Tools and ideas for LHC phenomenology

Emanuele Re

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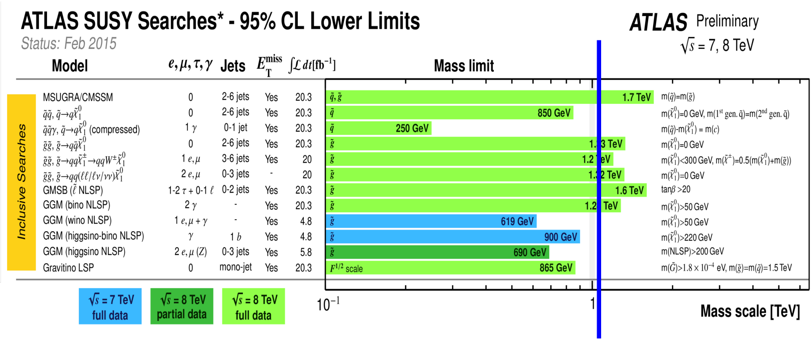
Montpellier, 18 March 2015

legacy of LHC Run I



- so far no sign of new Physics at the TeV scale from direct searches

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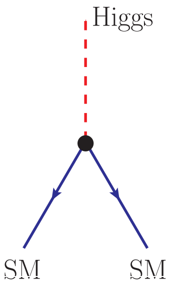

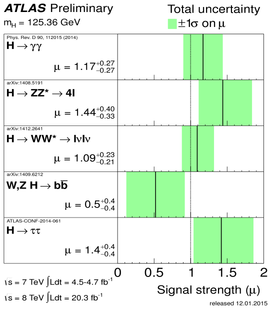

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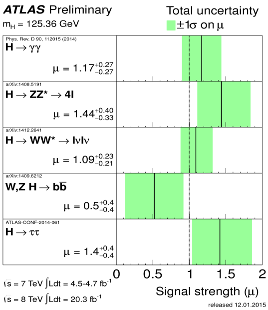
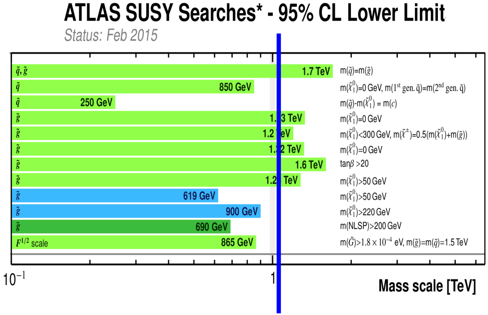
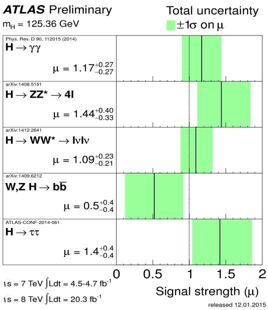
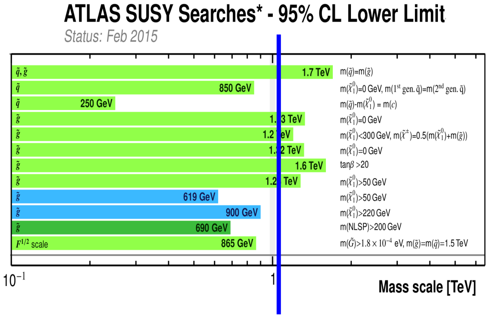




- so far no sign of new Physics at the TeV scale from direct searches
- Higgs couplings have started to be measured: SM-like values, within 20-30 %
- Situation will hopefully change at 13-14 TeV. Otherwise BSM hints likely from:
  - small deviations from SM backgrounds
  - indirect searches [Higgs couplings, precise extraction of SM parameters]

legacy of LHC Run I





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  - sma… …dden well]
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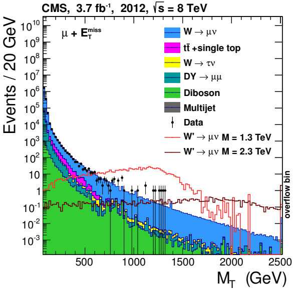
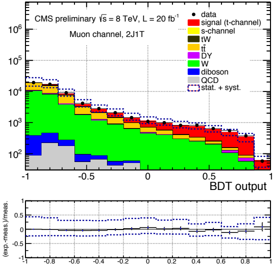
require accurate understanding of signals and backgrounds:
☞ “precision Physics”

Where are QCD precision and MC important?

1: s-channel resonance



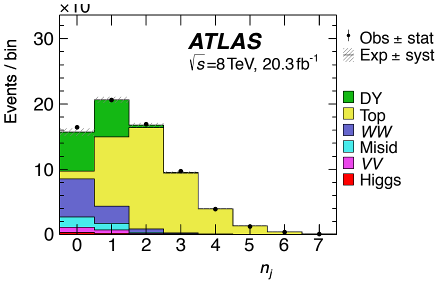
2: BDT output



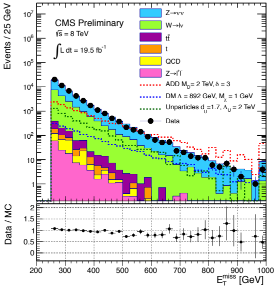
- s-channel resonance "easy" to discover; Higgs discovery in $\gamma\gamma$ and ZZ belongs to 1
- Some analysis techniques (e.g. 2) heavily relies on using MC event generators to separate signal and backgrounds
- MC very often needed also in more standard analysis...

Where are QCD precision and MC important?

3 : jet-binned x-section



4 : high-pt excess



- For 3 and 4, need to control as much as possible QCD effects (i.e. rates and shapes, and also uncertainties!).
- Similar issues when extracting a SM parameters very precisely (e.g. the W mass).

Where are QCD precision and MC important?

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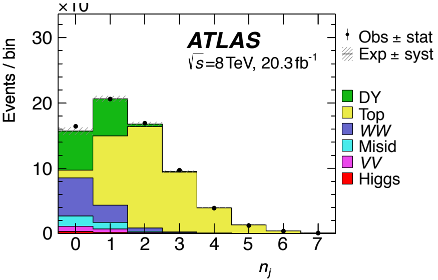

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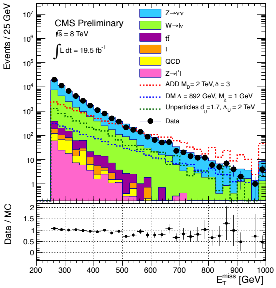
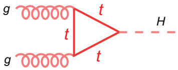


- at some level, MC event generators enter in almost all experimental analyses

precise tools $\Rightarrow$ smaller uncertainties on measured quantities
$\Downarrow$
“small” deviations from SM accessible

Event generators: what they are?

