FxFx Merging

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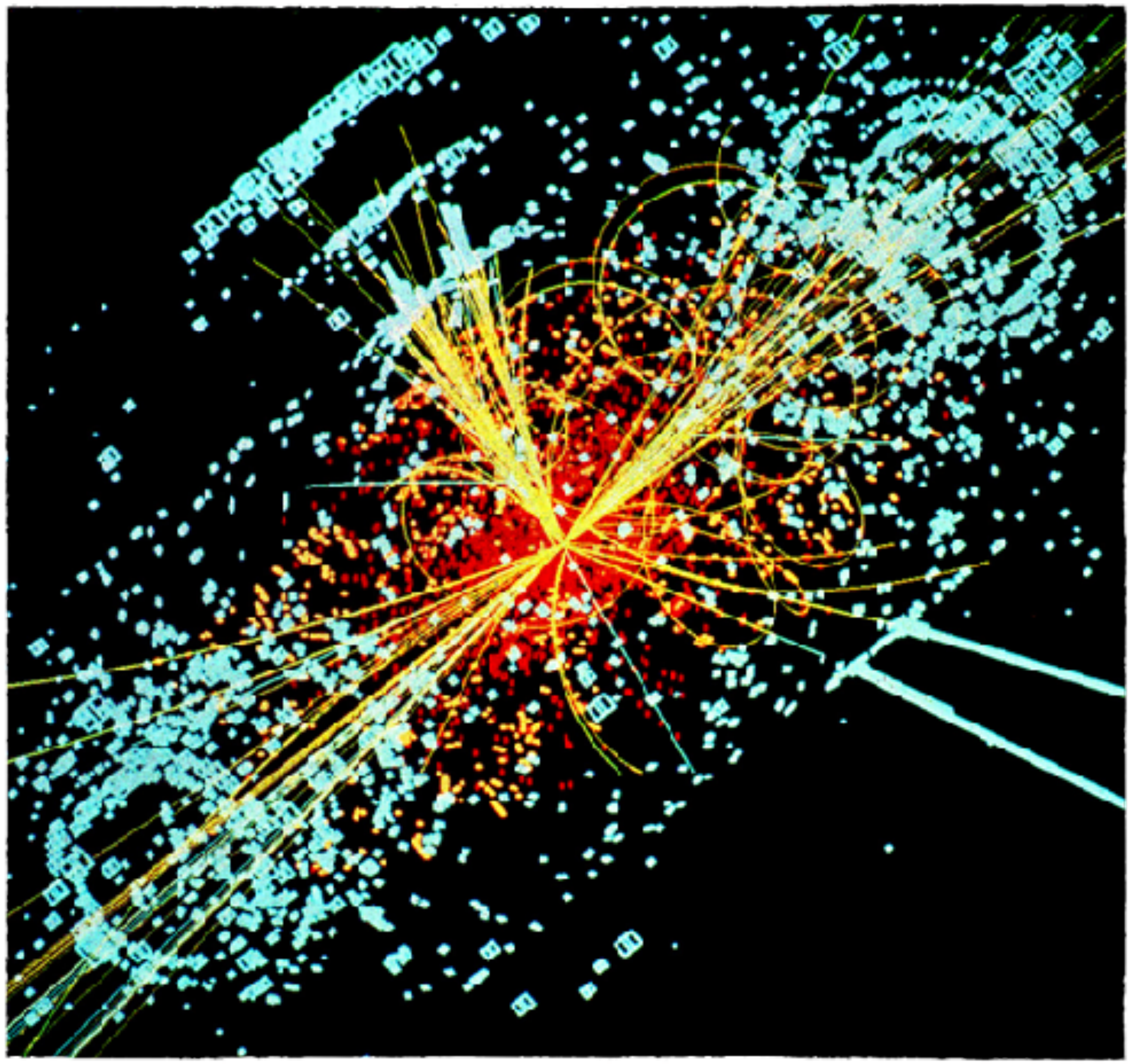
Large Hadron Collider

- The world's largest particle accelerator, the LHC, has been running extremely well during the last couple of years
- Higgs boson discovery!
- Run1 is complete (7/8 TeV collision energy) Run2 is ongoing (13/14 TeV collision energy)



Simulated Higgs boson event by CMS

Large Hadron Collider

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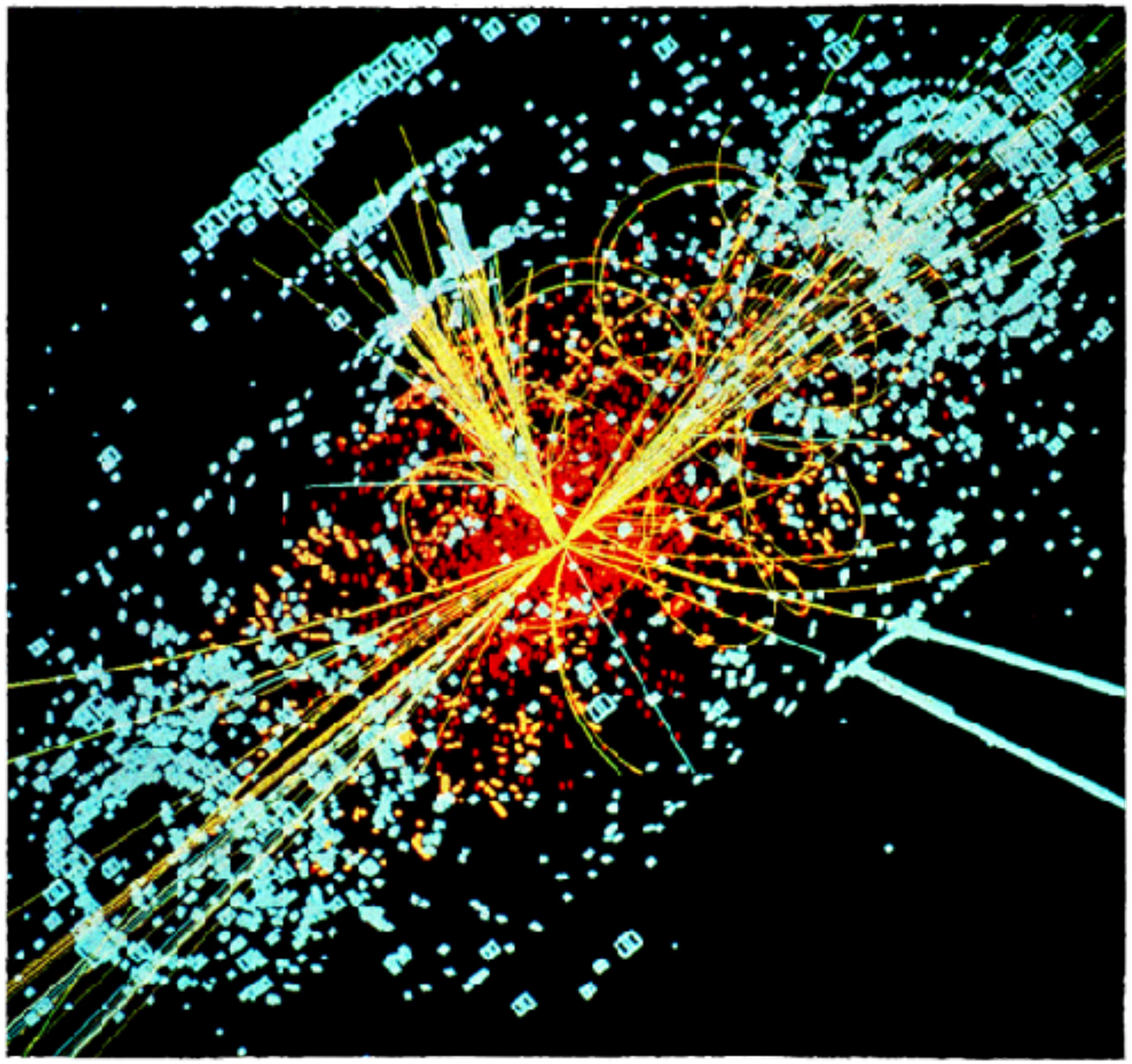
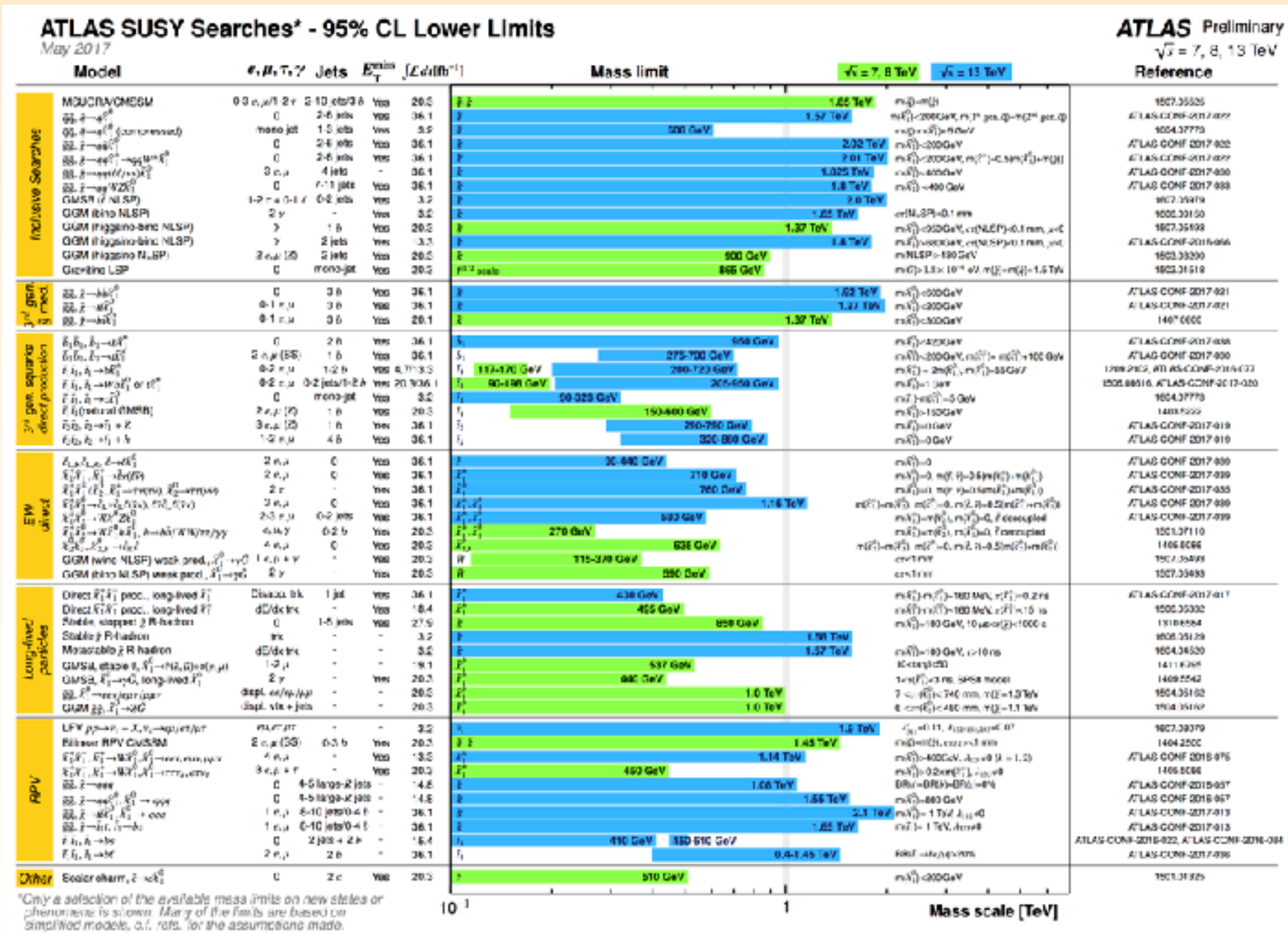
- Higgs boson discovery!
- Run1 is complete (7/8 TeV collision energy) Run2 is ongoing (13/14 TeV collision energy)
- Is the Higgs responsible for generating the masses of all fundamental particles?
  - ➡ Need to measure its coupling strength to all massive particles
  - ➡ This includes the Higgs self-coupling, of which we have no information so far



