Phenomenology 2017

May 8-10, University of Pittsburg

FYZIKÁLNÍ ÚSTAV
Akademie věd ČR, v.v.i.

Pavel Staroba

Fyzikální ústav Akademie věd ČR, v.v.i.

Overview

- Information about the conference
- Selected results

Topics of parallel sessions	Talks
Higgs physics	8
Top physics	8
QCD and Electroweak	8
Heavy Flavor	8
Neutrinos and Lepton Flavor	16
Cosmology & Astrophysics	8
Theoretical Developments	5
Future Colliders	8
BSM	27
BSM Higgs	16
Extra Dimensions & Composite Higgs	8
SUSY	23
DM	32
Dark Sector & ALPs	9
Novel Techniques & Tools	8

Plenary talks

SM and Higgs Measurements at LHC Peter Onyisi

Searches for BSM Physics at LHC Jim Hirschauer

Higgs Physics at the LHC Dieter Zeppenfeld

New Developments in MC Tools for New Physics Benjamin Fuks

Perspective in B Physics Experiments Urich Uwer

Flavor Physics in the LHC Era Alexander Lenz

Neutrino Physics at the Intensity Frontier Anne Schukraft

Muons as a Probe of New Physics Chris Polly

Recent Developments in Lattice Gauge Theory Christoph Lehner

New Dynamics in the Higgs Sector Tony Gherghetta

Physics with International Linear Collider Jurgen Reuter

Scattering Amplitudes for General Mass and Spin Nima Arkani-Hamed

Dark Matter Direct Detection Jianglai Liu

New Searches for Light Dark Matter Peter Graham

Cosmological Probes of Particle Physics Joel Myers

Astro-particle physics in the new era Alexander Friedland

Particle Physics Implications of Gravitational Waves Jose Miguel No Redondo

Future Perspectives in Particle Physics Raman Sundrum

SM & Higgs at the LHC

Peter Onyisi, *on behalf of ATLAS and CMS*

Pheno, 8 May 2017

The University of Texas at Austin

Introduction

- LHC: not just an "energy frontier" machine!
  - Enormous datasets of gauge bosons, top quarks, Higgs
- What can we study?
  - Precision SM parameters
  - all the nonperturbative stuff in proton collisions: parton distribution functions, underlying event
  - can we calculate well in the SM?
  - are there hints of BSM physics in "SM-like" interactions?
  - fundamental tests
- "Beyond the Standard Model" searches require understanding the Standard Model
  - no royal road to BSM ... ?

Process	2016 yield per experiment
$W \rightarrow \ell\nu$	700×10^6
$Z \rightarrow \ell\ell$	70×10^6
WZ	1.7×10^6
$t\bar{t}$	30×10^6
inclusive H	1.9×10^6
$t\bar{t}H$	18×10^3

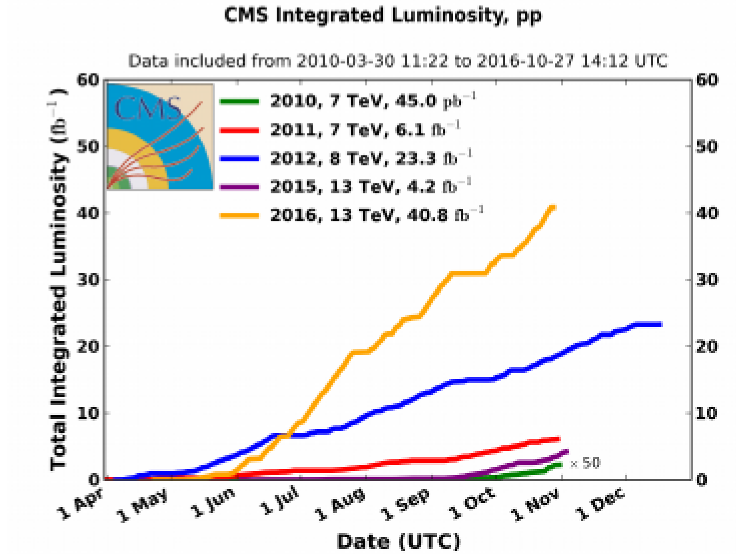
This talk: a few selected topics!

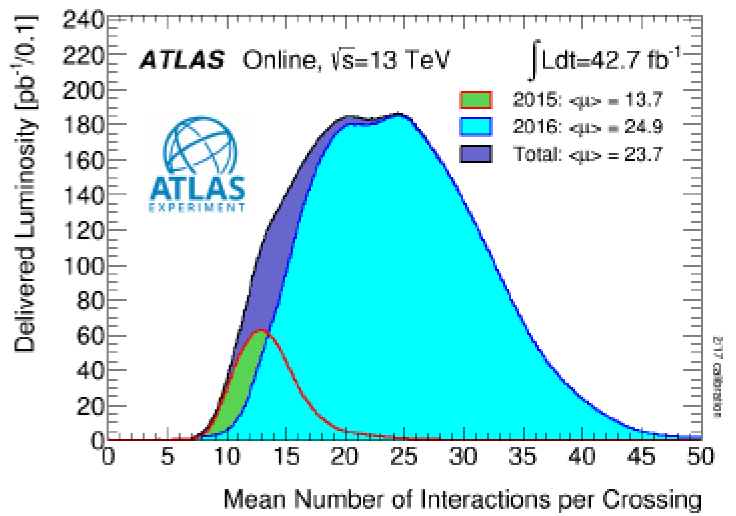
Will generally not show both experiments' versions of an analysis...

Datasets

- 2016: superb year of LHC data delivery
  - LHC design luminosity exceeded, high uptime
  - more data than all previous years combined
  - pileup mitigation strategies in place
- Many SM & top analyses utilize lower energy/lower pileup datasets
  - may take a long time to understand systematics for a dataset at required precision

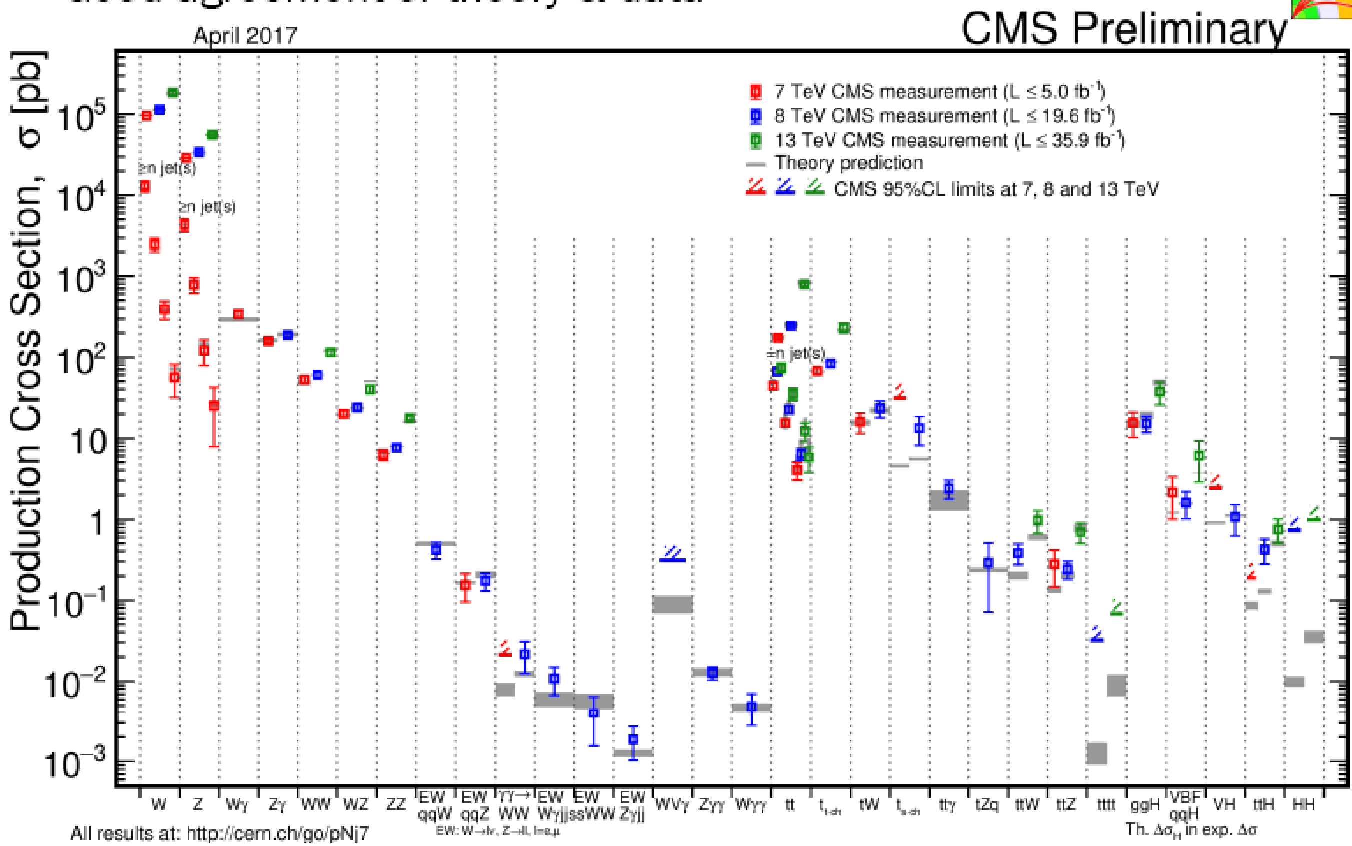
LHC 13 TeV delivered luminosity to date ~ 1.5% of HL-LHC





Cross Sections: view from 35,000 ft

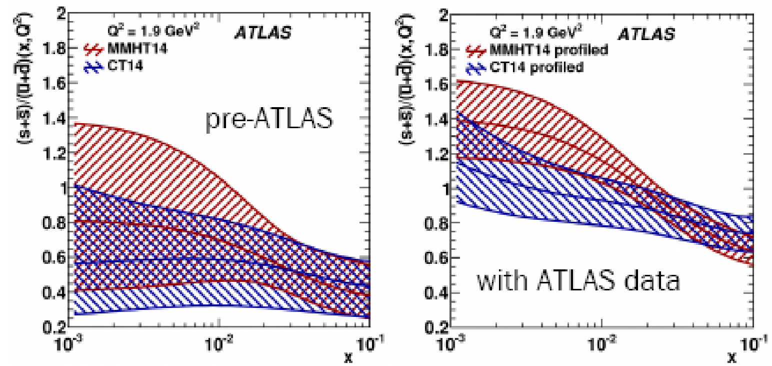
- Many measurements (many not in plot ...)
- Good agreement of theory & data



