RALLYE MONTE CARLO – GENEVA

MC Event Generators for the LHC

Jürgen Reuter

DESY Hamburg, Earth

DESY Theory Workshop 2012, DESY, Hamburg, Sep 28th, 2012

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> XXX ist ein Simulationsprogram für die Teilchenphysik. Dabei werden möglichst viele verschiedene Äste eines Zerfall-Baumes realisiert, indem man bei jeder Astgabel per pseudorandom einen Ast realisiert.

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- LHC: Collisions 2010/11 @ 7 TeV, 2012 @ 8 TeV

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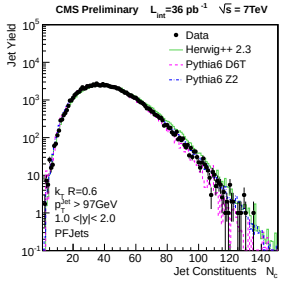

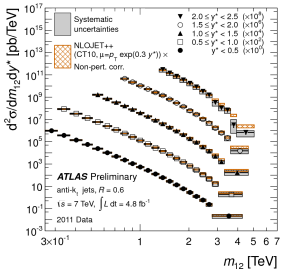

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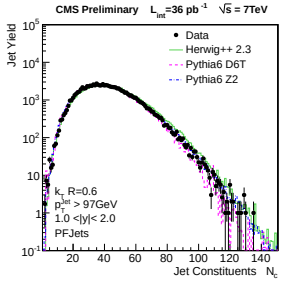
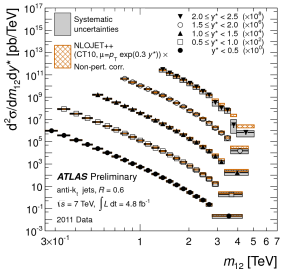
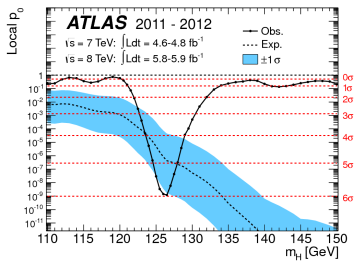
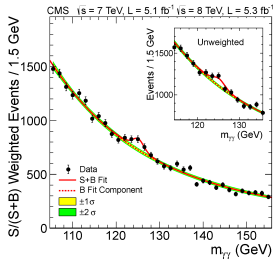




- Discovery of ”a boson at 125-126 GeV” (a.k.a. Higgs?)





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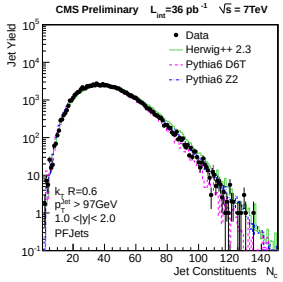

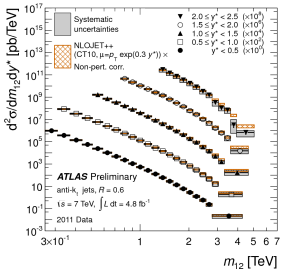

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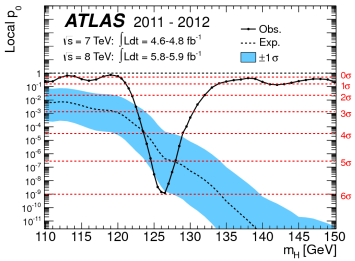

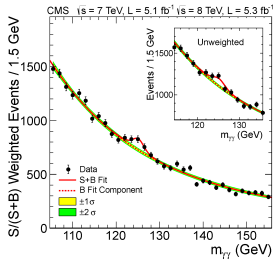

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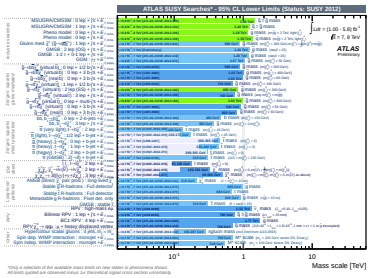

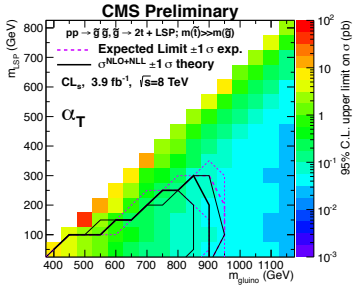

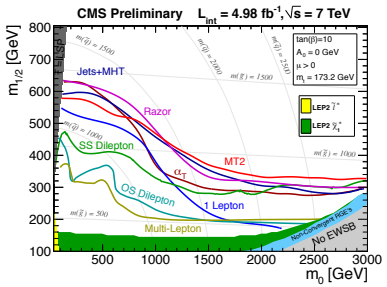

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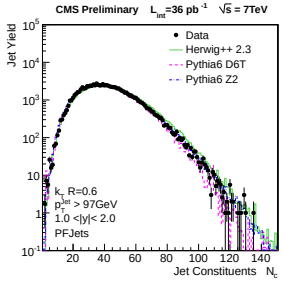

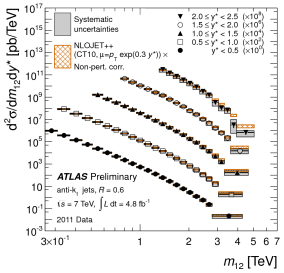

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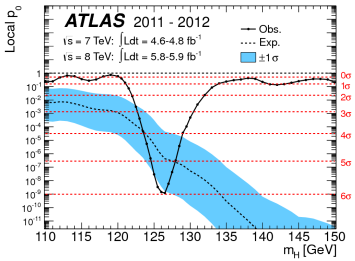

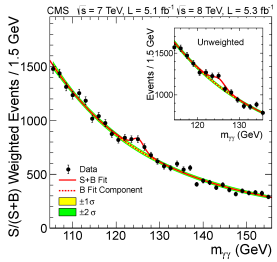

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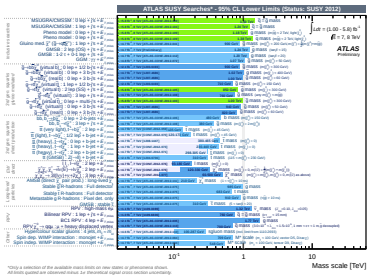

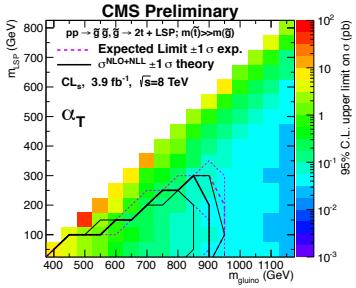

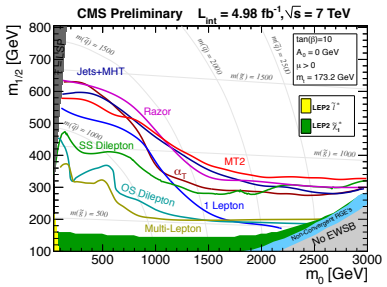

- All of them rely on Monte Carlos (even data-driven methods)

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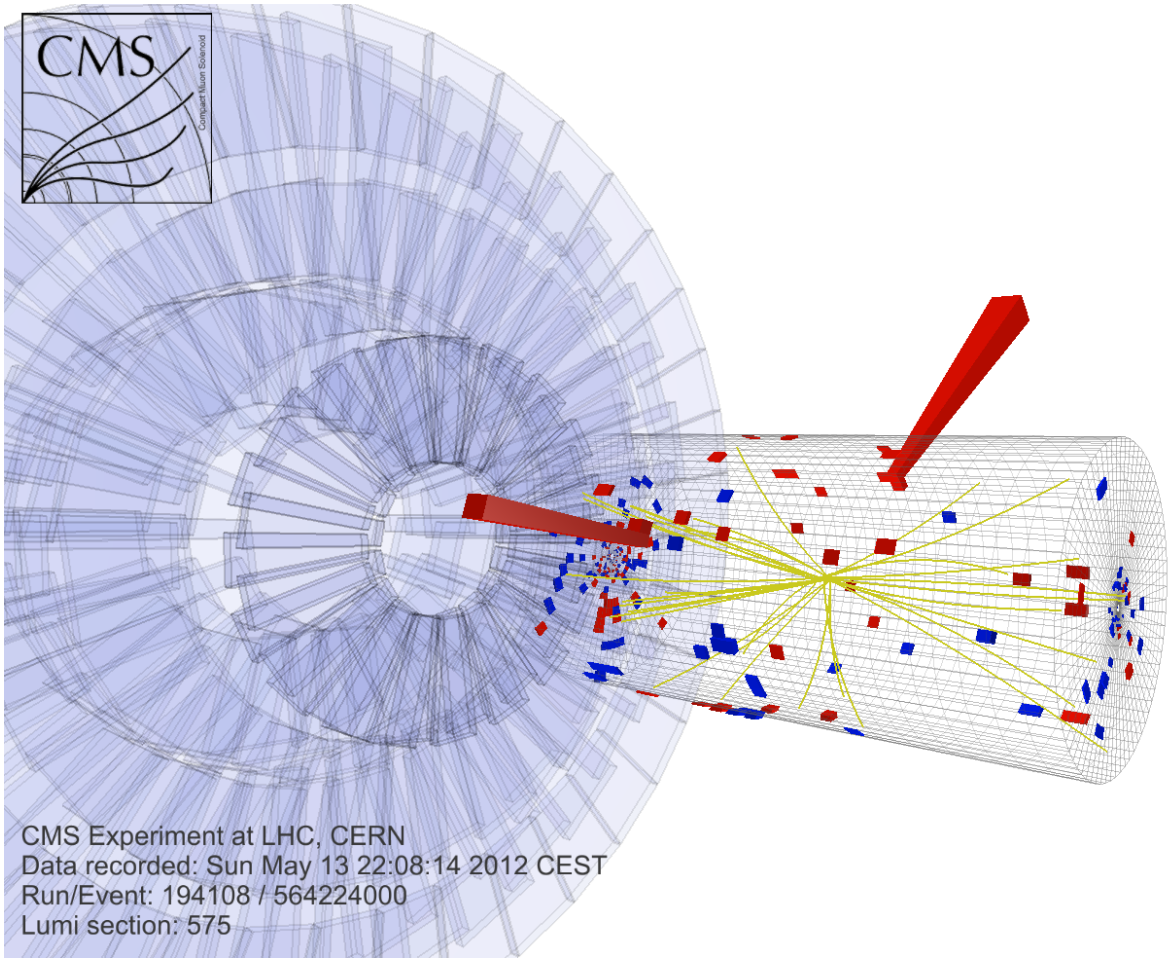