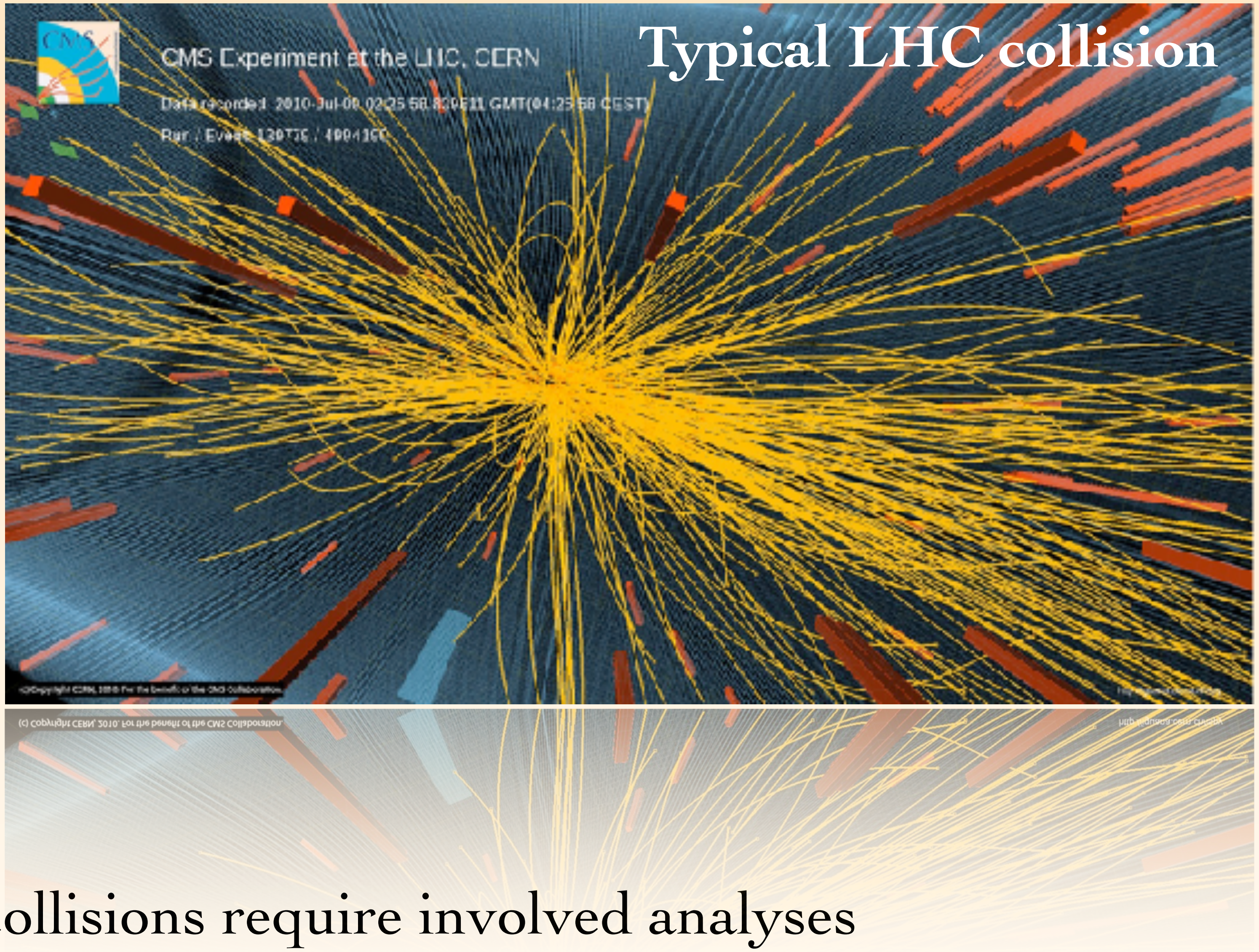
Simulated Higgs boson event by CMS

More!

- And there should be more!
- Dark matter, fine tuning problem, matter anti-matter asymmetry, etc., suggest the **existence of new particles and phenomena** that have not yet been discovered

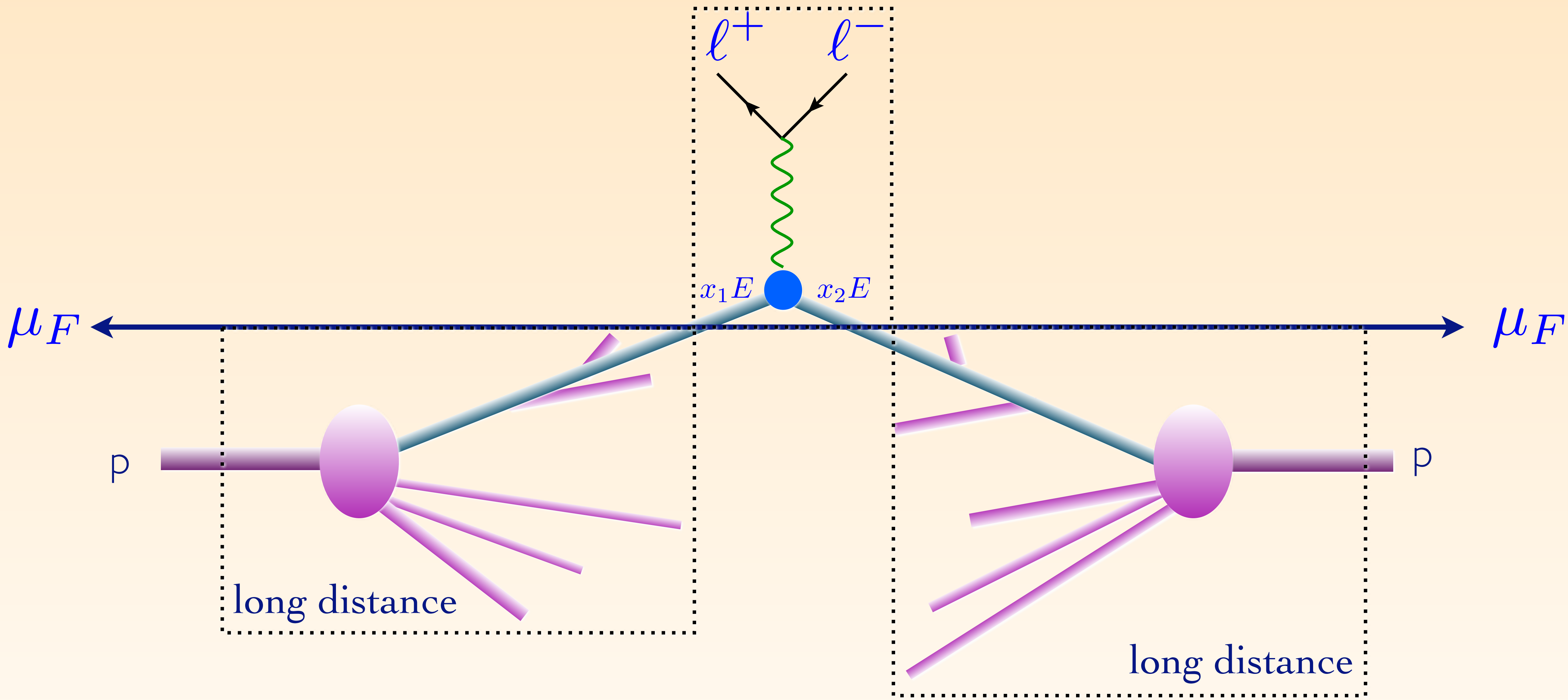


QCD RADIATION



- Messy collisions require involved analyses
  - State-of-the-art analyses require theory predictions and simulations
- Commonly used are **merging NLO matrix elements of various multiplicities** and **matching them to a parton shower**. Possibly including NNLO matrix elements for the lowest multiplicity

Master equation for hadron colliders



$$\sum_{a,b} \int dx_1 dx_2 d\Phi_{\rm FS}\, f_a(x_1,\mu_F) f_b(x_2,\mu_F)\, \hat\sigma_{ab\to X}(\hat s,\mu_F,\mu_R)$$

Phase-space integral

Parton density functions

Parton-level cross section

Master equation for hadron colliders

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Phase-space integral

Parton density functions

Parton-level cross section

Two ingredients necessary:

1. Parton distribution functions
(from experiment, but evolution from theory)

2. Parton-level cross section: short distance coefficients as an expansion in α_S
(from theory)

Perturbative expansion

$\hat{\sigma}_{ab\to X}(\hat{s},\mu_F,\mu_R)$ Parton-level cross section

- The parton-level cross section can be computed as a series in perturbation theory, using the coupling constant as an expansion parameter, schematically:

$$\hat{\sigma} = \sigma^{\text{Born}}\left(1 + \frac{\alpha_s}{2\pi}\sigma^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2\sigma^{(2)} + \left(\frac{\alpha_s}{2\pi}\right)^3\sigma^{(3)} + \dots\right)$$

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LO predictions

Perturbative expansion

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LO predictions

NLO corrections

Perturbative expansion

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LO predictions

NLO corrections

NNLO corrections

Perturbative expansion

$\hat{\sigma}_{ab\to X}(\hat{s}, \mu_F, \mu_R)$ Parton-level cross section

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LO predictions

NLO corrections

NNLO corrections

NNNLO corrections

Perturbative expansion

$\hat{\sigma}_{ab \to X}(\hat{s}, \mu_F, \mu_R)$ Parton-level cross section

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LO predictions

NLO corrections

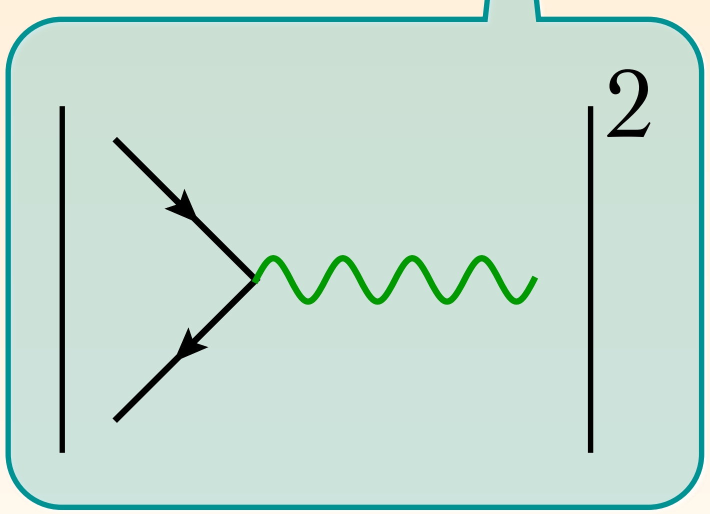
NNLO corrections

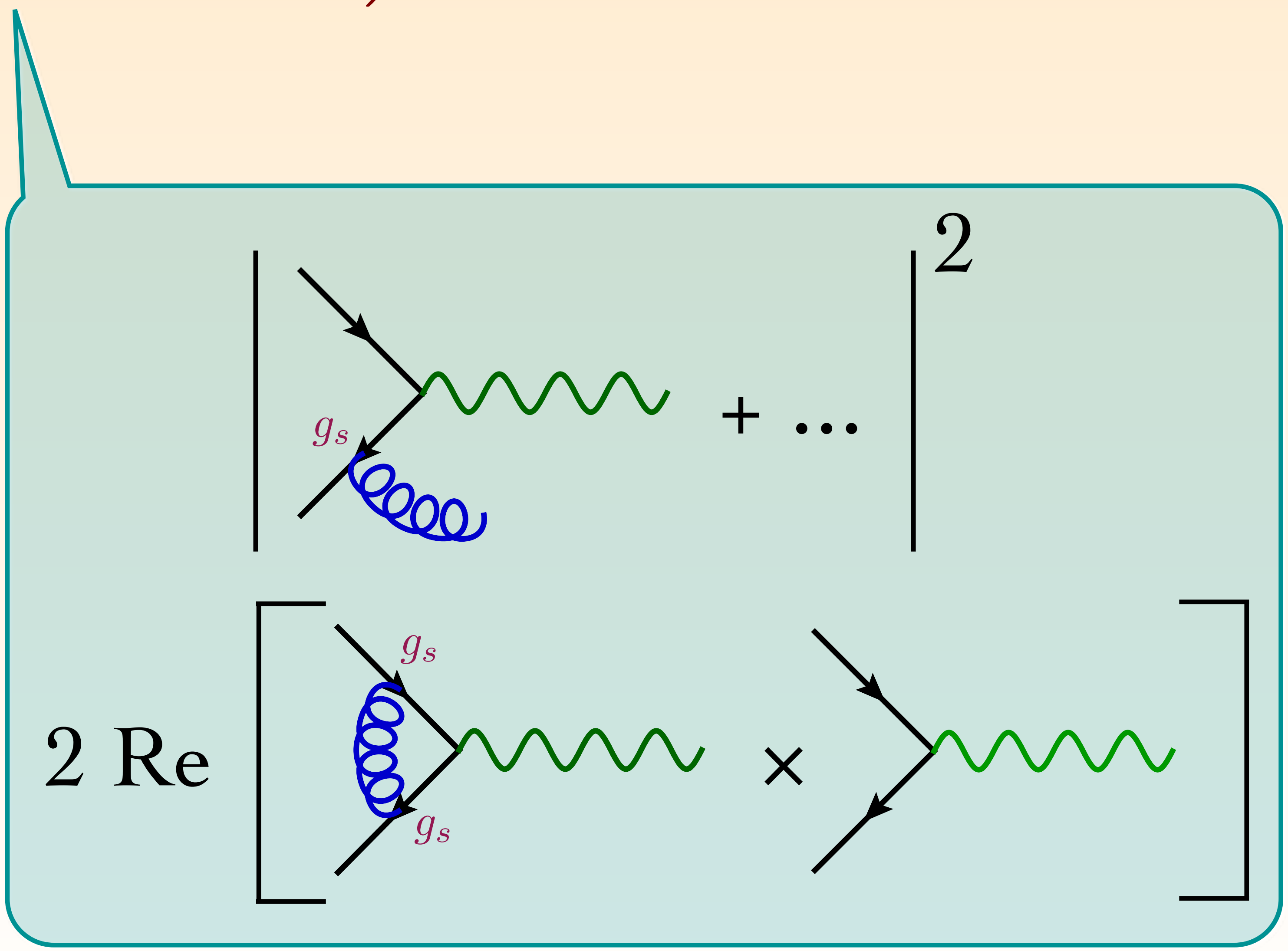
NNNLO corrections

- Including higher corrections improves predictions and reduces theoretical uncertainties