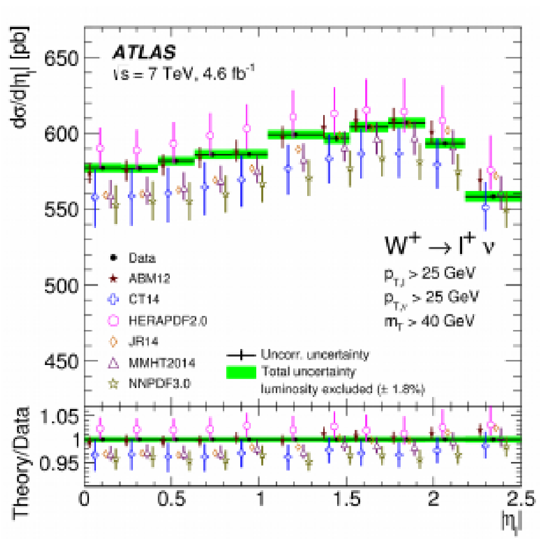
Proton Structure: PDF

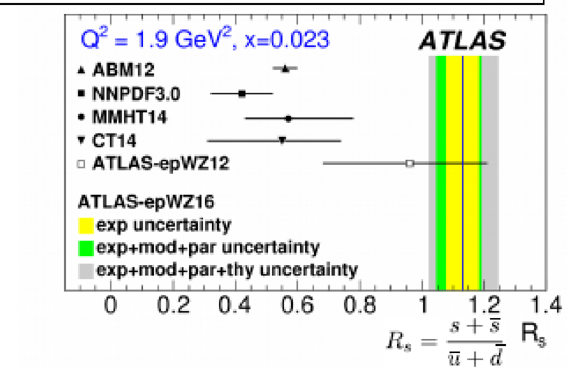
- Use high order perturbative calculations + precision data to constrain parton behavior
- e.g., W & Z differential cross sections

1612.03016, sub to EPJC



No evidence for suppression of strange sea

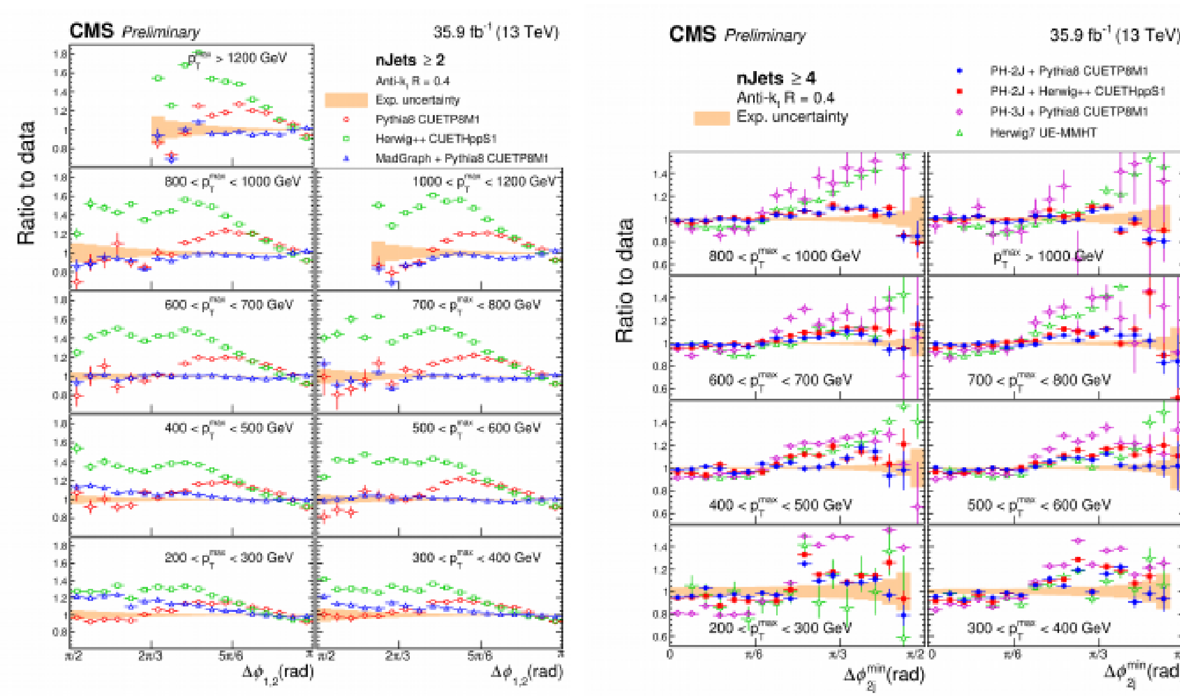




Multijets: QCD & Parton Shower

- Can we accurately simulate production of multiple jets (pure QCD)?
- e.g. azimuthal correlations of jets in ≥2, ≥3, ≥4 jet events
  - compare to a variety of calculations (different hard scatter matrix elements, parton showers). All generators have regions of difficulty

CMS-SMP-16-014



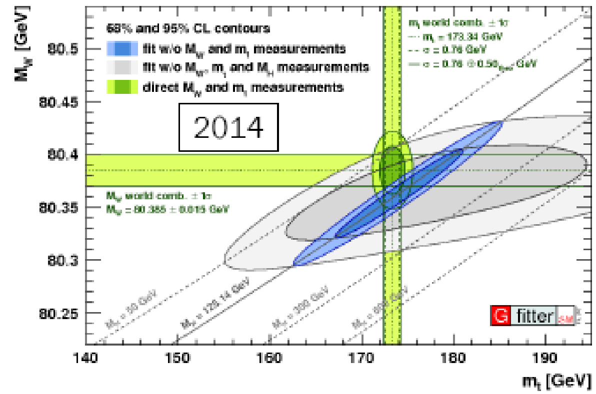
Overall, best performance from Herwig7

Particle Masses

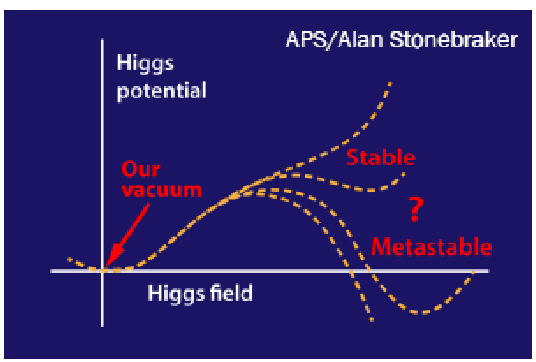
More than just stamp-collecting!

- W, H, t masses: consistent with other EW measurements?

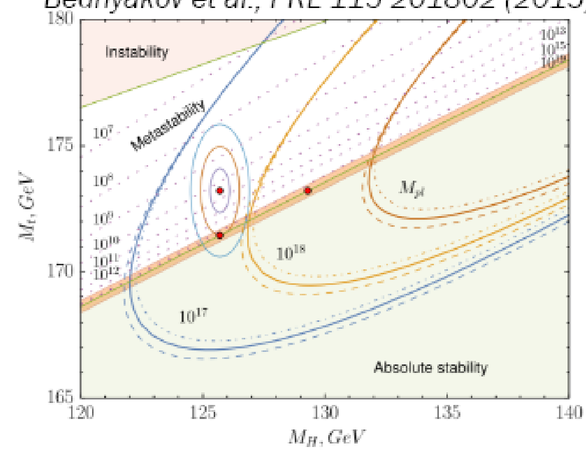
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$



- H, t masses: is there a deeper minimum of the Higgs potential? is SM EW vacuum metastable?

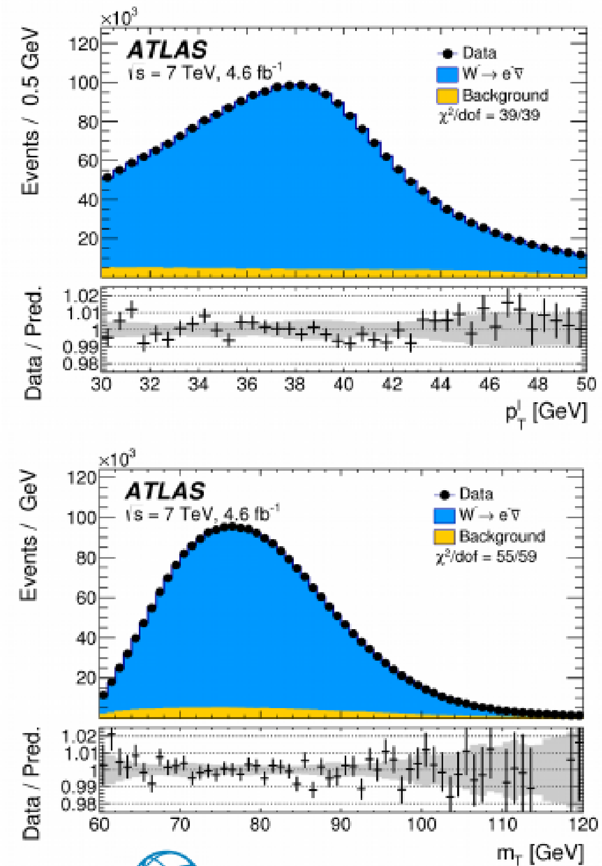


Bednyakov et al., PRL 115 201802 (2015)



W Mass

- First measurement of m_W at the LHC
- 7 TeV data alone: plenty of statistics
- Observables:
  - charged lepton p_T
  - reconstructed W m_T
- Use Z as standard candle for calibration, tuning, method validation
- Complications:
  - pp initial state: W^+ and W^- produced differently
  - large (~ 25%) contribution of $c\bar{s} \rightarrow$ W: sea quarks more important than at Tevatron
  - generators don't necessarily get boson polarization right

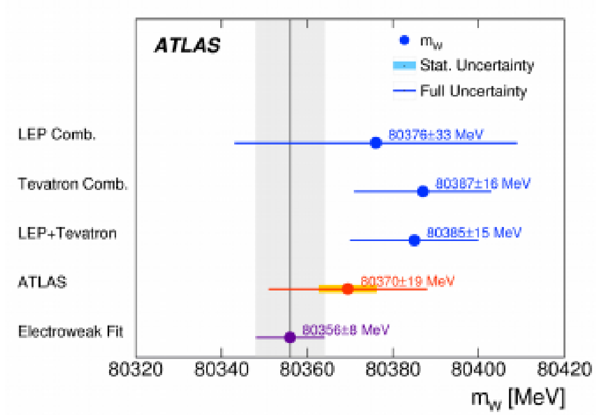


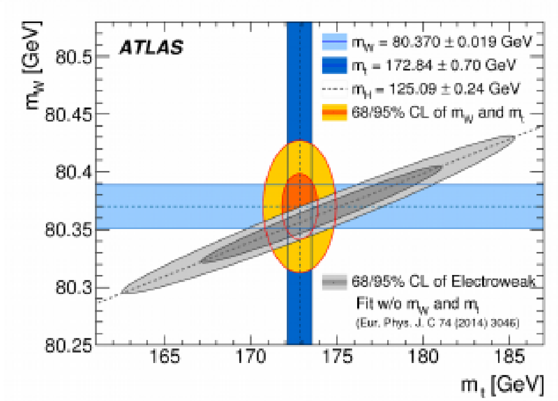
1701.07240, sub. to EPJ C

W Mass Result

$$m_W = 80370 \pm 7(\mathrm{stat}) \pm 11(\mathrm{exp\ syst}) \pm 14(\mathrm{mod\ syst})\ \mathrm{MeV}$$

