to measure the polarization of b quarks.
- The idea rests of looking at Λb baryons, which preserve the parent b polarization to good approximation.
- Calibrating this technique requires a source of polarized b's.
- Top decays provide one very naturally!

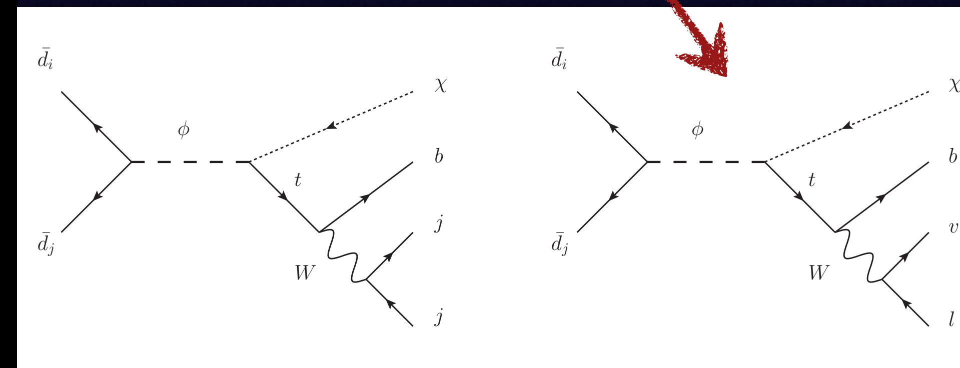


Yevgeny Kats
Top and SUSY

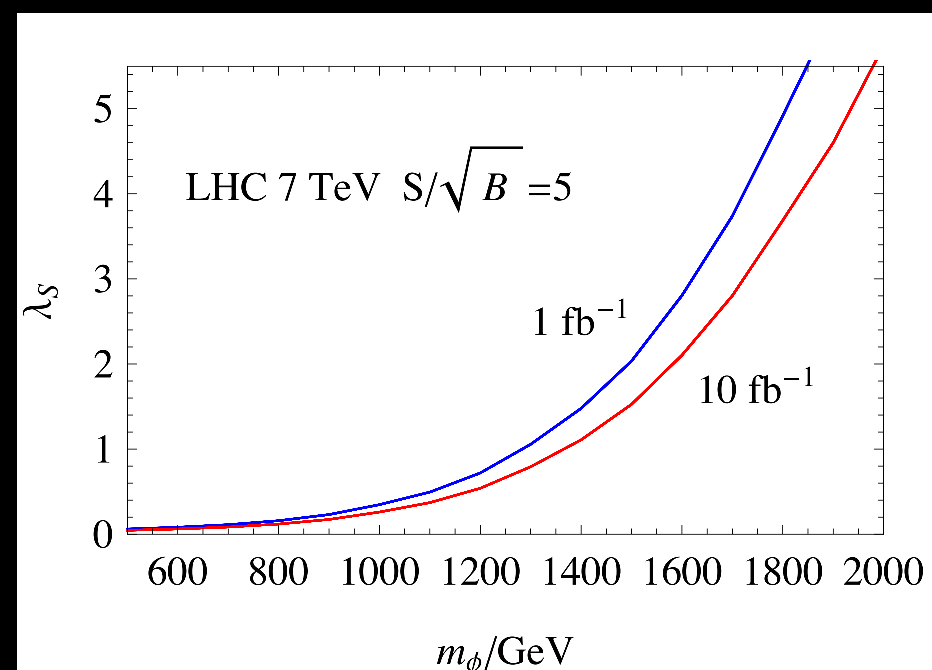
Mono Top

- Qing-Hong told us about signals producing a single top quark together with missing momentum.
- This “mono-top” signature probes theories where there are new neutral scalars with flavor-violating interactions or which decay to a top and an invisible particle.
- In these cases, the particles are unlikely to be dark matter, but this is still an interesting signal of e.g. R-parity violating SUSY via single-stop production.

see Theveneaux-Pelzer’s poster



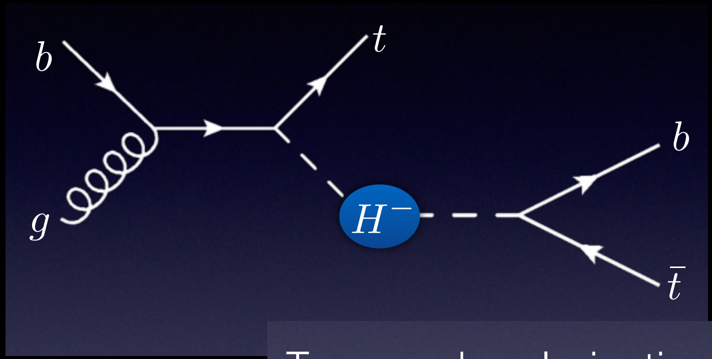
Andrea, Fuks, Maltoni, 1106.6199
Wang, Li, Shao, Zhang, 1109.5963



Qing-Hong Cao
Top and Exotic Models

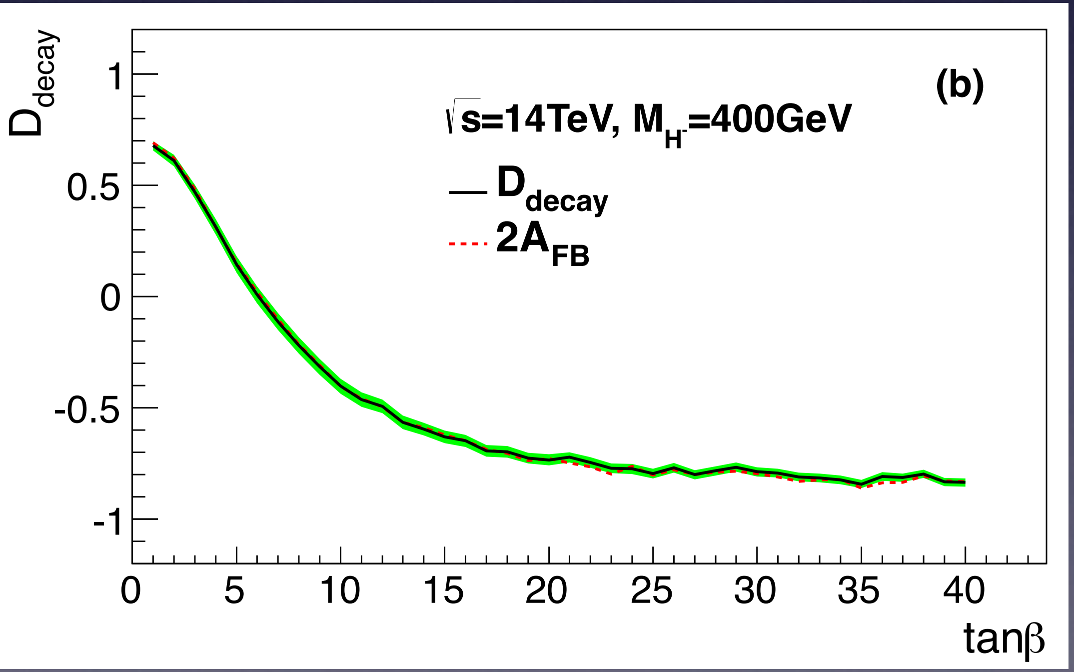
Charged Higgs

- A charged Higgs can decay into a top and a bottom quark, producing a polarized sample of tops.
- In a type-II 2HDM, the degree of polarization in the decay depends on tan β.
- One can produce the Higgs in association with a single top (in analogy to Wt), and its decay leads to a t tbar + b signature with very unusual kinematic structure (tb resonant).