NLO predictions

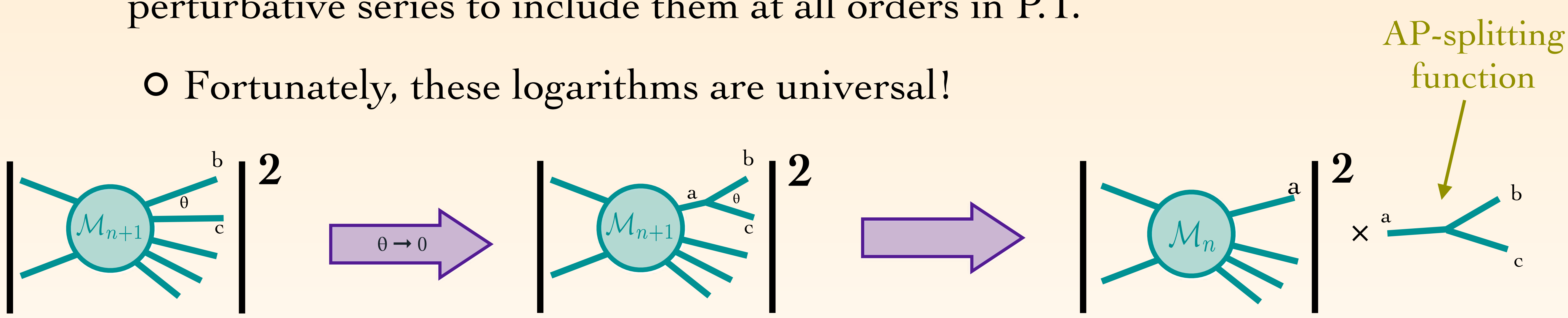
$$\hat{\sigma} = \sigma^{\text{Born}}\left(1 + \frac{\alpha_s}{2\pi}\sigma^{(1)} + \ldots\right)$$





Parton shower

- In collinear (and soft) regions of phase-space, perturbation theory breaks down: every power of α_s is accompanied by a large (double) logarithm $\log[Q^2/y]$
- Hence, for collinear (and soft) emissions need to rearrange (i.e. 'resum') the perturbative series to include them at all orders in P.T.
  - Fortunately, these logarithms are universal!



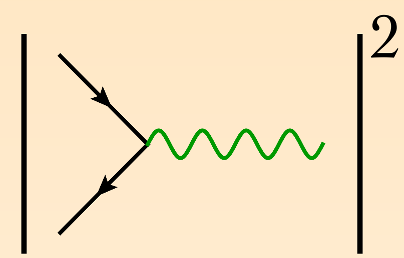
- Can include the leading logarithmic corrections through a parton shower algorithm, using the Sudakov form factor

$$\exp\Big[-R(v)\Big], \quad v = Q^2/y$$

What does this give us pictorially...?

- Let's start very simple and go from there...
- Let's consider
  - a very simple process: production of a single EW vector boson or Higgs boson
  - an observable most-sensitive to QCD radiation: k_T-jet resolution variable (with R=1), **$\sqrt{y}$ ~ $p_T(j)$** [$y_{01} \sim p_T^2(j_1)$; $y_{12} \sim p_T^2(j_2)$; etc]

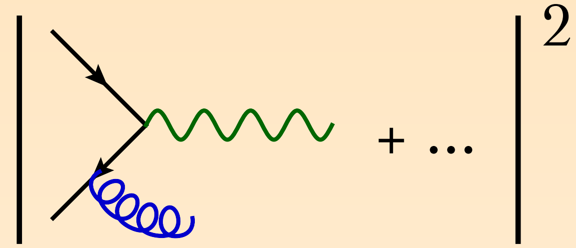
Leading Order V

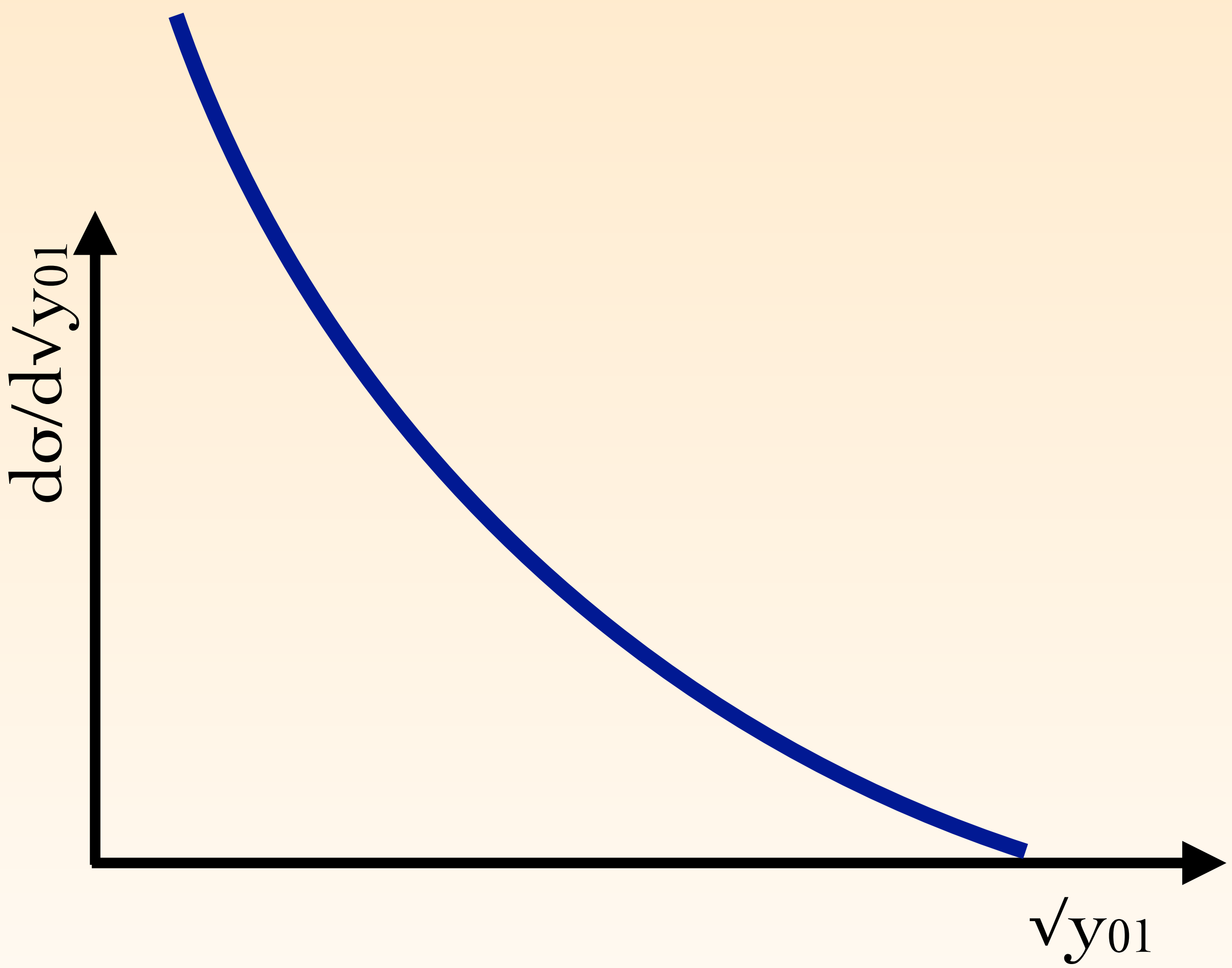


- Simplest prediction of all
- Just gives a delta-function at zero p_T due to energy-momentum conservation
- Cannot be used to make reliable predictions for this observable

Physical curve	No
Tail	N/A
Integral	LO
Extendible to multi-jet	Yes

Leading Order V+1 jet

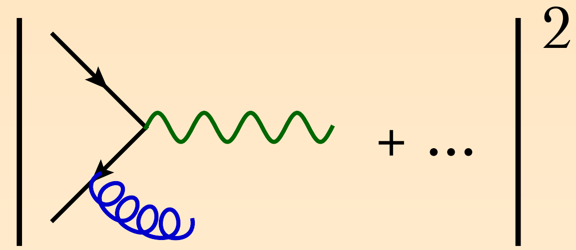


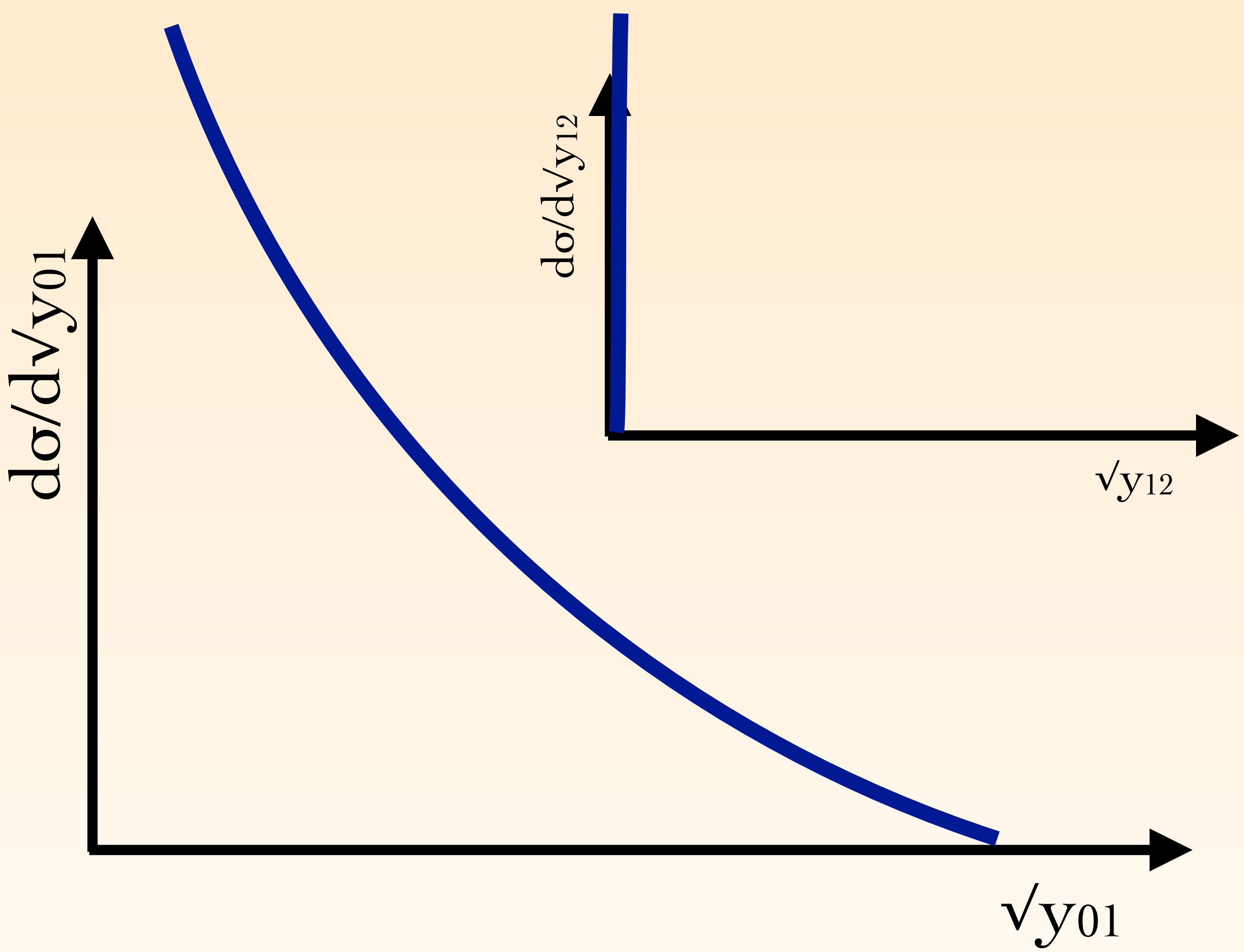


- Non-trivial distribution that is LO accurate
- Need a generation cut, otherwise the integral over the p_T spectrum diverges
- Cannot be used to make reliable predictions at low p_T