- Largest experimental systematics: lepton energy/momentum scale
- Largest modeling systematics are parton distribution functions, parton showers
  - relies on correlation of higher-order QCD corrections in W & Z
- Precision better than LEP combination, not far from Tevatron combination
- Better consistency with global EW fit than before

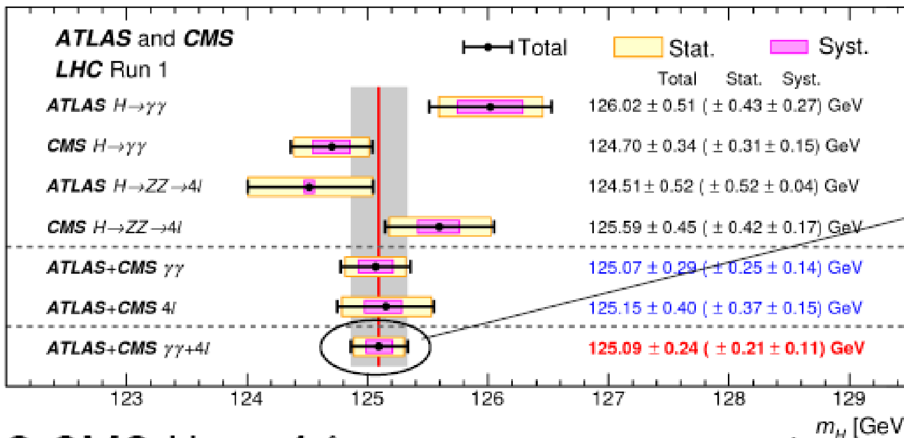




1701.07240, sub. to EPJ C

Higgs Mass

- Use fully-reconstructible decays $H \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$
  - Great potential for improvement: 4ℓ stats dominated



0.2% precision

Run 1 ATLAS+CMS, PRL 114, 191803

- Run 2 CMS $H \rightarrow 4\ell$ mass measurement
  - $H \rightarrow 4\ell$: in concert with other Higgs properties measurements

$$m_H = 125.26 \pm 0.20(\text{stat}) \pm 0.08(\text{syst})\ \text{GeV}$$

CMS-HIG-16-041

  - Better precision than LHC Run 1 combo
    (49 MeV smaller uncertainty than expected)

Top Mass

- Standard technique: test per-event compatibility of events with various mass hypotheses
  - Full/partial reconstruction, usually involving b-jets; could use J/ψ or B-hadron flight distance as proxy for b quark
  - Subject to jet and b-jet energy scale systematics, details of nonperturbative QCD in events
  - Also, what does MC generator top mass actually mean? Potentially O(GeV) shift between generator and "pole" mass
  - Top Yukawa coupling not expressed in pole scheme
- Alternative methods for pole mass:
  - measure $t\bar{t}$ cross section
  - shape of tt+1 jet total invariant mass

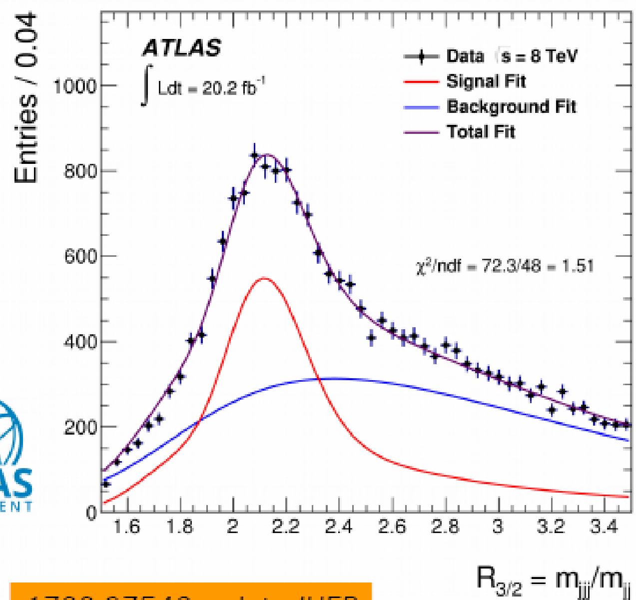
  } Theoretically under better control

Top Mass Examples

"standard" analysis: all-hadronic top decays

plotted: m(t)/m(W)

m_t = 173.72 ± 0.55 (stat) ± 1.01 (syst) GeV

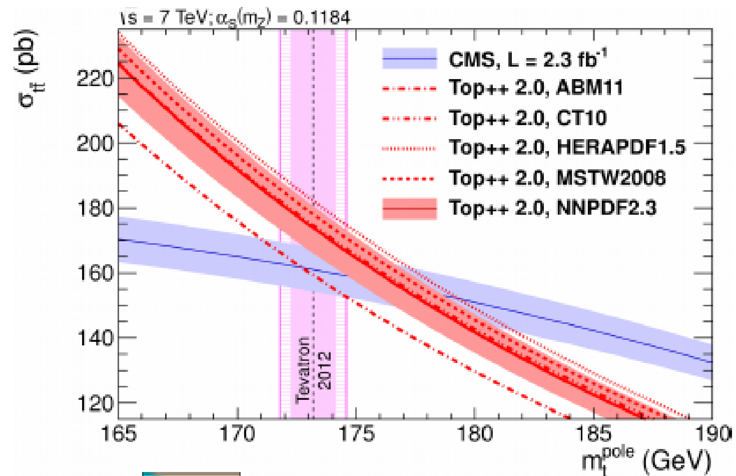


1702.07546, sub to JHEP

Interpret cross section from dileptonic decays (*pole mass*)

still depends on generator mass through acceptance

m_t = 176.7 + 3.0 – 2.8 GeV

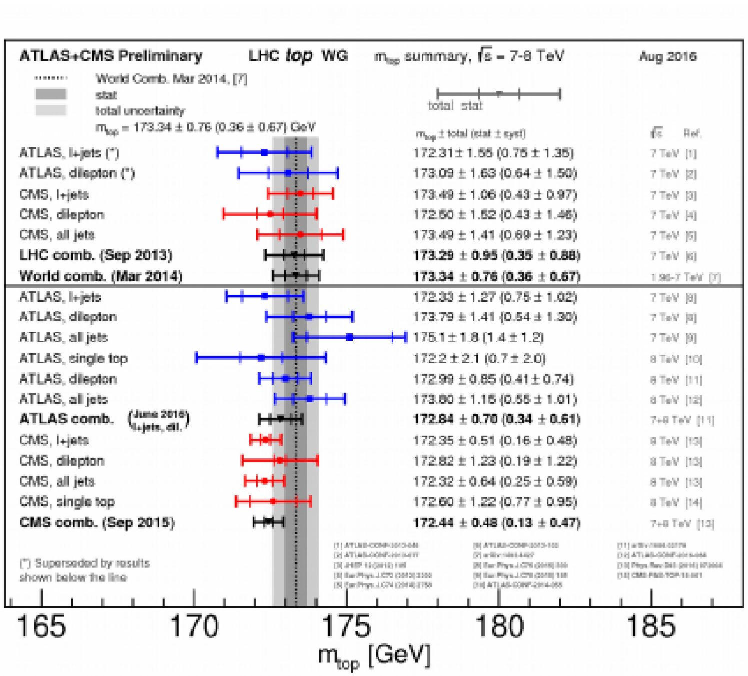


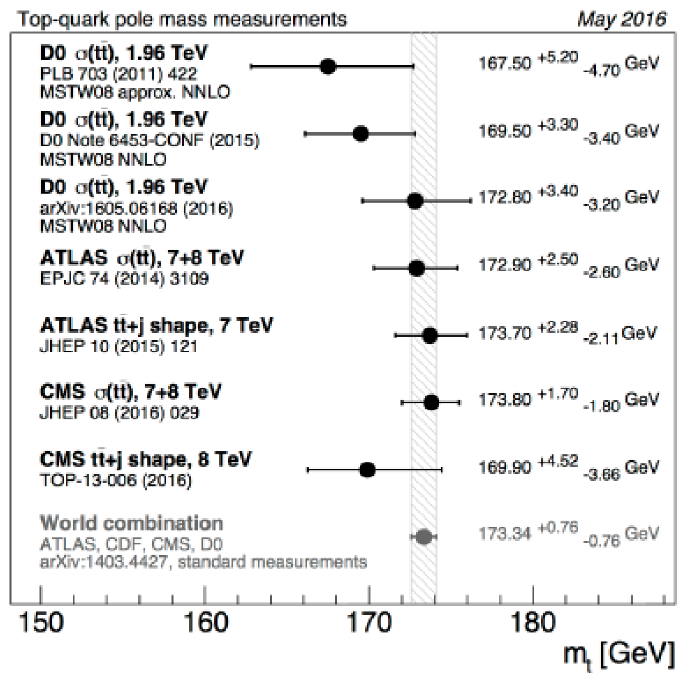
Phys Lett B 728, 496 (2014)

Top Mass Summary

- Standard methods are systematics limited at the ~ 0.5 GeV level
  - CMS projects ~ 0.2 GeV for HL-LHC
- Pole measurements at best ~ 1.8 GeV

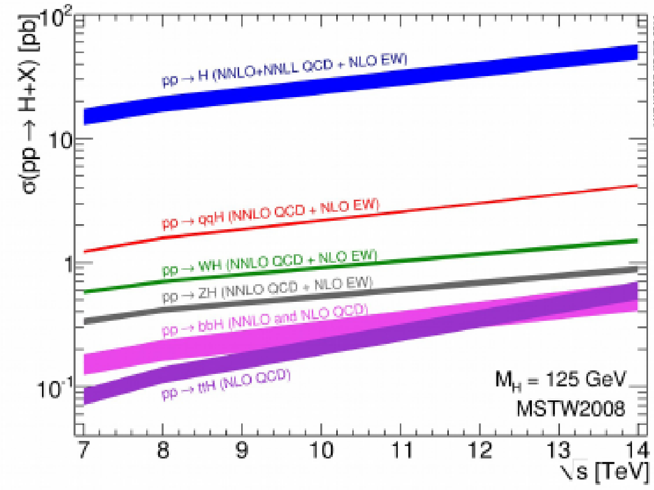
CMS-PAS-FTR-13-017





SM Higgs: Plan

- First phase of h(125) characterization "done"
  - no O(1) departures from SM
- Next phase:
  - precision gauge boson interactions; offshell couplings
  - confirm + precisely measure third generation fermion couplings
  - explore 2nd gen fermion couplings
  - further use of kinematic distributions to probe new physics (and SM) – EFT, simplified template cross sections, pseudo-observables…
  - high[er] precision mass



13 vs 8 TeV: σ(H) up x2 (ttH up x4)