Top-quark polarization depends on tanb

$$D_{\rm decay} \sim \frac{(m_t \cot\beta)^2 - (m_b \tan\beta)^2)}{(m_t \cot\beta)^2 + (m_b \tan\beta)^2)}$$



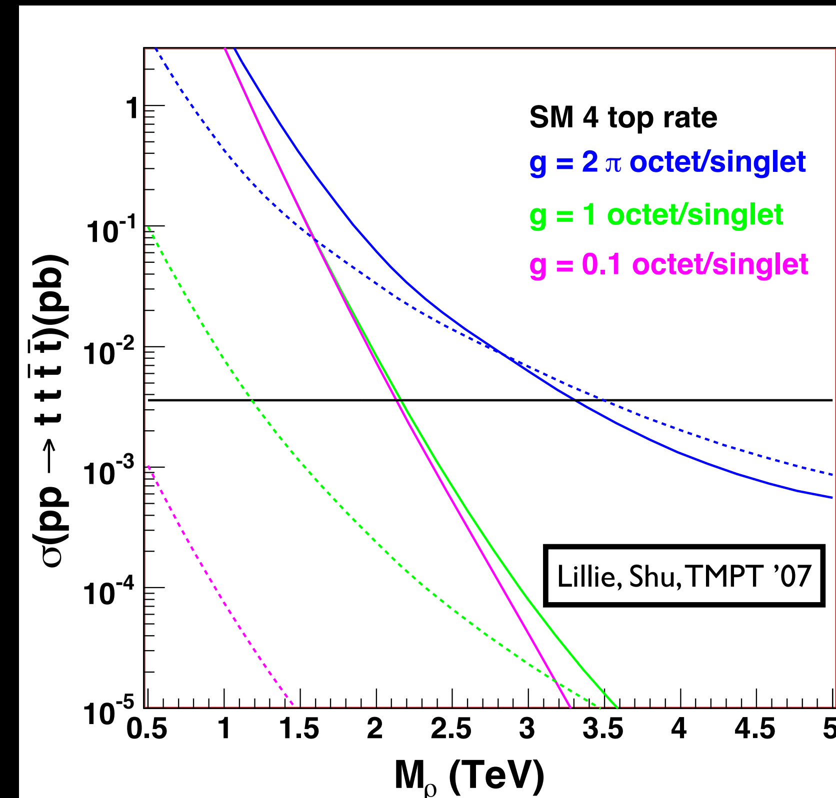
QHC, Wan, Wang, Zhu, 1301.6608

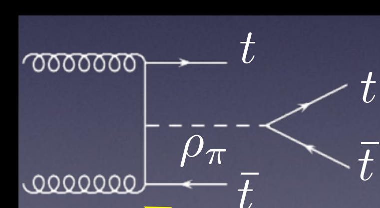
Qing-Hong Cao

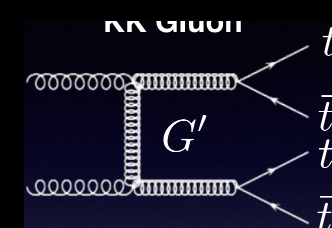
Top and Exotic Models

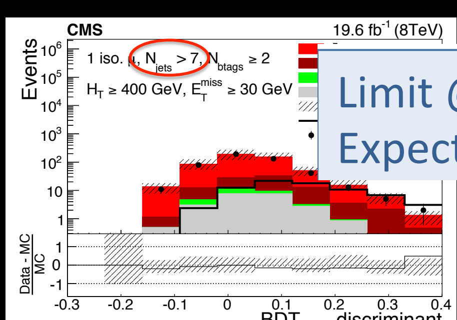
Four Tops

- As Qing-Hong pointed out, many kinds of theories produce large numbers of tops. For example, theories where top is composite.
- This points out an important consideration: consistent theories can be many times the SM rate. This is really a BSM search.
- While the SM is an important target, it is important to put meaningful bounds on BSM theories on our way to seeing it.









Limit @ 95%CL : $\sigma_{tttt} < 32$ fb

Expected: $\sigma_{tttt} < 32 \pm 17$ fb

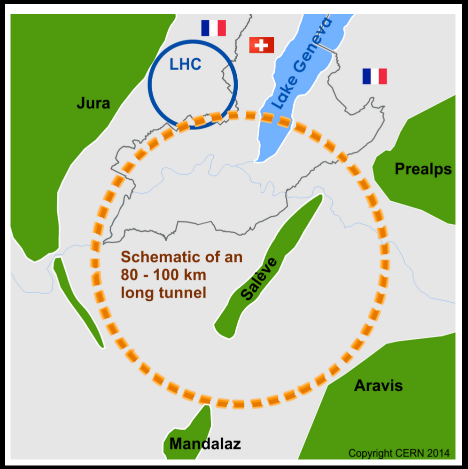
Qing-Hong also pointed out that the four top rate mediated by the Higgs is very sensitive to the Top Yukawa

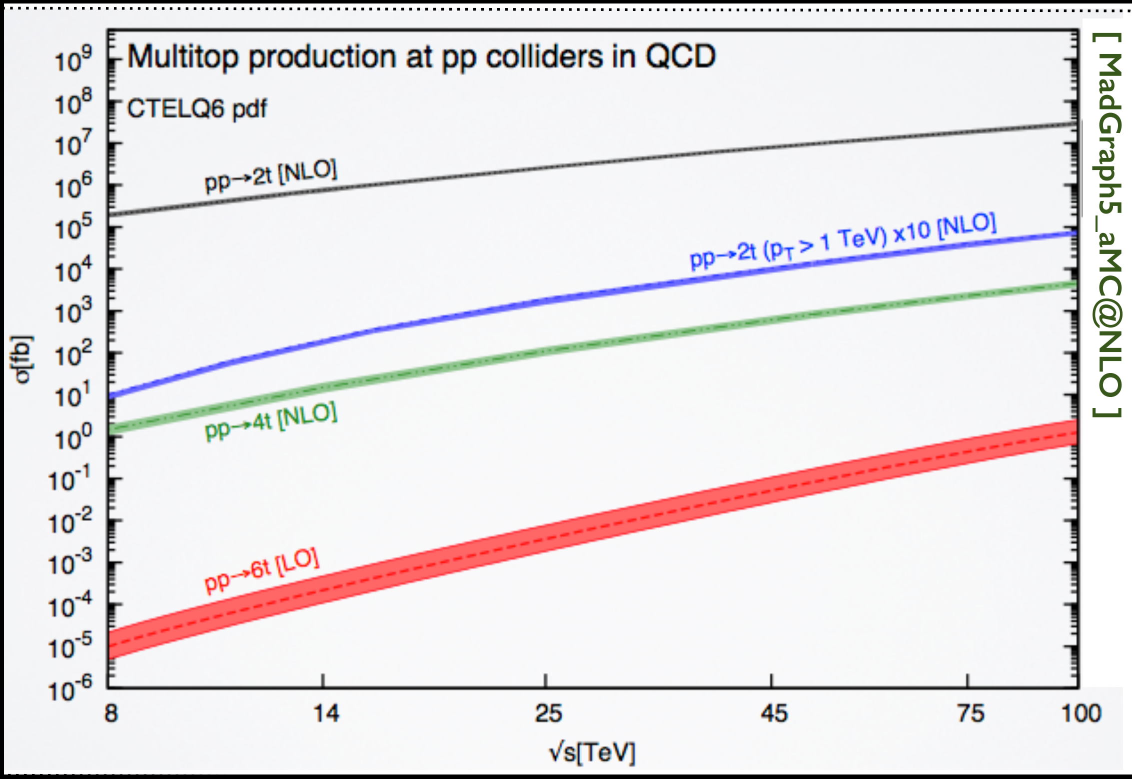
Qing-Hong Cao

Top and Exotic Models

Future Colliders

- In the far future, very high energy colliders could offer a unique perspective on the top.
- For example, a future circular collider could reach energies of order 100 TeV.
- Production of four or six tops in the SM could be feasible.