ideal world: high-energy collision and detection of elementary particles



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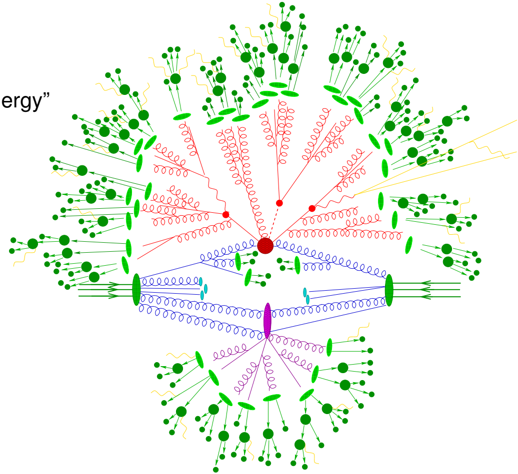
real world:

- collide non-elementary particles
- we detect e, μ, γ,hadrons, “missing energy”

- we want to predict final state
  - realistically
  - precisely
  - from first principles



[sherpa’s artistic view]

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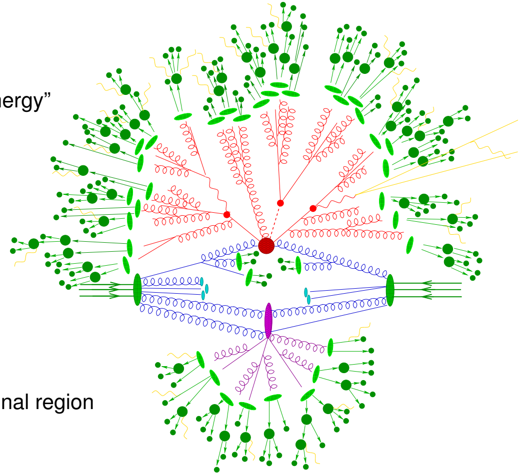
$\Rightarrow$ full event simulation needed to:
- compare theory and data
- estimate how backgrounds affect signal region
- test/build analysis techniques

soner or later, at some point a MC is used...



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Event generators: what they are?

ideal world: high-energy collision and detection of elementary particles
real world:

hard scattering

$\Lambda_{\text{QCD}} \ll \mu \approx Q$

- perturbation theory

parton shower

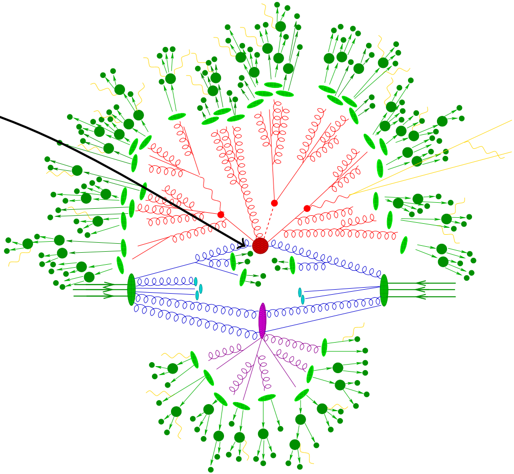
$\Lambda_{\text{QCD}} < \mu < Q$

- hierarchy of scales
- resummation of large logarithms

hadronisation

$\mu \approx \Lambda_{\text{QCD}}$

- non-perturbative model, tuned on e^+e^- data



[sherpa's artistic view]

all stages: QCD

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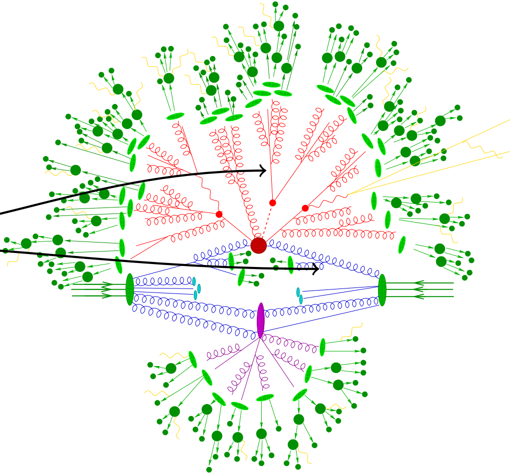

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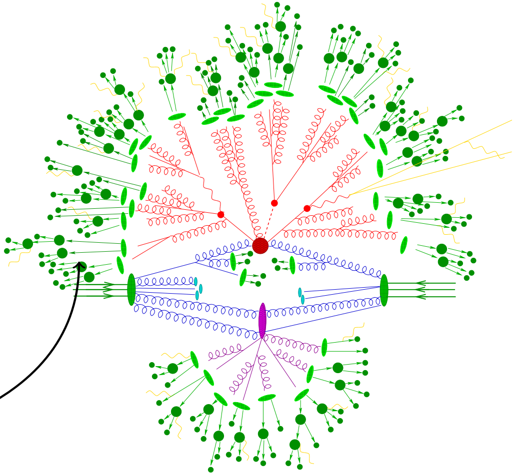


[sherpa's artistic view]

all stages: QCD

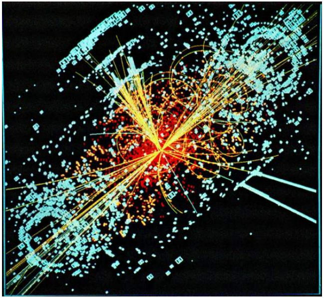
Event generators: what's the output?

- in practice: momenta of all outgoing leptons and hadrons:

IHEP	ID	IDPDG	IST	MO1	MO2	DA1	DA2	P-X	P-Y	P-Z	ENERGY
31	NU_E	12	1	29	22	0	0	60.53	37.24	-1185.0	1187.1
32	E+	-11	1	30	22	0	0	-22.80	2.59	-232.4	233.6
148	K+	321	1	109	9	0	0	-1.66	1.26	1.3	2.5
151	PI0	111	1	111	9	0	0	-0.01	0.05	11.4	11.4
152	PI+	211	1	111	9	0	0	-0.19	-0.13	2.0	2.0
153	PI-	-211	1	112	9	0	0	0.84	-1.07	1626.0	1626.0
154	K+	321	1	112	9	0	0	0.48	-0.63	945.7	945.7
155	PI0	111	1	113	9	0	0	-0.37	-1.16	64.8	64.8
156	PI-	-211	1	113	9	0	0	-0.20	-0.02	3.1	3.1
158	PI0	111	1	114	9	0	0	-0.17	-0.11	0.2	0.3
159	PI0	111	1	115	18	0	0	0.18	-0.74	-267.8	267.8
160	PI-	-211	1	115	18	0	0	-0.21	-0.13	-259.4	259.4
161	N	2112	1	116	23	0	0	-8.45	-27.55	-394.6	395.7
162	NBAR	-2112	1	116	23	0	0	-2.49	-11.05	-154.0	154.4
163	PI0	111	1	117	23	0	0	-0.45	-2.04	-26.6	26.6
164	PI0	111	1	117	23	0	0	0.00	-3.70	-56.0	56.1
167	K+	321	1	119	23	0	0	-0.40	-0.19	-8.1	8.1
186	PBAR	-2212	1	130	9	0	0	0.10	0.17	-0.3	1.0