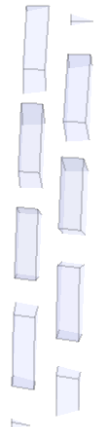

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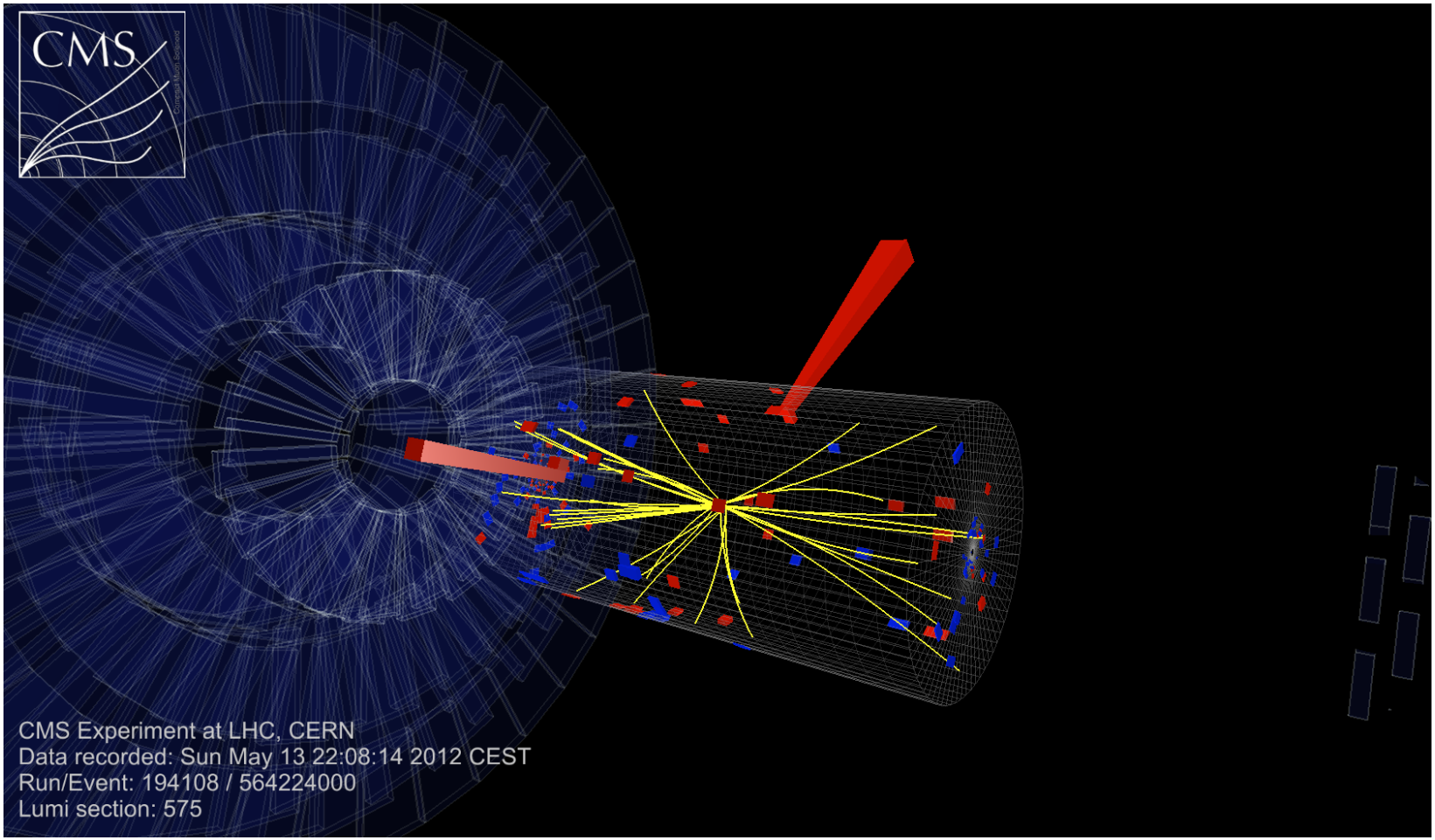

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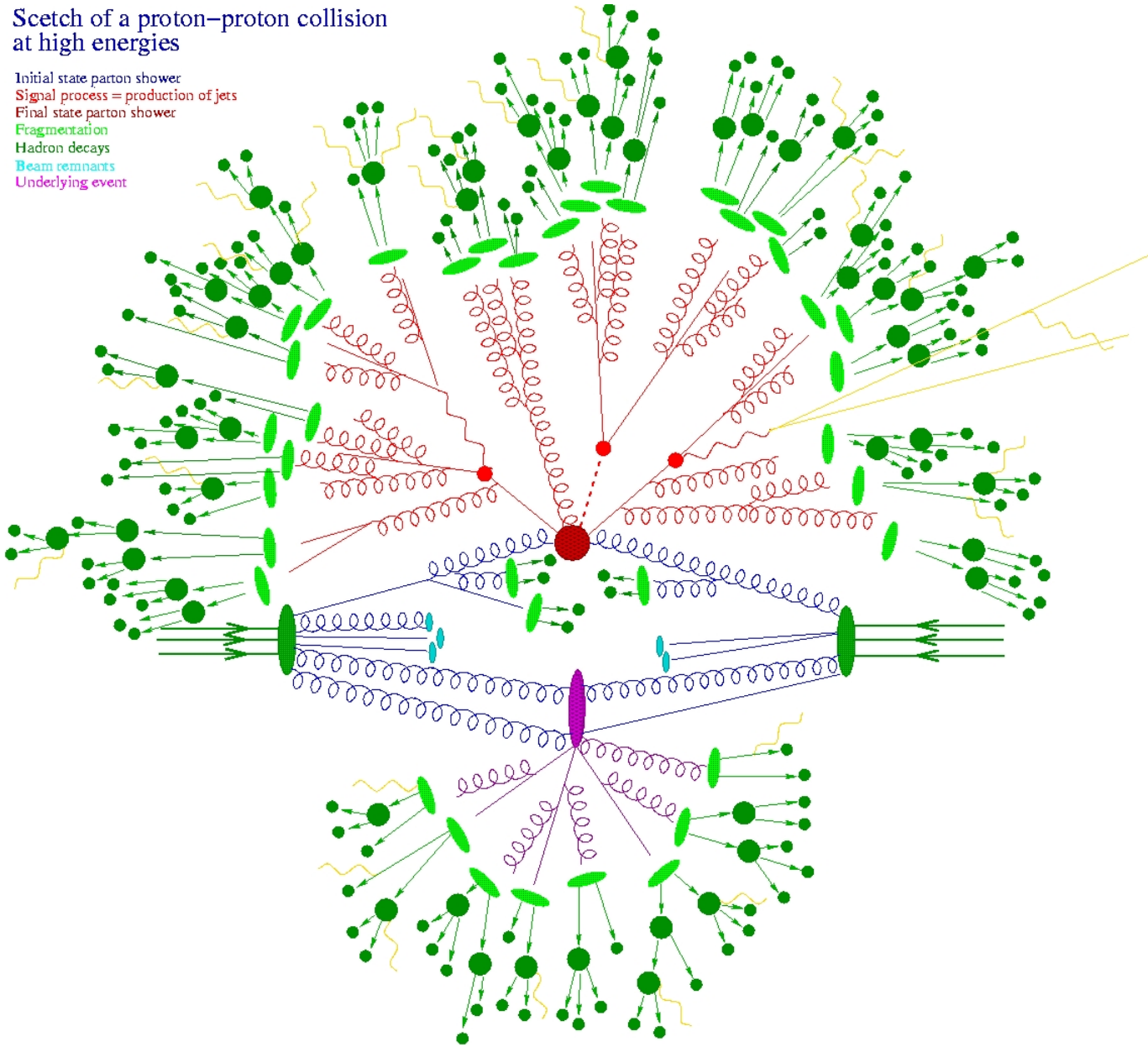

Definitions+Taxonomy: Monte Carlo/Event Generators

- Full or Multi-Purpose MC Generator:
  only when containing showers and hadronization
  (aka: as hadron level MC, opposite: parton level MC)
- Shower Monte Carlo: contains only showering
- Event Generator: only when generating positive weights
- Multi-Particle Event Generator: allows for at least $2 \to 6$ processes
- Generator Generator: only when ”arbitrary” processes can be chosen by the user
- BSM MC: must (OK: should) contain at least the MSSM, Z', and one non-SUSY model
- Dedicated tools: designed for special purposes (NLO bkgd. processes, black holes, you name it)
- Best tool on the market: depends on who is giving the talk/what you wanna do/whom you ask

Components of MC/Connections to other topics

- Beams (read: hadrons/PDFs
  taken from PDF people $\longrightarrow$ (cf. Delgado's talk)

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- Portability
  Programm needs to work $\Rightarrow$ often practical, but not very physical solutions $\rightarrow$)

Matrix Element Generation of (tree) amplitudes

- Modern collider simulations need $2 \to 8$, even $2 \to 10$ processes (with radiation even $2 \to \mathcal{O}(100)$)
- Number of Feynman diagrams grows factorially
- Berends-Giele Recursion Relations Berends, Giele
  - manual calculations
- HELAS Hagiwara et al.,
  - manual partial common subexpression elimination
- Madgraph Stelzer et al., AMEGIC++, COMIX Krauss et al.:
  - partial common subexpression elimination

  $\Rightarrow$ partial elimination of redundancy
- ALPHA Caravaglios & Moretti:
  - tree level scattering amplitude is Legendre transform of Lagragian
  - can be performed numerically, using only $P^*(n)$ independent variables
- HELAC Papadopoulos et al.:
  - ALPHA algorithm reformulated as recursive numerical solution of Schwinger-Dyson equ.
- O'Mega Ohl/JRR:
  - systematic elimination of all redundancies
  - symbolic, generation of compilable code

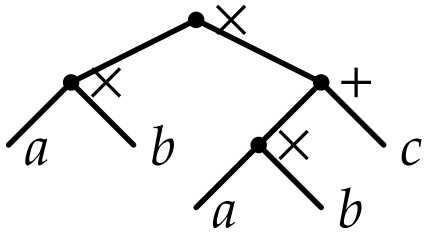
Efficient/optimal tree matrix elements

Moretti/Ohl/JRR, 2001; Kilian/Ohl/JRR/Speckner, 2012

$\Rightarrow$ Replace forest of tree diagrams by
Directed Acyclical Graph (DAG) of the algebraic expression.