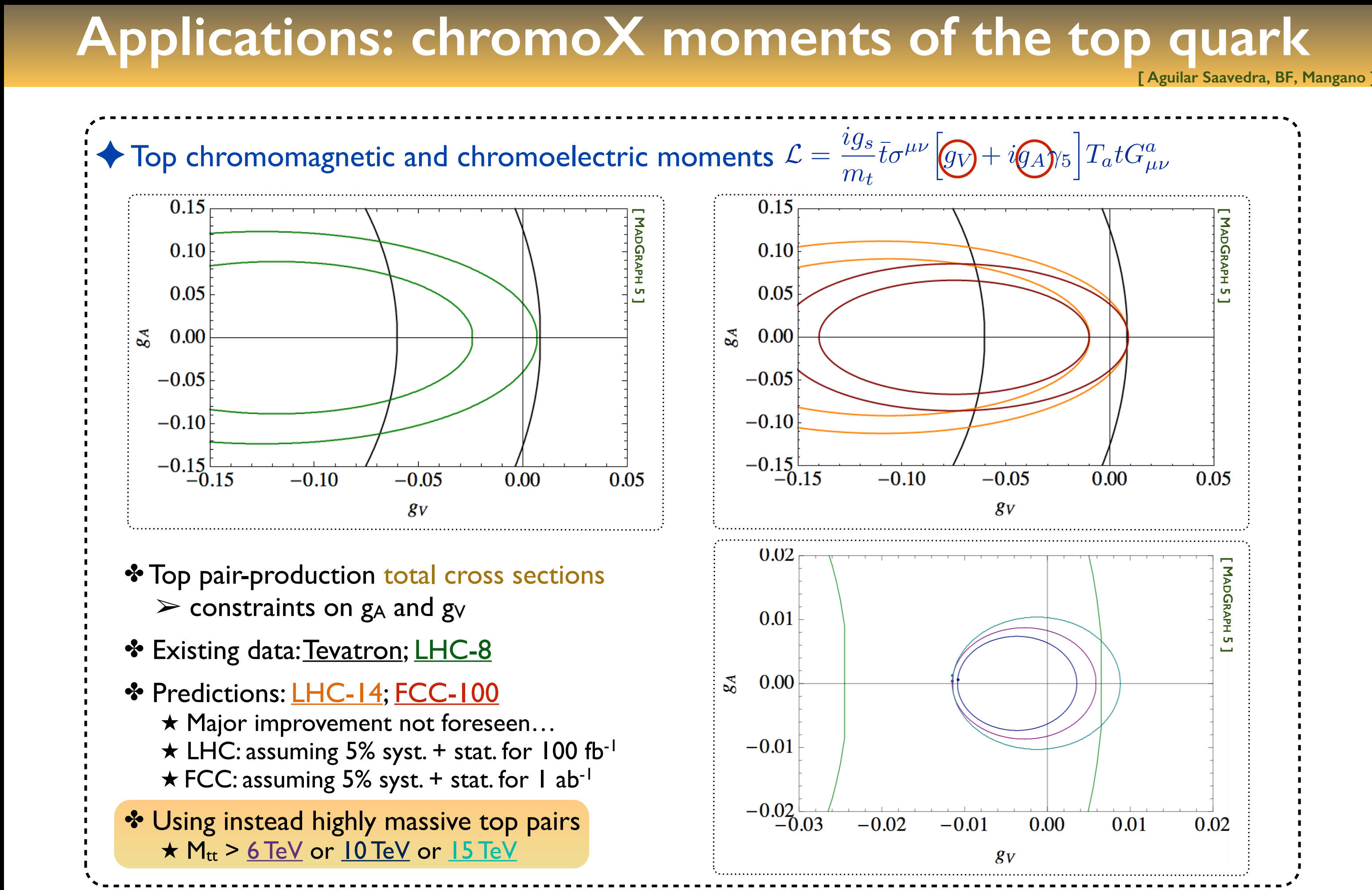




Benjamin Fuks

Perspective at FCC

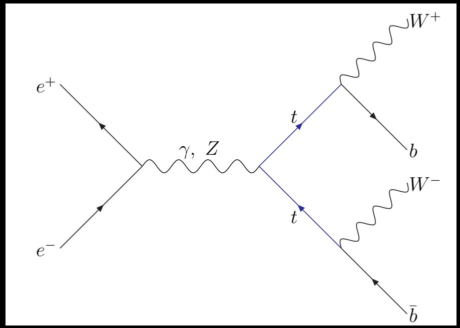
Future Colliders



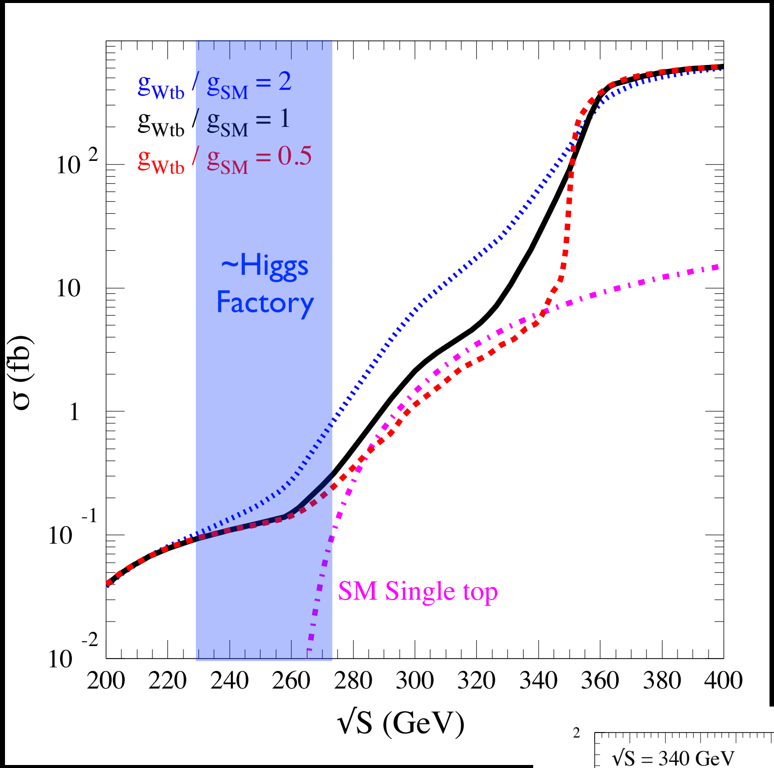
Benjamin Fuks
Perspective at FCC

- The high rate of top production offers a very precise determination of anomalous couplings, such as e.g. a chromo-magnetic or -electric moment of the top quark.

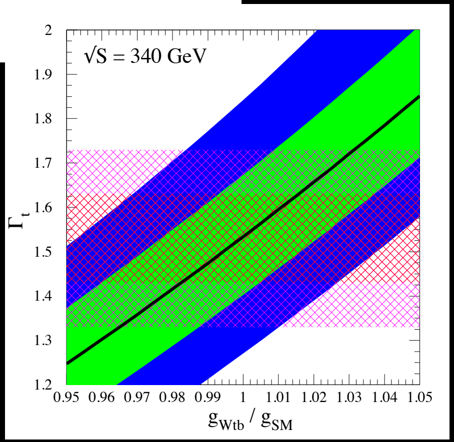
Future e+e-



- Off-shell tops can be useful at the ILC. By tuning the collider energy, one can get to a regime where one top is typically on-shell, and the other off-shell.
- Once the top goes off-shell, there is enhanced sensitivity to the W-t-b interaction.
- Percent level measurements are possible at a Higgs factory.
- (There should be something that can be said about Z-t-t as well).