Physical curve	Only at high-p_T
Tail	LO
Integral	∞
Extendible to multi-jet	Yes

Leading Order V+1 jet





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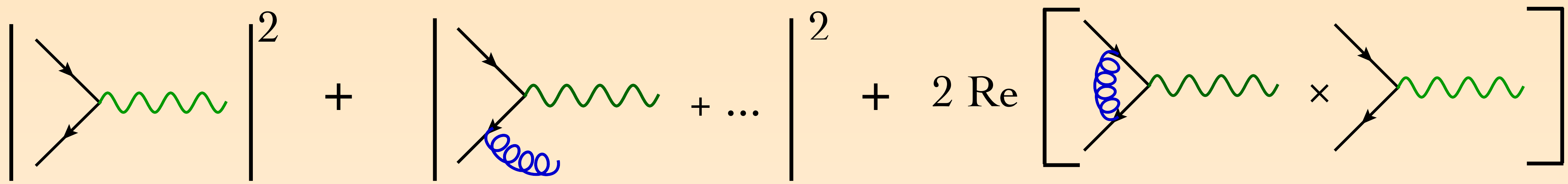
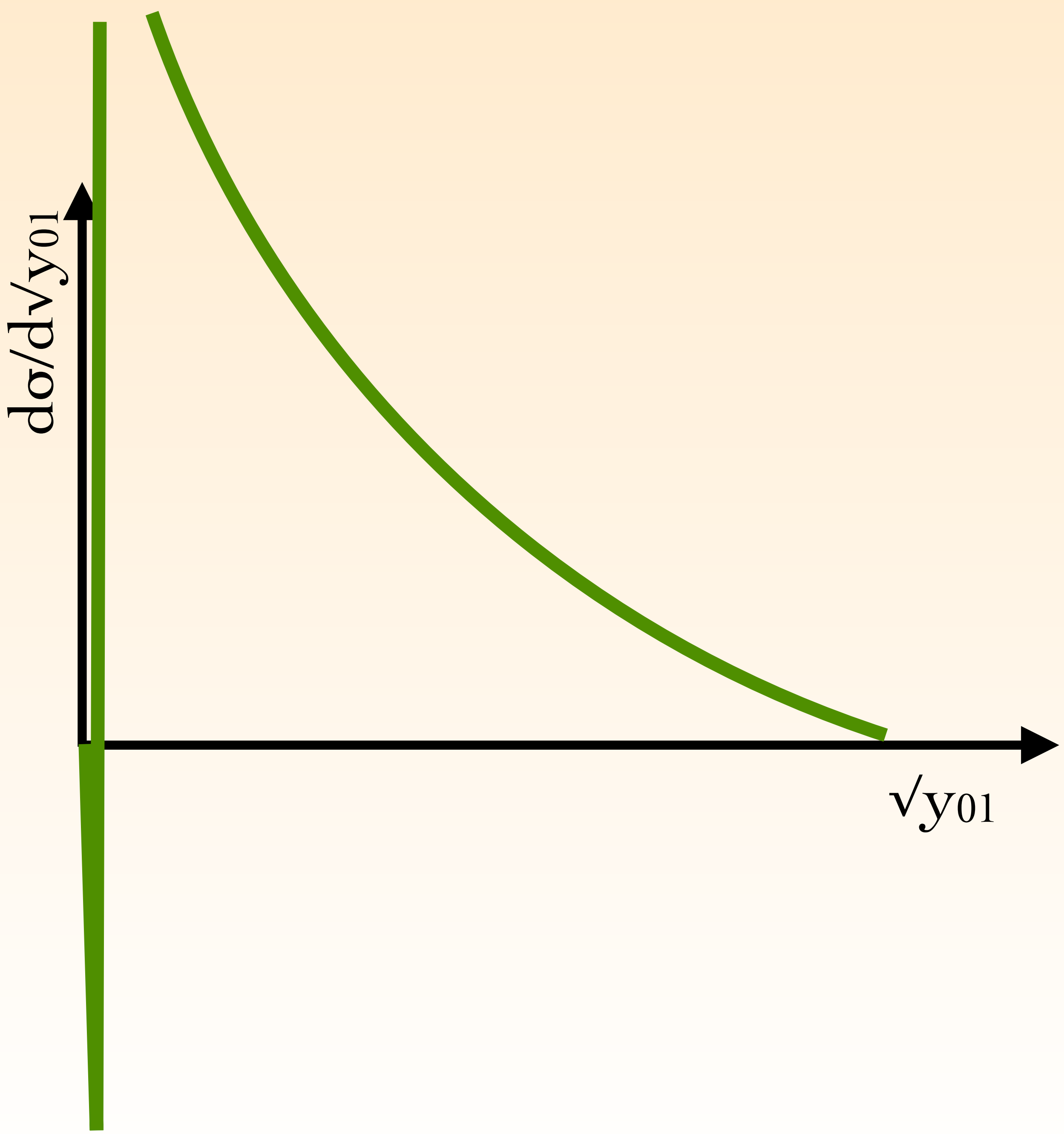
- Cannot be used to make reliable predictions at low p_T

Physical curve	Only at high-p_T
Tail	LO
Integral	∞
Extendible to multi-jet	Yes

Next-to-leading order V

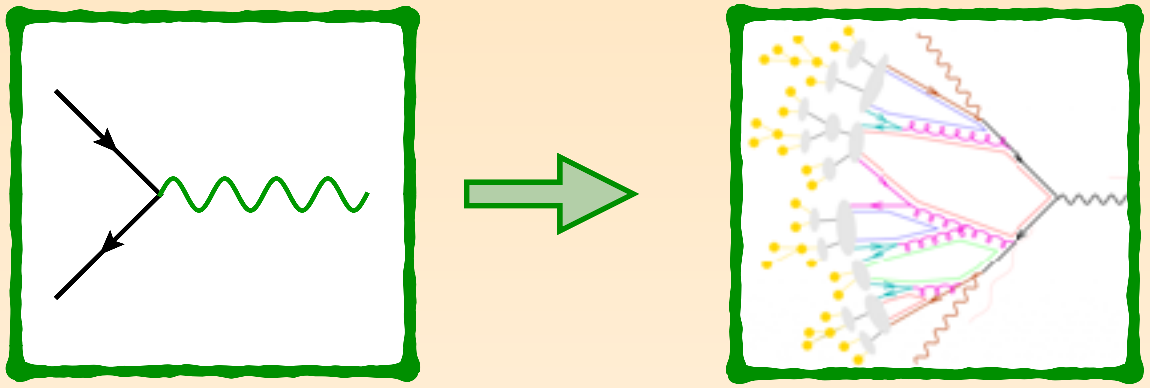


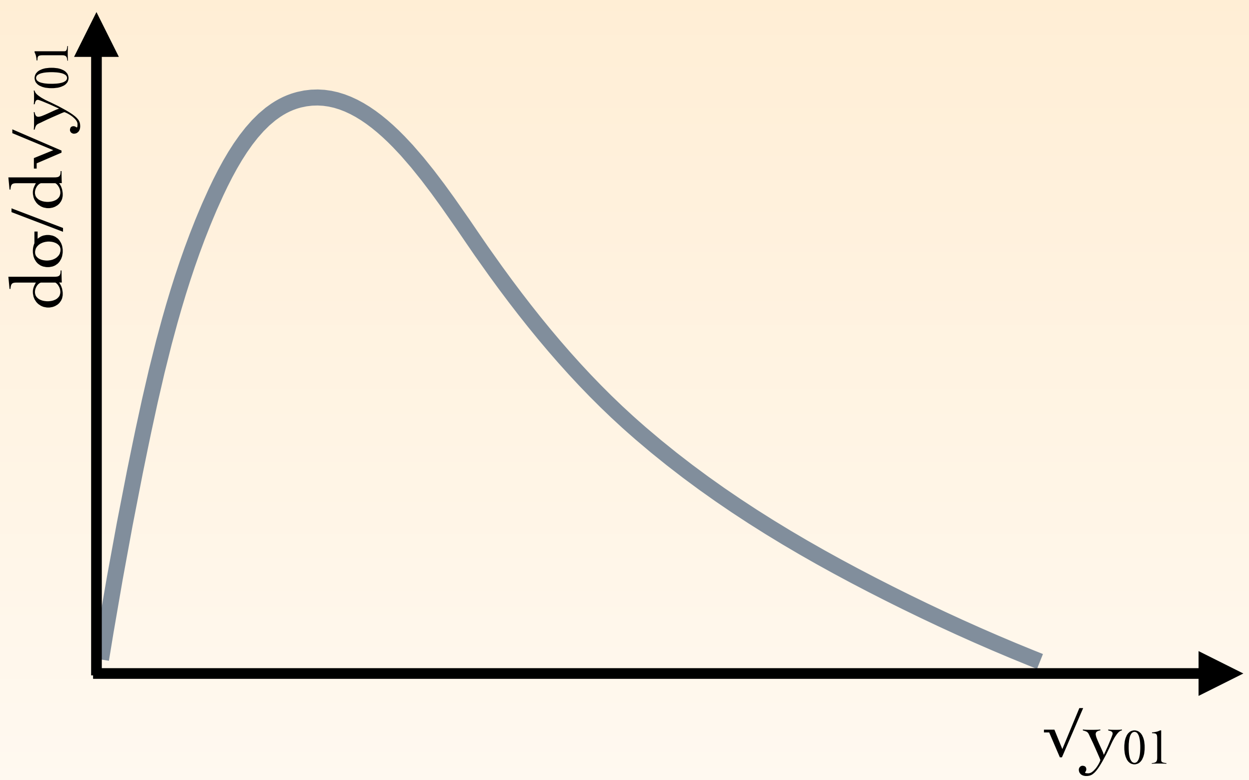


- Integral is NLO accurate
- Curve is non-physical at low p_T: divergent real-emission corrections are compensated for by divergent virtual corrections
- Including higher order corrections (NNLO, etc), does not fix the non-physical behaviour at small pT

