WHAT ARE WE SUPPOSED TO DO?

• Indico is **explicit** on the objective for today:

> This is the final event of the Workshop on Physics at HL-LHC, and perspectives for HE-LHC, which started with the kickoff meeting of October 30 2017.

> This jamboree will present the findings of the five WGs, documented in the respective Reports. It will be an ideal occasion to celebrate the success of the Workshop, and to reflect on the impressive prospects of the future LHC programme!

Let’s follow orders now.
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But why? Partly because WG1 chapter is on arXiv!

And How?
By going through p120-160!

... and the 1377 pages in Vol. 2 on the arXiv yesterday!

6 Top quark physics

Precision measurements of top quark properties present an important test of the SM. As the heaviest particle in the SM, the top quark plays an important role for the electroweak symmetry breaking and becomes a sensitive probe for physics beyond the SM.
LHC / HL-LHC PLAN

- Scenarios for projections
  - HL-LHC pp running at 14 TeV, 200 PU \((5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1})\), 3/ab or 4/ab in the ‘ultimate’ scenario
  - HE-LHC pp running at 27 TeV, 15/ab
LUMINOSITY AND UNCERTAINTIES
LUMINOSITY AND UNCERTAINTIES

“Frequently made assumptions”

- uncertainties in object performance
  - machine upgrades (PU≈200) and detector approximately compensate
- theoretical uncertainties reduce by factor 2
  - PDF, better PS tunes, ME corrections, etc.
- statistical uncertainty scales with luminosity
- we will be able to afford computing
  - do not consider statistical uncertainty of MC
- more details in the backup
• A great many things have to come together
  1. state of the art theoretical tools/calculations
     • estimate of 10+ years of future development
  2. low-level understanding of sub-detector performance
  3. object performance – realistic projections
  4. novel analysis ideas that incorporate 1-3
SETTING THE STAGE FOR PHYSICS WITH THE TOP QUARK


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• first question: How far do we reach in top quark pair kinematics?

• Let’s set the stage with the differential top cross section theory calculation
  • NNLO QCD for HL-LHC 14 TeV with 3/ab
  • NLO QCD for HE-LHC 27 TeV with 15/ab
  • NB: EWK corrections will be essential

Cumulative $M_{tt}$ distribution for HL-LHC

Equivalent count currently (36/fb) at $M_{tt} \gtrsim 2.5$ TeV

$\approx$10 events $M_{tt} > 7$ TeV
SETTING THE STAGE FOR PHYSICS WITH THE TOP QUARK


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≈20 events

\[ p_T > 2.5 \text{ TeV} \]

TeV scale jets/leptons collimated to slim jets: \( \Delta R = 0.13 \)

(16cm @ CMS ECAL)
A great many things have to come together
1. state of the art theoretical tools/calculations
   • estimate of 10+ years of future development
2. low-level understanding of sub-detector performance
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4. novel analysis ideas that incorporate 1-3

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**PRECISION FROM THE BULK**

- differential top cross section measurement (HL-LHC 3/ab, 14 TeV)
- extrapolation based on Delphes, single lepton channel
- PU mitigation for $E_T^{\text{miss}}$ required

- profit from tracking coverage to $|\eta|<4$
- unfolding purity and stability similar to Run-II, despite the higher PU
**PRECISION FROM THE BULK**

- **differential top cross section** measurement (HL-LHC 3/ab, 14 TeV)
- extrapolation based on Delphes, single lepton channel
- PU mitigation for $E_T^{\text{miss}}$ required

Puppi $E_T^{\text{miss}}$ resolution for $p_T(Z) > 30$

- profit from tracking coverage to $|\eta| < 4$
- unfolding purity and stability similar to Run-II, despite the higher PU
uncertainty on differential top x-sec $\mathcal{O}(5\%)$

- significant impact on high $x$ gluon PDF
- complemented with forward tops:
**PRECISION FROM THE BULK AND FROM HIGH ETA**