Batra, TMPT '06



Future Computations

- Future colliders and precision measurements are going to need improved theoretical tools to extract the physics.
- The NLO --> NNLO revolution continues to go strong, with many important signal and background processes coming under theoretical control.
- Automation allows one to achieve a NLO standard of theoretical accuracy at the LHC.
- Techniques to include electroweak corrections are in development.

NLO multi-particle revolution and automation

- various new 1-loop techniques
- many $2 \to 4(5,6)$ processes at NLO QCD: $5j$, $W+5j$, $Z+4j$, $H+3j$, $WWjj$, $WZjj$, $\gamma\gamma+3j$, $b\bar{b}b\bar{b}$, $W\gamma\gamma j$, $WWb\bar{b}$, $t\bar{t}b\bar{b}$, $t\bar{t}jj$, $t\bar{t}t\bar{t}$, $t\bar{t}\gamma\gamma$, ...
- various new 1-loop tools: CutTools, Samurai, Helac-NLO, MadLoop, GoSam, BlackHat, Ninja, NJet, OpenLoops, Collier, Recola

Full automation of NLO and Monte Carlo tools

- IR subtraction, integration, NLO matching and multi-jet merging,...
- tools: MadGraph/aMC@NLO, Powheg/Powhel, Sherpa, Herwig, Pythia

Great potential to promote NLO to standard TH accuracy at LHC

- wide range of NLO simulations possible
- further efficiency improvements crucial for challenging processes
- understanding of underlying physics and TH uncertainties can be non-trivial

Most results in this talk based on OpenLoops [Cascioli, Maierhöfer, S.P. '12]

Recent results with OpenLoops (Higgs and Top phenomenology)

- NLO for $pp \to W^+W^-b\bar{b}$ with $m_b > 0$, [Cascioli, Kallweit, Maierhöfer, S. P., arXiv:1312.0546]
- S–MC@NLO $pp \to t\bar{t}b\bar{b}$ with $m_b > 0$, [Cascioli, Maierhöfer, Moretti, S. P. , Siegert, arXiv:1309.5912]
- MEPS@NLO for $\ell\ell\nu\nu$+0,1 jets, [Cascioli, Höche, Krauss, Maierhöfer, S. P. , Siegert, arXiv:1309.0500]
- NLO merging for $pp \to HH$+0,1 jets, [Maierhöfer, Papaefstathiou, arXiv:1401.0007]
- MEPS@NLO for $t\bar{t}$+0,1,2 jets, [Höche, Krauss, Maierhöfer, S. P. , Schönherr, Siegert arXiv:1402.6293]
- MEPS@NLO for WWW+0,1 jets, [Höche, Krauss, S. P. , Schönherr, Thompson arXiv:1403.7516]
- NNLO for $pp \to \gamma Z$ production, [Grazzini, Kallweit, Rathlev, Torre, arXiv:1309.7000]
- NNLO for $q\bar{q} \to t\bar{t}$ production, [Abelof, Gehrmann–de Ridder, Maierhöfer, S.P. , arXiv:1404.6493]
- NNLO for $pp \to ZZ$ production, [Cascioli, Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, S.P. , Rathlev, Tancredi, Weihs, arXiv:1405.2219]
- NNLO for $pp \to W^+W^-$ production, [Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, S.P. , Rathlev, Tancredi arXiv:1408.5243]

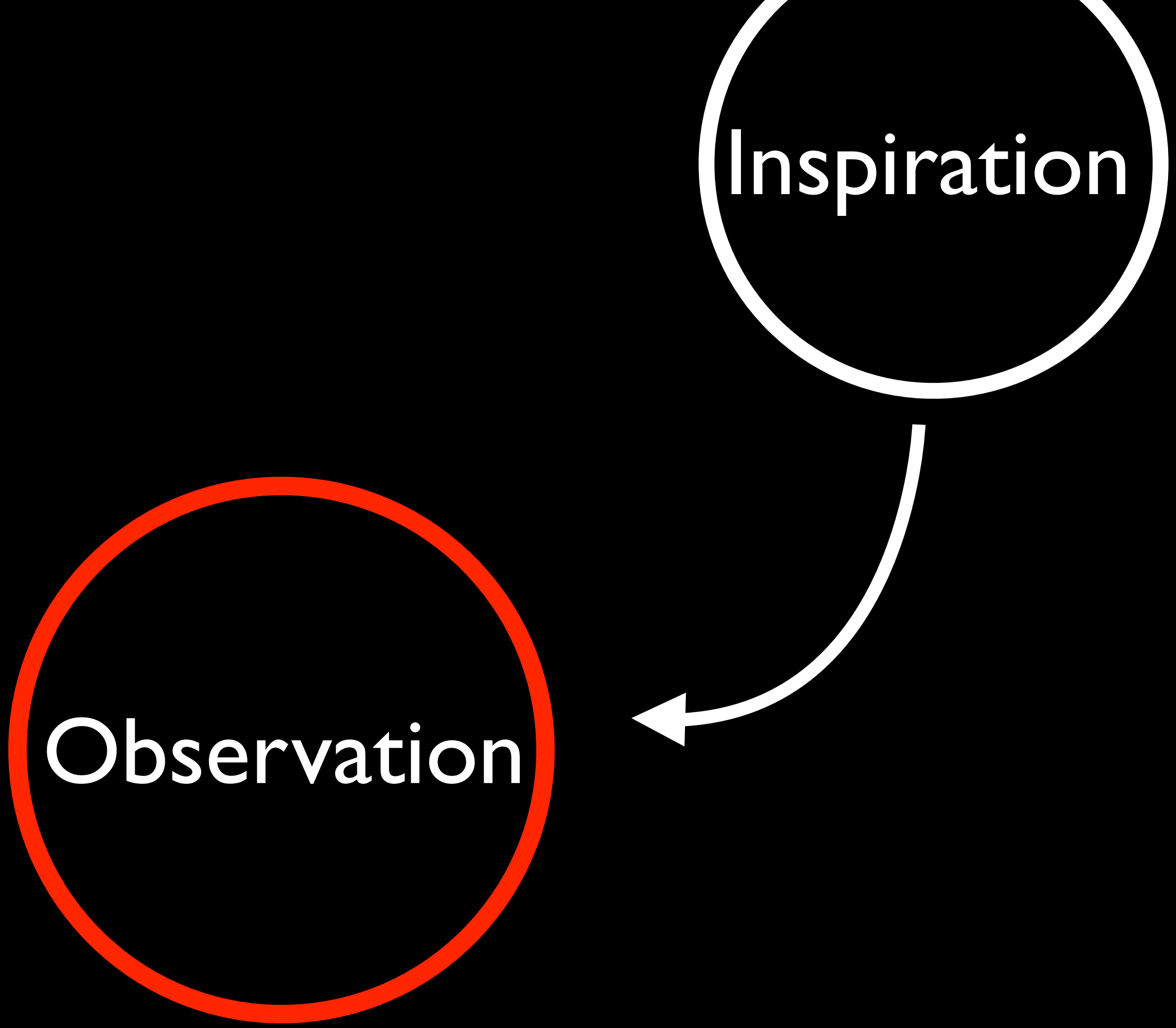
Several challenging NLO, S–MC@NLO, MEPS@NLO and NNLO studies
thanks to high automation, flexibility and CPU performance