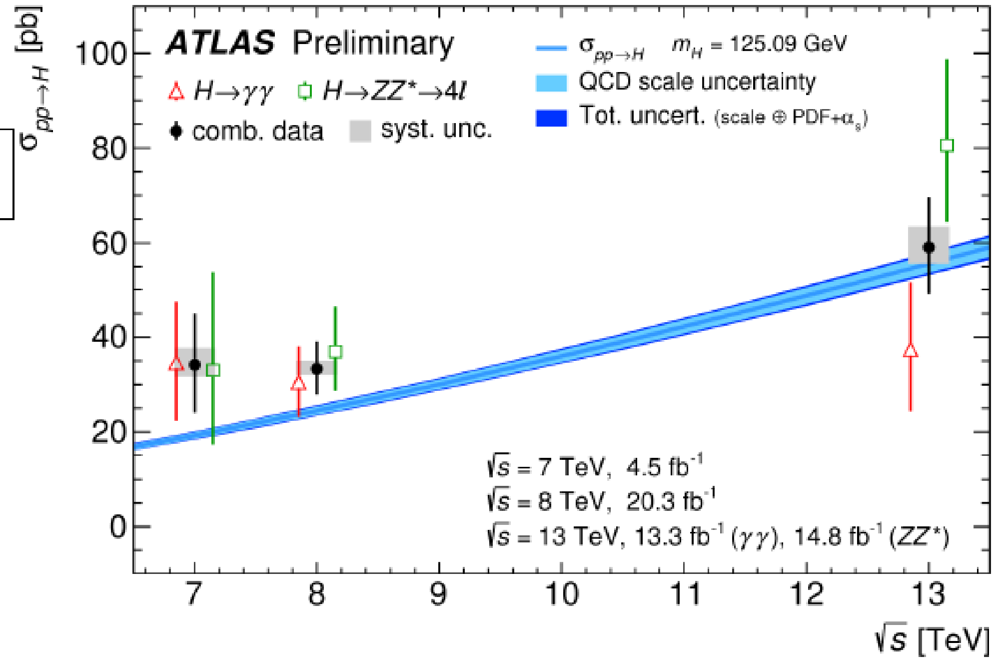
Matched by progress in theory:
→ N^3LO inclusive ggF cross section
→ NNLO differential ggF
→ NLO interference between offshell H and gg → VV
→ Updated generators

ATLAS 4 ℓ, γγ Combination

γγ: better sensitivity for rarer production modes

ATLAS-CONF-2016-081

Total σ, extrap. from fiducial σ



$$\sigma(pp \to H + X) = 59.0^{+9.7}_{-9.2}(\text{stat})^{+4.4}_{-3.5}(\text{syst})\ \text{pb}\ \text{(ATLAS)}$$

$$\sigma(pp \to H + X) = 55.5^{+2.4}_{-3.4}\ \text{pb}\ (\text{N}^3\text{LO theo})$$

Summary

- Probing the Standard Model in great detail is mandatory
  - Test the consistency of the electroweak sector
  - Show we can calculate complex processes
  - Understand backgrounds for difficult new physics searches
- LHC is a factory for W, Z, top, Higgs
  - with large datasets, able to do exquisite precision and rare process searches
  - so far good consistency with SM
- Can make important improvements with additional integrated luminosity
- Future is bright!

LPTHE

IUF

UPMC SORBONNE UNIVERSITÉS

New developments in Monte Carlo tools for new physics

Fuks Benjamin

LPTHE - CNRS - UPMC

Phenomenology 2017 Symposium

University of Pittsburgh, 08 May 2017

The quest for new physics at the LHC

- Path towards the characterization of (potentially observed) new physics
  - Getting information on the nature of an observation
    - Fitting (and interpreting) deviations by some new physics signals
    - Leading order Monte Carlo tools and techniques can do a proper job
  - Final words on the nature of any potential new physics
    - Accurate measurements of the model parameters
    - More precise predictions are mandatory

- New physics is a standard in many tools today
  - Result of 20 years of developments
  - NLO and loop-induced processes can now be simulated automatically
  - BSM precision simulations are standard in MG5_aMC@NLO

Outline

1. Automating NLO calculations in QCD for new physics

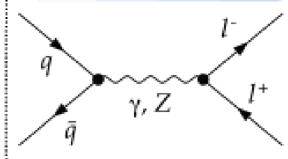
2. Selection of phenomenology examples: SUSY, VLQ, DM, EFT, W’

3. Summary - conclusions

Fixed-order predictions

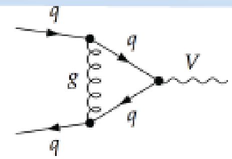
- Leading-order (LO): $d\sigma \approx d\sigma^{(0)}$
  - Easily calculable
    - ★ Automated for any theory and any process
  - Very naive
    - ★ Rough estimate for many observables (large uncertainties)
    - ★ Cannot be used for any observable (e.g., dilepton p_T)

The Drell-Yan example

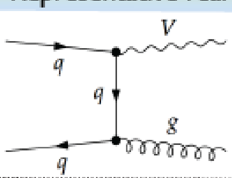


- Next-to-leading-order (NLO): $d\sigma \approx d\sigma^{(0)} + \alpha_s\, d\sigma^{(1)}$
  - Two contributions: virtual loop and real emission
    - ★ Both divergent
    - ★ The sum is finite (KLN theorem)
  - Reduction of the theoretical uncertainties
    - ★ First order where loops compensate trees
  - Better description of the process
    - ★ Impact of extra radiation
    - ★ More initial states included
    - ★ Sometimes not precise enough

The Drell-Yan example: Representative virtual

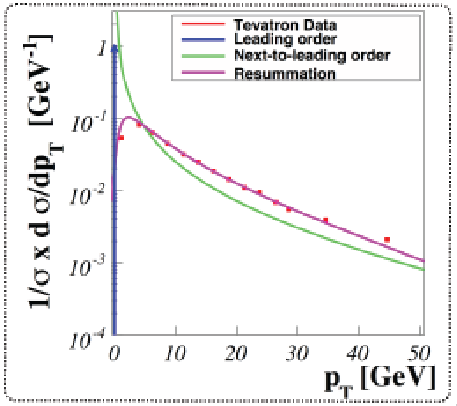


Representative real



Matrix-element / parton shower matching

- Problems with NLO (fixed-order) calculations
  - Soft and collinear radiation ➢ large logarithms
  - Spoil the convergence of the perturbative series



- Matching with parton showers

  - Resummation of the soft and collinear radiation
  - Predictions for a fully exclusive description of the collisions
  - Suitable for going beyond the parton level (hadronization, detector simulation)

Virtual contributions

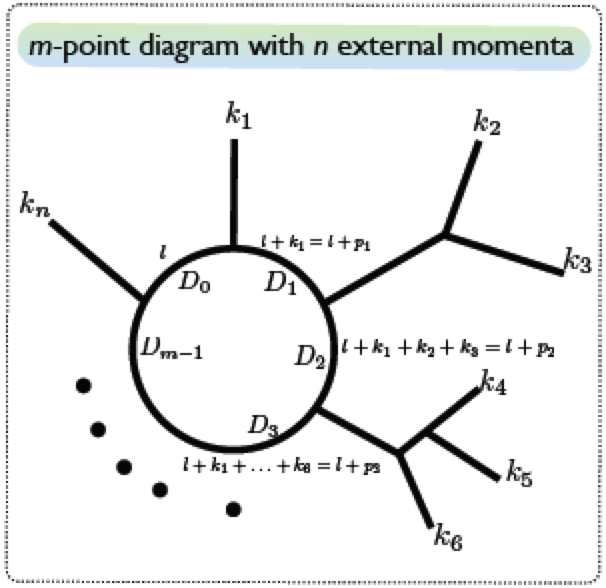
✦ Loop diagram calculations

- ✤ Calculations to be done in d=4-2ε dimensions
  - ★ Divergences made explicit ($1/\varepsilon^2$, $1/\varepsilon$)
  - ★ Numerical challenge
- ✤ Rewriting loop integrals with scalar integrals

$$\int \mathrm{d}^d\ell \frac{N(\ell)}{D_0 D_1 \cdots D_{m-1}} = \sum a_i \int \mathrm{d}^d\ell \frac{1}{D_{i_0} D_{i_1} \cdots}$$

  - ★ Involves integrals with up to four denominators
  - ★ The decomposition basis is finite

The basis integrals can be calculated once and for all



The rational terms

- The loop momentum lives in a *d*-dimensional space
  - The reduction should be done in *d* dimensions and not in 4 dimensions

$$\int \mathrm{d}^d\ell \frac{N(\ell,\tilde{\ell})}{\bar{D}_0\bar{D}_1\cdots\bar{D}_{m-1}} \quad \text{with } \bar{\ell} = \ell + \tilde{\ell}$$

D-dim, 4-dim, (-2ε)-dim

  - Numerical methods works in four dimensions: need to be compensated!

- The R_1 terms originate from the denominators

$$\frac{1}{\bar{D}} = \frac{1}{D}\left(1 - \frac{\tilde{\ell}^2}{\bar{D}}\right)$$

  - These extra pieces can be calculated generically (3 integrals in total)

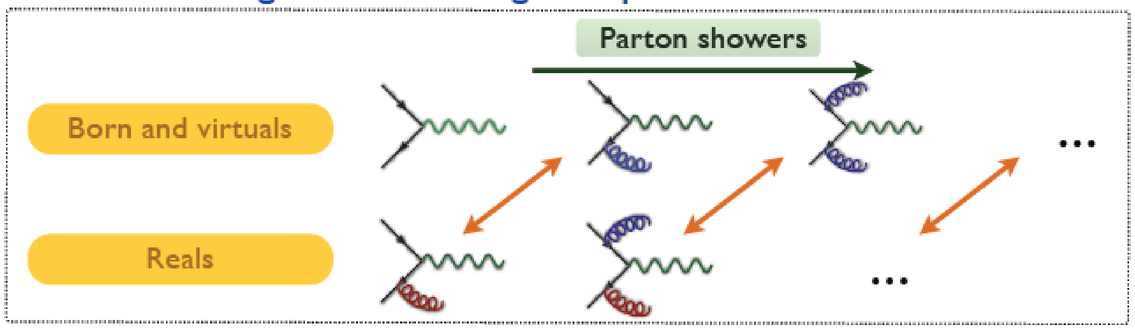
- The R_2 terms originate from the numerator
  - Process-dependent contributions proportional to $\tilde{\ell}^2$
  - In a renormalizable theory, there is a finite number of such R_2 pieces
    - ★ They can be calculated once and for all for a specific model (➢ NLOCT) [Degrande (CPC'15)]
      - ➢ *R_2 counterterm Feynman rules*

Matching fixed order with parton showers

- Subtracting the poles
  - The structure of the poles appearing at NLO is known ➢ subtraction methods
    - ★ $\mathcal{C}$ subtracted from the reals ➢ makes them finite
    - ★ $\mathcal{C}$ integrated and added back to the virtuals ➢ makes them finite
    - ★ Integrals can be made numerically (in four dimensions)

$$\sigma_{NLO} = \int \mathrm{d}^4\Phi_n\, \mathcal{B} + \int \mathrm{d}^4\Phi_{n+1} \Big[\mathcal{R} - \mathcal{C}\Big] + \int \mathrm{d}^4\Phi_n \Big[\int_{\mathrm{loop}} \mathrm{d}^d\ell\, \mathcal{V} + \int \mathrm{d}^d\Phi_1 \mathcal{C}\Big]$$