- uncertainty on differential top x-section $O(5\%)$
- significant impact on high $x$ gluon PDF
- complemented with forward tops:
  1. 300/fb LHCb data probe high-$x$ PDFs with partially reconstructed top quarks
  2. quark PDFs: use differential charge asymmetry vs. lepton $\eta$ 

sensitivity from 300/fb of LHCb data in (partial) t and $tt$ final states

- differential $l^\pm b$ charge asymmetry prospects from LHCb (300/fb for HL/LHC)
- sensitivity to quark PDFs
**TOP MASS**

- **simple concept:**
  1. pick out jets from top
  2. pair up the right jets to each top
  3. calculate mass

- **challenges (a selection):**
  - efficient $b$ tagging (combinatorics)
  - moderate $p_T$ triggers
  - systematic relating the ‘MC mass’ to a well defined parameter in a ren. scheme to 100 MeV
  - precision JES & $E_T^{miss}$, lepton $E$ scale

- top mass measurement requires precision on all fronts!

---

0.17 GeV → 0.1 %

dominated by JES

---
• simple concept:
  1. pick out jets from top
  2. pair up the right jets to each top
  3. calculate mass

• challenges (a selection)
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  • moderate \( p_T \) triggers
  • systematic relating the ‘MC mass’ to a well defined parameter in a ren. scheme to 100 MeV
  • precision JES & \( E_T^{\text{miss}} \), lepton E scale

• Mitigate JES by considering 0.04% BR with a J/Psi: 
  \[ t\bar{t} \rightarrow (W^+b)(W^-\bar{b}) \rightarrow (\ell\nu\ell J/\psi(\rightarrow \mu^+\mu^-)X)(qq'\bar{b}) \]
**FLAVOR CHANGING NEUTRAL CURRENTS**

- **FCNC BR suppressed** to $10^{-12} - 10^{-15}$ in SM by GIM mechanism
- sensitive probe **BSM models** (2HDM, SUSY, RPV, …)
- traditionally use **anomalous coupling Lagrangian**:

$$\mathcal{L}_{FCNC} = \sum_{q=u,c} \left[ \sqrt{2} g_s \frac{k_{tqg}}{\Lambda} (\bar{q} \sigma^{\mu\nu} T^a (f^L_{gq} P_L + f^R_{gq} P_R) t) G^a_{\mu\nu} \\
+ \frac{g}{\sqrt{2}} k_{tqH} (\bar{q} (f^L_{Hq} P_L + f^R_{Hq} P_R) t) H \\
+ e \frac{k_{tq\gamma}}{\Lambda} (\bar{q} \sigma^{\mu\nu} (f^L_{\gamma q} P_L + f^R_{\gamma q} P_R) i) F_{\mu\nu} \\
+ \frac{g}{\sqrt{2} c_W} \frac{k_{tqZ}}{\Lambda} (\bar{q} \sigma^{\mu\nu} (f^L_{Zq} P_L + f^R_{Zq} P_R) t) Z_{\mu\nu} \\
+ \frac{g}{4 c_W} \zeta_{tqZ} (\bar{q} \gamma^\mu (f^L_{Zq} P_L + f^R_{Zq} P_R) t) Z_\mu \right] + h.c.$$

- In practice, often simplify chiral structure, e.g. $f^R = 1$
- $q = u,c$ with more sensitivity to $u$ (higher x-sec)
ATLAS and CMS on FCNC

- Comprehensive studies by ATLAS ($tZq$) and CMS ($tqg$)
- Both simulate dedicated signal and background samples and follow the Run-II strategies
- CMS uses BNN on kinematic input
- ATLAS uses $\chi^2$ constructed under FCNC hypothesis
- Improvement typically one order of magnitude

<table>
<thead>
<tr>
<th>SM-EFT limits:</th>
<th>Expected limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>C_{uB}^{(31)}</td>
</tr>
<tr>
<td>$</td>
<td>C_{uW}^{(31)}</td>
</tr>
<tr>
<td>$</td>
<td>C_{uB}^{(32)}</td>
</tr>
<tr>
<td>$</td>
<td>C_{uW}^{(32)}</td>
</tr>
</tbody>
</table>
THE NEED FOR A COMMON LANGUAGE