Ω

$$ab(ab+c) =$$



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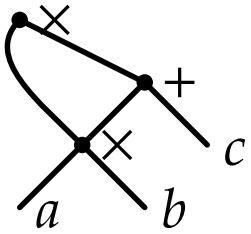

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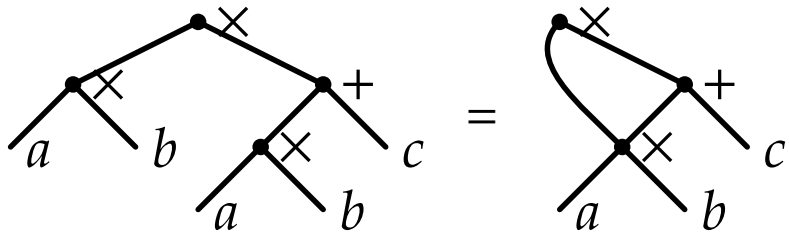

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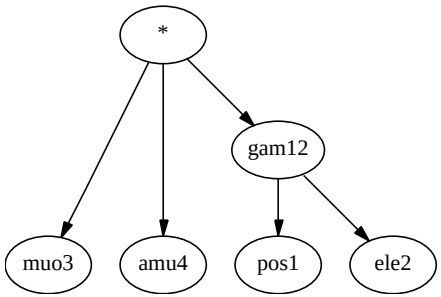

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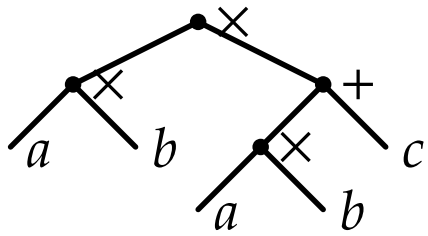

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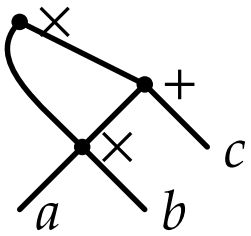

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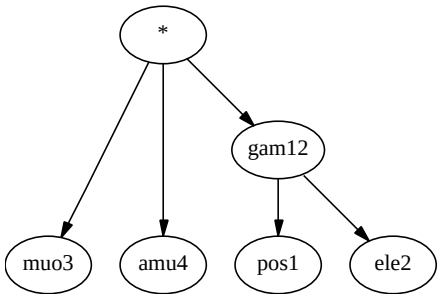

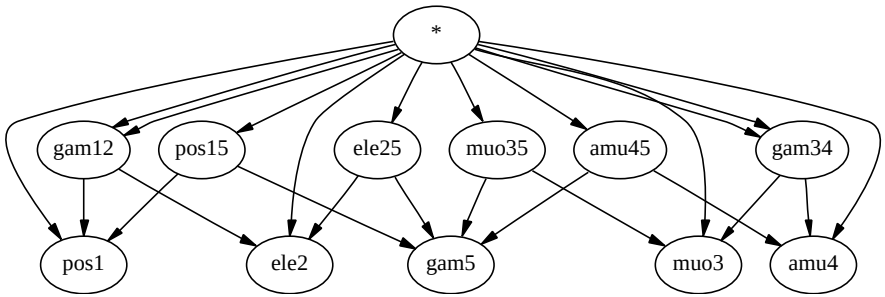

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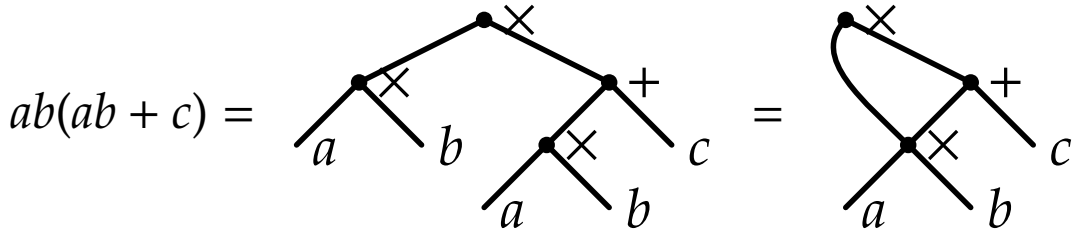

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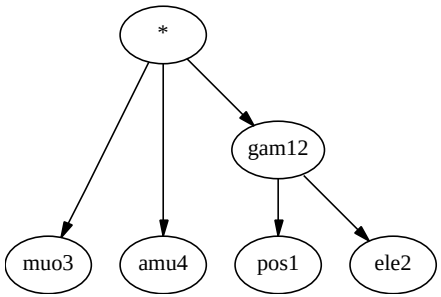
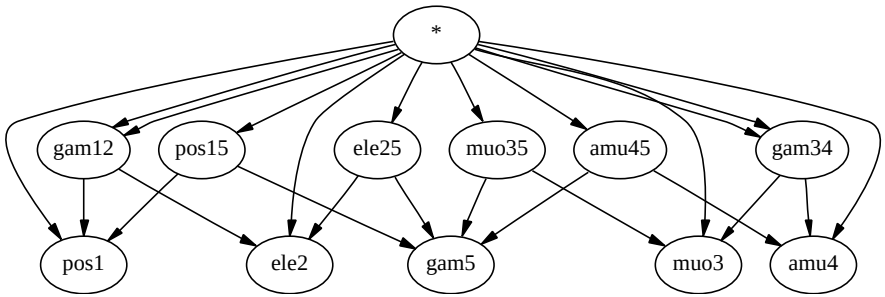
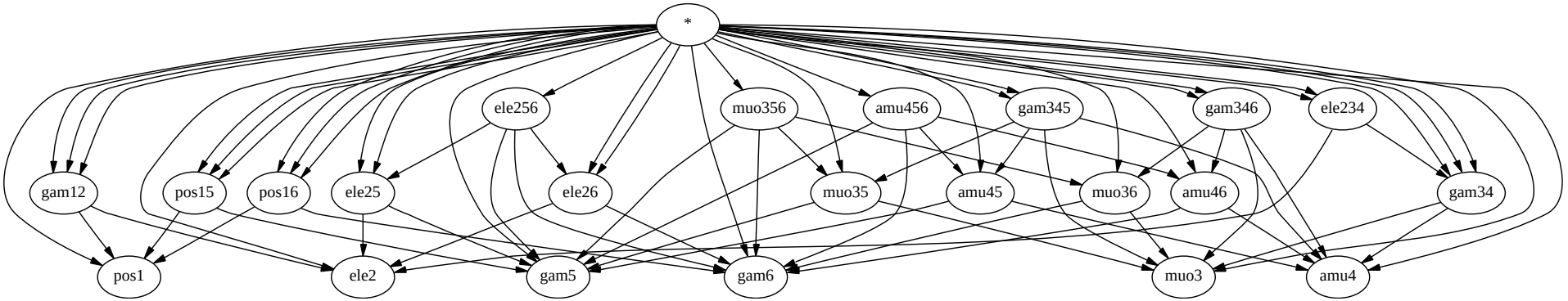
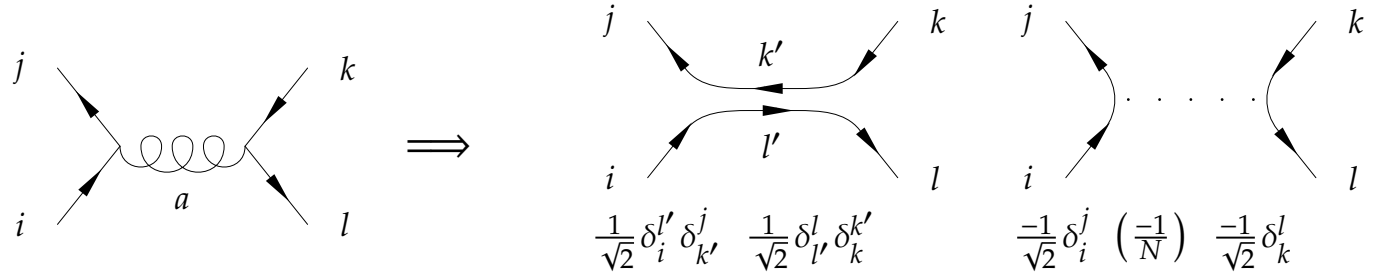






Obstacles: Color / Flavor / Loops?

- **Color**
  - Most programs use color algebra decomposition $\mathrm{tr}[T^a T^b T^a T^b] = -\frac{1}{4}(N - 1/N)$
  - Not possible for recursive algorithms
  - Solution: color-flow algorithm 't Hooft, 1974; Maltoni et al., 2003



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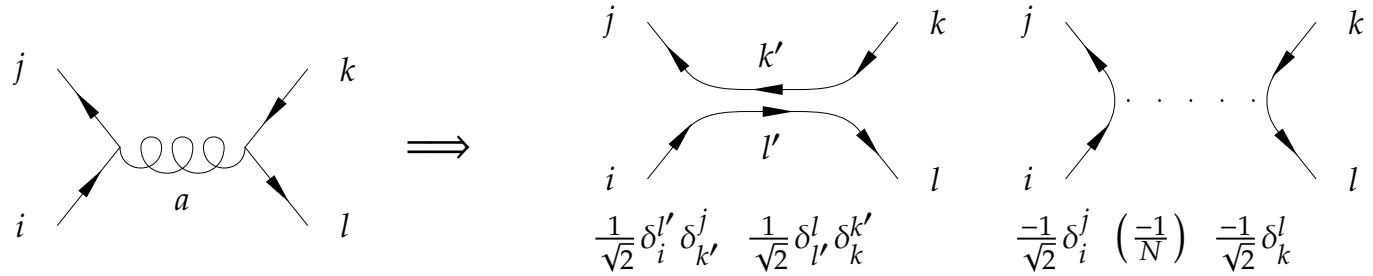

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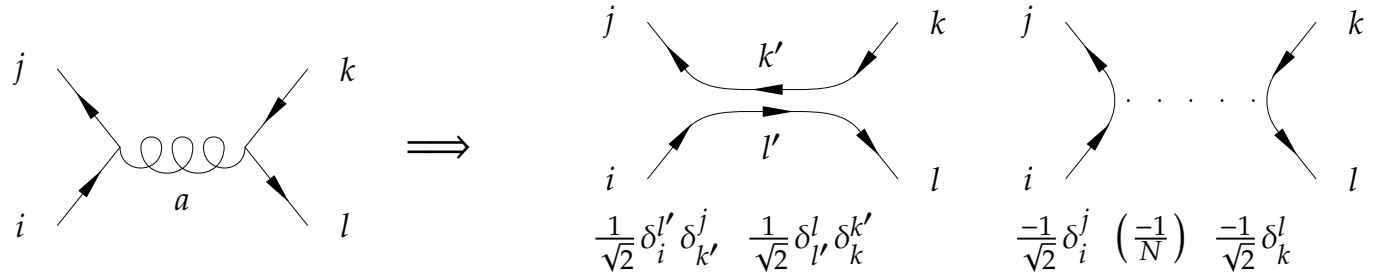

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  - simple tree level algorithm $n \to n+1$ doesn't work for loop diagrams because of non-uniqueness of loop representation
  - most efficient, but black-box tool for multi loop diagrams `QGRAF` Nogueira, 1991
  - Approaches for loops by trees (Feynman's tree theorem) Catani et al., Kilian et al.
  - Efficient tree-level diagrams ⇒ Unitarity cuts, OPP methods Ossola/Papadopoulos/Pittau, hep-ph/0609007

cf. Pozzorini's talk

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- Tailor-made phase space setup for special programs

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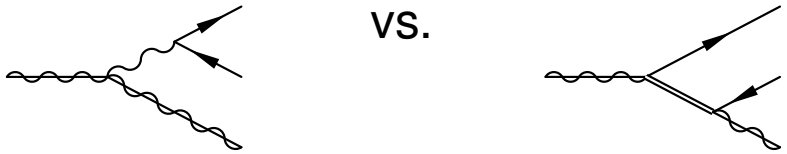

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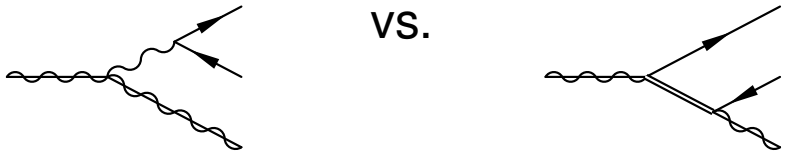