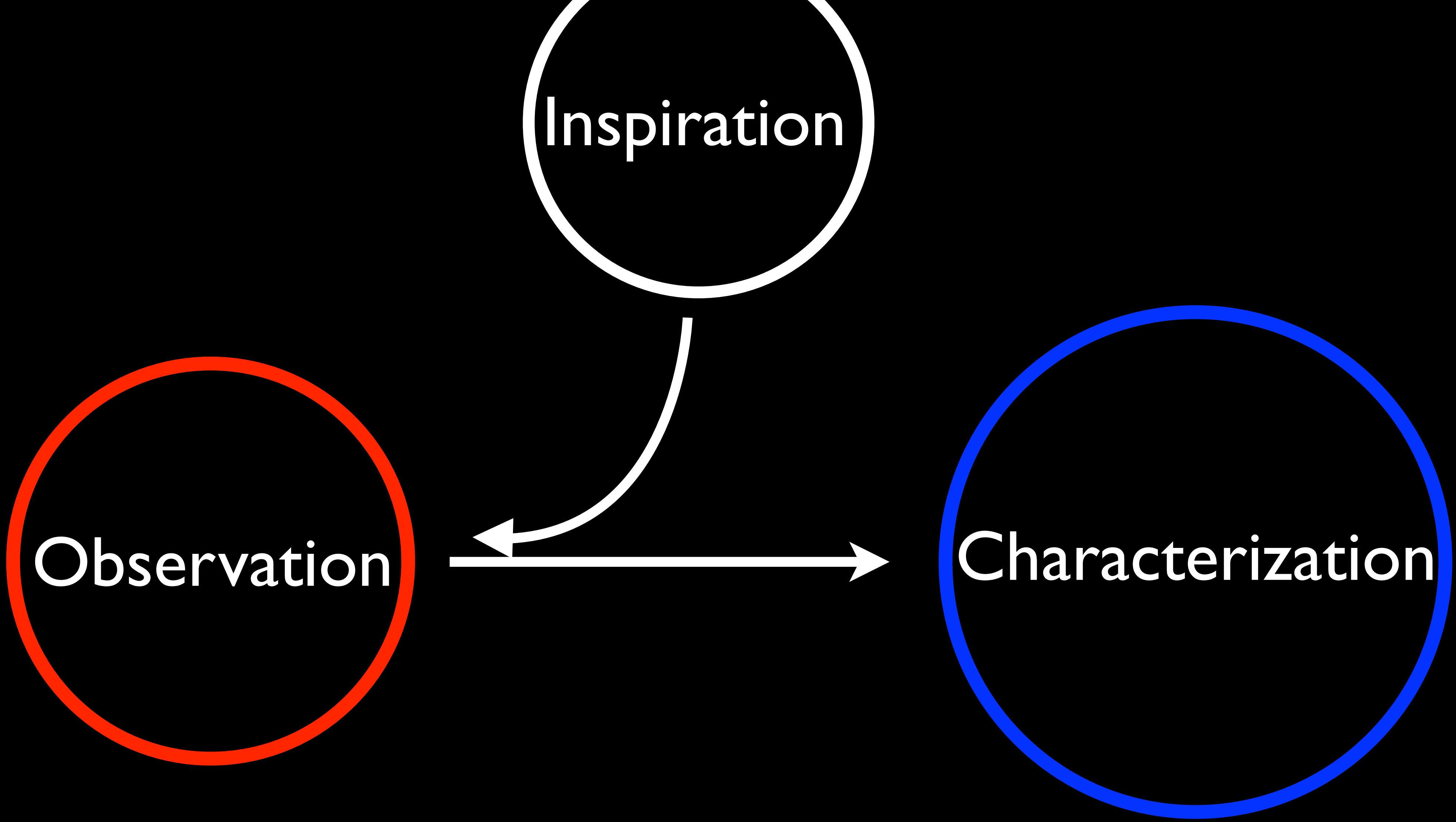
Stefano Pozzorini

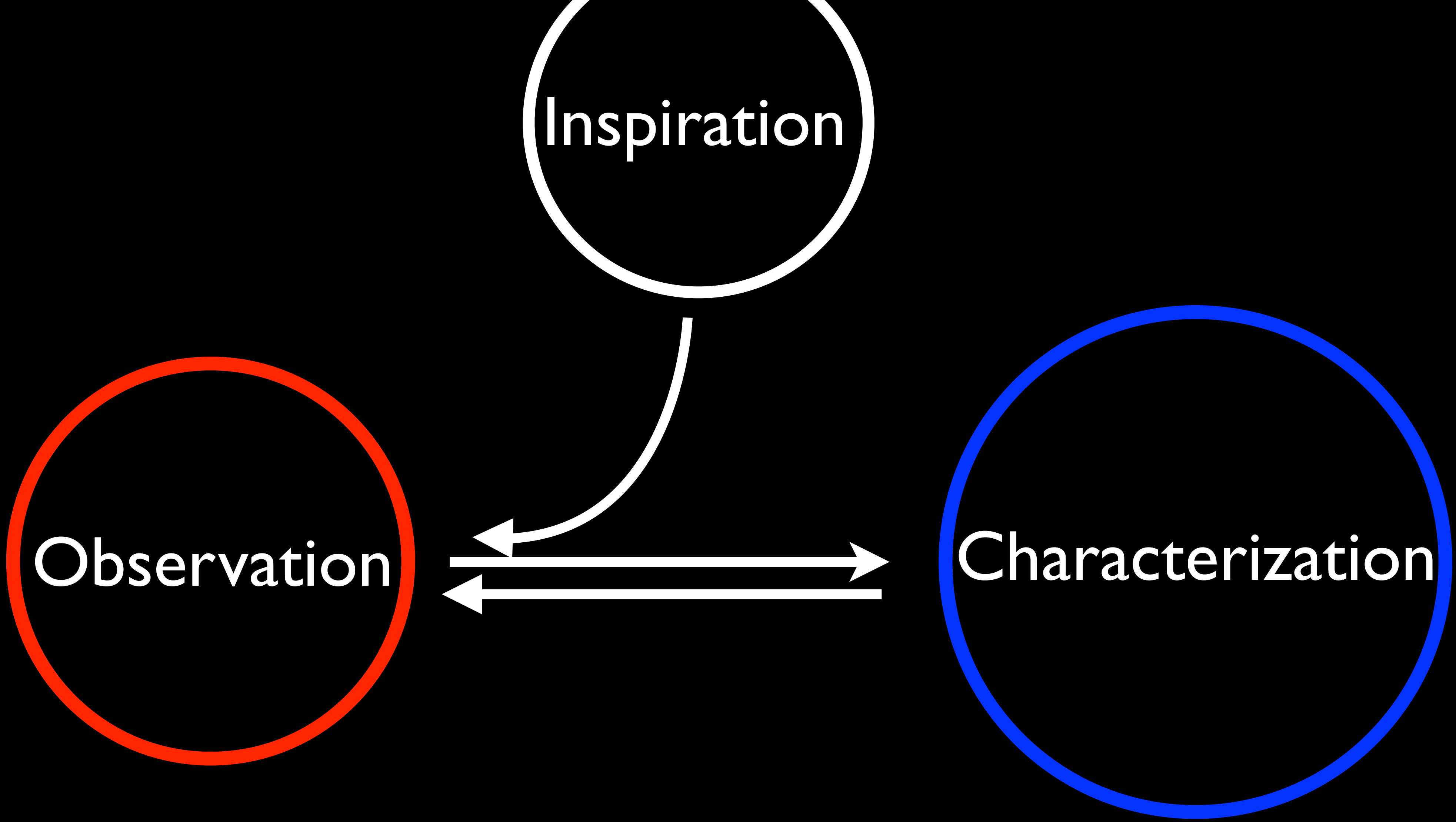
Perspective on New Generators

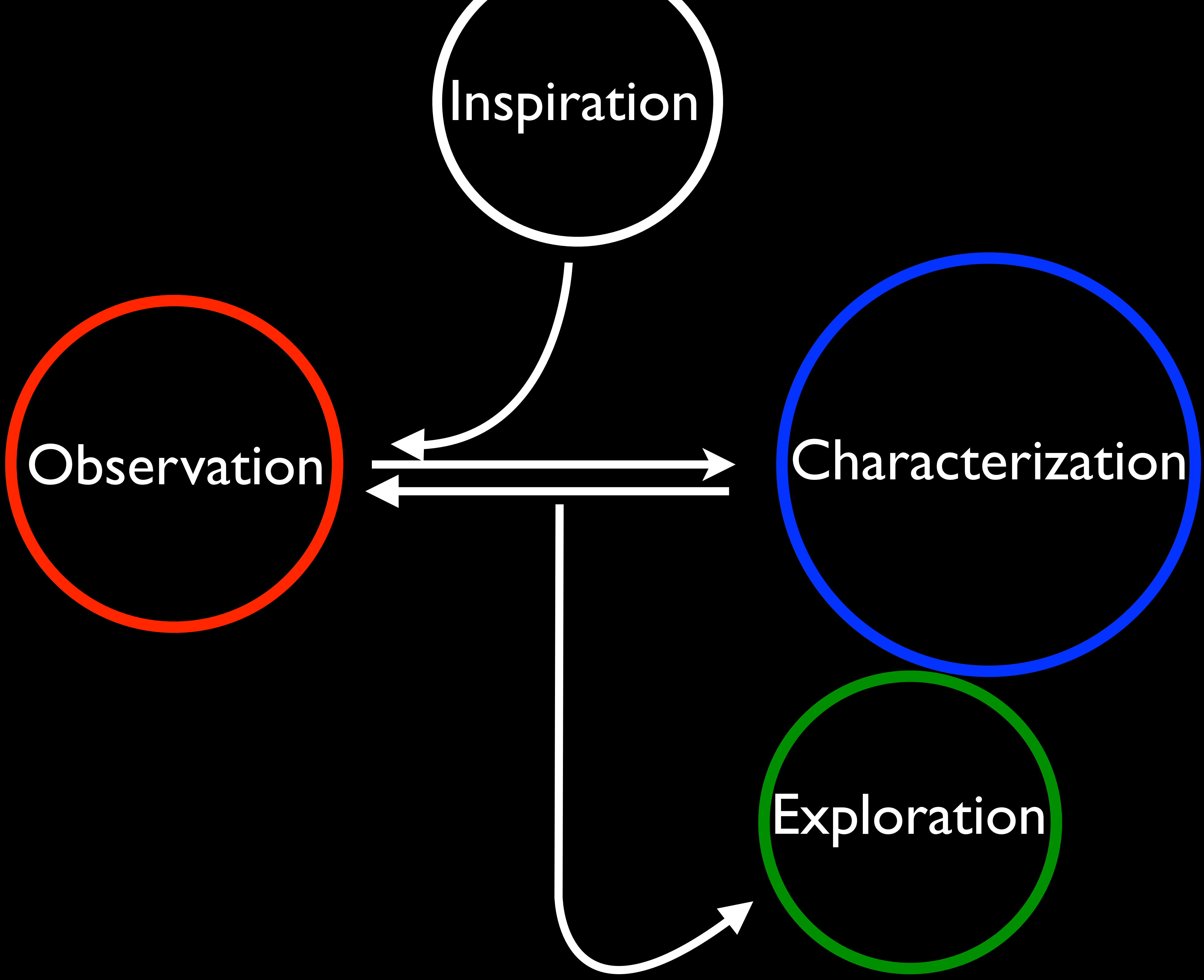
Summary

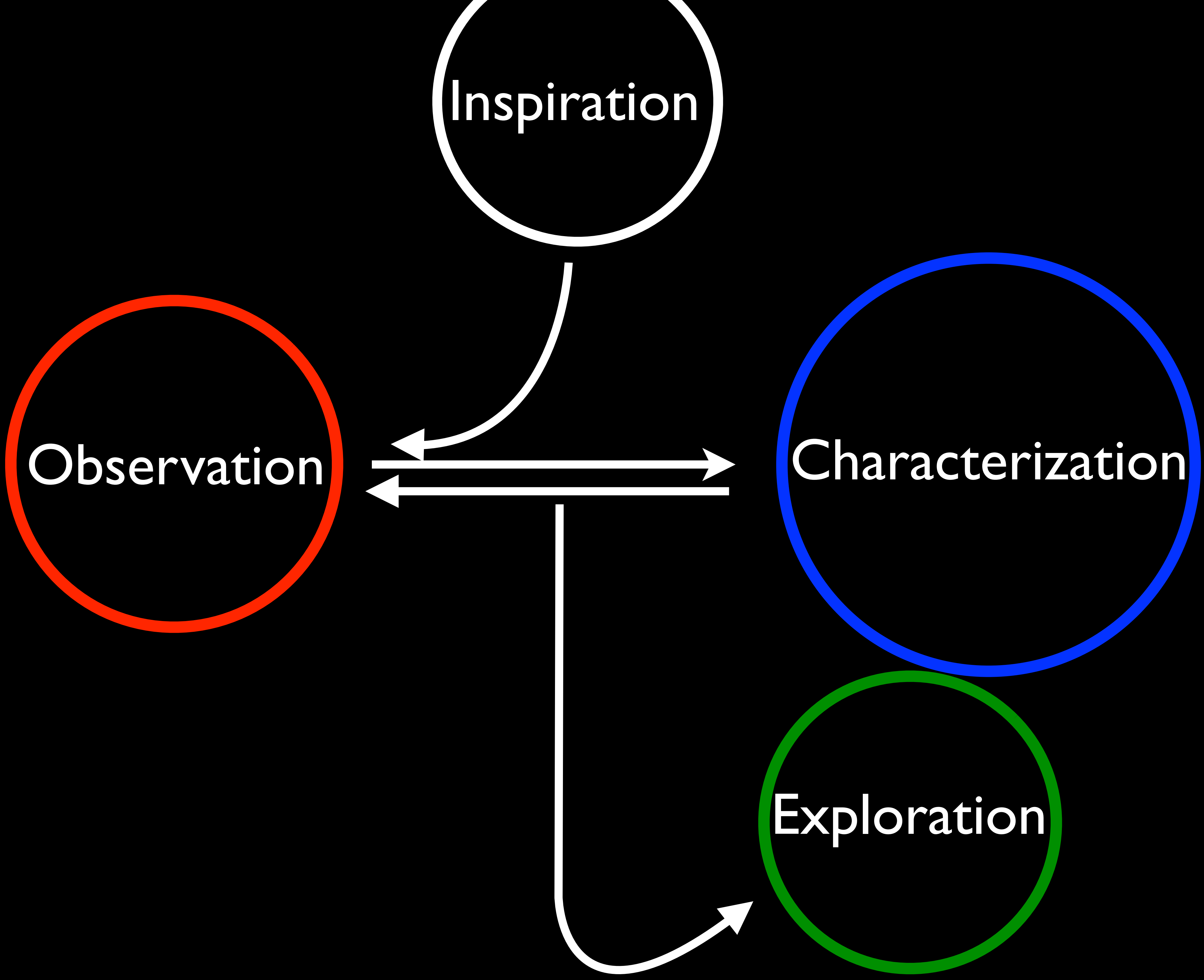
Inspiration