Plan of the talk

1. review how these tools work
2. discuss how their accuracy can be improved
3. show recent "NNLO matched to parton showers" results (NNLOPS)



parton showers and fixed order

Parton showers I

- connect the hard scattering ($\mu \approx Q$) with the final state hadrons ($\mu \approx \Lambda_{\text{QCD}}$)
- need to simulate production of many quarks and gluons

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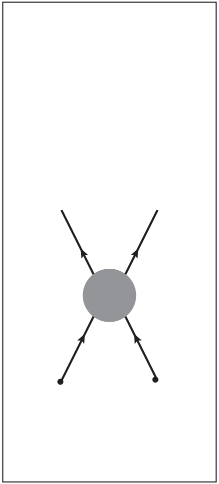

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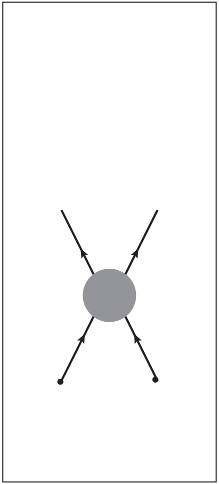

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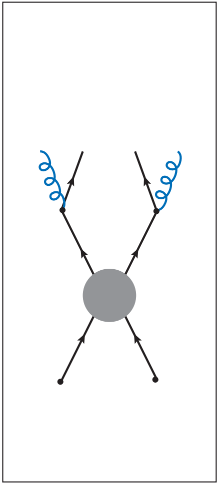

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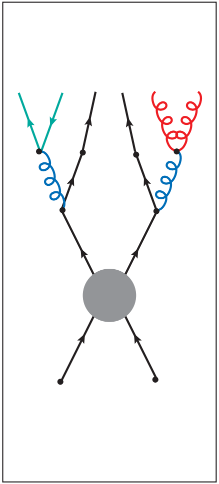

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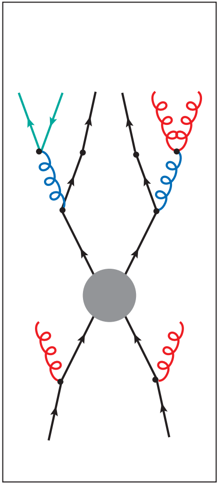

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3. soft-collinear emissions are ennhanced:

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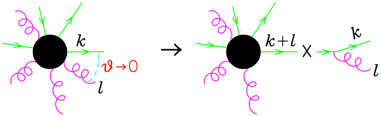
4. in soft-collinear limit, factorization properties of QCD amplitudes



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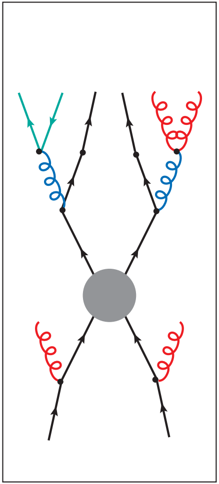
$z = k^0/(k^0+l^0)$	quark energy fraction
$t = \left\{(k+l)^2, l_T^2, E^2\theta^2\right\}$	splitting hardness
$P_{q,qg}(z) = C_F\frac{1+z^2}{1-z}$	AP splitting function



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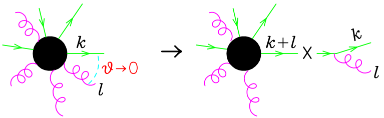

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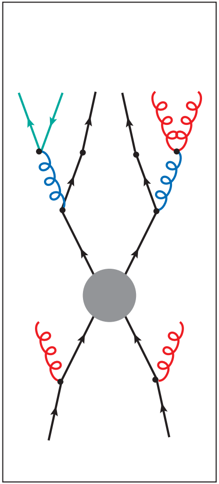

→ probabilistic interpretation!

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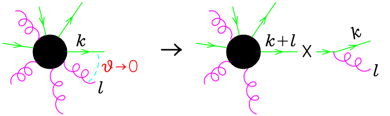

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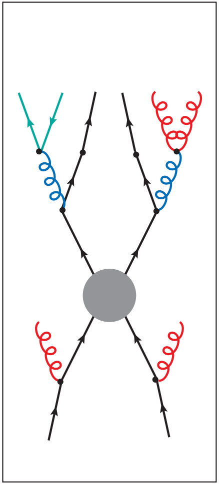


→ probabilistic interpretation!

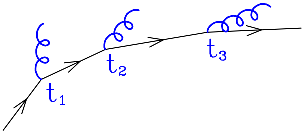
[notice: $\alpha_S L^2$]

Parton showers II

5. dominant contributions for multiparticle production due to strongly ordered emissions

$$t_1 > t_2 > t_3 ...$$

6. at any given order, we also have virtual corrections: include them with the same approximation



- LL virtual contributions: Sudakov form factor for each internal line:

$$\Delta_a(t_i, t_{i+1}) = \exp\left[-\sum_{(bc)} \int_{t_{i+1}}^{t_i} \frac{dt'}{t'} \int \frac{\alpha_s(t')}{2\pi} P_{a,bc}(z)\, dz \right]$$

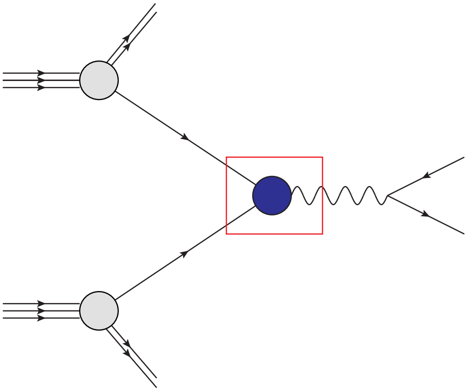
- Δ_a corresponds to the probability of having no resolved emission between t_i and t_{i+1} off a line of flavour a

☞ resummation of collinear logarithms

[very soft/collinear emissions are suppressed - all order effect!]

Parton showers: summary

$$d\sigma_{\text{SMC}} = \underbrace{|\mathcal{M}_B|^2 d\Phi_B}_{d\sigma_B} \Bigg\{ \qquad \Bigg\}$$



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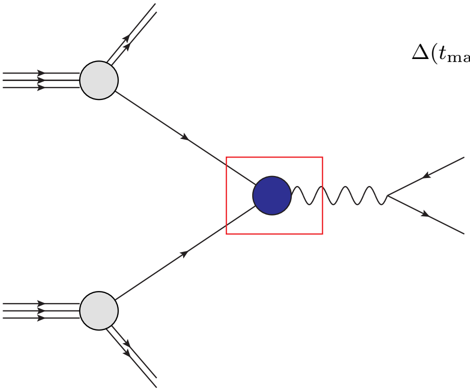
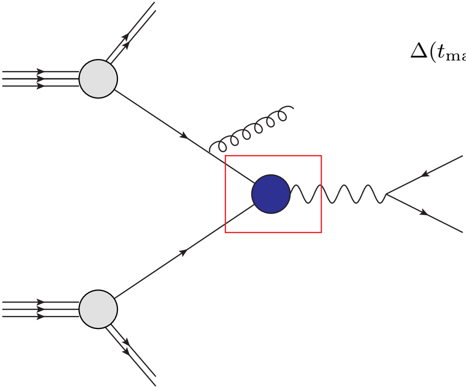
$$d\sigma_{\text{SMC}} = \underbrace{|\mathcal{M}_B|^2 d\Phi_B}_{d\sigma_B} \left\{ \Delta(t_{\max}, t_0) \right.\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \left. \right\}$$



$$\Delta(t_{\max}, t) = \exp\left\{ -\int_t^{t_{\max}} d\Phi'_r \, \frac{\alpha_s}{2\pi} \frac{1}{t'} P(z') \right\}$$