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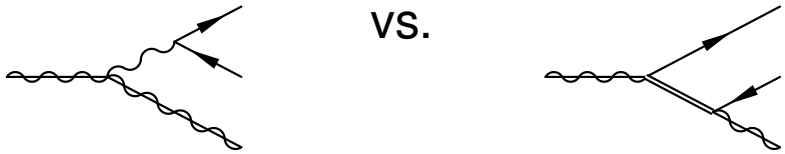

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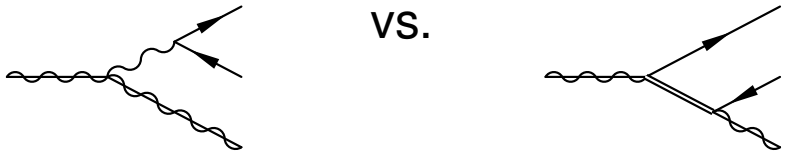

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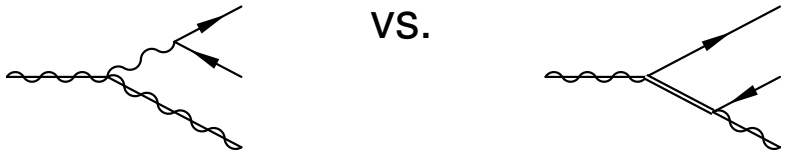

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- Radiation-like setup: QCD shower/dipole phase space etc.
- Final (most costly) step: unweighting events $\Rightarrow$ adapted grids should map integrand as close to a constant as possible

Parton Shower

Parton Shower

Parton Showers

- Problem: need to describe $2 \to 10 - 100$ QCD processes
- MEs may available in leading color: PS not
- QCD emission dominated by large logs: $\alpha_s^n \log^{2n} \frac{Q}{Q_0} \sim 1$:

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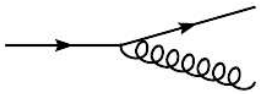
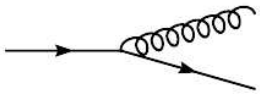
Universal DGLAP splitting kernels for collinear limit:

$$\mathrm{d}\sigma = \sigma_0 \sum_{\text{jets}} \frac{\mathrm{d}\theta^2}{\theta^2} \frac{\alpha_S}{2\pi} P(z)\mathrm{d}z$$



$$P_{q\to qg}(z) = C_F \frac{1+z^2}{1-z}$$

$$P_{g\to gg}(z) = C_A \frac{(1-z(1-z))^2}{z(1-z)}$$



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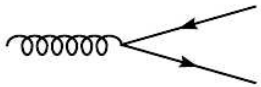

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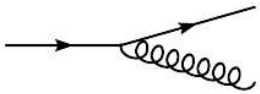

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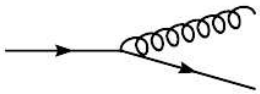

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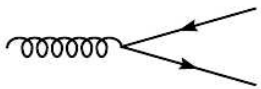

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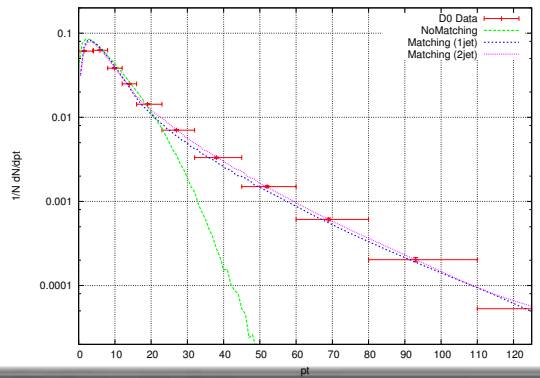
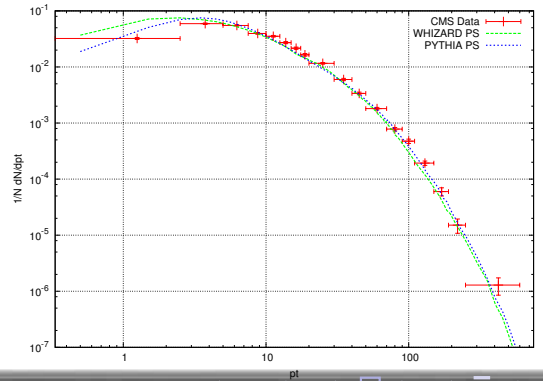
- Many possible evolution variables: θ, Q, $p_\perp$ $\tilde{q}$, t
  - θ: HERWIG
  - Q: PYTHIA ≤ 6.3, SHERPA, WHIZARD (analytic)
  - $p_\perp$: PYTHIA ≥ 6.4, ARIADNE, CS-SHERPA, WHIZARD
  - $\tilde{q}$: HERWIG++

- Independent collinear emission: probabilistic picture/Sudakov factor

$$dP(\text{next emission at } t) = \frac{dt}{t}\int_{z_-}^{z^+}\frac{\alpha_s(z,t)}{2\pi}\hat{P}(z,t)dz \quad \exp\left[-\int_{t_0}^{t}\frac{dt}{t}\int_{z_-}^{z^+}\frac{\alpha_s(z,t)}{2\pi}\hat{P}(z,t)dz\right]$$

- Soft emission: angular ordering → color coherence: important effects
- $1 \to 2$ splitting: tweaked kinematics
- $2 \to 3$ splitting: ”exact” kinematics, recoil
  Catani-Seymour/dipole shower Lönnblad, 1992; Schumann/Krauss,0709.1027
  antennae showers Giele/Kosower/Skands,0707.3652
- Generally: veto approach (store weights: Giele/Kosower/Skands, 1102.2126)
- Heuristics: scale, evolution param., avail. PS, integr. limits, regularization, ...
- New approach: ”analytic PS” (Geneva algorithm) Bauer/Schwartz/Tackmann/Thaler
  - Analytic determination of shower weights
  - allows reweighting on an event-by-event basis
  - Full FSR, generalization to ISR Schmidt/JRR/Kilian/Wiesler; 1112.1039

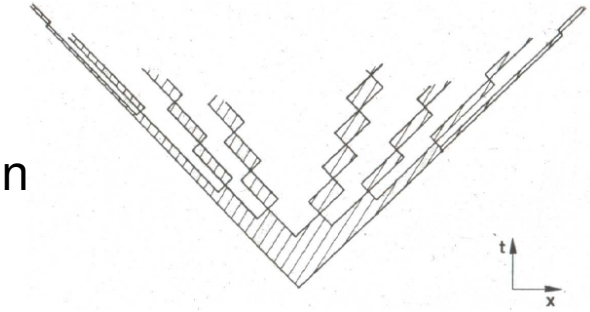




Matrix element/parton shower matching/merging

- **Problem:** Additional hard jet produced by the parton shower
  - Jets generated in regions where soft-collinear approx. invalid
  - not the whole phase space populated (dirty trick: Power Shower)
  - General rule: matrix element OK for high p_T, overshoot infrared, showers OK in the infrared, undershoot high p_T
- Solution: **Merge ME and PS**:
- Explicit corrections of $2 \to 2$+PS with $2 \to 3$ MEs (PYTHIA/HERWIG)
- Matching with LO MEs:
  - CKKW(-L): Catani/Krauss/Kuhn/Webber, Lönnblad
    - first hardest emission by full MEs
    - preserve shower-evolution equations (logarithmic accuracy)
    - phase-space slicing to avoid double counting $\Rightarrow$ veto shower emissions above scales
    - reweight MEs with pseudo-shower history (Sudakov factors)
  - MLM: Mangano
    - generate all shower history, throw away those that run into ME region
  - new CS-inspired phase-space separation criterion (SHERPA)
  - Matching allows samples of different jet multiplicity:
    $$W + X|_{\text{incl.}} = W + 0j\big|_{\text{incl.}} + W + 1j\big|_{\text{incl.}} + W + 2j\big|_{\text{incl.}} + \ldots$$
- Merging with NLO MEs: Lavesson/Lönnblad, 0811.2912; Höche/Kraus/Schönherr/Siegert, 1111.1220, 1207.5030/1; Plätzer/Gieseke, 1109.6256; Torrielli/Frixione, 1002.4293; etc. etc.
  - MC@NLO
  - POWHEG scheme
  - Catani-Seymour dipoles/Antennae

Hadronization: Lund or Cluster or What?

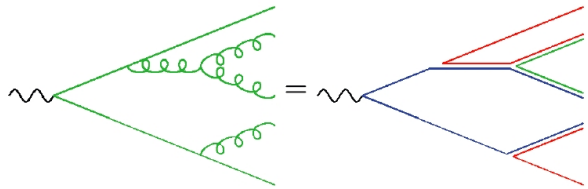


- Old models: flux tubes, independent fragmentation
- Independent fragmentation: dresses bare quarks

  "last quark", Lorentz invariance, infrared safety

- **Lund string model:** based on old string model for strong interactions
  - invented without PS in mind
  - strong physical motivation
  - universal description of data (ee fit $\rightarrow$ hadron)
  - Plethora of parameters: $\mathcal{O}(1) \sim$ per hadron

- **Cluster fragmentation model:** (uses preconfinement)
  - Parton shower orders partons in color space
  - Large N_C limit: planar graphs dominate
  - Cluster is continuum of high-mass resonances, then decays into hadrons
  - No spin info, just phase space
  - Suppression of heavier particles (esp. baryons)
  - Cluster spectrum determined by parton shower (pert. theory)



- **Summary:** All programs use either Lund or cluster (independent fragmentation only for inclusive cross sections)

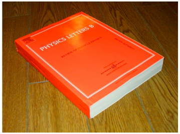
Hadronic decays

$$
\begin{aligned}
B^{*0} &\to \gamma B^0 \\
&\hookrightarrow \bar{B}^0 \\
&\hookrightarrow e^- \bar{\nu}_e D^{*+} \\
&\hookrightarrow \pi^+ D^0 \\
&\hookrightarrow K^- \rho^+ \\
&\hookrightarrow \pi^+ \pi^0 \\
&\hookrightarrow e^+ e^- \gamma
\end{aligned}
$$

- radiative EM decay
- weak mixing
- weak decay
- strong decay
- weak decay, ρ mass smeared
- ρ^+ polarized, angular correlations
- Dalitz decay, m_{ee} peaked