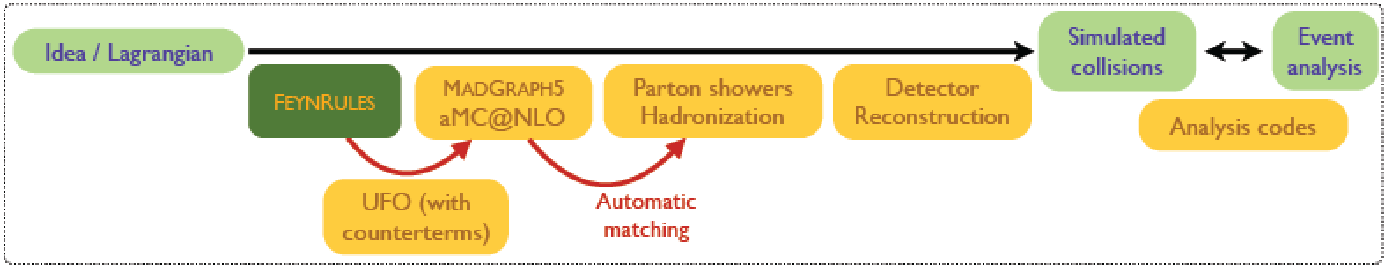
- Double counting when matching with parton showers: another subtraction



- Two sources of double counting that compensate each other (shower unitarity)
  - ★ Radiation: both at the level of the reals and of the shower
  - ★ No radiation: both in the virtuals and in the no-emission probability

Automated NLO simulations with MG5_aMC

✦ A comprehensive approach to Monte Carlo simulations



✦ From Lagrangians to analyzed NLO simulated collisions

- FEYNRULES is linked to the NLOCT module [Alloul, Christensen, Degrande, Duhr & BF (CPC'14)] [Degrande (CPC'15)] [Degrande, Duhr, BF, Mattelaer & Reither (CPC'12)] [Degrande, Duhr, BF, Hirschi, Mattelaer, Shao *et al.* (*in prep.*)]
  - ★ Calculation of UV and R_2 counterterms
  - ★ Export of the information to the UFO

✦ Matching with parton showers within MG5_aMC@NLO

- Monte Carlo subtraction terms automatically handled

[Alwall, Frederix, Frixione, Hirschi, Mattelaer, Shao, Stelzer, Torrielli & Zaro (JHEP'14)]

Supersymmetry

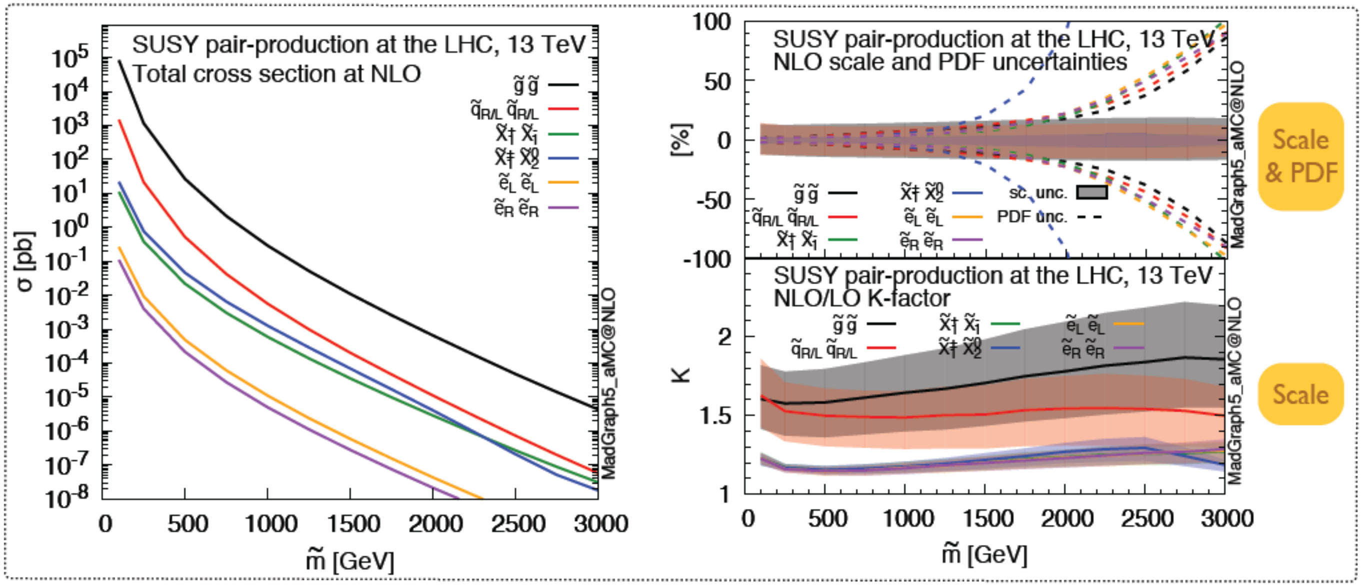
In this talk: focus on the MSSM

[Degrande, BF, Hirschi, Proudom & Shao (PRD'15; PLB'16)]
[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (to appear)]

Total supersymmetric cross sections

[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (to appear)]

✦ Total rates at 13 TeV for SUSY particle pair production



★ Central scales: average SUSY mass

★ Parton densities: NNPDF 3.0

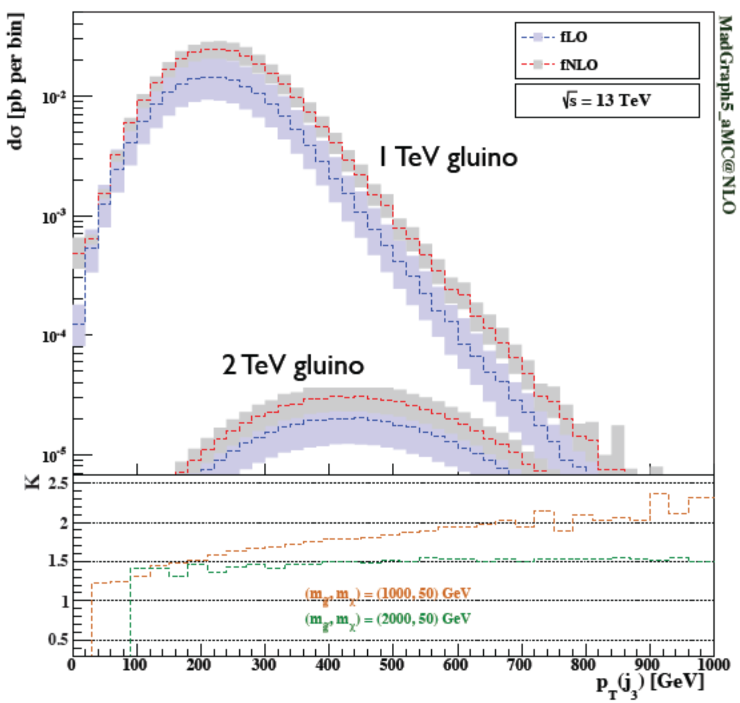
✦ Impact of the NLO corrections

- ✤ Strong processes: cross section enhancement of 50%-100% (genuine NLO effects)
- ✤ Scale uncertainties of 10-15% (strong) or a few % (electroweak)
- ✤ Huge PDF uncertainties in the high mass region (expected to be self cured)

Fixed-order distributions: jet properties

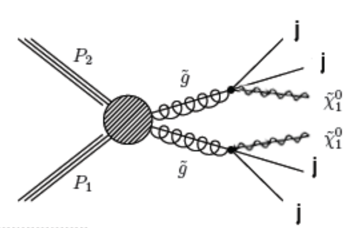
[Degrande, BF, Hirschi, Proudom & Shao (PLB'16)]

3rd jet p_T



- ✤ Mixed effects: origin of the third jet
  - ★ Sometimes a decay jet (hard)
  - ★ Sometimes a radiation jet (soft)
    - ➢ not for the 1st and 2nd jets
- ✤ Constant *K*-factors not accurate
- ✤ NLO effects
  - ★ Crucial for a precise signal description
  - ★ Normalization modification
  - ★ Distortion of the shapes
  - ★ Reduction of the theoretical uncertainties

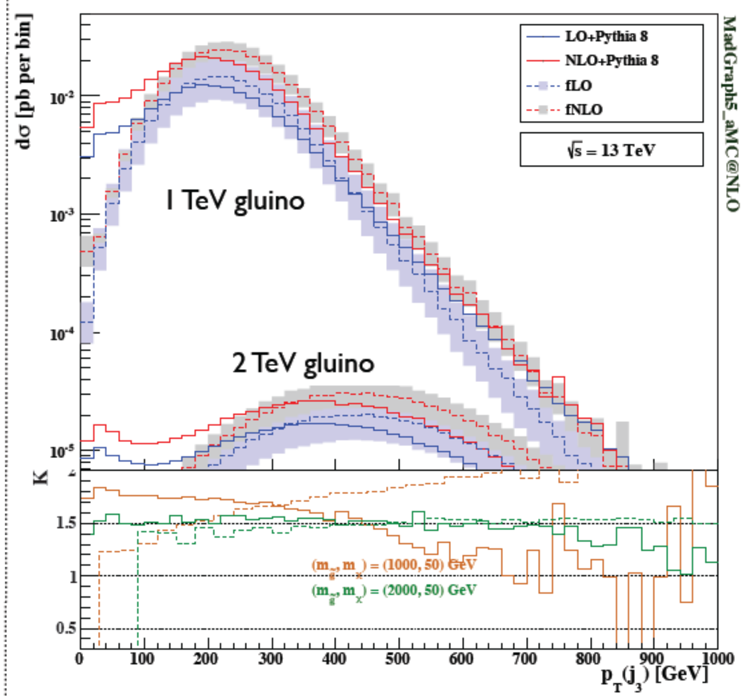
Gluino - multijet + MET



NLO+PS distributions: jet properties

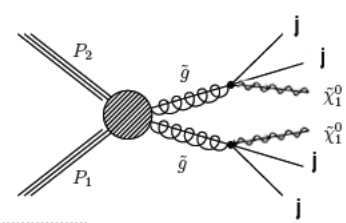
[Degrande, BF, Hirschi, Proudom & Shao (PLB'16)]

3rd jet p_T



- Parton showers populate the low-p_T region
  - ★ Emitted partons often not reclustered back
  - ★ Extra softer jets
  - ★ Distortion of the spectrum
  - ★ Effects milder for hard p_T (the matrix element drives the shape)
- Mixed effects: origin of the third jet
  - ★ Sometimes a decay jet
  - ★ Sometimes a radiation jet
  - ★ Entanglement of the two effects: two peaks