Parton showers: summary

$$d\sigma_{\text{SMC}} = \underbrace{|\mathcal{M}_B|^2 d\Phi_B}_{d\sigma_B} \Big\{ \Delta(t_{\max}, t_0) + \Delta(t_{\max}, t) \quad \underbrace{d\mathcal{P}_{\text{emis}}(t)}_{\frac{\alpha_s}{2\pi} \ \frac{1}{t} P(z) \ d\Phi_r} \Big\}$$



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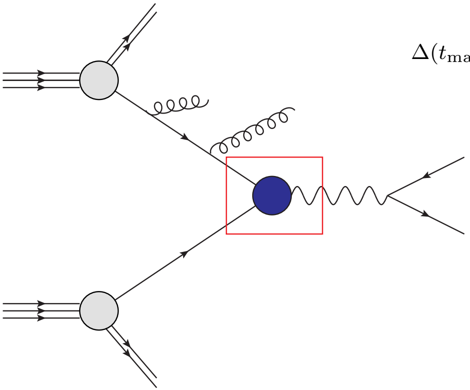
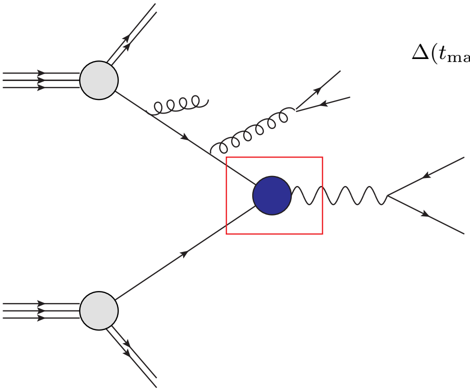


$$\Delta(t_{\max}, t) = \exp\left\{ - \int_t^{t_{\max}} d\Phi'_r \, \frac{\alpha_s}{2\pi} \frac{1}{t'} P(z') \right\}$$

Parton showers: summary

$$d\sigma_{\rm SMC} = \underbrace{|\mathcal{M}_B|^2 d\Phi_B}_{d\sigma_B} \Big\{ \Delta(t_{\rm max}, t_0) + \Delta(t_{\rm max}, t) \underbrace{d\mathcal{P}_{\rm emis}(t)}_{\frac{\alpha_s}{2\pi}\ \frac{1}{t} P(z)\ d\Phi_r} \underbrace{\{\Delta(t, t_0) + \Delta(t, t') d\mathcal{P}_{\rm emis}(t')\}}_{t' < t} \Big\}$$



$$\Delta(t_{\rm max}, t) = \exp\left\{ - \int_t^{t_{\rm max}} d\Phi'_r \, \frac{\alpha_s}{2\pi} \frac{1}{t'} P(z') \right\}$$

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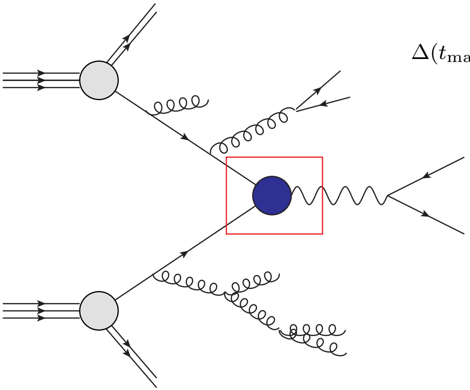

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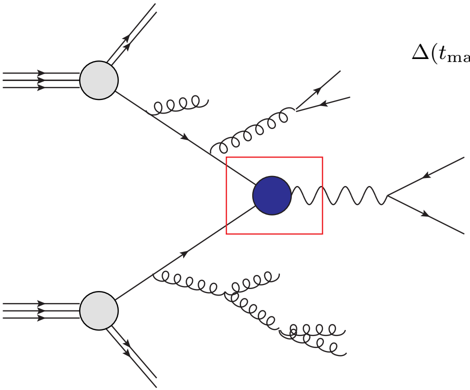
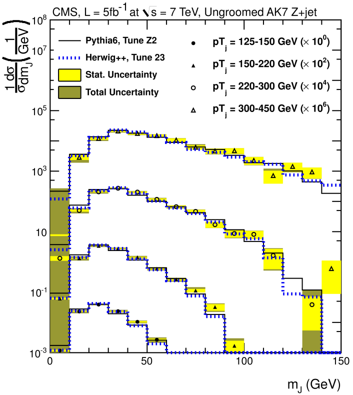


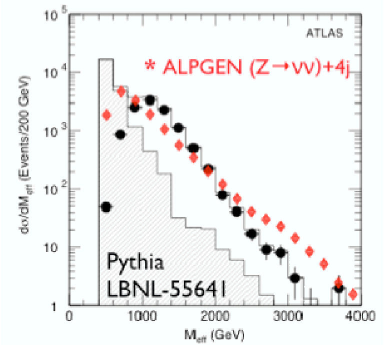
$$\Delta(t_{\max}, t) = \exp\left\{ - \int_t^{t_{\max}} d\Phi'_r \, \frac{\alpha_s}{2\pi} \frac{1}{t'} P(z') \right\}$$

This is “LOPS”

- A parton shower changes shapes, not the overall normalization, which stays LO (*unitarity*)

Do they work?





plot from [Gianotti,Mangano 0504221]

- ok when observables dominated by soft-collinear radiation [✓]
- not surprisingly, they fail when looking for hard multijet kinematics [✗]
- they are only LO+LL accurate (whereas we want (N)NLO QCD corrections) [✗]

⇒ Not enough if interested in precision (10% or less), or in multijet regions

Next-to-Leading Order

$\alpha_S \sim 0.1 \Rightarrow$ to improve the accuracy, use exact perturbative expansion

$$d\sigma = d\sigma_{\text{LO}} + \left(\frac{\alpha_S}{2\pi}\right) d\sigma_{\text{NLO}} + \left(\frac{\alpha_S}{2\pi}\right)^2 d\sigma_{\text{NNLO}} + \ldots$$

LO: *Leading Order*
NLO: *Next-to-Leading Order*
...