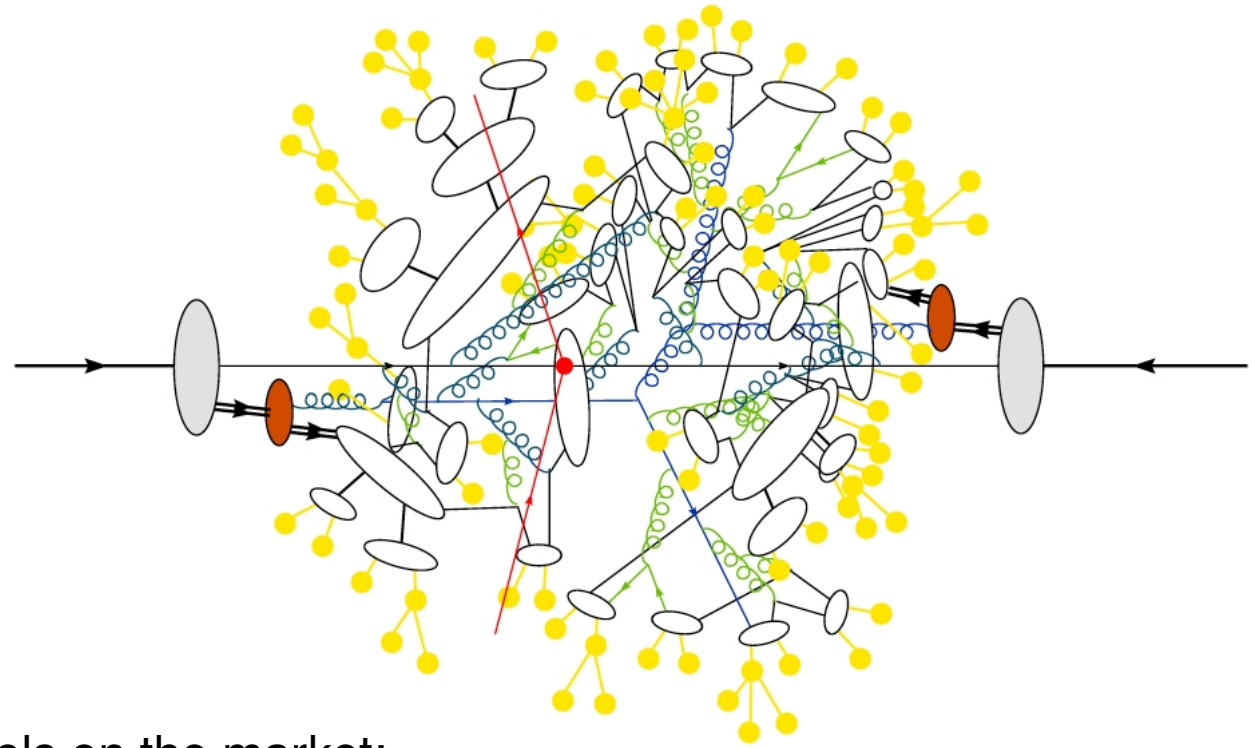
100s of particles, 1000s of decay modes, form factors, PDG unitarity violation, ...

with courtesy from S. Gieseke


PHYSICS LETTERS B

Underlying Event (aka Multiple Interactions, UE/MI)

- Various definitions:
  - everything that is not of interest
  - multiple parton interactions (MPI) from same bunch
  - beam remnants: soft interactions and ISR



- Many models on the market:
  - Eikonal approximation of optical theorem
  - Adding more than one hard interaction
  - Lots of dirty details: what to do about ....???
- Still best reference: PYTHIA manual !!!

On the shoulders of GEANT

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- Full detector simulation: GEANT4, http://geant4.cern.ch

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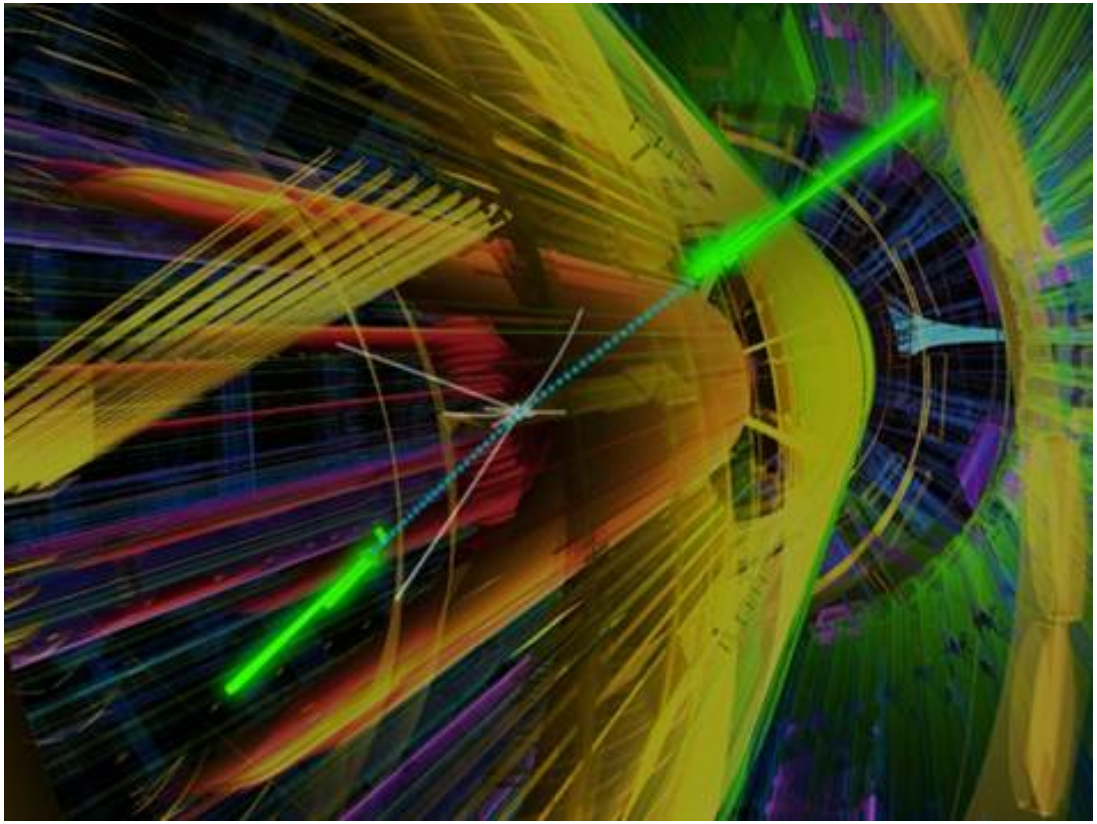

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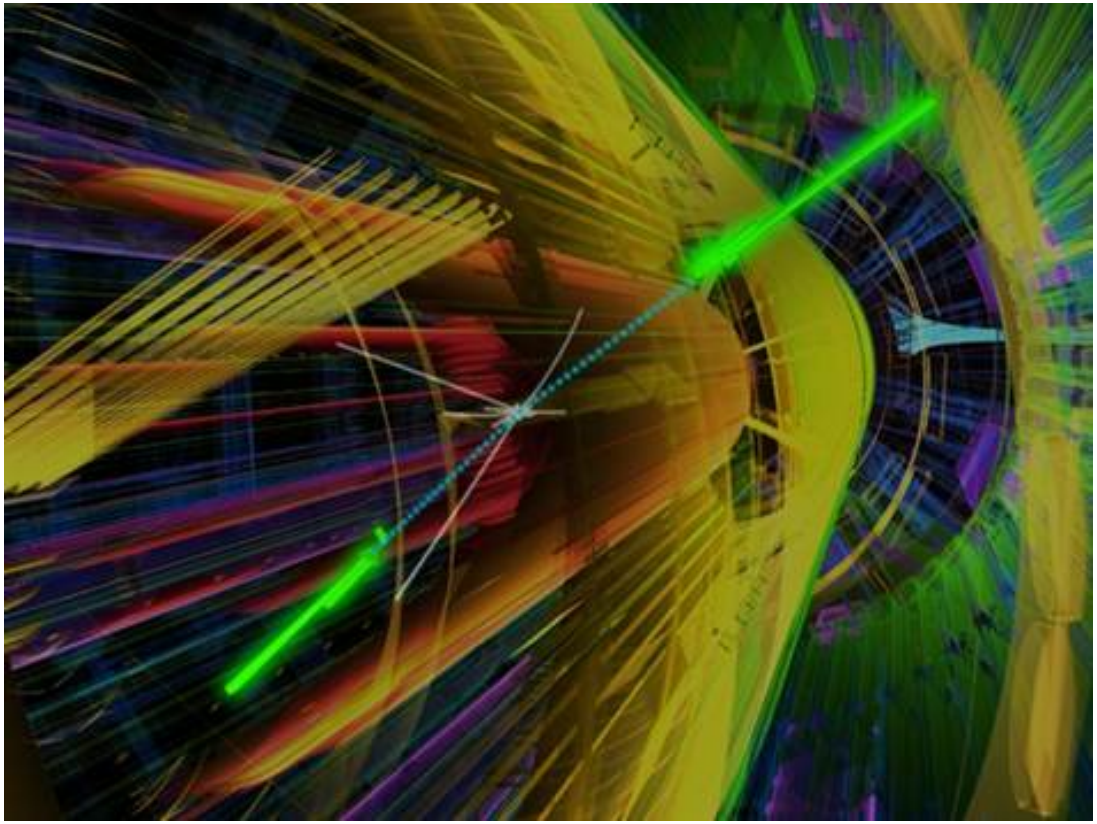
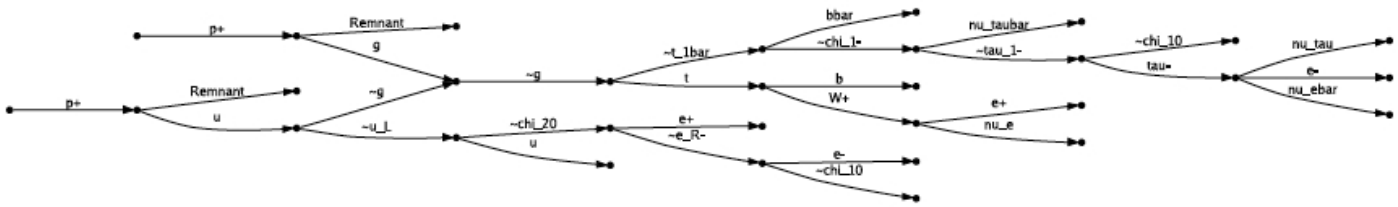


- E.g.: electromagnetic shower shapes in $H \to \gamma\gamma$
- Versatile tool beyond particle physics (3500 citations)

HERWIG++

- Acronym: **H**adron **E**mission **R**eactions **W**ith **I**nterfering **G**luons
- Authors/location: S. Gieseke, P. Marchesini P. Richardson, M. Seymour, B. Webber + postdocs/PhDs; Durham/Manchester/Karlsruhe
- Current version 2.6.0 `http://projects.hepforge.org/herwig`
- Reference arXiv:0803.0883
- Prog. language: C++ (new adaptation of older `FORTRAN 77` program)
- contains parton shower (angular ordered), POWHEG matching
- contains hadronization (cluster fragmentation model)
- contains multiple interactions/UE (`JIMMY`)
- No arbitrary processes: hardcoded library for SM processes (but: BSM chains)
- BSM: MSSM/UED/RS, FeynRules, only as decay chains with spin correlations
- No multi-leg matrix elements: cascade set-up, but including spin density matrices



PYTHIA (6 vs. 8)

- Acronym: none (wise and mighty seer from the ancient times)
- Authors/location: T. Sjöstrand, S. Mrenna, P. Skands et al.; Lund/Fermilab/CERN
- Current version: 6.4.26 + 8.1.70 `http://projects.hepforge.org/pythia6` and `http://home.thep.lu.se/~torbjorn/pythia.html`
- Reference: arXiv:hep-ph/0603175 and arXiv:0710.3820 [hep-ph]
- Prog. Language: `FORTRAN 77` (PYTHIA 6) `C++` (PYTHIA 8)
- parton shower (virt. $\to p_\perp$ ordered, dipole shower [v8])
- Hadronization (Lund string model)
- No arbitrary processes: fixed process library
- BSM: in v6 a bit everything, not yet in v8
- Remarks:
  - Most (fine???-) tuned tool of the world
  - based on the JETSET jet simulator
  - no automatized ME/PS matching yet