• **top quark:** SM probe in wildly different settings
  • systematically limited high precision differential x-sec meas.
  • rare-event type searches (4t, …)
  • everything in between ( T/T+Z/W/H/γ, FCNC, … )

→ uncertainties evolve differently with time
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→ uncertainties evolve differently with time

LHC results
7/8/13 TeV/14 TeV/27 TeV
and Tevatron/LEP/EWPT

plethora of BSM predictions, PDF fits, evolving with time

increasing PU, evolving detector, improving precision on the backgrounds

… partial comparisons have a short life.
WHEN WE ALL GATHER…

… we propose a search for 6 top quarks …

… by combining 47 muon observables in another MVA …

… interpreted in my 24 parameter model …
EFFECTIVE FIELD THEORY

• generic extension of the Standard Model

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{SM}^{(4)} + \sum \frac{C_x}{\Lambda^2} O_{6,x} + h.c. \]

• defined in unbroken phase of SM → complex pattern after EWSB

• limited & well defined approximations
  • global way to look for NP in SM measurements
  • parameterizes deviations from higher-order SM predictions

• EFT provides guidance to exp. searches

\[ \sigma = \sigma_{SM} + \sum_i \frac{1}{\Lambda^2} C_i \sigma_i + \sum_{i \leq j} \frac{1}{\Lambda^4} C_i C_j \sigma_{ij}. \]
  • e.g. on combination strategy in TT+X (respects gauge symmetries)
  • e.g. on where to include include 4-f ops (global hierarchy)
  • can derive \( \sigma( C ) \) on event level analytically → curse of dimensionality is lifted.

\[ O_{6,x} \] 59 dim-6 gauge-invariant ops.
\[ C_x \] Wilson coefficients (complex)
\[ \Lambda \] scale of dim-6 interactions

Compare with anomalous coupling approach:
• often break gauge symmetries
• no global hierarchy of effects
• less well defined assumptions
• pro: simpler interpretation
FOUR TOP PRODUCTION

- 4 tops: complete NLO cross section known and EWK contributions not small (10%)

ATLAS and CMS studies in 2 same charge leptons or 3 lepton channel, ≥ 6 jet, ≥ 3 b-tagged jets

Uncertainty in fake/nonPrompt is leading systematic, total uncertainty in meas. x-sec is 11% (ATLAS)

Expect evidence for tttt with 300/fb at 14 TeV

<table>
<thead>
<tr>
<th>$\sigma$ [fb]</th>
<th>LO + NLO</th>
<th>LO(+NLO)</th>
<th>$\frac{LO(+NLO)}{LO_{QCD}(+NLO_{QCD})}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 TeV</td>
<td>15.83$^{+13%}_{-21%}$</td>
<td>1.11 (1.08)</td>
<td></td>
</tr>
<tr>
<td>27 TeV</td>
<td>143.93$^{+17%}_{-20%}$</td>
<td>1.11 (1.06)</td>
<td></td>
</tr>
</tbody>
</table>
• 4 tops: complete NLO cross section known and EWK contributions not small (10%)

• EFT limit on qqtt operator reflects 4\textsuperscript{th} power

<table>
<thead>
<tr>
<th>( \sigma [\text{fb}] )</th>
<th>( \text{LO} + \text{NLO} )</th>
<th>( \frac{\text{LO}(+\text{NLO})}{\text{LO}_QCD(+\text{NLO}_QCD)} )</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
</tbody>
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• ATLAS and CMS studies in 2 same charge leptons or 3 lepton channel, \( \geq 6 \) jet, \( \geq 3 \) b-tagged jets

• Uncertainty in fake/nonPrompt is leading systematic, total uncertainty in meas. x-sec is 11\% (ATLAS)

• Expect evidence for tttt with 300/fb at 14 TeV

• Sensitivity to top Yukawa coupling modification is high
  • 14 TeV 3/ab \( \sigma (\bar{t}ttt) = 13.14 - 2.01 \kappa_t^2 + 1.52 \kappa_t^4 \) [fb] 
  • 27 TeV 15/ab \( \sigma (\bar{t}ttt) = 115.10 - 15.57 \kappa_t^2 + 11.73 \kappa_t^4 \) [fb]
• W boson helicity measurements, asymmetries and single top production are able to constrain potential anomalous $W_{tb}$ couplings:

\[
\mathcal{L}_{W_{tb}} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W^-_\mu \\
- \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (g_L P_L + g_R P_R) t W^-_\mu + \text{h.c.}
\]