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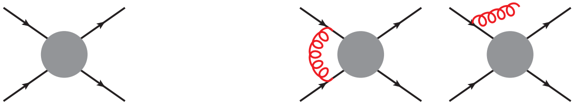

$$d\sigma = d\Phi_n \Big\{ \underbrace{B(\Phi_n)}_{\text{LO}} + \frac{\alpha_s}{2\pi}\Big[\underbrace{V(\Phi_n) + R(\Phi_{n+1})\, d\Phi_r}_{\text{NLO}}\Big] \Big\}$$

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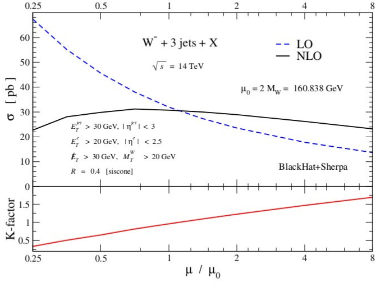
☞ Why NLO is important?

- first order where rates are reliable
- shapes are, in general, better described
- possible to attach sensible theoretical uncertainties



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☞ Why NLO is important?

- first order where rates are reliable
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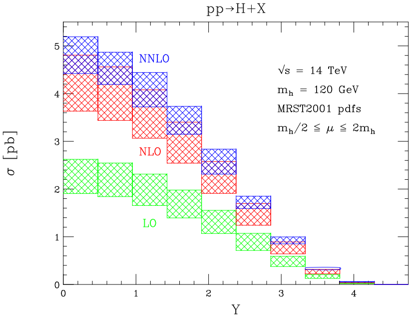
☞ When NNLO is needed?

- NLO corrections large
- very high-precision needed

⇒ Drell-Yan, Higgs, $t\bar{t}$ production



plot from [Anastasiou et al., '03]

PS vs. NLO

NLO

- ✓ precision
- ✓ nowadays this is the standard
- ✗ limited multiplicity
- ✗ (fail when resummation needed)

parton showers

- ✓ realistic + flexible tools
- ✓ widely used by experimental coll's
- ✗ limited precision (LO)
- ✗ (fail when multiple hard jets)

☞ can we merge them and build an NLOPS generator?

Problem:

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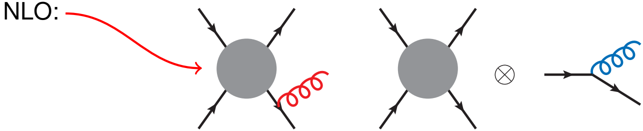
<u>Problem:</u> overlapping regions!



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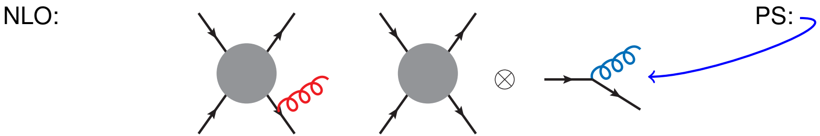

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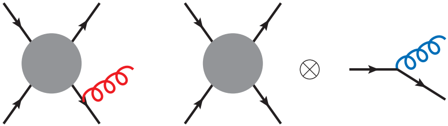


✓ many proposals, 2 well-established methods available to solve this problem: `MC@NLO` and `POWHEG` [Frixione-Webber '03, Nason '04]

matching NLO and PS

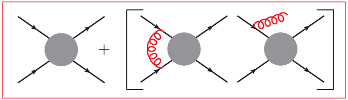
- POWHEG (POsitive Weight Hardest Emission Generator)

NLOPS: POWHEG I

$$d\sigma_{\mathrm{POW}} = d\Phi_n \quad \bar{B}(\Phi_n) \quad \left\{ \Delta(\Phi_n; k_{\mathrm{T}}^{\mathrm{min}}) + \Delta(\Phi_n; k_{\mathrm{T}}) \frac{\alpha_s}{2\pi} \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)} \, d\Phi_r \right\}$$

NLOPS: POWHEG I

$$B(\Phi_n) \Rightarrow \bar{B}(\Phi_n) = B(\Phi_n) + \frac{\alpha_s}{2\pi}\left[V(\Phi_n) + \int R(\Phi_{n+1})\, d\Phi_r\right]$$



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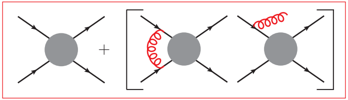

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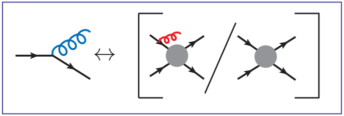

$$\Delta(t_{\mathrm{m}}, t) \Rightarrow \Delta(\Phi_n; k_{\mathrm{T}}) = \exp\left\{-\frac{\alpha_s}{2\pi} \int \frac{R(\Phi_n, \Phi'_r)}{B(\Phi_n)} \theta(k'_{\mathrm{T}} - k_{\mathrm{T}})\, d\Phi'_r\right\}$$

NLOPS: POWHEG II

$$d\sigma_{\mathrm{POW}} = d\Phi_n \; \bar{B}(\Phi_n) \left\{ \Delta(\Phi_n; k_{\mathrm{T}}^{\mathrm{min}}) + \Delta(\Phi_n; k_{\mathrm{T}}) \frac{\alpha_s}{2\pi} \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)} \, d\Phi_r \right\}$$

[+ p_{T}-*vetoing subsequent emissions*, to avoid double-counting]

- inclusive observables: @NLO
- first hard emission: full tree level ME
- (N)LL resummation of collinear/soft logs
- extra jets in the shower approximation

This is “NLOPS”

NLOPS: POWHEG II

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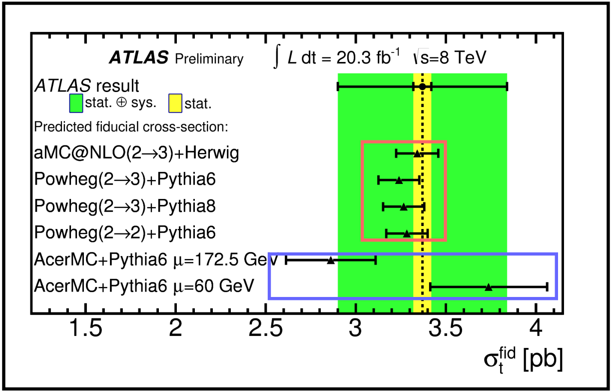
This is "NLOPS"

POWHEG BOX

[Alioli,Nason,Oleari,ER '10]

- large library of SM processes, (largely) automated
- widely used by LHC collaborations and other theorists
- not really a closed chapter; some important issues are still to be addressed...