SHERPA

- Acronym: **S**imulation of **H**igh-**E**nergy **R**eactions with **PA**rticles
- Authors/location: F. Krauss, S. Höche, S. Schumann, et al.; Durham/SLAC/Göttingen
- Current version 1.4.1 `http://projects.hepforge.org/sherpa`
- Prog. language: C++ (1st program in community!)
- Reference arXiv:0811.4622 [hep-ph]
- Several parton showers ($p_\perp$ ordered, Catani-Seymour)
- Hadronization package (cluster fragmentation)
- Multiple Interactions: several independent approaches
- Arbitrary processes: a generator generator
- BSM: MSSM, UED, RS, FeynRules
- Remarks:
  - First program to implement CKKW matching
  - Very serious work towards inclusion of NLO MEs

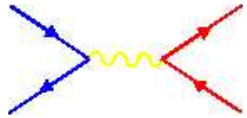
CompHep/CalcHep

- Acronym: **COMP**utations/**CALC**ulations in **H**igh-**E**nergy **P**hysics
- Authors/location: E. Boos, S. Sherstnev, S. Pukhov, A. Belyaev et al.; Moscow/Southampton/Pittsburgh
- Current version 4.5.1/3.3.6 `http://comphep.sinp.msu.ru`
- Reference arXiv: hep-ph/0403113
- Prog. language: `FORTRAN 77`
- no parton shower
- no hadronization
- Arbitrary processes: a generator generator
- BSM: MSSM, Little Higgs, UED, Moose Models, FeynRules, own Feynman rules generator (LANHEP)
- Remarks:
  - very easy BSM model file syntax
  - uses trace technology: limited to $2 \to 3 - 4$
  - has to use `FORM` to simplify

ALPGEN

- Acronym: **ALP**HA **Gen**erator
- Authors/location: M. Mangano, M. Moretti, F. Piccinini, R. Pittau; CERN
- Current version 2.14 `http://mlm.home.cern.ch/mlm/alpgen`
- Reference arXiv: hep-ph/0206293
- Prog. language: `FORTRAN 77` (partially `FORTRAN 95`)
- no parton shower
- no hadronization
- no arbitrary processes: library of fixed processes
- no BSM
- Remarks:
  - first to implement MLM ME/PS matching
  - Take care: no complete jet processes: not more than 3 quark pairs!
  - very fast and efficient ME (plus importance sampling over subprocesses)

MadGraph/MadEvent



- Acronym: **MA**trix element and **D**iagrams for **EVENT** generation
- Authors/location: T. Stelzer/F. Maltoni/J. Alwall/R. Frederix et al.; Illinois/Louvain/Taiwan
- Current version 5 `http://madgraph.hep.uiuc.edu`
- Reference arXiv:1106.0522 [hep-ph]
- Prog. language: `FORTRAN 77`, `Python`
- no parton shower
- no hadronization
- Arbitrary processes: a generator generator (Madgraph)
- BSM: MSSM, 2HDM, FeynRules
- Remarks:
  - no longer based on the HELAS library
  - Webinterface for easy usage
  - ME/PS matching implemented
  - MadDipole/MadLoop etc. aiming at inclusion of NLO calculations
  - Many tools/interfaces for e.g. analyses

Helac/PHEGAS

- Acronym: **PH**as**E** space **G**ener**A**tor for **S**imulations
- Authors/location: C. Papadopoulos, M. Worek, A. Cafarella; Athens/Wuppertal
- Current version 1.2.2 `http://helac-phegas.web.cern.ch/helac-phegas`
- Prog. language: `FORTRAN 95`
- Reference arXiv:0710.2427 [hep-ph]

- no parton shower
- no hadronization
- Arbitrary processes: a generator generator (HELAC)
- No BSM
- Remarks:
  - Contains very fast and efficient matrix elements (in a numerical form)
  - MLM matching scheme implemented
  - MC over helicities and colors

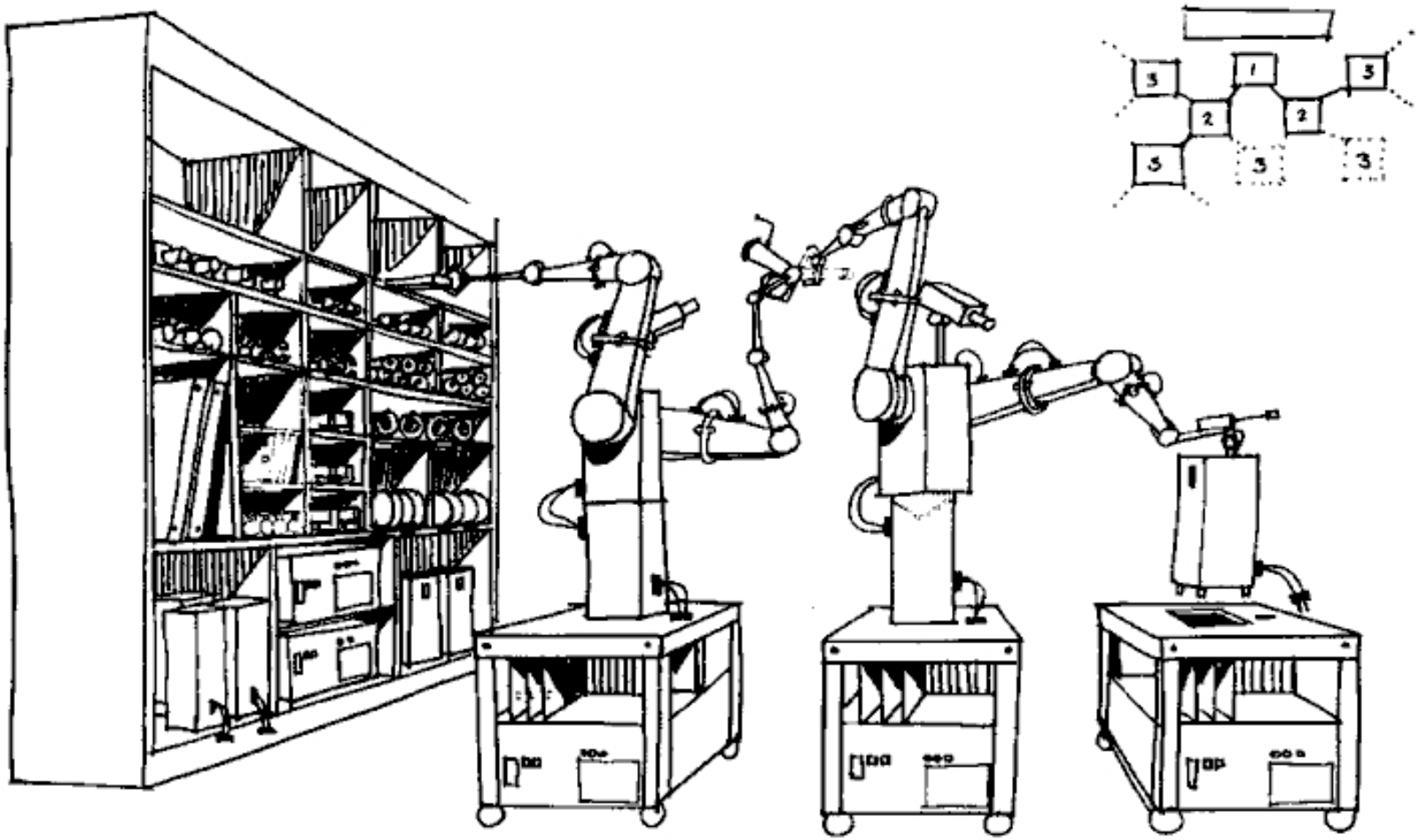
WHIZARD

- Acronym: **W**, **HI**ggs, **Z**, **A**nd **R**espective **D**ecays (deprecated)
- Authors/location: W. Kilian, T. Ohl, JRR + PhDs; DESY/Freiburg/Siegen/Würzburg
- Current version: 2.1.1 `http://projects.hepforge.org/whizard` and `http://whizard.event-generator.org`
- Reference arXiv: 0708.4233 [hep-ph]
- Languages: `OCaml` and `FORTRAN 2003`
- parton shower ($p_\perp$ ordered) and analytic
- no hadronization
- underlying event: preliminary version in v2.1.1
- Arbitrary processes: a generator generator (O'Mega)
- BSM: (N)MSSM, UED, Little Higgs, Moose Models
- 2.0 features: ME/PS matching, cascades, new versatile user interface and syntax, WHIZARD as a shared library

Dedicated NLO Tools

- A lot of tools on the market: just a sketchy overview here
- MCFM (**M**onte **C**arlo for **F**e**M**tobarn processes)
  - K. Ellis, J. Campbell, C. Williams (Fermilab/Glasgow), `http://mcfm.fnal.gov`, `FORTRAN 77` v6.3 (several sub-publications)
  - parton-level NLO tool for W, Z, H and jets at hadron colliders (can be linked to hadronic tools)
  - important: contains spin correlations for decays
- MC@NLO
  - S. Frixione, F. Stoeckli, B. Webber, C. White (Cambridge/Glasgow), `http://www.hep.phy.cam.ac.uk/theory/webber/MCatNLO`, v4.09, `FORTRAN 77` arXiv: hep-ph/0204244
  - needs `HERWIG` for parton shower
  - contains a working prescription for matching NLO calculations and parton showers ("MC@NLO scheme")
  - does not contain decays of particles/spin correlations only partially
- VBFNLO (parton-level NLO MC for vector boson fusion)
  - D. Zeppenfeld + 16 people (Karlsruhe et al.), `http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb`, v2.6.1, `FORTRAN 77` arXiv:1207.4975 [hep-ph]
  - based on the HELAS library
  - includes strong NLO/EW corrections, all decays with full spin correlations
- many, many more!!! (HAWK, FEWZ, GRACE, GR@PPA, etc. etc.)