Physical curve	Only at high-p_T
Tail	LO
Integral	NLO
Extendible to multi-jet	Yes

(N)LO+PS V



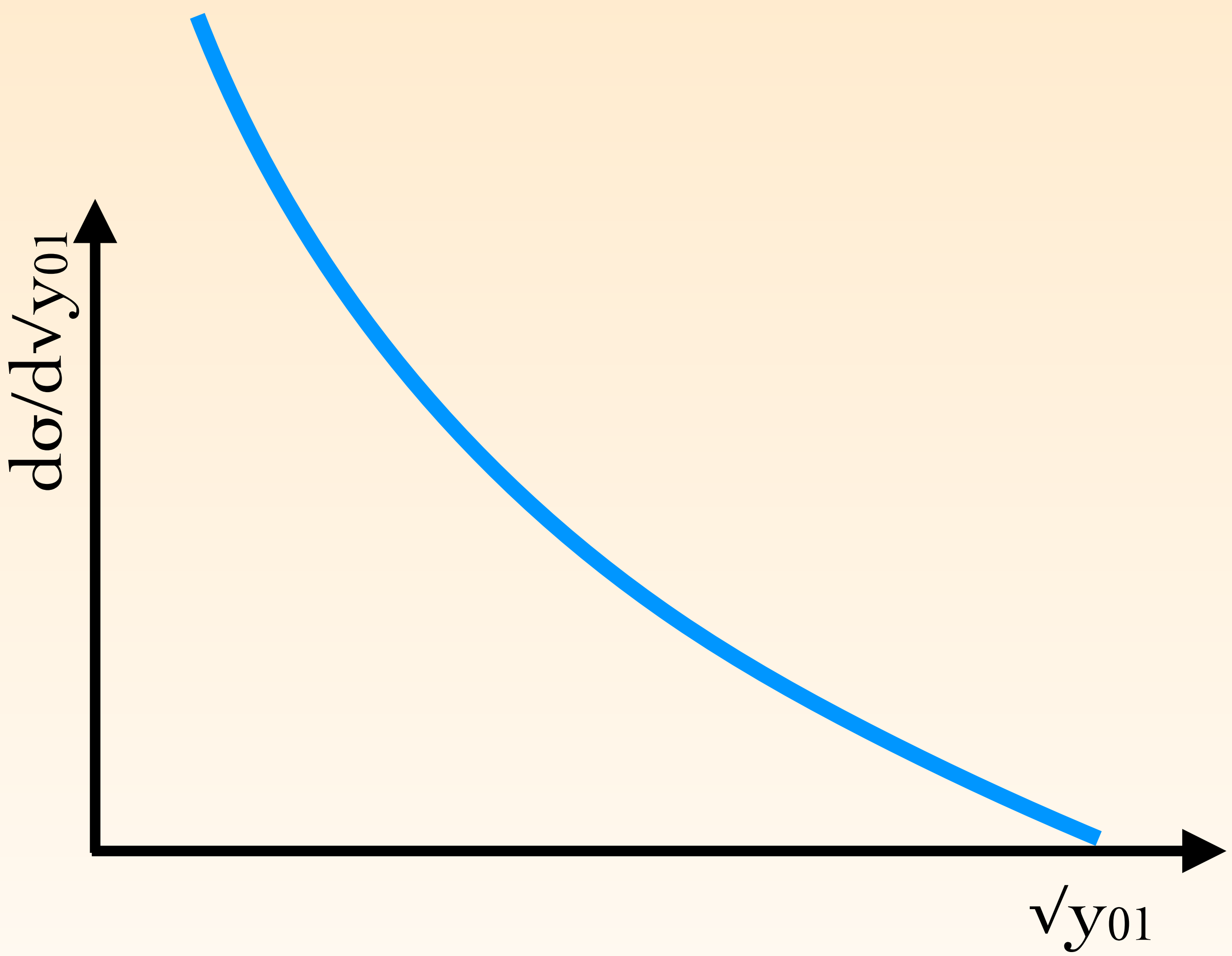


MC@NLO: [Frixione, Webber (2002)]
POWHEG: [Nason (2004)]

- To get a physical shape at low p_T need to resum radiation at all orders
- Can either be done analytically, or with a **parton shower**
- Parton shower also includes hadronisation and other non-factorisable corrections
- Most used methods at NLO are MC@NLO and POWHEG

Physical curve	**Yes**
Tail	**LO**
Integral	**NLO**
Extendible to multi-jet	**Yes**

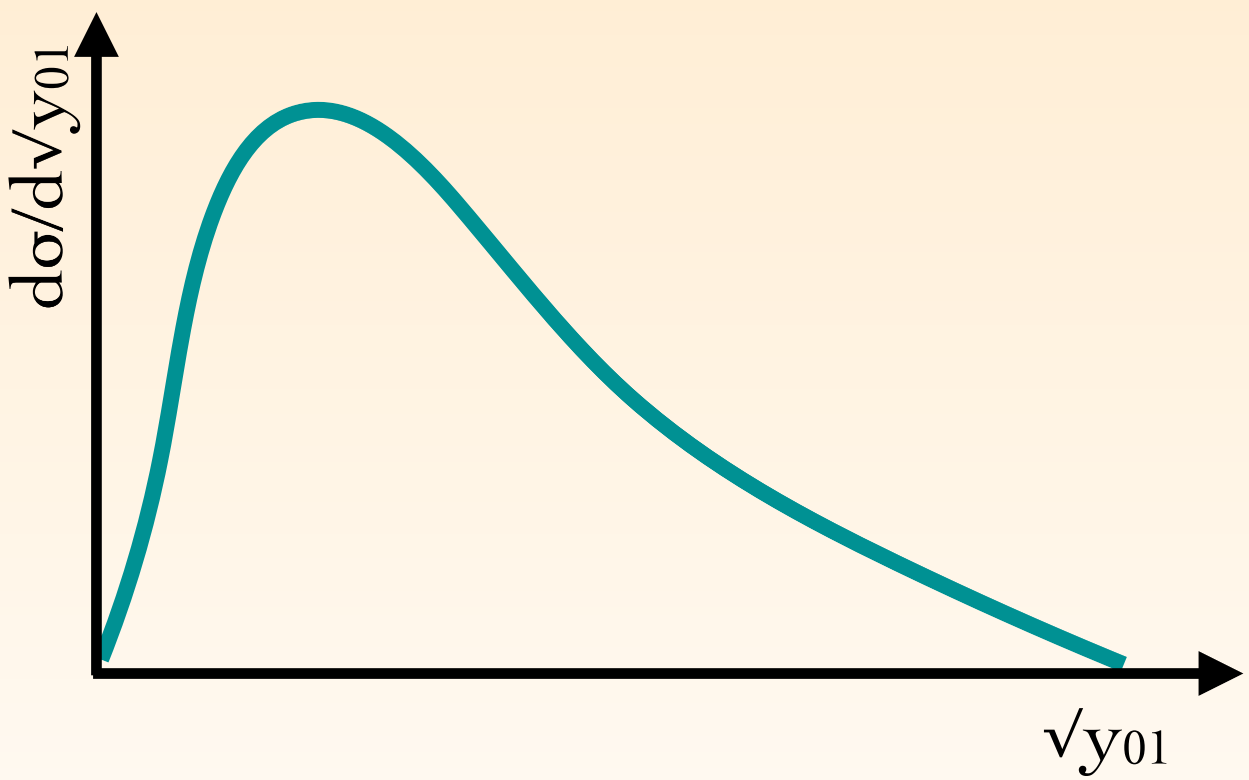
NLO(+PS) V+1 JET



- Distribution diverges at small p_T
- Have to put a generation cut
- Parton shower can easily be added, but this does not solve the low-p_T problem

Physical curve	Only at high-p_T
Tail	NLO
Integral	∞
Extendible to multi-jet	Yes

MINLO V+1JET



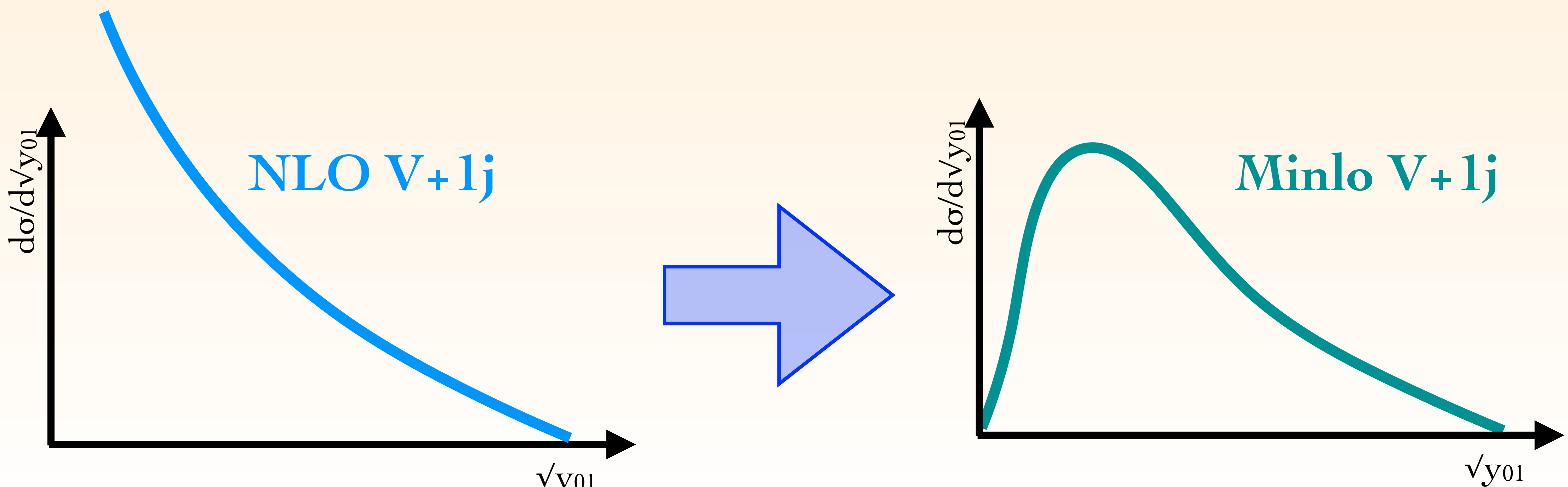
[Hamilton, Nason, Zanderighi (2012)]

- Include suitable Sudakov Form factors in the NLO V+1j predictions
- Distributions is NLO accurate
- Integral is not NLO accurate: the difference starts at $O(\alpha_s^{3/2})$
- Parton shower can easily be attached

Physical curve	Yes
Tail	NLO
Integral	LO+
Extendible to multi-jet	Yes

Minlo

- The Minlo approach can be summarised as follows:
  - Renormalisation and factorisation scale setting, a la CKKW
  - Together with matching to the Sudakov form factor, $\exp\Big[-R(v)\Big], \quad v = Q^2/y_{01}$
    - Matching requires to subtract the O(alpha_s) expansion of the Sudakov form factor times the Born to prevent double counting with the NLO corrections
  - NLO accuracy of V+1j observables is not hampered by the scale setting and inclusion of the form factor: differences are beyond NLO



MINLO

[Hamilton, Nason, Zanderighi (2012)]

✦ Start from a NLO calculation with one extra jet

1. Set μ_R everywhere it occurs and likewise for all μ_F set $\mu_F \to \mu_F \sqrt{v}$:

$$d\sigma \to d\sigma' = d\sigma \; (\mu_R = K_R \max(Q_{\mathcal{B}}, Q_{\mathcal{B}\mathrm{J}}),\; \mu_F \to K_F \sqrt{y}) \; . \tag{2.22}$$

2. Replace the additional power of $\bar{\alpha}_{\mathrm{S}}$ that accompanies the NLO corrections according to

$$d\sigma' \to d\sigma'' = d\sigma' \; \left(\bar{\alpha}_{\mathrm{S}}^{\mathrm{NLO}}\left(\mu_R^2\right) \to \bar{\alpha}_{\mathrm{S}}\left(K_R^2\, y\right)\right) \; . \tag{2.23}$$

3. Multiply the LO component by the $\mathcal{O}\left(\bar{\alpha}_{\mathrm{S}}\right)$ expansion of the inverse of the Sudakov form factor times $\bar{\alpha}_s\left(K_R^2\, y\right)/\bar{\alpha}_s\left(\mu_R^2\right)$:

$$d\sigma'' \to d\sigma''' = d\sigma'' - d\sigma''|_{\mathrm{LO}}\, \bar{\alpha}_{\mathrm{S}}\left(K_R^2\, y\right)\left(G_{12}L^2 + \left(G_{11} + 2S_1 + \bar{\beta}_0\right)L + 2\bar{\beta}_0 \ln \frac{\mu_R}{K_R\, Q}\right) \tag{2.24}$$

4. Multiply by the Sudakov form factor times $\bar{\alpha}_s\left(K_R^2\, y\right)/\bar{\alpha}_s\left(\mu_R^2\right)$:

$$d\sigma''' \to d\sigma_{\mathcal{M}} = \exp\left[-R\left(v\right)\right] \frac{\bar{\alpha}_s\left(K_R^2\, y\right)}{\bar{\alpha}_s\left(\mu_R^2\right)}\, d\sigma''' \, . \tag{2.25}$$

Minlo decomposed

$$d\sigma_{\mathcal{M}} = d\sigma_{\mathcal{R}} + d\sigma_{\mathcal{MR}} + d\sigma_{\mathcal{F}}$$

Resummed cross section. (Almost) identical to known LL/NNLL$_\sigma$ results

Logarithmically enhanced terms for y->0 that are not captured by dσ_R

Finite terms in the limit y->0 (coming from real emission corrections)

Resummed cross section

$d\sigma_{\mathcal{M}} = d\sigma_{\mathcal{R}} + d\sigma_{\mathcal{MR}} + d\sigma_{\mathcal{F}}$

Resummed cross section

$d\sigma_{\mathcal{M}} = d\sigma_{\mathcal{R}} + d\sigma_{\mathcal{MR}} + d\sigma_{\mathcal{F}}$

[Banfi, Salam, Zanderighi (2005); Dokshitzer, Diakonov, Troian (1980)]

$$\frac{d\sigma_{\mathcal{R}}}{d\Phi dL} = \frac{d\sigma_0}{d\Phi} \left[1 + \bar{\alpha}_S\left(\mu_R^2\right) \mathcal{H}_1\left(\mu_R^2\right)\right] \frac{d}{dL} \left[\exp\left[-R\left(v\right)\right] \mathcal{L}\left(\{x_\ell\}, \mu_F, v\right)\right]$$