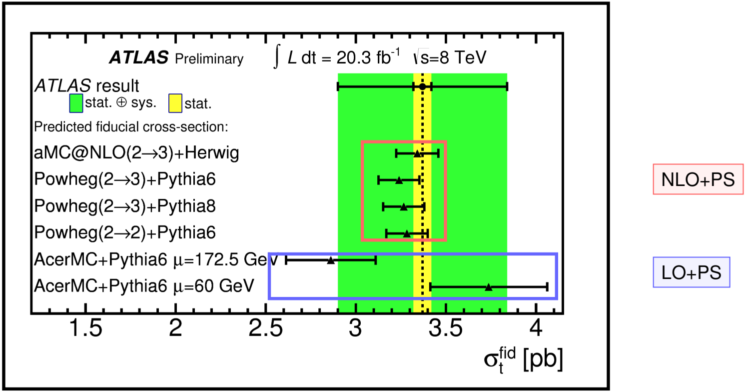
NLOPS: POWHEG II



NLO+PS

LO+PS

NLOPS: POWHEG II



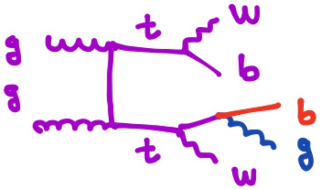
...a couple of possible BSM applications...

$t\bar{t}$ and top-mass measurement

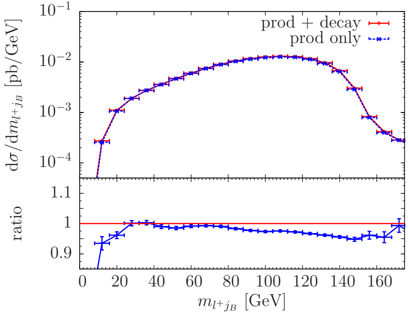
- Improvement on measurement of the top-mass at the LHC will probably come from combination of different strategies: total x-section, $t\bar{t}$ + jet, leptonic spectra, $b\ell$ endpoint,...
  [see *e.g.* TOP LHC Working Group or MITP Workshop 2014]

- Some techniques rely on looking into the kinematics of visible particles from top-decay

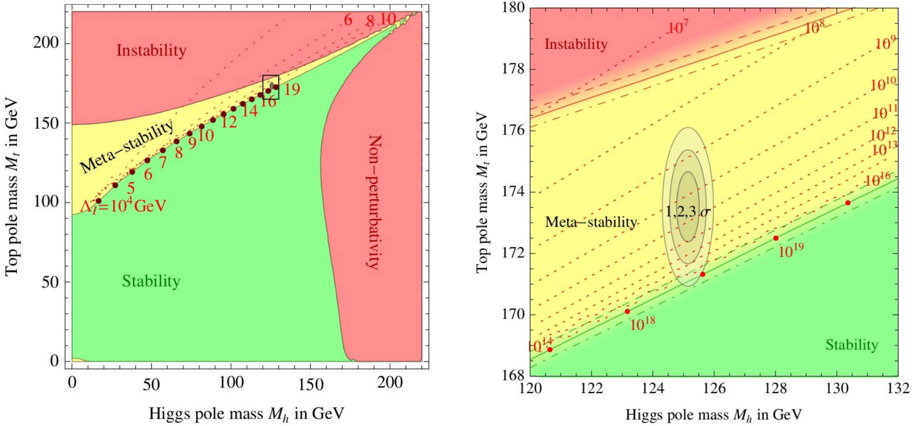
- Important that simulations are very accurate, and associated errors are quantified: recently, NLO+PS with NLO in production and decay [Campbell,Ellis,Nason,ER '14]



[left plot stolen from R. Franceschini slide @ TOP LHC WG]



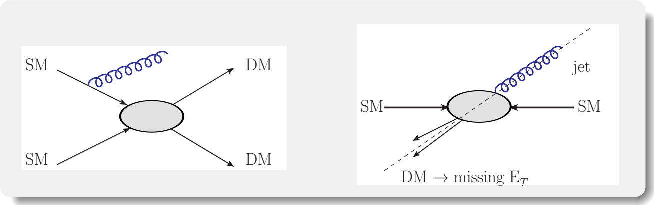
BSM example I

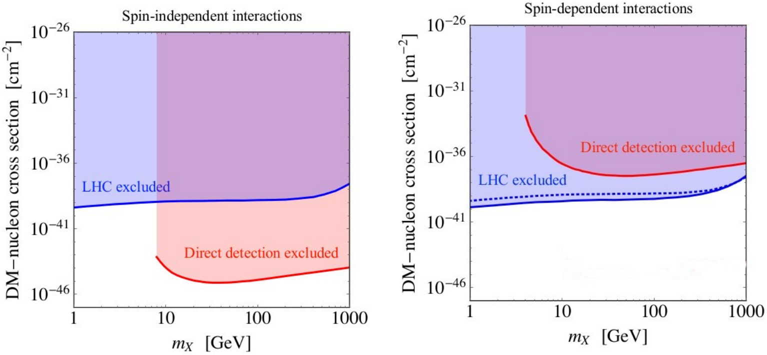


plot from [Giudice et al. '13]

$$m_t \approx 173 \pm 1 \text{ GeV}$$

BSM example II: LHC and Dark-Matter searches

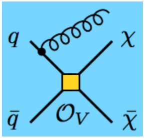


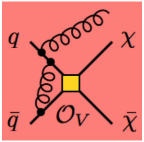


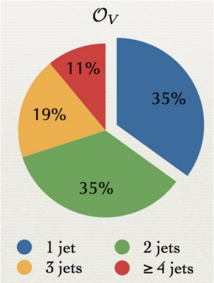
BSM example II: LHC and Dark-Matter searches

- studied QCD corrections to monojet searches

[Haisch,Kahlhoefer,ER '13]



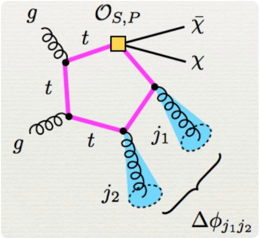


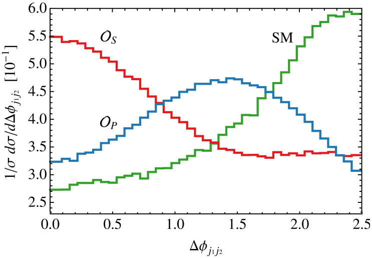


- ATLAS and CMS cuts are such that a large fraction of events has 2 or more jets

---

- for some DM-SM interactions, using VBF cuts: [Haisch,Hibbs,ER '13, see also Cotta,Hewett et al. '13]





NLO+PS merging and NNLO+PS

NNLO+PS: why and where?

NLO(+PS) not always enough: NNLO needed when

1. large NLO/LO “K-factor”
   [as in Higgs Physics]

2. very high precision needed
   [e.g. Drell-Yan, top pairs]

- last couple of years:
  huge progress in NNLO

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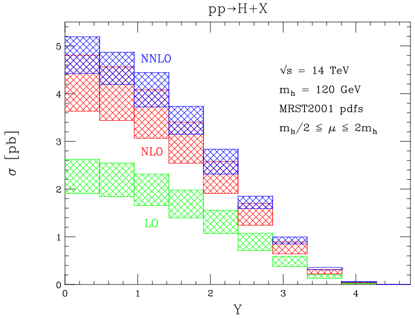

[Anastasiou et al., ’03]

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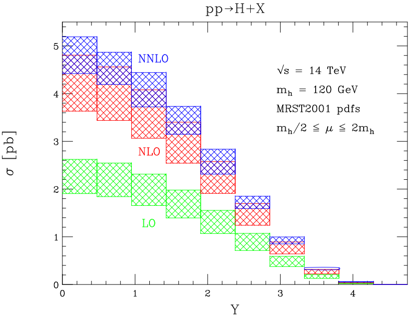

[Anastasiou et al., '03]

Q: can we merge NNLO and PS?