Automat(izat)ion of NLO

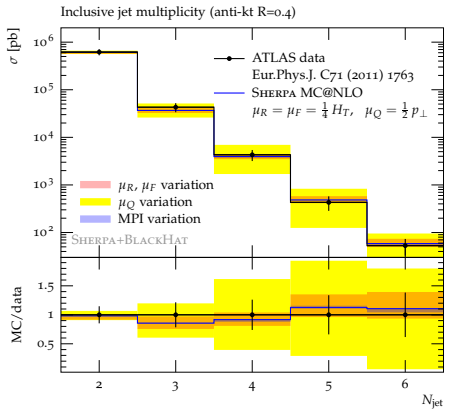


Automat(izat)ion of NLO

- Attempts to automatize NLO (QCD) corrections
- Agreement to talk between MC and NLO: BLHA, Binoth et al., 1001.1307
- Implementations rely on subtraction formalism: Catani/Seymour, hep-ph/9605323
  - Sherpa implementation Gleisberg/Krauss, 0709.2881
  - Helac implementation Czakon/Papadopoulos/Worek, 0905.0883
  - AutoDipole Hasegawa/Moch/Uwer, 0911.4371
  - MadDipole Frederix/Gehrmann/Greiner, 1004.2905
  - WHIZARD implementation Speckner, only QED yet
  - More schemes: FKS, antenna subtraction and implementation
- NLO matrix elements from specialized packages: combinations: Sherpa/BlackHat, aMC@NLO, MadGolem, more ...
- No real automation yet:

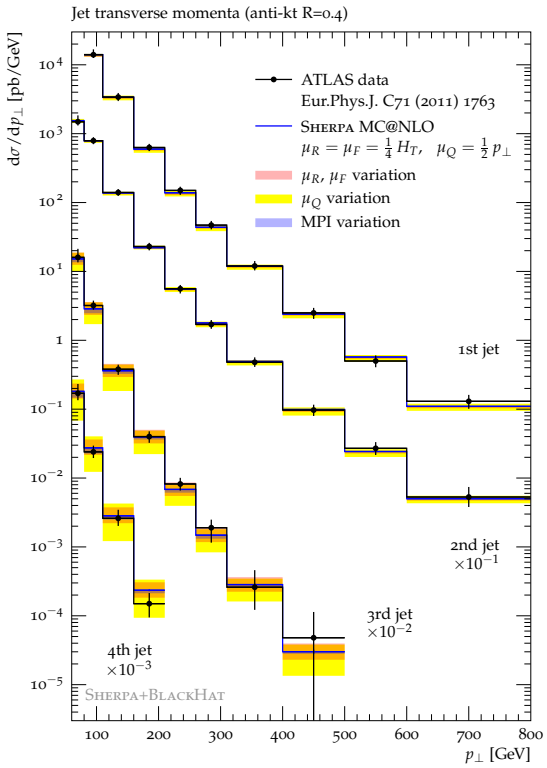
  But incredible progress (joint effort of many people)

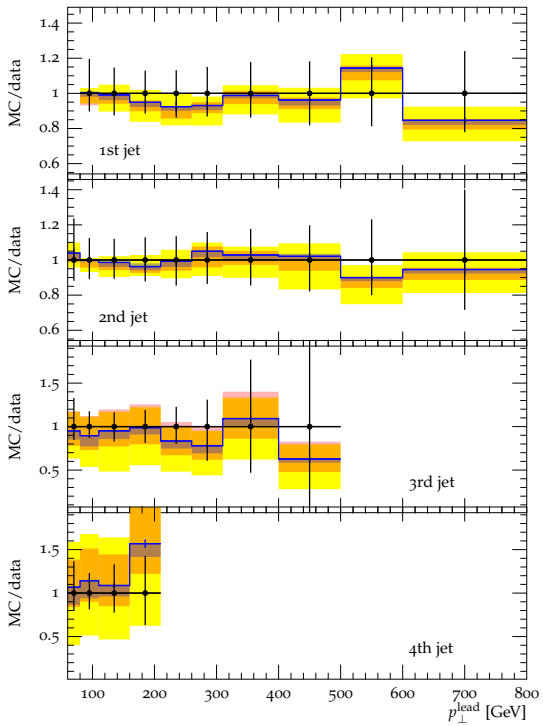
Success of Monte Carlo description

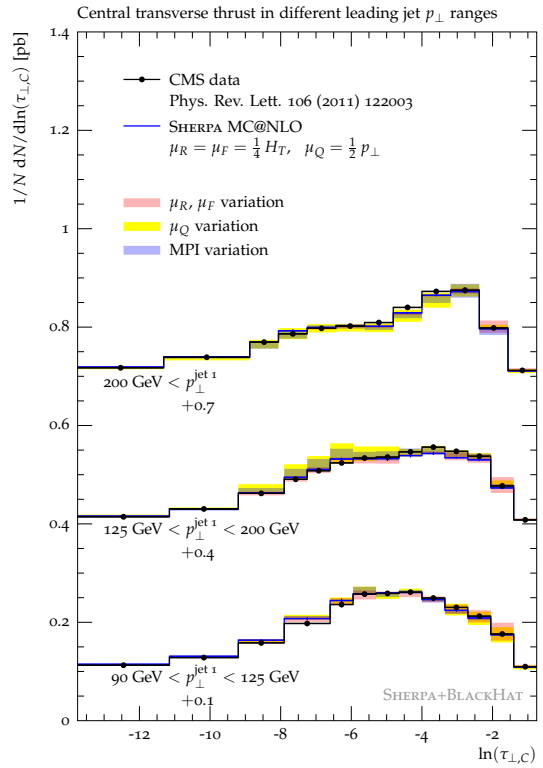


- Inclusive jet rates ATLAS
- Jet p_T ATLAS, Central transverse thrust CMS

Höche/Schönherr, 1208.2815



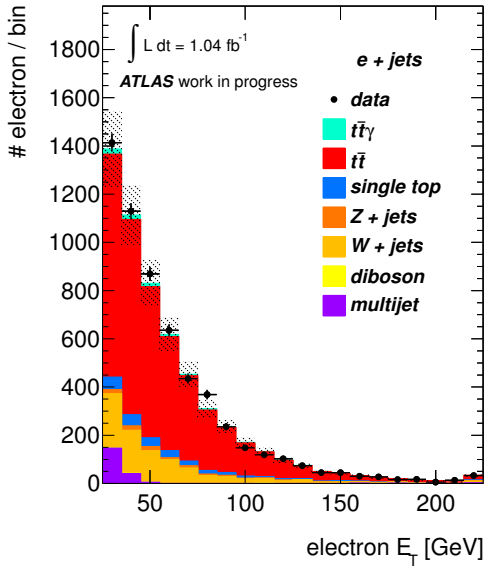


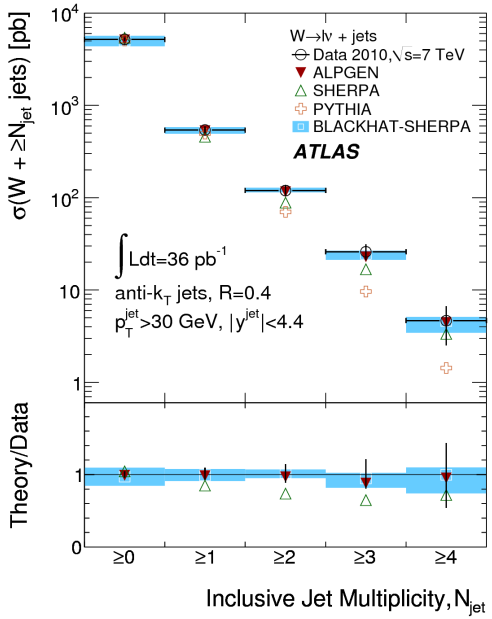


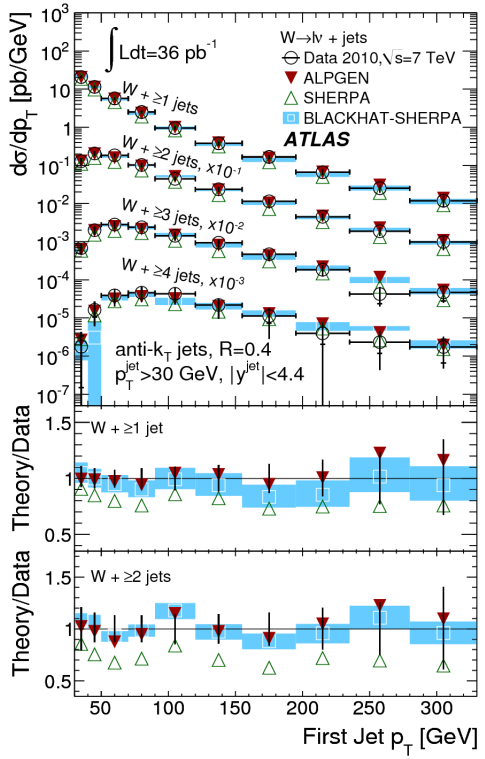
- Very good agreement with experiments

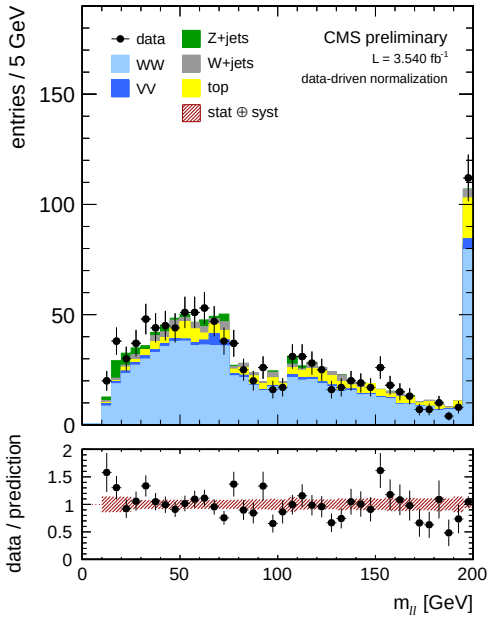
Success of Monte Carlo description

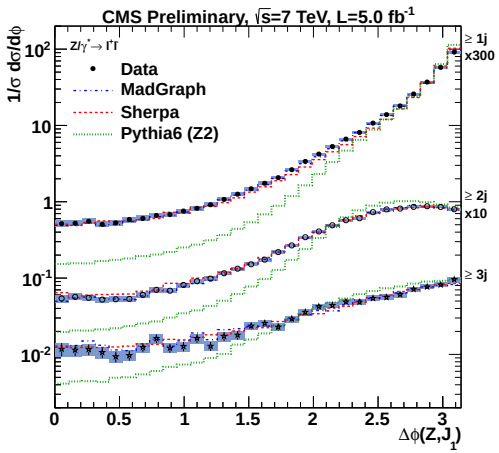
1201.1276,1206.5696,1209.3553,CMS-PAS-EWK-11-021

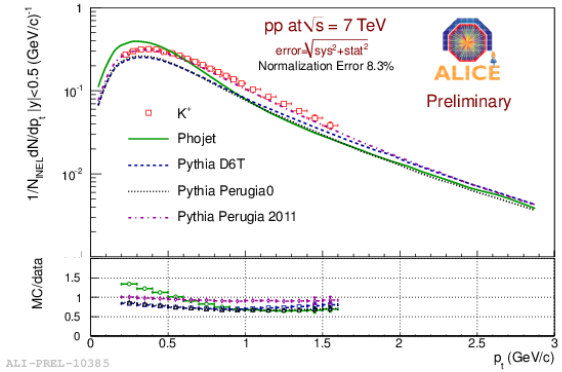












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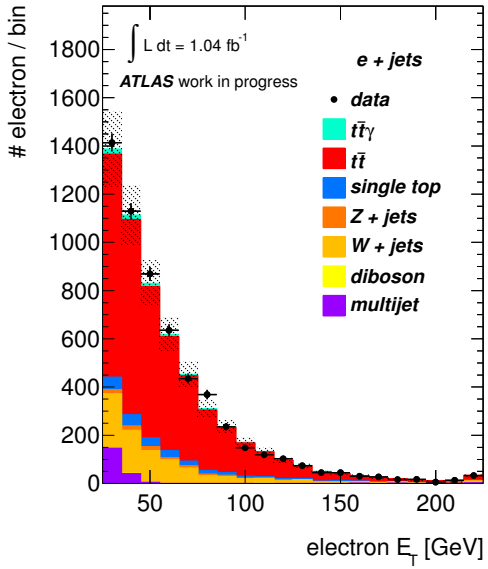