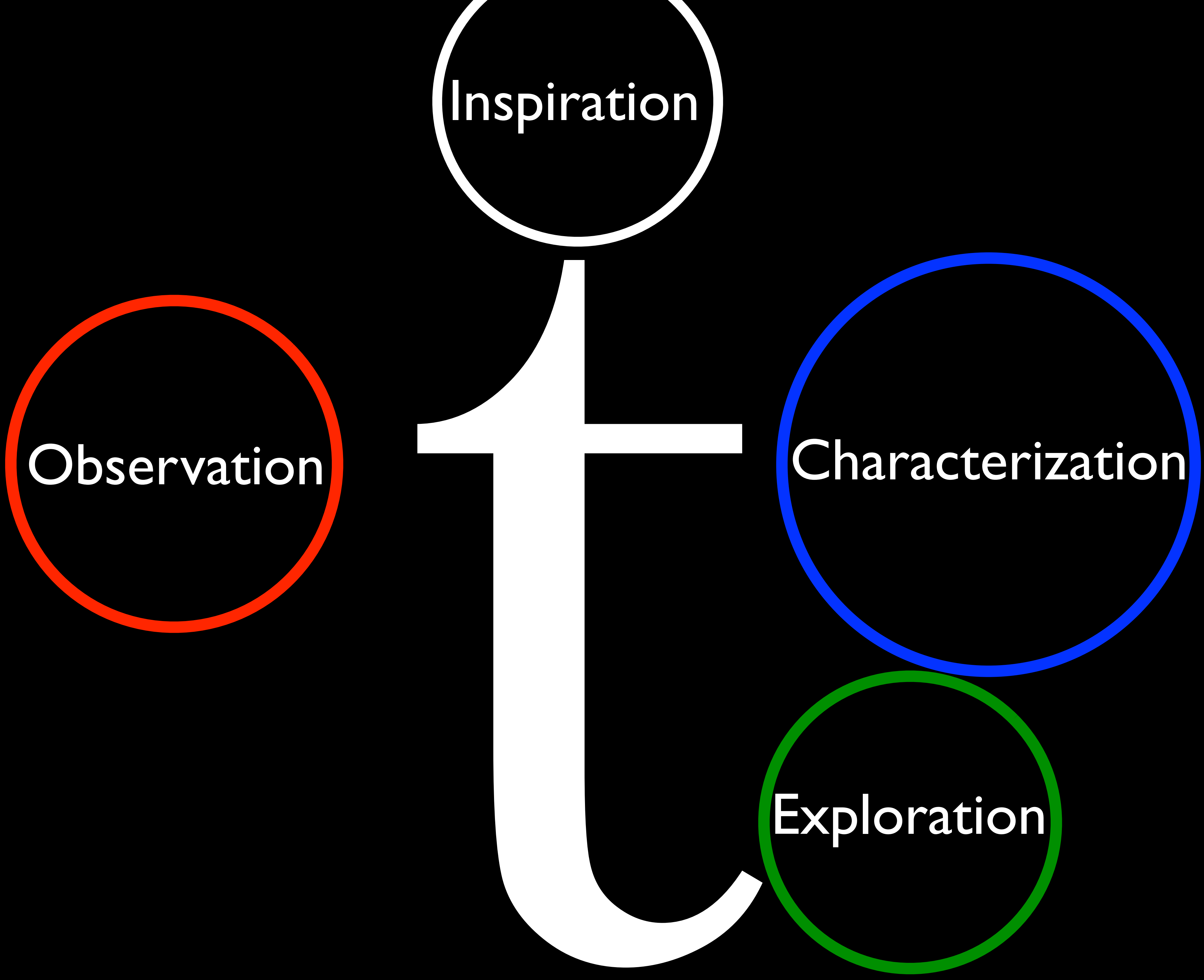

Inspiration
Observation


Inspiration
Observation
Characterization


Inspiration
Observation
Characterization


Inspiration
Observation
Characterization
Exploration


Inspiration