• comprehensive list of measurements
  • W boson helicity from Tevatron & LHC (8 TeV)
  • $A_{FB}$ from LHC (8 TeV)
  • single top x-sec from Tevatron and LHC (7/8/13)

• Extrapolate to 3/ab & include scaled results
  • Reconstruction level uncertainties were kept (b-tagging was divided by two)
**TOP-Z/γ COUPLING MEASUREMENT**

- ATLAS/CMSL Delphes based study using $p_T(Z)$ and $p_T(γ)$. Constraint operators modifying t-Z/γ coupling
- ATLAS constraints ttγ (1l/2l) and CMS constraints ttZ (3l)
- theoretical uncertainties scaled to 50%
- expect an improvement in sensitivity by factor 4-6

ATLAS projection $\leftarrow$ linear relations $\rightarrow$ CMS Delphes based result

<table>
<thead>
<tr>
<th>Operator</th>
<th>$\sigma_{tZ}$</th>
<th>$\sigma_{tγ}$</th>
<th>$\sigma_{tW}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single lepton</td>
<td>[-0.5,0.3]</td>
<td>[-0.1,0.1]</td>
<td>[-0.3,0.5]</td>
</tr>
<tr>
<td>Dilepton</td>
<td>[-0.6,0.4]</td>
<td>[-0.1,0.1]</td>
<td>[-0.4,0.3]</td>
</tr>
</tbody>
</table>

Wilson coefficient 68% CL $(\Lambda/\text{TeV})^2$ 95% CL $(\Lambda/\text{TeV})^2$

- $C_{ttZ}$: [-1.65, 3.37], [-2.89, 6.76]
- $C_{ttγ}$: [-1.35, 2.92], [-2.33, 6.69]
- $C_{tZ}$: [-0.37, 0.36], [-0.52, 0.51]
- $C_{tW}$: [-0.38, 0.36], [-0.54, 0.51]

$\approx$ factor 4 better than 77/fb at 13 TeV
SUMMARY

• A lot of work has been done!
  • It’s really time to celebrate.
  • I apologize for any perceived imbalance in the results presented

• HL/HE LHC significantly extend the kinematic reach for top quarks

• Push deeper into the precision frontier with top quark pairs (PDF) and the top mass

• More and more precise results on top BSM require a common language

• In top quark physics, experimental precision meets theoretical accuracy
  • Effective field theory is a way forward that can efficiently handle both

• Work remains to be done: More ‘novel ideas’ need to be conceived.
  • Can’t happen in a vacuum. The ground work is here now.
# Uncertainty Details (Top Mass)

<table>
<thead>
<tr>
<th>Source</th>
<th>Value (GeV)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8 TeV, 19.7 fb⁻¹</td>
<td>14 TeV, 0.3 ab⁻¹</td>
</tr>
<tr>
<td>Method calibration</td>
<td>±0.04</td>
<td>±0.02</td>
</tr>
<tr>
<td>Lepton energy scale</td>
<td>+0.01</td>
<td>±0.01</td>
</tr>
<tr>
<td>Global JES</td>
<td>±0.13</td>
<td>±0.12</td>
</tr>
<tr>
<td>Flavor-dependent JES</td>
<td>±0.19</td>
<td>±0.17</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>−0.03</td>
<td>±0.02</td>
</tr>
<tr>
<td>$p_T^{\text{miss}}$ scale</td>
<td>+0.04</td>
<td>±0.04</td>
</tr>
<tr>
<td>b tagging efficiency</td>
<td>+0.06</td>
<td>±0.03</td>
</tr>
<tr>
<td>Pileup</td>
<td>−0.04</td>
<td>±0.04</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>+0.03</td>
<td>±0.01</td>
</tr>
<tr>
<td>ME generator</td>
<td>−0.12 ± 0.08</td>
<td>−</td>
</tr>
<tr>
<td>Ren. and fact. scales</td>
<td>−0.09 ± 0.07</td>
<td>±0.06</td>
</tr>
<tr>
<td>ME-PS matching</td>
<td>+0.03 ± 0.07</td>
<td>±0.06</td>
</tr>
<tr>
<td>Top quark $p_T$</td>
<td>+0.02</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>b fragmentation</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Semileptonic b hadron decays</td>
<td>−0.16</td>
<td>±0.11</td>
</tr>
<tr>
<td>Underlying event</td>
<td>+0.08 ± 0.11</td>
<td>±0.14</td>
</tr>
<tr>
<td>Color reconnection</td>
<td>+0.01 ± 0.09</td>
<td>±0.05</td>
</tr>
<tr>
<td>PDF</td>
<td>±0.04</td>
<td>±0.03</td>
</tr>
<tr>
<td>Systematic uncertainty</td>
<td>±0.48</td>
<td>±0.30</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>±0.16</td>
<td>±0.04</td>
</tr>
<tr>
<td>Total</td>
<td>±0.51</td>
<td>±0.31</td>
</tr>
</tbody>
</table>
COMMON SYSTEMATICS