LO cross section

(Hard) virtual contributions

Sudakov form factor

Luminosity factor

$L = \log(1/v) = \log(Q^2/y)$

- Well-known formula; used e.g. in the Caesar approach
  - Sudakov form factor exp[-R] not identical to what's (originally) used in Minlo. But Minlo approach can be improved to incorporate these terms (not relevant when colour is trivial)
- Written as **total derivative**: straight-forward to show that this is NLO correct in phase-space Φ up to $d\sigma_F$ after integration over L and expanding in α_S
- However, not NLO correct in the $d\Phi dL$ phase space (i.e., tail is not NLO correct)

Accuracy of Minlo

$$d\sigma_{\mathcal{M}} = d\sigma_{\mathcal{R}} + d\sigma_{\mathcal{MR}} + d\sigma_{\mathcal{F}}$$

- Explicit derivation, using the general form of the differential NLO V+1j cross sections in the small y limit,

$$\frac{d\sigma_{\mathcal{S}}}{d\Phi dL} = \frac{d\sigma_0}{d\Phi} \sum_{n=1}^{2} \sum_{m=0}^{2n-1} H_{nm} \bar{\alpha}_{\mathrm{S}}^{n} \left(\mu_R^2\right) L^m$$

gives

$$\frac{d\sigma_{\mathcal{MR}}}{d\Phi dL} = \frac{d\sigma_0}{d\Phi} \exp\left[-R\left(v\right)\right] \prod_{\ell=1}^{n_i} \frac{q^{(\ell)}\left(x_\ell, \mu_F^2 v\right)}{q^{(\ell)}\left(x_\ell, \mu_F^2\right)} \left[\bar{\alpha}_{\mathrm{S}}^2 \left(K_R^2 y\right) \left[\widetilde{R}_{21}\, L + \widetilde{R}_{20}\right] + \bar{\alpha}_s^3 \left(K_R^2 y\right) L^2 \widetilde{R}_{32}\right]$$

Only non-zero when exp[R] and Minlo Sudakov exponent are different, or when exp[R] is not NNLL$_\sigma$ accurate. Therefore, **assume that it is known**

Unknown coefficient!

Known coefficient

Minlo accuracy for (inclusive) 0-jet observables

$$d\sigma_{\mathcal{M}} = d\sigma_{\mathcal{R}} + d\sigma_{\mathcal{MR}} + d\sigma_{\mathcal{F}}$$

$$\int \frac{d}{dL'} \log^m \frac{Q^2}{y} \alpha_S^n(y) \exp\Big[- R(v)\Big] \approx \Big[\alpha_S(Q^2)\Big]^{n-\frac{m+1}{2}}$$

$$\frac{d\sigma_{\mathcal{MR}}}{d\Phi dL} = \frac{d\sigma_0}{d\Phi} \exp\left[-R\left(v\right)\right] \prod_{\ell=1}^{n_i} \frac{q^{(\ell)}\left(x_\ell, \mu_F^2 v\right)}{q^{(\ell)}\left(x_\ell, \mu_F^2\right)} \left[\bar{\alpha}_S^2\left(K_R^2 y\right)\left[\widetilde{R}_{21}\, L + \widetilde{R}_{20}\right] + \bar{\alpha}_s^3\left(K_R^2 y\right) L^2\, \widetilde{R}_{32}\right]$$

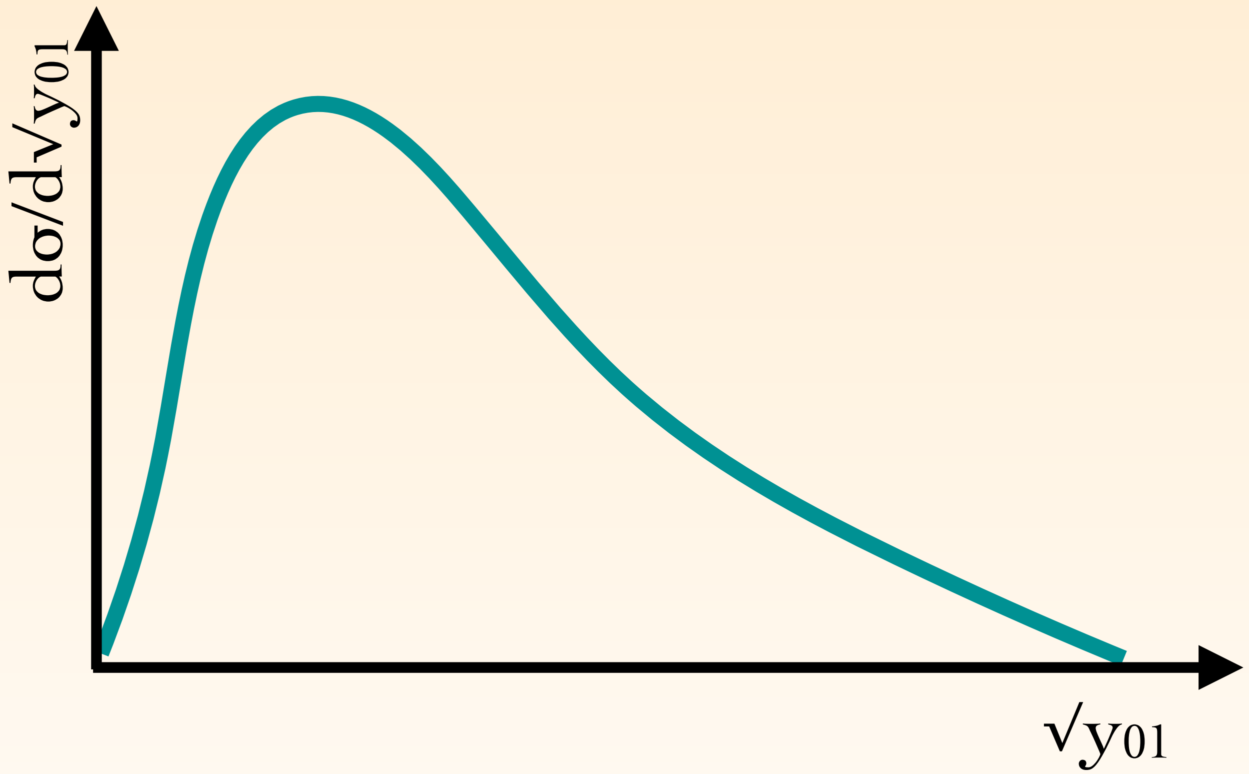
- After integration over the logarithm L (taking $R_{21}=0$, which is okay for the processes considered here) this results into terms of

$$\int dL' \, \frac{d\sigma_{\mathcal{MR}}}{d\Phi dL'} = -\frac{d\sigma_0}{d\Phi} \left[\widetilde{R}_{20} - \bar{\beta}_0 \mathcal{H}_1\left(\mu_R^2\right)\right] \sqrt{\frac{\pi}{2}} \frac{1}{\left|2G_{12}\right|^{1/2}} \bar{\alpha}_S^{3/2} \left(1 + \mathcal{O}\left(\sqrt{\bar{\alpha}_S}\right)\right)$$

- Hence, diff. 0-jet cross section is not NLO accurate with NLO-1jet Minlo

[Hamilton, Nason, Oleari, Zanderighi (2012); RF, Hamilton (2015)]

MINLO V+1JET

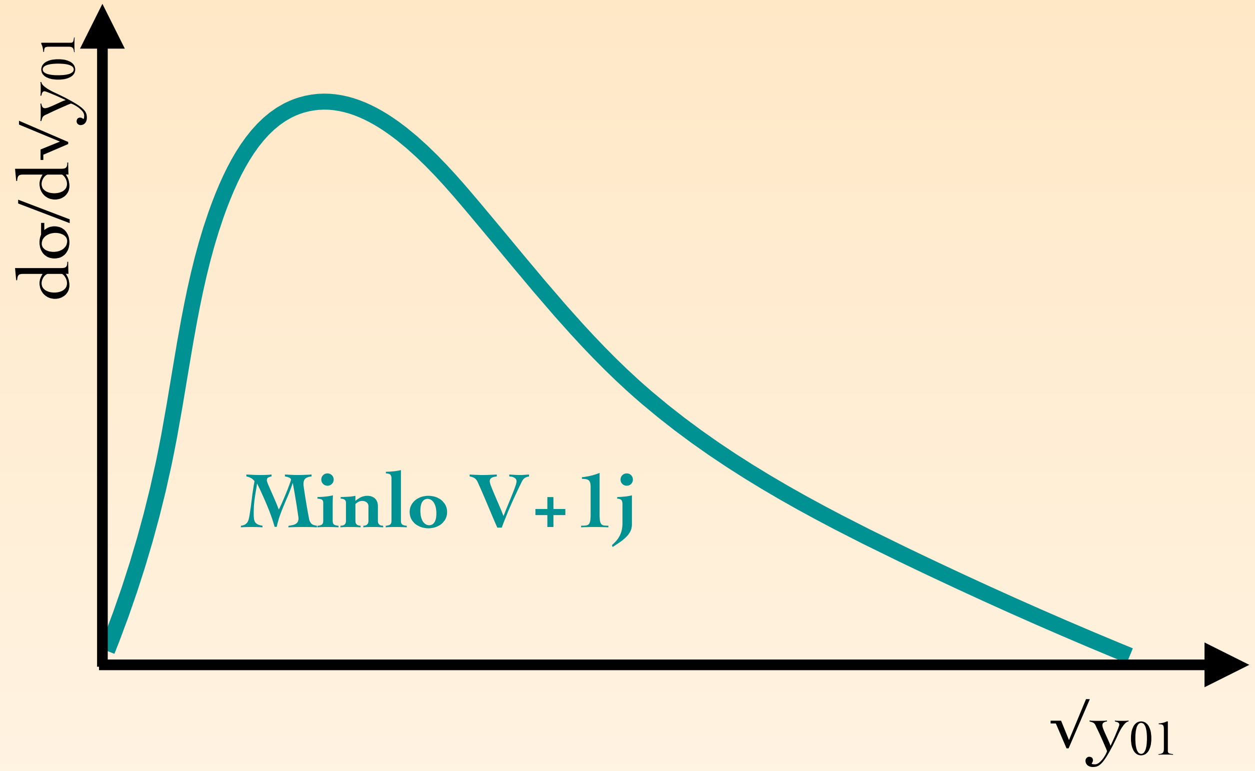


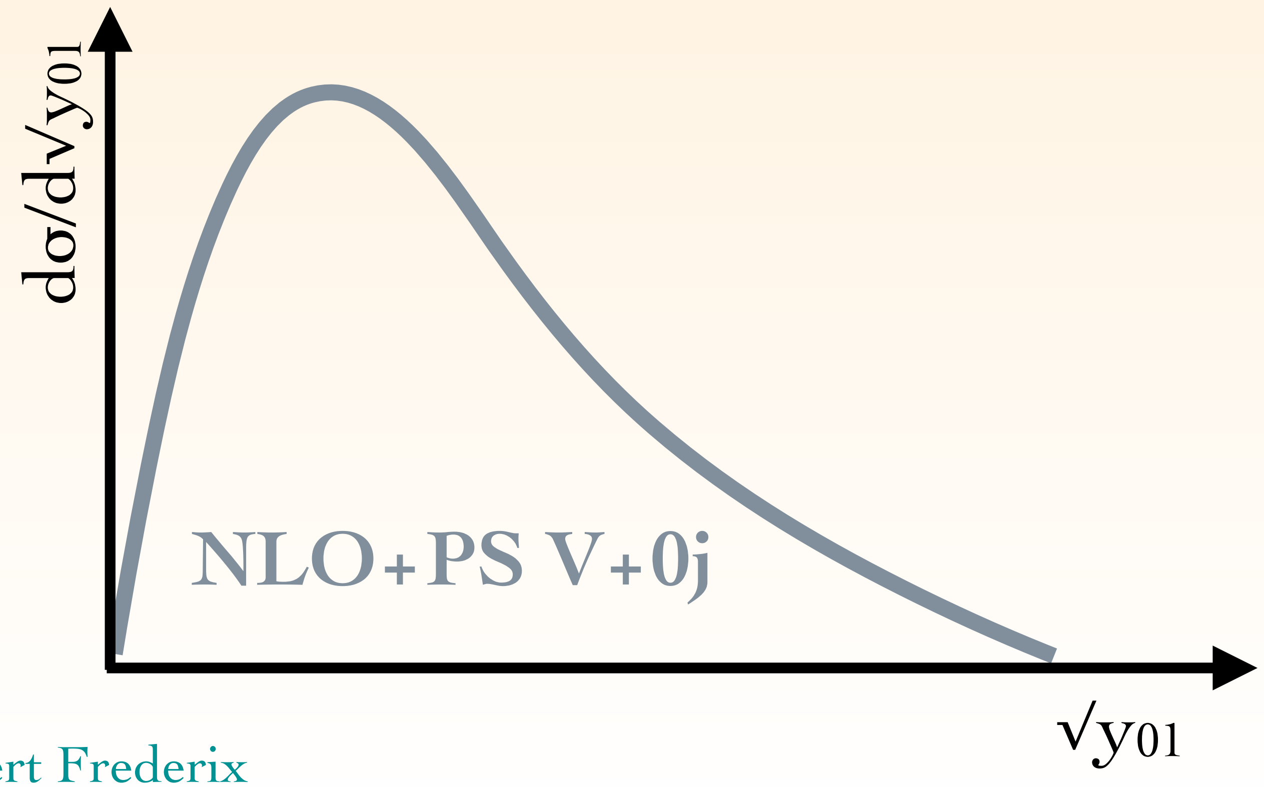
[Hamilton, Nason, Zanderighi (2012)]