Observation
Characterization
Exploration


Inspiration
Observation
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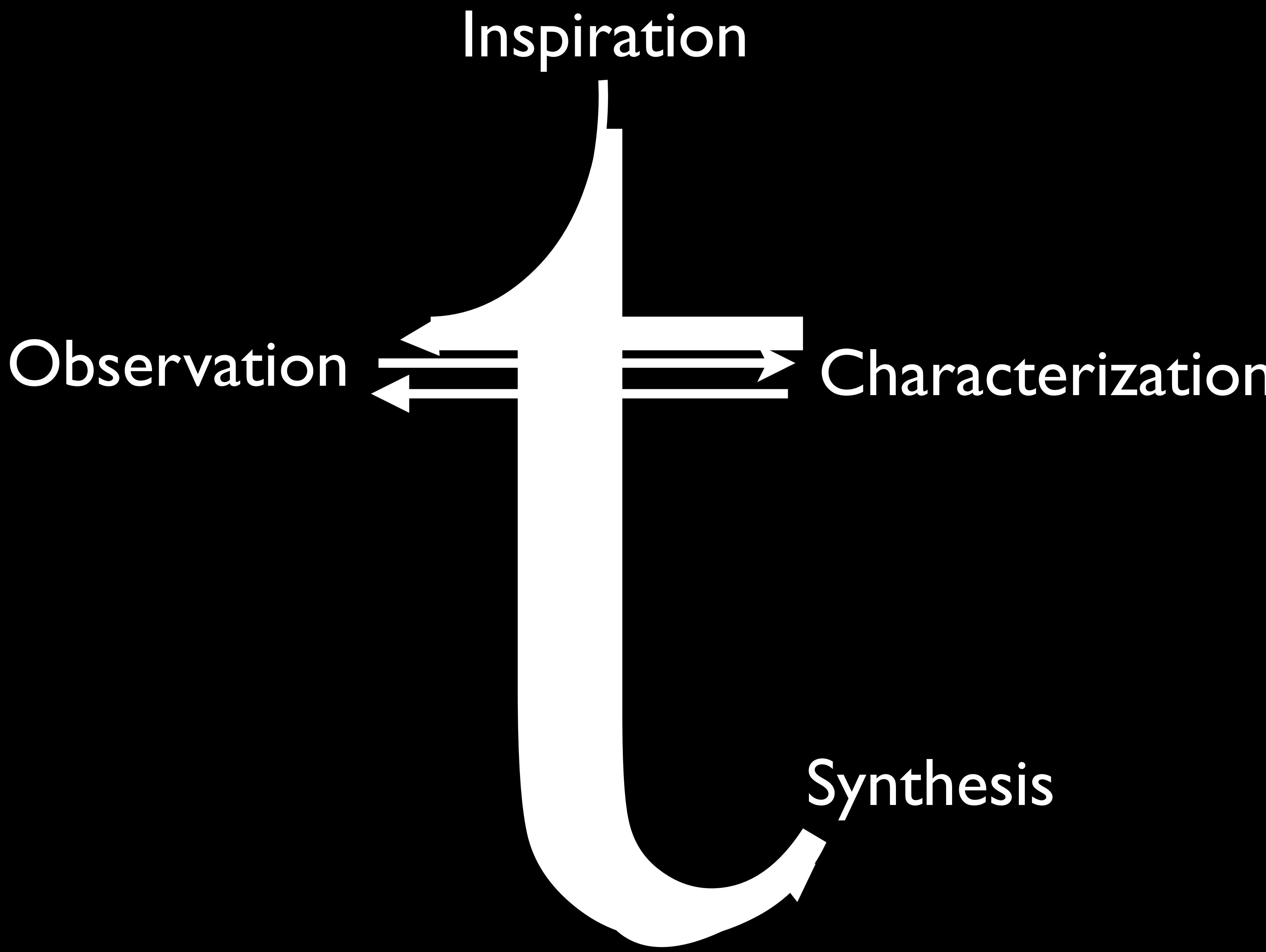
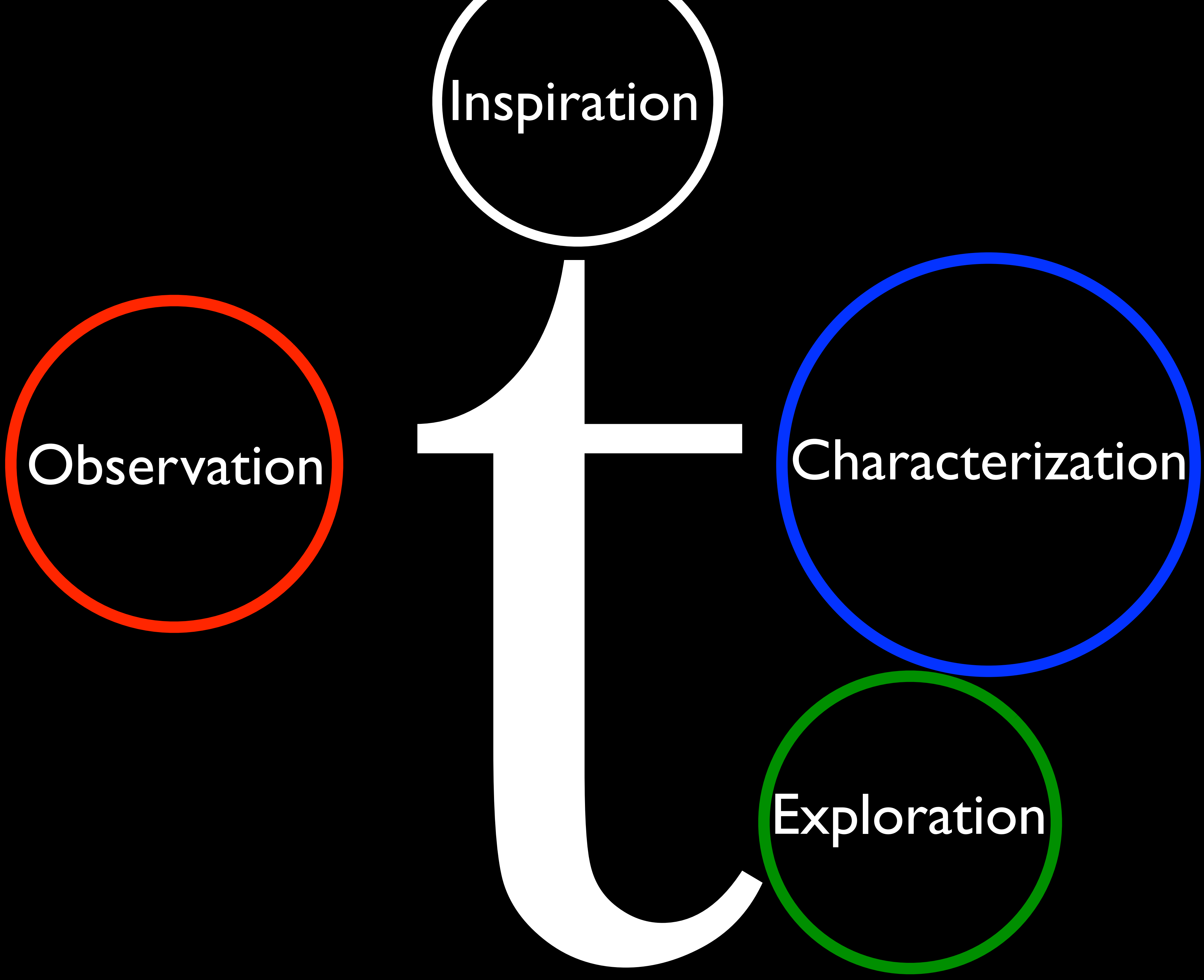
Characterization
Exploration