Gluino - multijet + MET

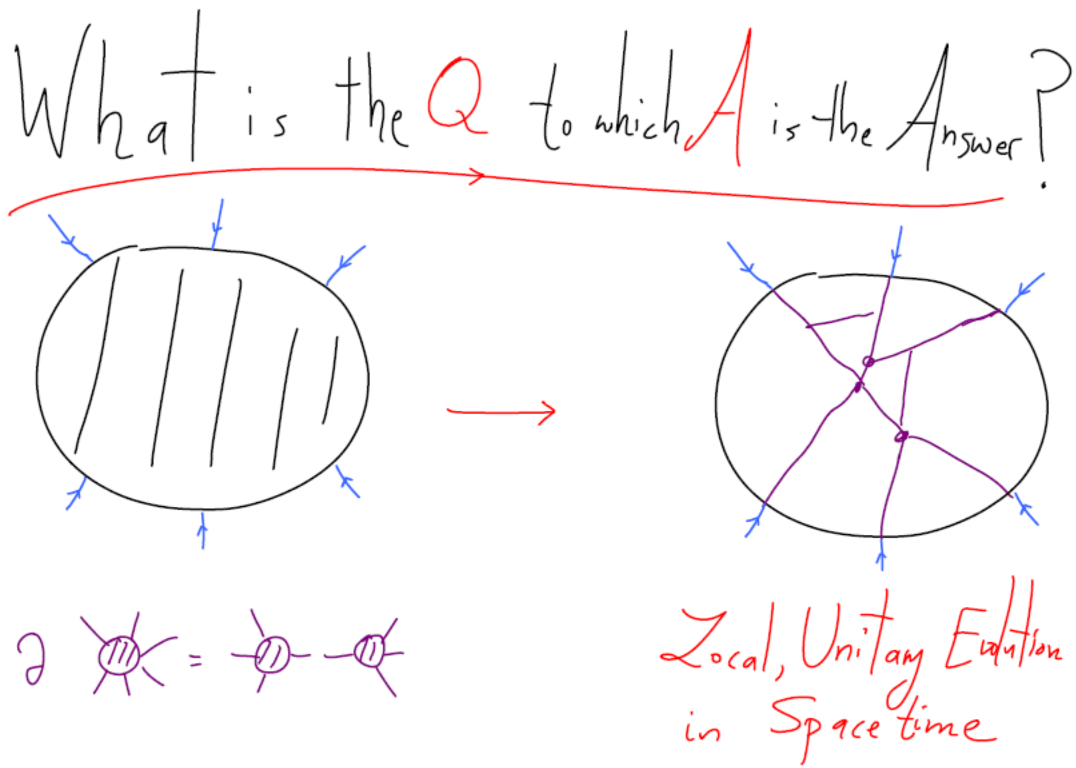


Summary

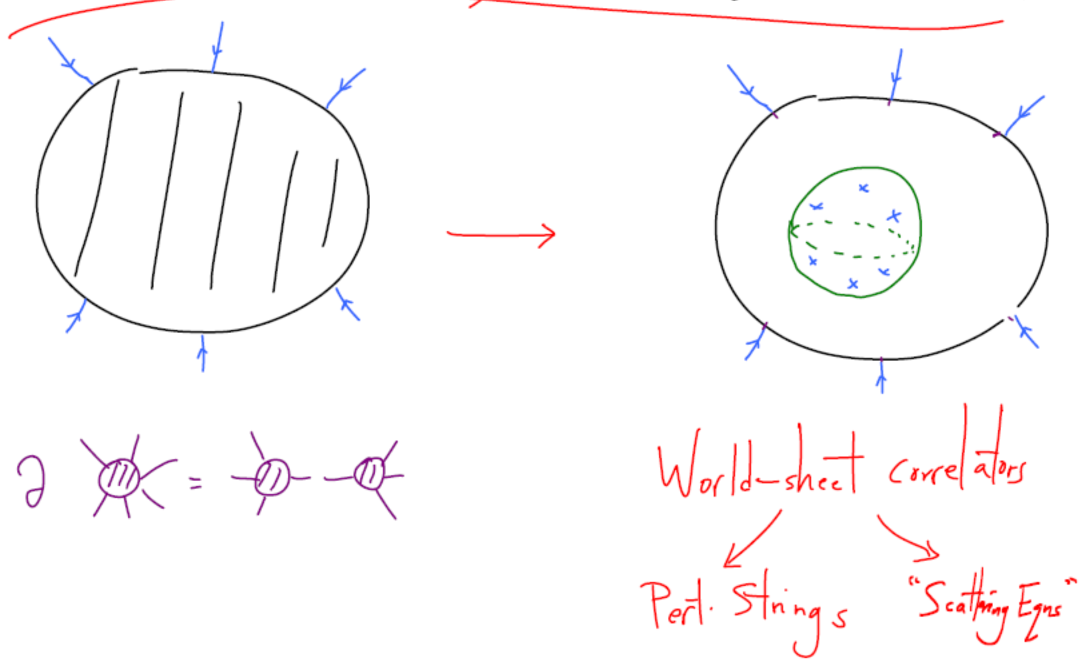
- NLO-QCD simulations for new physics are now the state of the art
  - Via a joint use of FeynRules and MadGraph5_aMC@NLO
  - Divergences (UV, R_2, IR) and MC subtraction terms are automatically handled
  - Loop-induced processes can be studied as well
  - The same machinery can be used for resummation calculations (jet vetoes)

- Many models are already publicly available (on the FeynRules website)
  - Supersymmetry (MSSM and simplified models)
  - BSM Higgs models
  - Dark matter simplified model
  - Higgs and top effective field theories
  - Vector-like quark models
  - Z'/W' models (with a right neutrino) → See talk by R. Ruiz for a phenomenological example

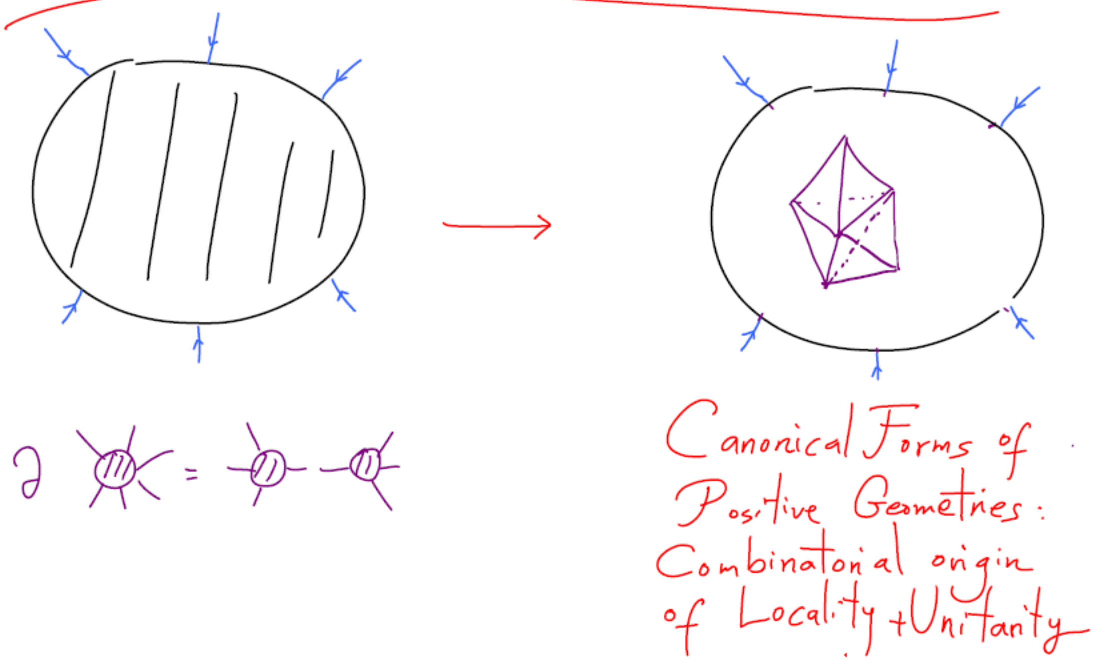
Scattering Amplitudes in the Real World

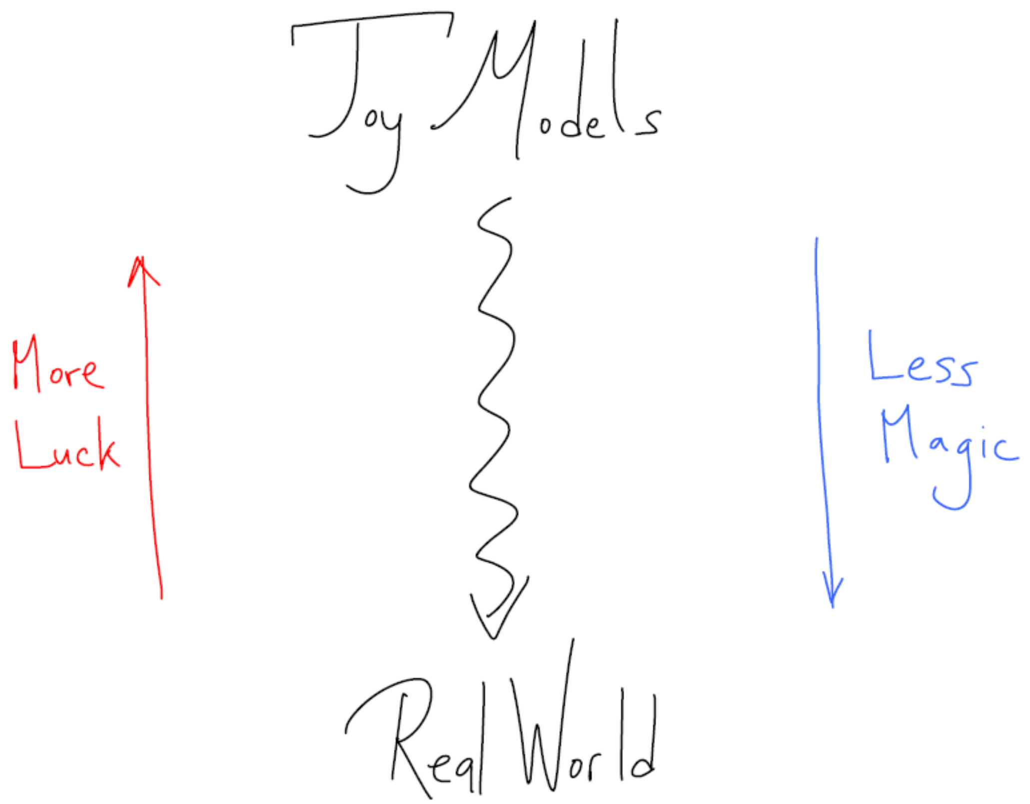

What is the Q to which A is the Answer?
Local, Unitary Evolution
in Spacetime

What is the Q to which A the answer?