- ✦ Include suitable Sudakov Form factors in the NLO V+1j predictions
- ✦ Distributions is NLO accurate
- ✦ Integral is not NLO accurate: the difference starts at $O(\alpha_s^{3/2})$
- ✦ Parton shower can easily be attached

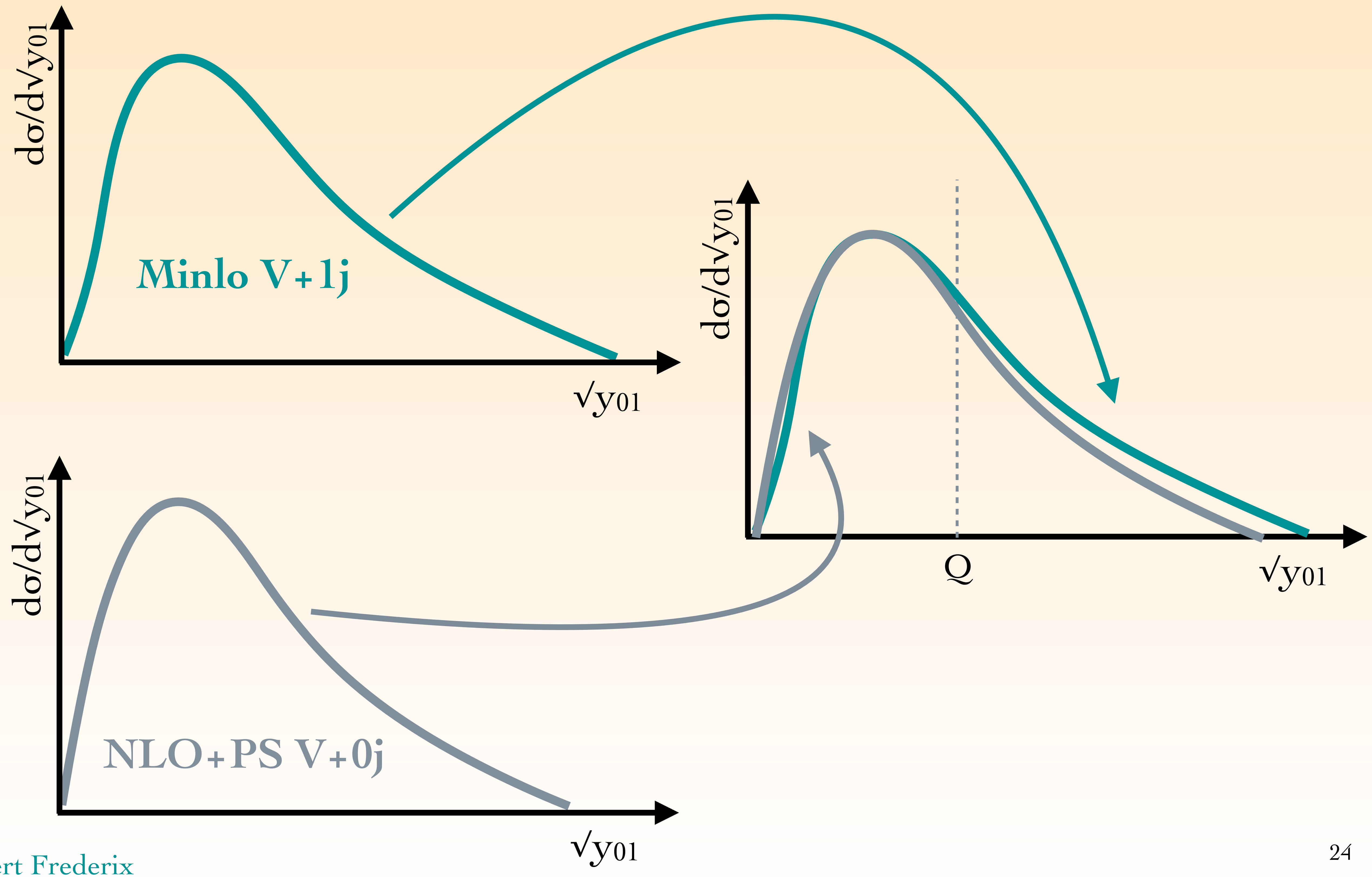
Physical curve	Yes
Tail	NLO
Integral	LO+
Extendible to multi-jet	Yes

Getting 0-jet observables NLO correct





Getting 0-jet observables NLO correct



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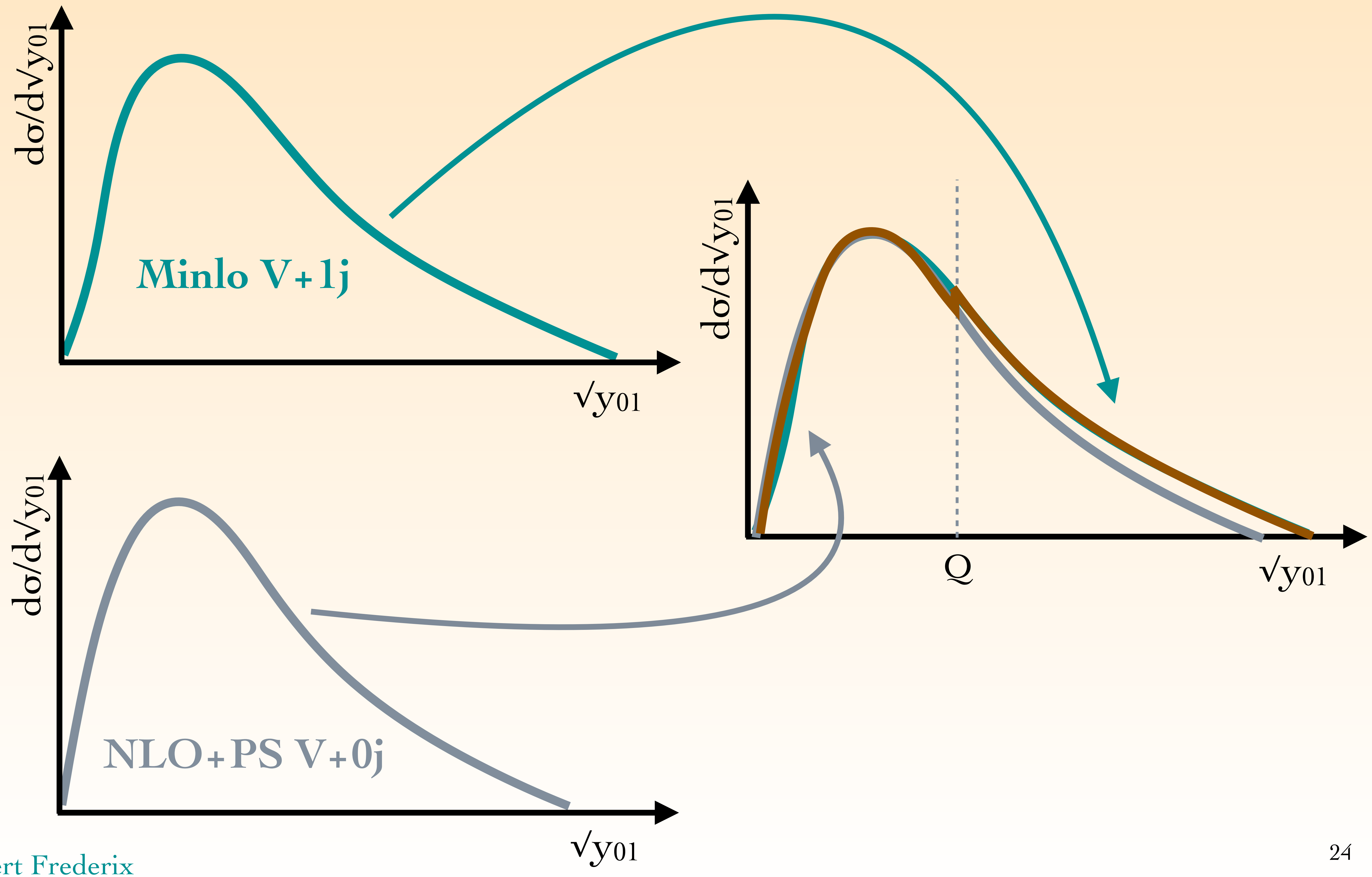
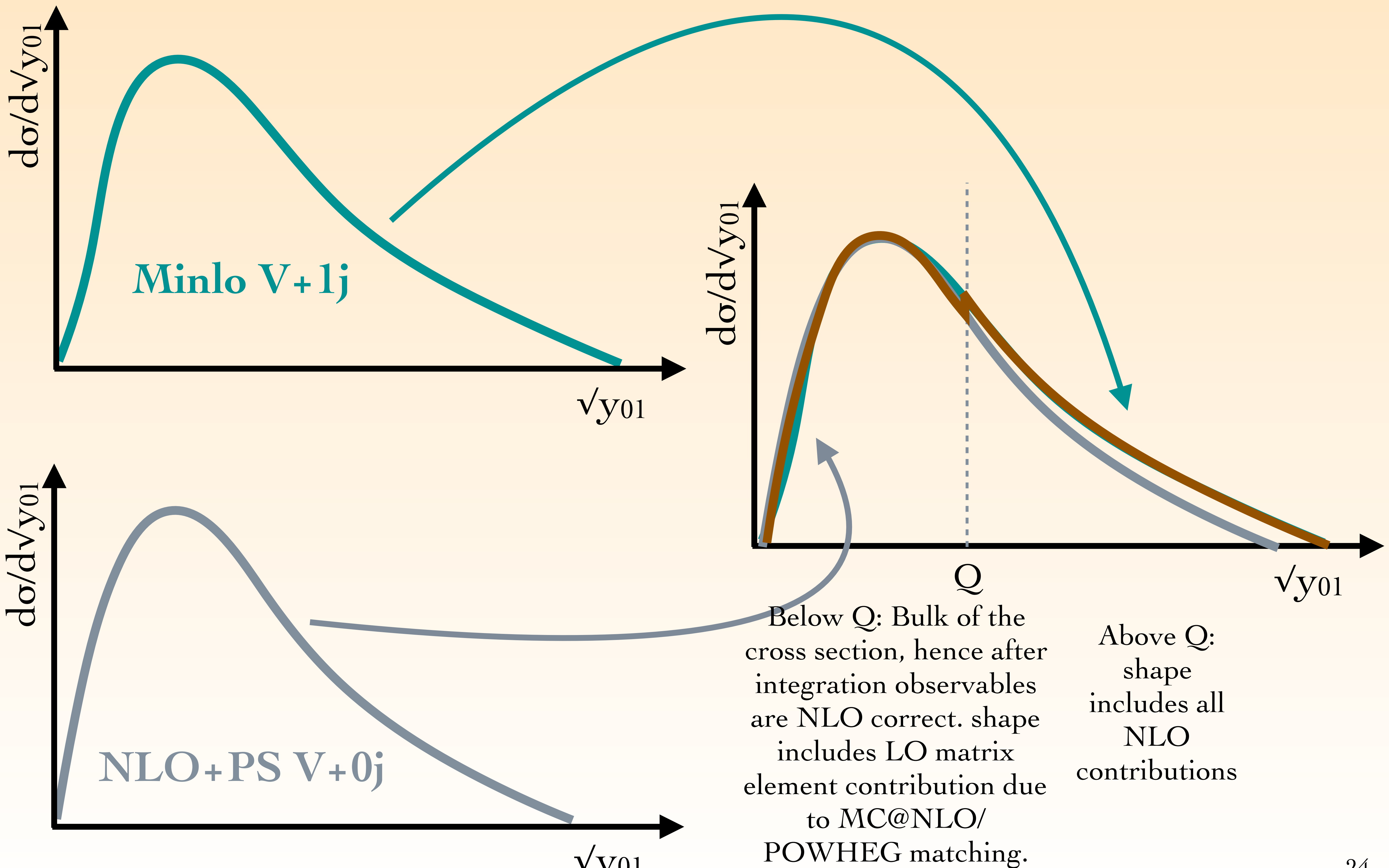