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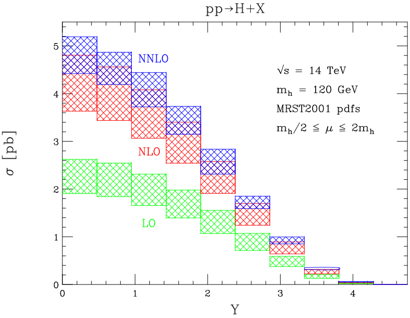

Q: can we merge NNLO and PS?

[Anastasiou et al., '03]

☞ realistic event generation with state-of-the-art perturbative accuracy !
☞ important for precision studies for several processes

- method presented here: based on POWHEG+MiNLO, used so far for
  - Higgs production [Hamilton,Nason,ER,Zanderighi, 1309.0017]
  - neutral & charged Drell-Yan [Karlberg,ER,Zanderighi, 1407.2940]

towards NNLO+PS

- what do we need and what do we already have?

	H (inclusive)	H+j (inclusive)	H+2j (inclusive)
H @ NLOPS	NLO	LO	shower
HJ @ NLOPS	/	NLO	LO
H @ NNLOPS	NNLO	NLO	LO

towards NNLO+PS

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H @ NNLOPS	NNLO	NLO	LO

☞ a merged H-HJ generator is almost OK

towards NNLO+PS

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H @ NNLOPS	NNLO	NLO	LO

☞ a merged H-HJ generator is almost OK

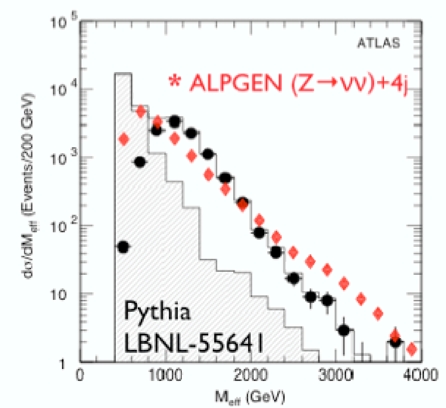
- many of the multijet NLO+PS merging approaches work by combining 2 (or more) NLO+PS generators, introducing a merging scale*

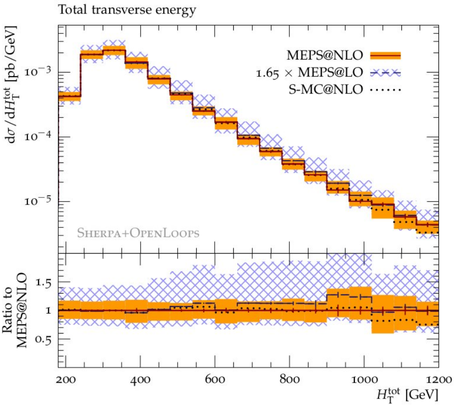
- POWHEG + MiNLO [Multiscale Improved NLO]. [Hamilton et al. '12]

  No need of merging scale: it extends the validity of a NLO+PS computation with jets in the final state to phase-space regions where jets become unresolved

* [Hoeche,Krauss, et al.,1207.5030] [Frederix,Frixione,1209.6215] [Lonnblad,Prestel,1211.7278] [Platzer,1211.5467] [Alioli,Bauer, et al.,1211.7049] ...

NLOPS merging & BSM



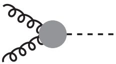


- left: LO+PS
- right: NLO+PS merging

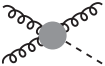
Sherpa+OpenLoops [Hoeche,Krauss et al. 1402.6293]

POWHEG → MiNLO → NNLO+PS

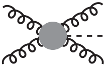
Higgs at NNLO:



loops: 0 1 2



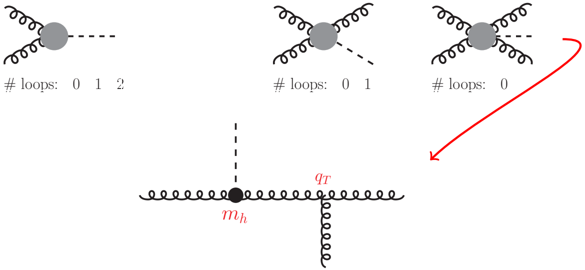
loops: 0 1



loops: 0

POWHEG → MiNLO → NNLO+PS

Higgs at NNLO:



(a) 1 and 2 jets: POWHEG H+1j

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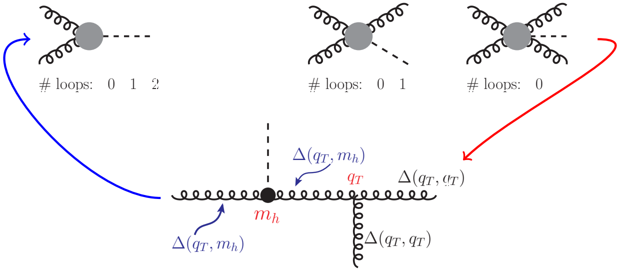

(b) - integrate down to $q_T = 0$ with MiNLO
- “Improved MiNLO” allows to build a H-HJ @ NLOPS generator

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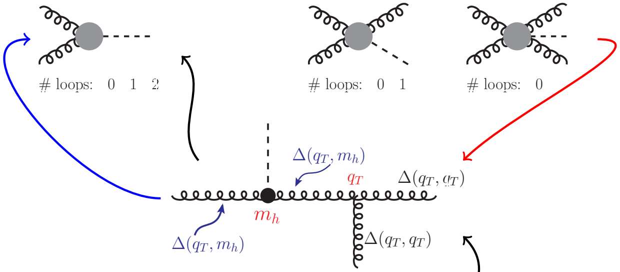

(c) 2 loops missing: from exact fixed-order NNLO

$$W(y) = \frac{d\sigma(y)_{\text{NNLO}}}{d\sigma(y)_{\text{MiNLO}}}$$

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MiNLO

MiNLO

“Improved” MiNLO & NLOPS merging

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“Improved” MiNLO & NLOPS merging: details

Higgs at NNLO+PS: details

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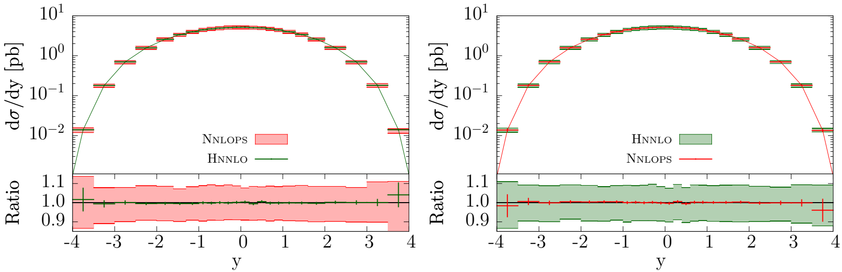
H@NNLOPS (fully incl.)