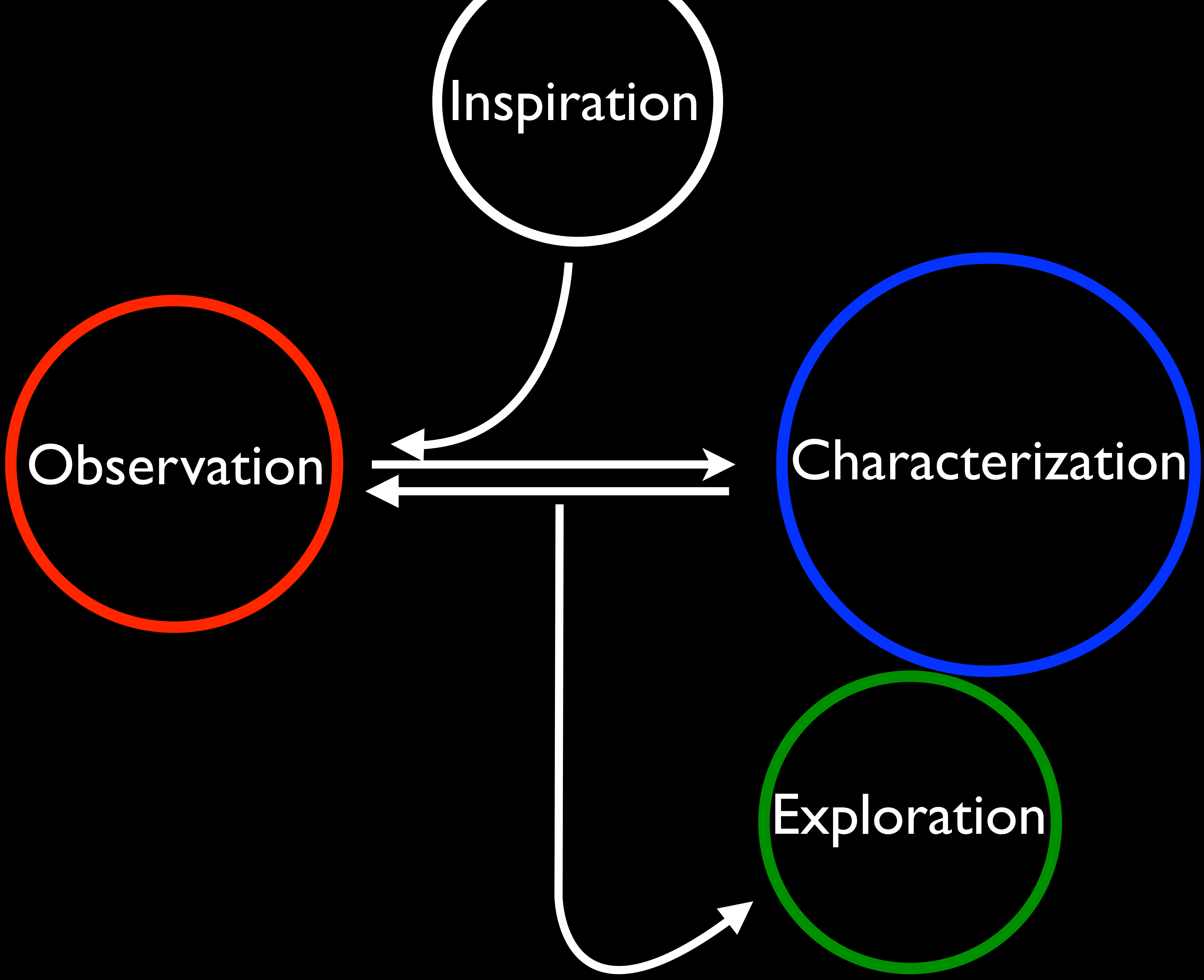
What I Learned

- Theorists are more likely to go over time on their presentations.
  - Experimentalists have figured this out.
  - I am willing to bet this talk is another data point.
- Top experimentalists tend to be more sophisticated than their purely BSM counter-parts when it comes to QCD, MC, ...
- Top physics is going strong!
  - So many wonderful experimental results... I really have no idea how Christian is going to cope!
  - Precision measurements and computations make unparalleled progress.
  - Exploration of the complicated observables and high energy or rare processes both theoretically and experimentally are well underway.

Thank you!


Inspiration
Observation
Characterization
Synthesis


Inspiration
Observation
Characterization
Exploration


Inspiration
Observation
Characterization
Exploration