- Renormalization and factorization scales (includes ME and PS): factor 1/2 (improve with more data and more studies)
- Top pt: factor 1/3 or even less (more differential cross sections, NLO generators, 2D-differential NNLO predictions used for differential k-factors.)
- MC statistics: no uncertainty
- https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCCommonSystematics

<table>
<thead>
<tr>
<th>Object Efficiency</th>
<th>uncertainty</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>muon reco+ID (all WP)</td>
<td>0.1%</td>
<td></td>
</tr>
<tr>
<td>muon reco+ID+isolation (all WP)</td>
<td>0.5%</td>
<td></td>
</tr>
<tr>
<td>Electrons/photons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>electron reco+ID (incl. isolation), all WP (pt &gt; 20 GeV)</td>
<td>0.5%</td>
<td></td>
</tr>
<tr>
<td>photon reco+ID+incl. isolation)</td>
<td>~2% (??)</td>
<td></td>
</tr>
<tr>
<td>tau</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tau reco+ID+isolation (all WP)</td>
<td>5% as in Run2</td>
<td>recommend 2.5% for analyses where tau efficiency is one of the dominant uncertainties</td>
</tr>
<tr>
<td>flavor tagging</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b-jets (all working points)</td>
<td>~ 1% for 30&lt;pt&lt;300 GeV, 2-6% for pt&gt;300 GeV</td>
<td></td>
</tr>
<tr>
<td>c-jets (all working points)</td>
<td>~2%</td>
<td></td>
</tr>
<tr>
<td>light jets (loose WP)</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>light jets (medium WP)</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>light jets (tight WP)</td>
<td>15%</td>
<td></td>
</tr>
<tr>
<td>subjet b-tagging</td>
<td></td>
<td></td>
</tr>
<tr>
<td>double-b tag</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JES abs. scale</td>
<td>0.1-0.2%</td>
<td></td>
</tr>
<tr>
<td>JES rel. scale</td>
<td>0.1-0.5%</td>
<td></td>
</tr>
<tr>
<td>JES pile up</td>
<td>0-2%</td>
<td></td>
</tr>
<tr>
<td>JES Jet Flavour</td>
<td>0.75%</td>
<td></td>
</tr>
<tr>
<td>JES JER</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet substructure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet mass scale uncertainty</td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>Jet mass resolution</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>W tagging efficiency</td>
<td>10% (governed by Herwig vs Pythia)</td>
<td>1%</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td></td>
<td>1%</td>
</tr>
</tbody>
</table>
Fig. 70: Expected signal yields (top-left), migration matrices (top-right), and its properties (bottom) for measurements of $p_T(t_h)$ for the HL-LHC (Phase-2) simulation. The purity is defined as the fraction of parton-level top quarks in the same bin at the detector level, the stability as the fraction of detector-level top quarks in the same bin at the parton level, and the bin efficiency as the ratio of the number of events found in a certain bin at detector level and the number of events found at parton-level in the same bin.