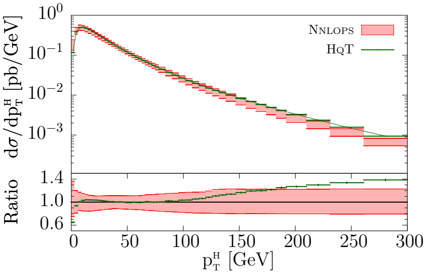
- NNLO with $\mu = m_H/2$, HJ–MiNLO "core scale" m_H [NNLO from HNNLO, Catani,Grazzini]
- $(7_{\rm Mi} \times 3_{\rm NN})$ pts scale var. in NNLOPS, 7pts in NNLO

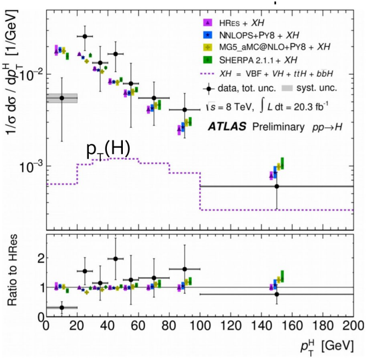


☞ Notice: band is 10% (at NLO would be $\sim$ 20-30%) [✓]

[Until and including $\mathcal{O}(\alpha_S^4)$, PS effects don't affect y_H (first 2 emissions controlled properly at $\mathcal{O}(\alpha_S^4)$ by MiNLO+POWHEG)]

H@NNLOPS (p_T^H)





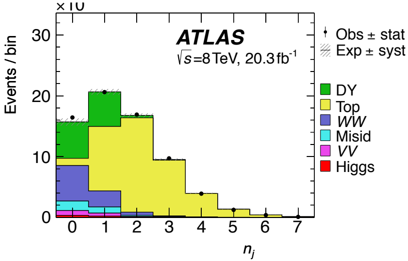
- `HqT`: NNLL+NNLO, $\mu_R = \mu_F = m_H/2$ [7pts], $Q_{\rm res} \equiv m_H/2$ [`HqT`, Bozzi et al.]

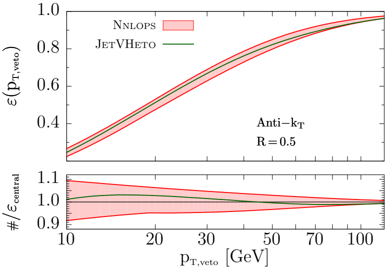
✓ uncertainty bands of HqT contain `NNLOPS` at low-/moderate p_T

- very good agreement with HqT resummation ["∼ expected", since $Q_{\rm res} \equiv m_H/2$, and $\beta = 1/2$]

☞ Separation of $H \to WW$ from $t\bar{t}$ bkg: x-sec binned in $N_{\rm jet}$

0-jet bin ⇔ jet-veto accurate predictions needed !





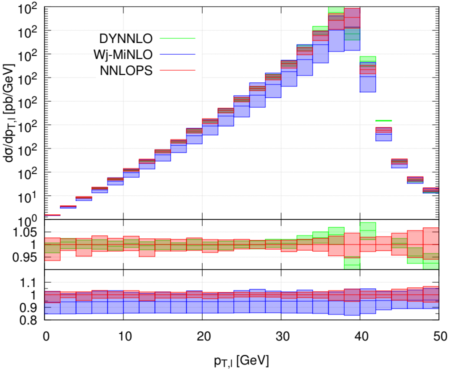
$$\varepsilon\left(p_{\rm T,veto}\right) = \frac{\Sigma(p_{\rm T,veto})}{\sigma^{\rm tot}} = \frac{1}{\sigma^{\rm tot}} \int d\sigma\, \theta\left(p_{\rm T,veto} - p_{\rm T}^{\rm j_1}\right)$$

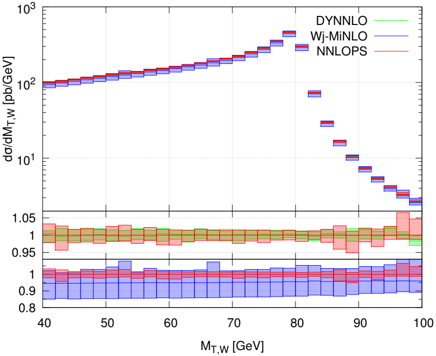
- `JetVHeto`: NNLL resum, $\mu_R = \mu_F = m_H/2$ [7pts], $Q_{\rm res} \equiv m_H/2$, (a)-scheme only

  [`JetVHeto`, Banfi et al.]

- nice agreement, differences never more than 5-6 %

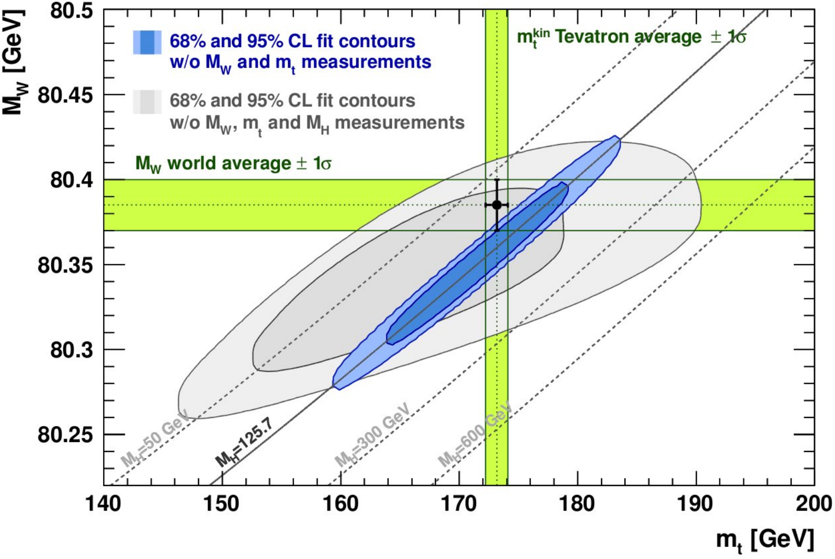
Drell-Yan @NNLOPS





....measure W mass very precisely....

consistency of SM



$$m_W = 80385 \pm 15 \text{ MeV}$$

Conclusions and Outlook

- Especially in absence of very clear singals of new-physics, accurate tools are needed for LHC phenomenology
- In the last decade, impressive amount of progress: new ideas, and automated tools

$\Rightarrow$ briefly reviewed how Event Generators work, and how they can be upgraded to NLO

$\Rightarrow$ shown results of merging NLOPS for different jet-multiplicities *without* merging scale

$\Rightarrow$ shown first working examples of NNLOPS

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Thank you for your attention!