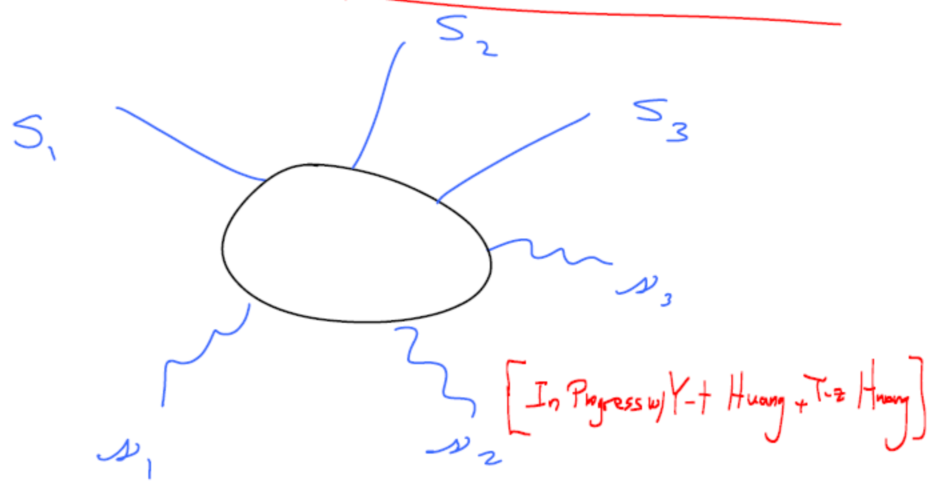


What is the Q to which A the answer?



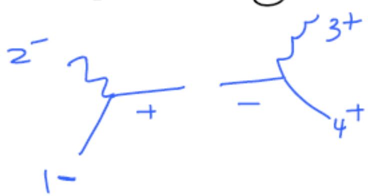

Toy Models
More Luck
Less Magic
Real World

S-Matrix Rules For General m, S:



(Massless) Higher Spin Ruled out by GR/YM

e.g. charged spin s:



$$: \frac{\langle 12\rangle^2 [34]^2 \langle 1|(2-3)|4]^{2s-2}}{u^{2s-1}} \longleftarrow \text{impossible for } s \geq \frac{3}{2}$$

Only consistent 4pt: Spins $\{0, \frac{1}{2}, 1, \frac{3}{2}, 2\}$

- YM → 1
- $\mathcal{N} \leq 8$ SUSY → $\frac{3}{2}$
- unique, GR → 2

* Obviously: no Lagrangian, no Quantum Fields...
* Analyticity (here = only poles!) imprint of Causality
* CPT + Antiparticles hardwired by ↑
* Spin-Statistics, Weinberg-Witten + Coleman-Mandula elementary consequences

* Modern S-Matrix program: exploit locality + unitarity to determine amplitudes
  (Responsible: Symmetries → Simplicity)

* But conversely: look for a new picture for what amplitudes "really are", where space-time + Hilbert space don't appear — see locality + unitarity as derived notions
  (Magic)

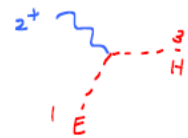
It is possible to do everything we normally cover in intro QFT, (e.g. $(g-2)_e$, β-function, Higgs mechanism ...) in this way: Direct Route from Principles:

Poincaré + Locality + Causality $\Longrightarrow$ Physics

Higgs Mechanism: "IR Deformation"

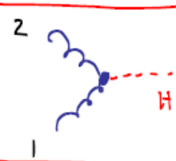
Ex: Photon + Charged Scalar in UV:

$$g\,\frac{\langle 12\rangle\langle 32\rangle}{\langle 13\rangle}$$

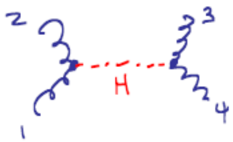


$$g\,\frac{[12][32]}{[13]}$$

$\Downarrow$



$$\frac{g}{m_\gamma}\,\langle \mathbf{1}\mathbf{2}\rangle[\mathbf{1}\mathbf{2}]$$



$$\frac{g^2}{m_\gamma^2}\left\{ \frac{\langle \mathbf{1}\mathbf{2}\rangle[\mathbf{1}\mathbf{2}]\langle \mathbf{3}\mathbf{4}\rangle[\mathbf{3}\mathbf{4}]}{s-m_H^2} + t + u \right\}$$

HE for long. modes

$$\frac{g^2}{m_\gamma^2}\, m_H^2 = \lambda \Longrightarrow \boxed{\frac{m_H^2}{\lambda} = \frac{m_\gamma^2}{g^2}}$$

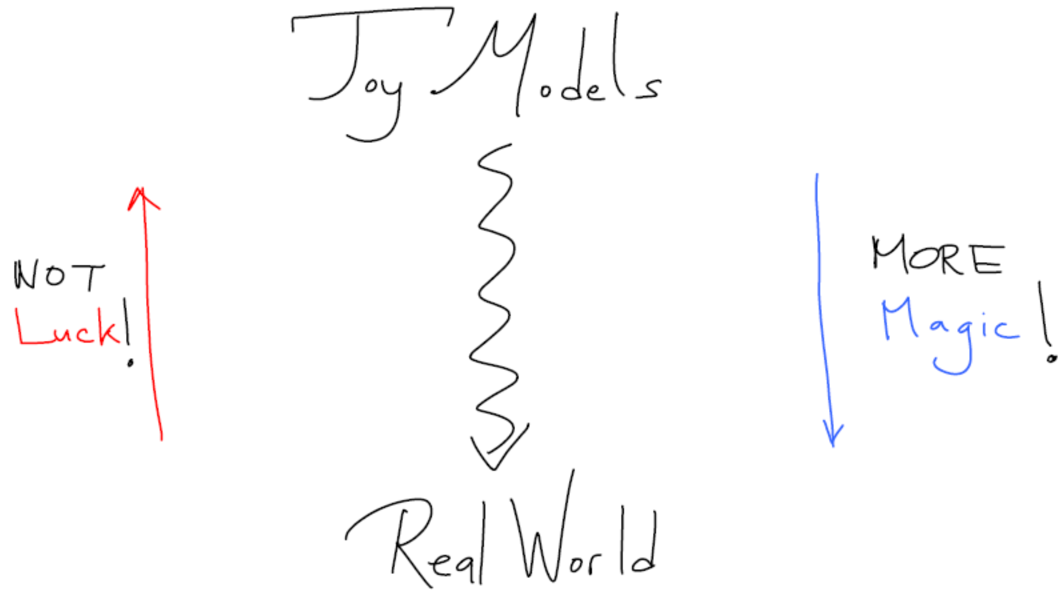
Ex. for students: Derive From Top-Down, + also do the "Super-Higgs" mechanism

{Time is Ripe to
Compute all Planar $\mathcal{N}=4$ amps on
the Coulomb Branch, w/ Rutger Boels
+ Yutin}

* It will be interesting to systematically understand SM from this purely on-shell perspective — and at the same time look for "magic" — like some hidden positive geometry underlying it.

* Note that [trivially + unsurprisingly] we never encounter any aspect of the hierarchy problem in this way of doing things.

"Hierarchy Problem is meaningful only in theories where the Weak Scale is Calculable"



HUGE amount of WORK / FUN to realize this!

NATURAL INCLINATIONS & HIDDEN MOTIVES

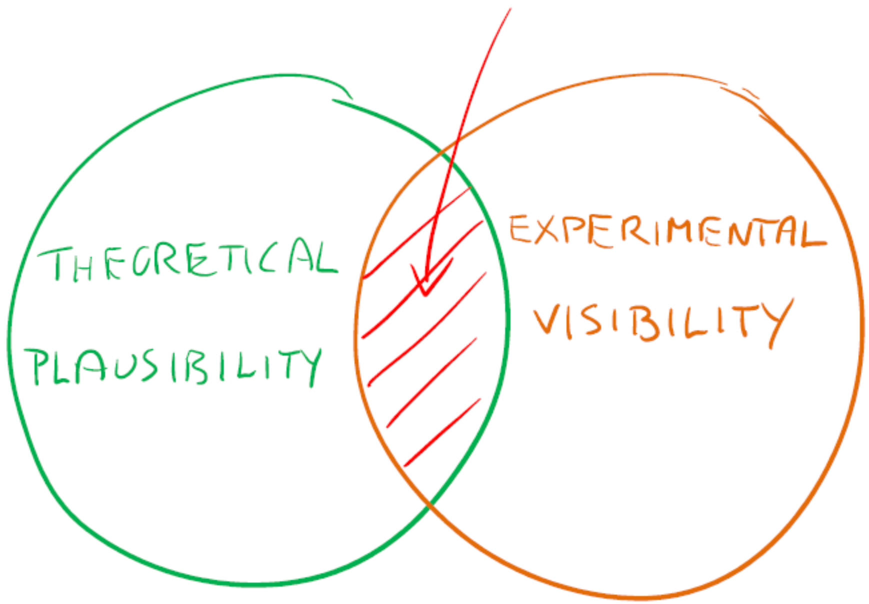
Raman Sundrum
University of Maryland

WE ARE IN PUZZLING, CHALLENGING SITUATION

with SM triumphant on most fronts,

except DARK MATTER, whose identity & nature have resisted direct detection, indirect detection & collider searches.

LOOK HERE!



There ARE rich set of quantum field theoretical mechanisms, but few beautiful & complete models. Theory can guide Expt. to lead the way.

CIRCUMSTANTIAL EVIDENCE FOR NATURALNESS

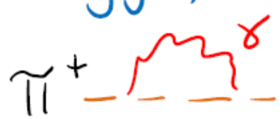
$\exists$ lots of elementary spin-$\frac{1}{2}$ & spin-1, assorted flavors & colors.

$\exists$ elementary spin-2

Maybe elementary spin-3/2, hard to see

Higher spins CAN'T be elementary

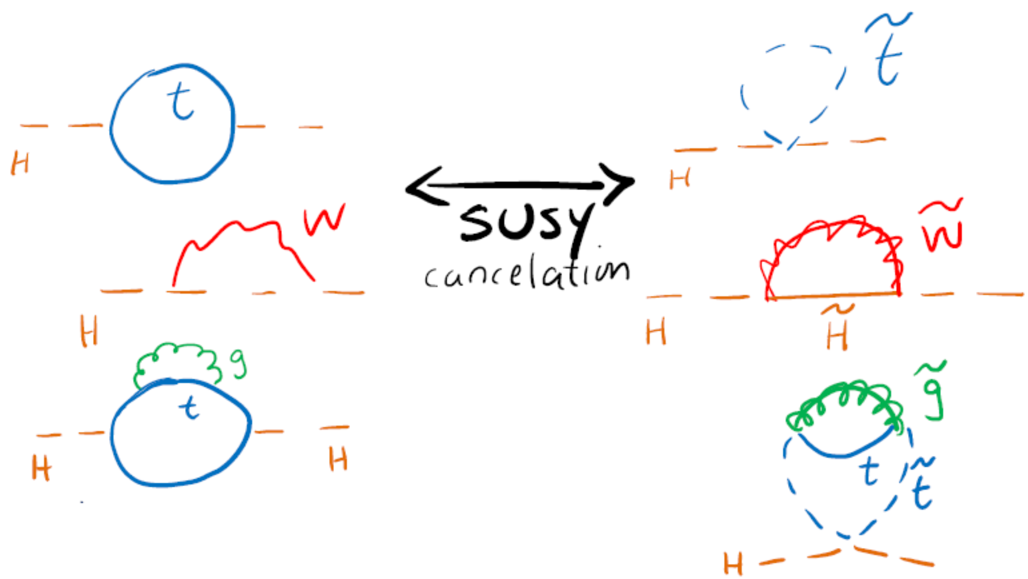
But till Higgs, no elementary spin-0

Composite 

$\sim \alpha_{SM} \Lambda^2_{hadronic} \sim (m^2_{\pi^+} - m^2_{\pi^0})_{expt.}$

naturally

SUSY

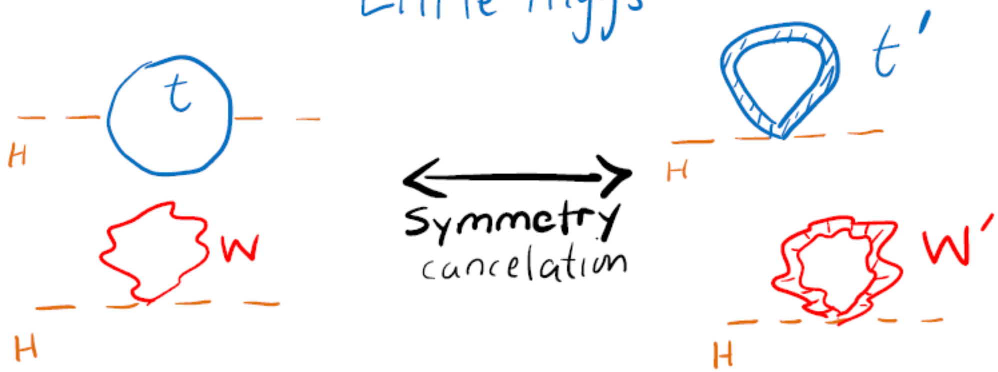


SUSY searches not yet decisive, but also disconcerting

$m_h = 125$ GeV larger than simple, natural estimates!