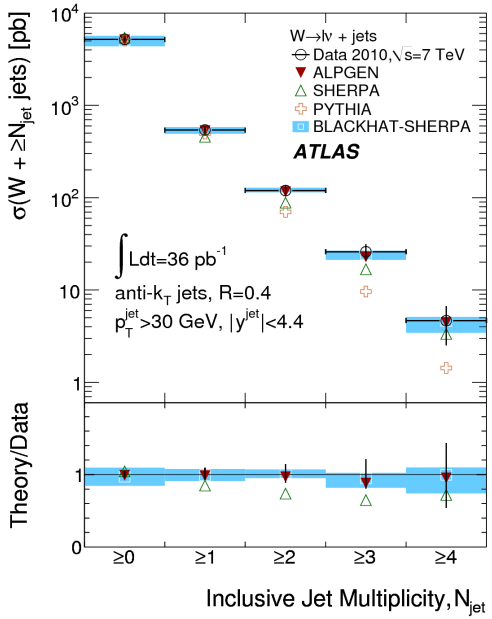

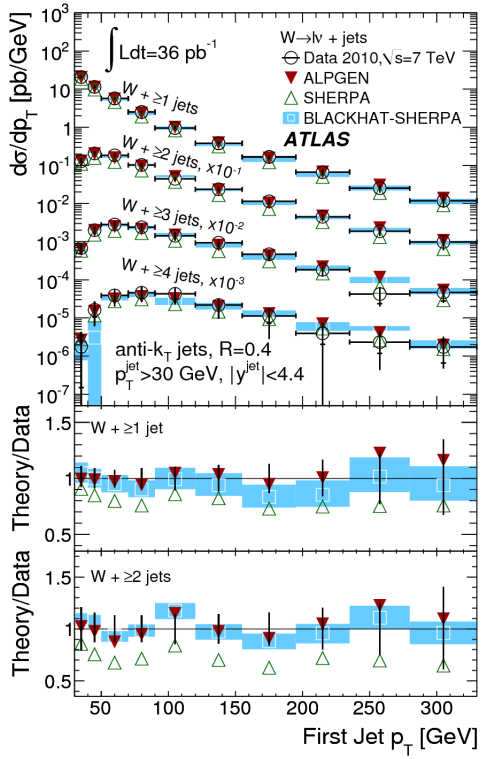

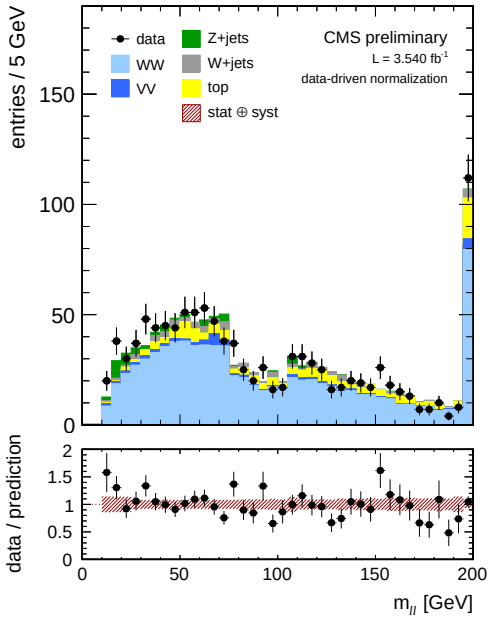

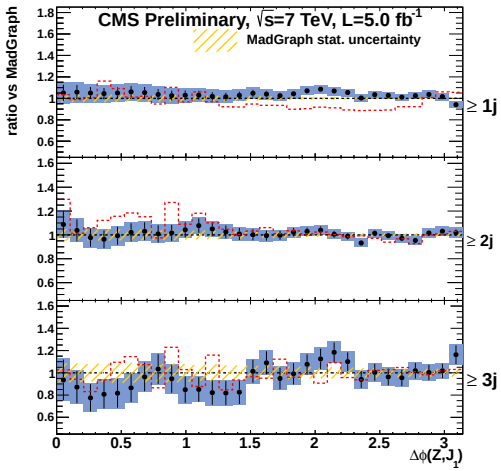

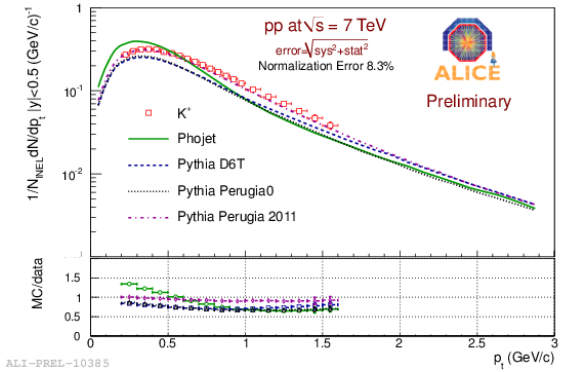

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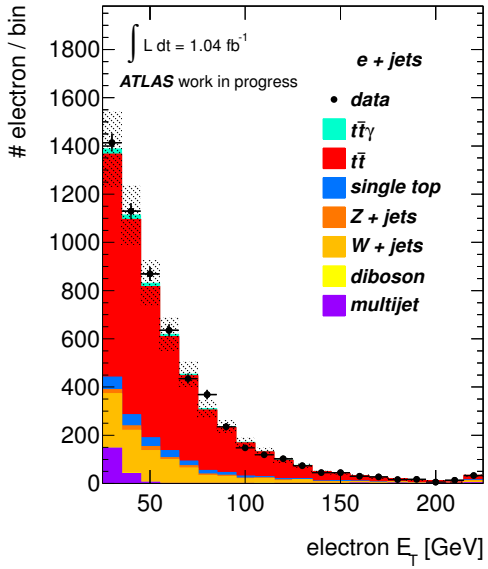

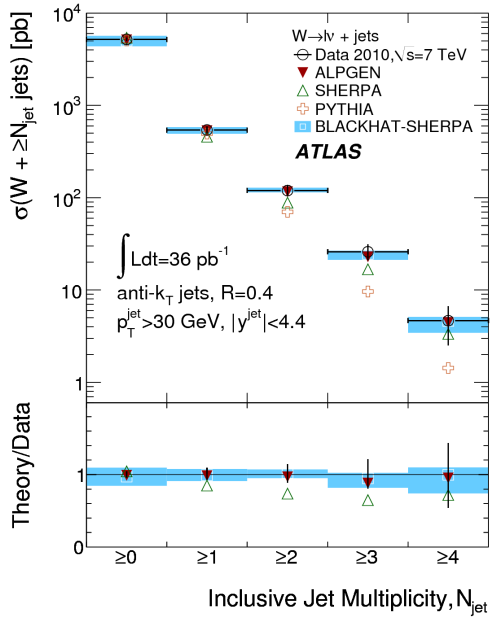

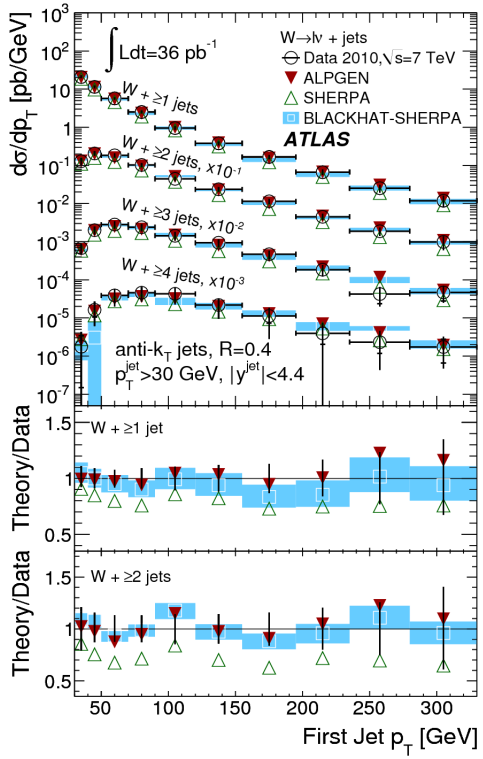

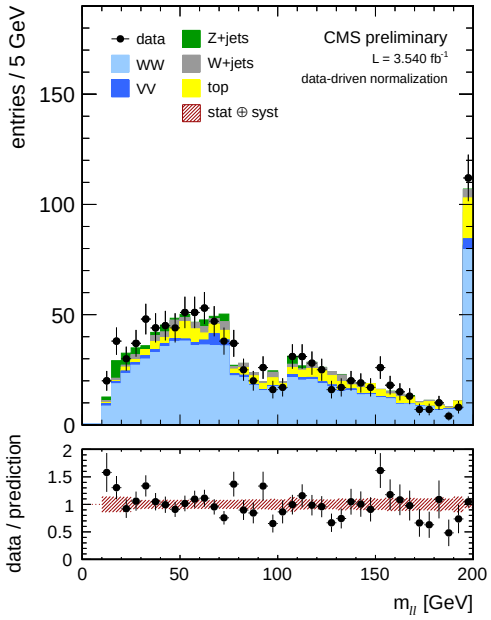

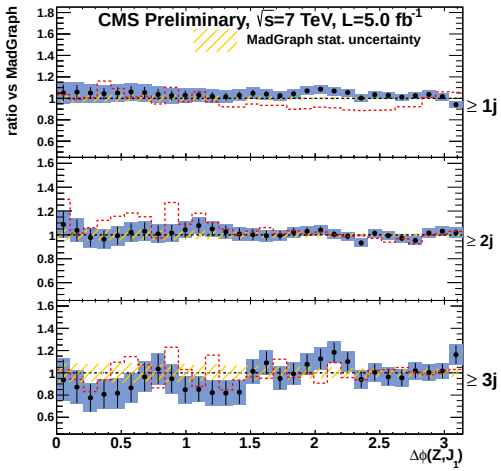

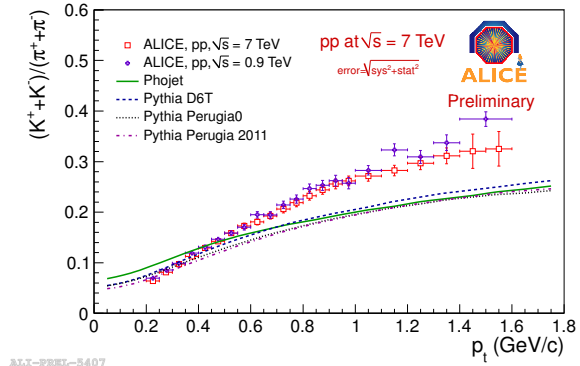

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- MC Advertisement:
  - MC Methods in Natural Sciences, Engineering, Economics, DESY, 15.-17.2.2013
  - MC4BSM 2013, DESY, 17.-19.4.2013

Monte Carlos: Battle of legs vs. loops

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