OTHER SYMMETRIES ?

Little Higgs Arkani-Hamed, Cohen, Georgi '01



[Protective Sym., G_{SM}] = 0

⇒ t' colored W' EW coupled

Such structure also describes central composites in Composite Higgs scenario

NEW COLLIDERS NEEDED
to model-independently
& decisively test NATURALNESS

Lepton colliders to precisely test
Higgs/EW sector

~100TeV hadron colliders to
explicitly hunt new particles.

See Curtin, Saraswat '15
strategy

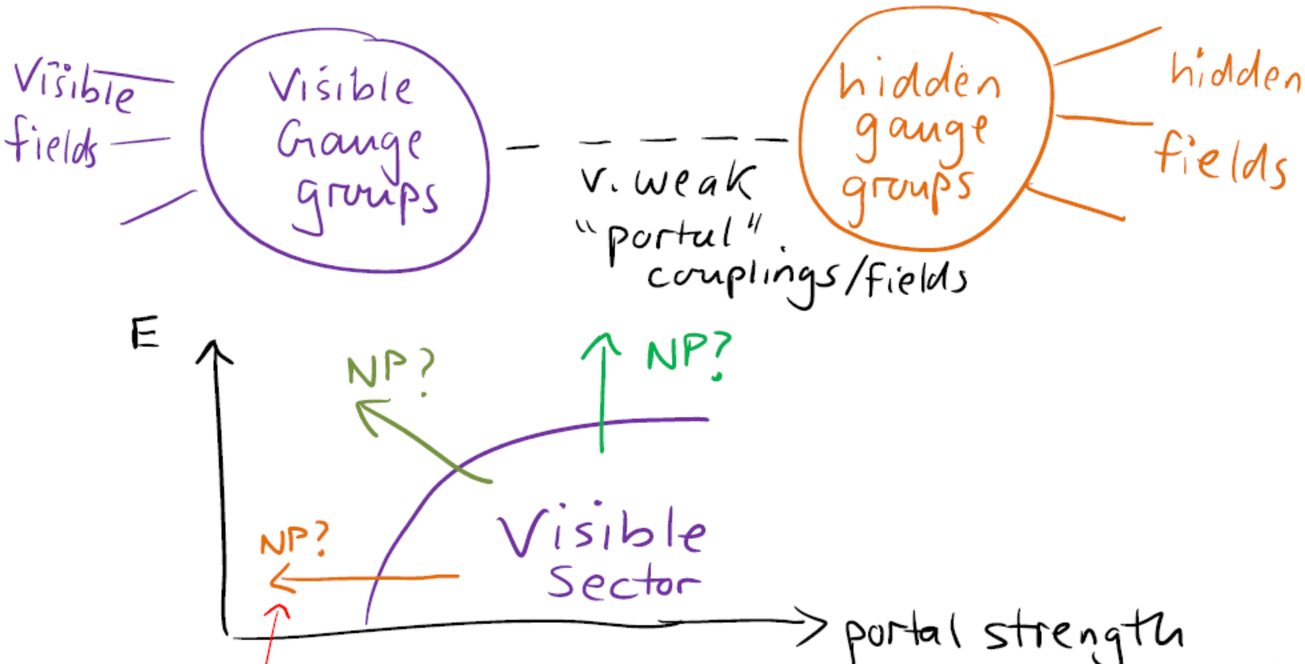
Of course LHC MUST PUSH TO ITS LIMITS ON CENTRAL NATURALNESS CHANNELS

There are also many (subtle) BSM possibilities, below & above TeV, with no apparent connection to naturalness. Plausible ?

OR COULD THERE BE A HIDDEN CONNECTION TO NATURALNESS ?

HIDDEN MORAL

Gauge Theories Rule!



LOW PRODUCTION, BUT ROBUST OPPORTUNITY IN DV events

EXISTING LHC DETECTORS

have ongoing DV searches
for variety of final SM states

They will considerably improve over time

But how long can lifetimes be?

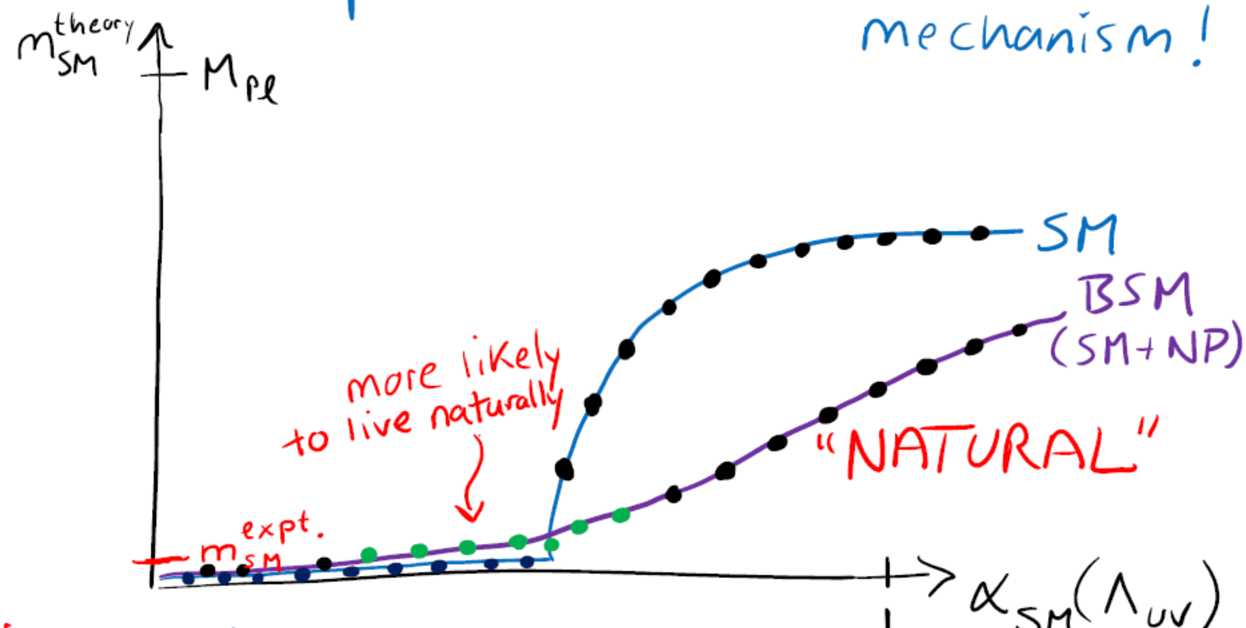
$\tau_{WIMP} <$ 1 second to not disrupt
BIG BANG NUCLEOSYNTHESIS

Displaced events on Moon!

ANTHROPIC PRINCIPLE

IS PRINCIPLE OF LAST RESORT

compared with NATURAL EFT mechanism!



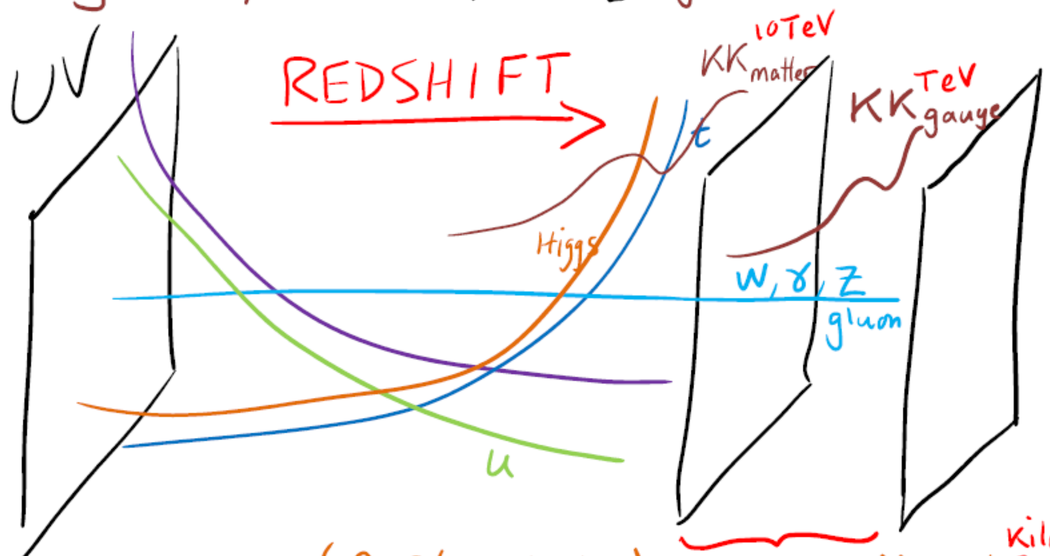
c/w Cosmological Constant Problem has no known natural mechanism. Anthropics applies as last resort

FRUSTRATED NATURALNESS

+ NATURAL FLAVOR-BLIND IR EXTENSION

Agashe, Du, Hong, Sundrum '16
Agashe, Collins, Du, Hong, Kim, Mishra '16

$\Rightarrow$ Subtle multi-resonances of SM gauge bosons & subleading decays to h, t, W_L, Z_L signals naturalness connection



(AdS/CFT dual to) Vectorlike Confinement

Kilic, Okui, Sundrum '08 '09

COSMOLOGY

Gives rich complementary setting for particle physics, with its own naturalness issues & new physics possibilities.

Can also give alternative approaches to Hierarchy Problem.

Eg. "Relaxion" Graham, Kaplan, Rajendran '15

"N-Naturalness" Arkani-Hamed, Cohen, D'Agnolo, Hook, Kim, Pinner '16