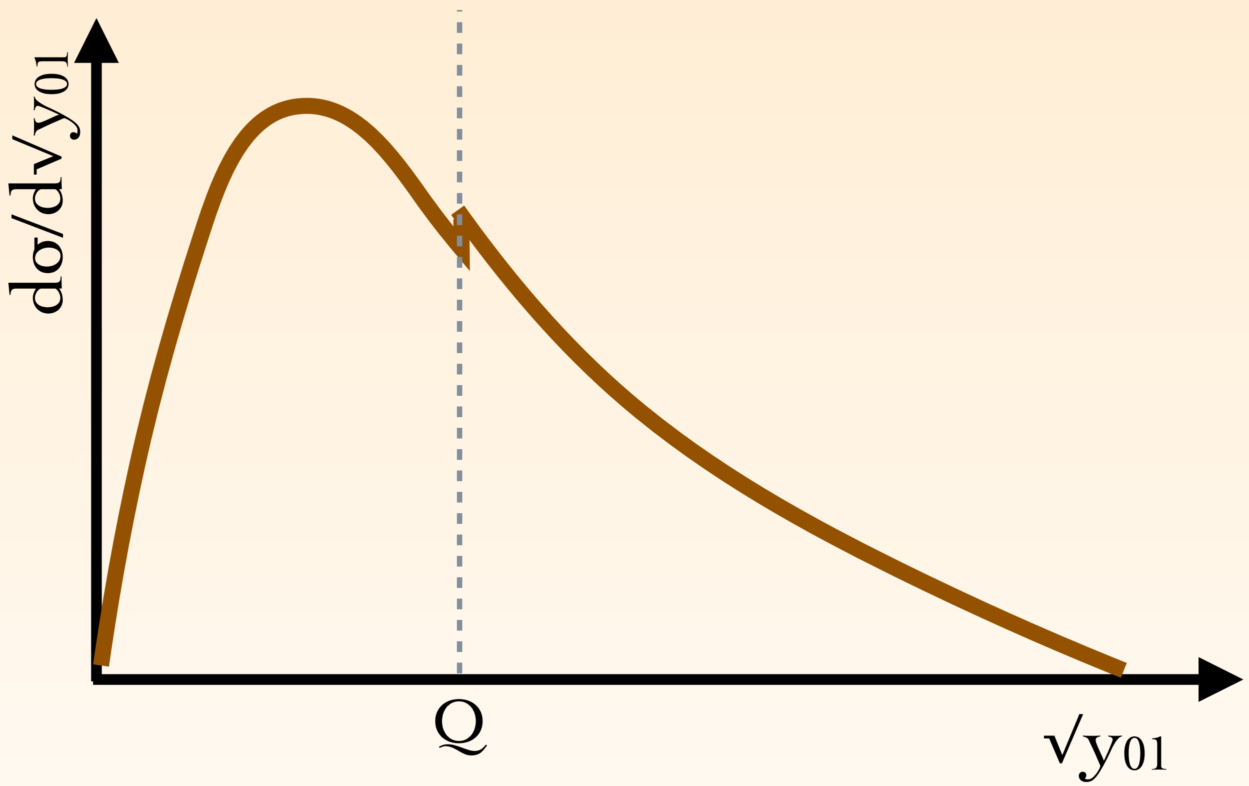
Getting 0-jet observables NLO correct



Below Q: Bulk of the cross section, hence after integration observables are NLO correct. shape includes LO matrix element contribution due to MC@NLO/ POWHEG matching.

Above Q: shape includes all NLO contributions

FxFx / Meps@nlo: V & V+1j merging



FxFx: [RF, Frixione (2012)]
MEPS@NLO: [Hoeche, Krauss, Schonherr, Siegert; +Gehrmann (2012)]

- Merge NLO+PS for V with Minlo for V+1j, at "merging scale" Q
- Above Q the tail is NLO accurate
- For not-too-small Q, integral is NLO accurate
- Used by ATLAS & CMS for LHC run II analyses
- Easily extendible to multi-jet

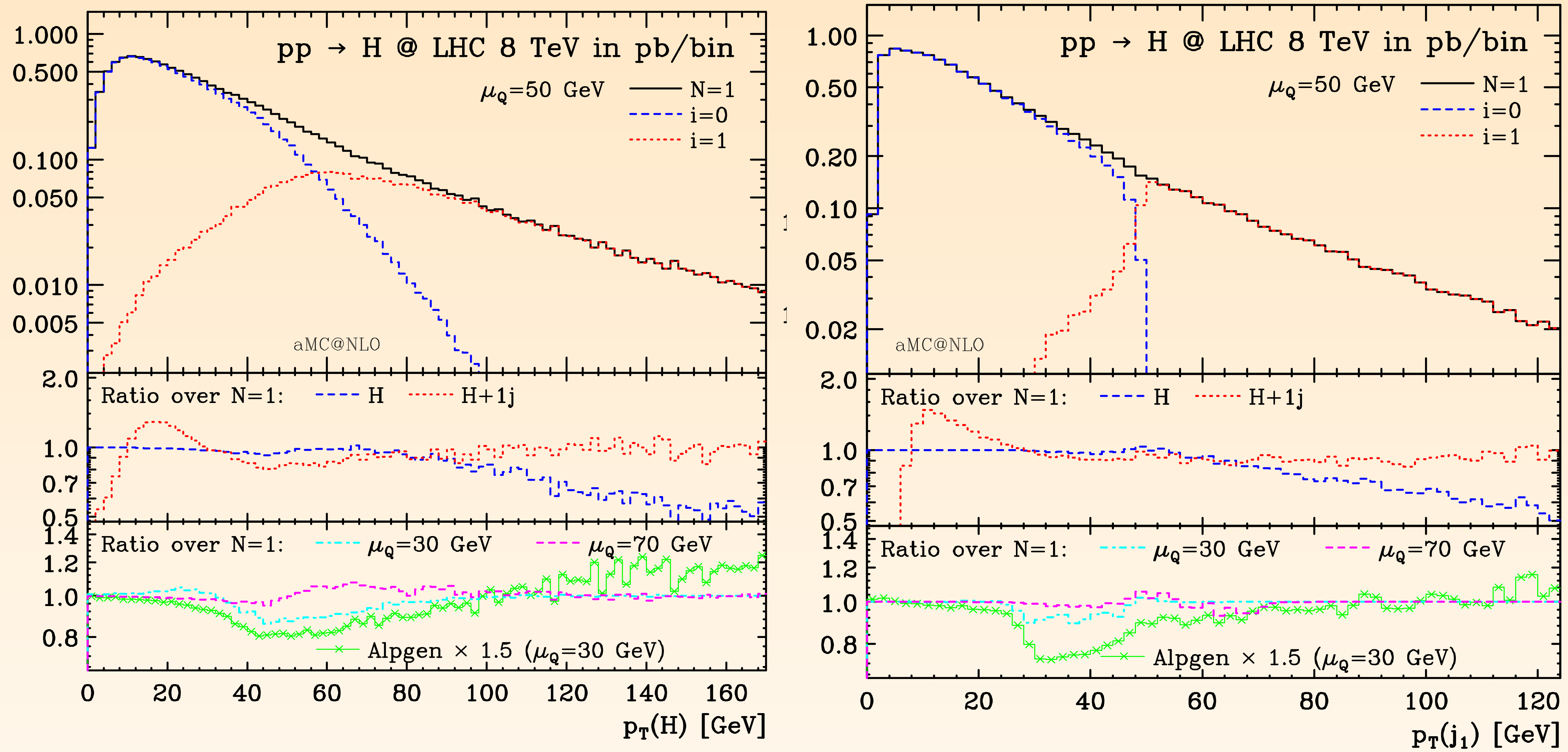
Physical curve	"Yes"
Tail	NLO
Integral	"NLO" (depending on Q)
Extendible to multi-jet	Yes

Differences between FxFx & MEPS@NLO

- Both FxFx and MEPS@NLO merging are based on making MC@NLO calculation for jet-multiplicities *exclusive* in more jets
  - Veto additional radiation; resum dependence on the veto scale (=merging scale)
- Major difference is in the way this exclusivity is applied
  - CKKW-L approach (i.e. Sudakov rejection based on shower kernels)
    - Used in Sherpa's "MEPS@NLO"
    - Using shower kernels prevents for a direct link with Minlo approach (and comparison to analytic resummation and accuracy), but prevents issues with mismatch in k_T and shower ordering values
  - Minlo (CKKW) from hard scale down to the scale of the softest jet not affected by veto; MLM-type rejection from there down to merging scale
    - Used in MadGraph5_aMC@NLO w/ Pythia/Herwig: "FxFx merging"
    - Direct link with Minlo, and MLM-type rejection prevents mismatches in ordering values.

FxFx merging: Higgs boson production

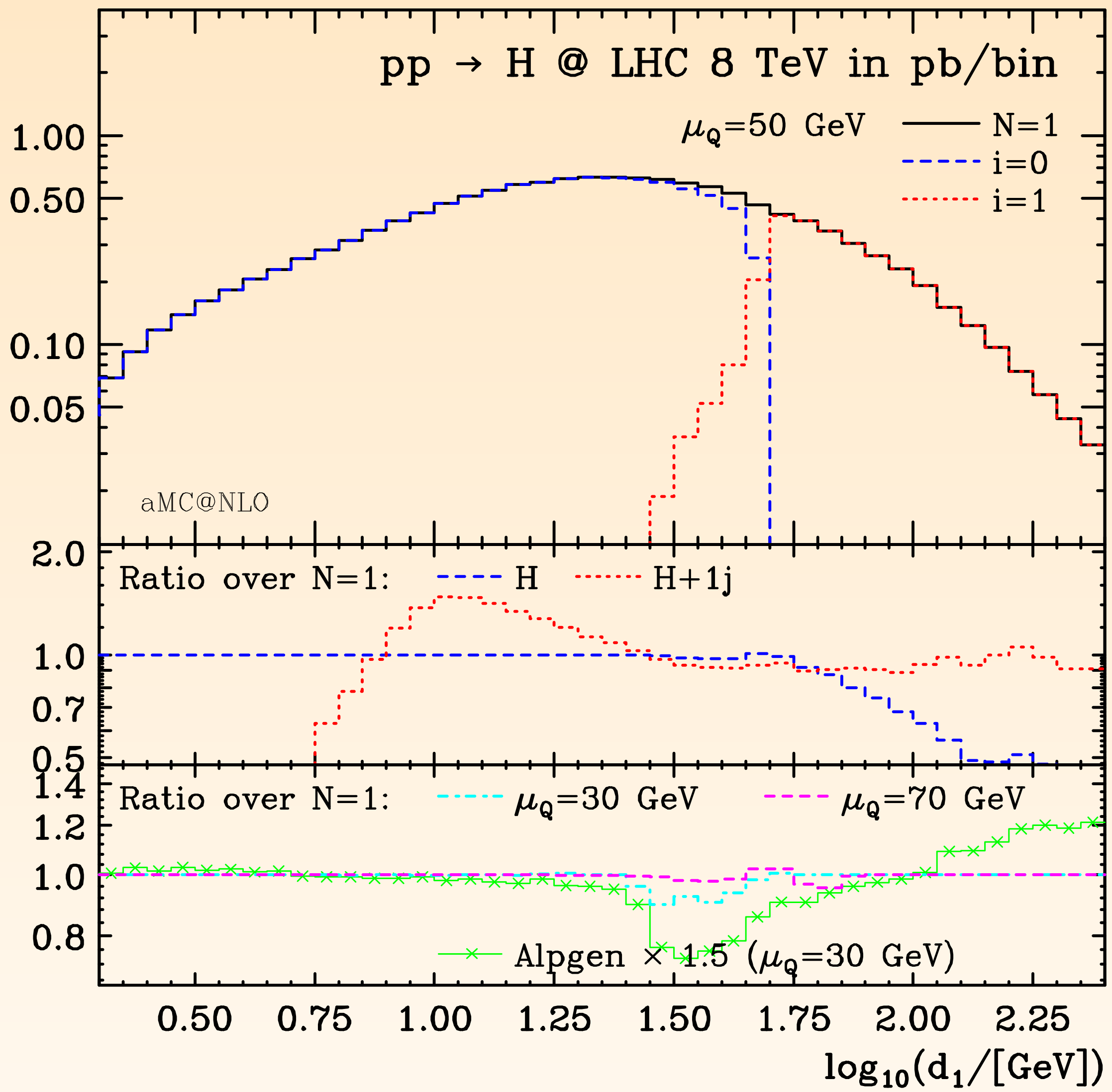
RF & Frixione, 2012

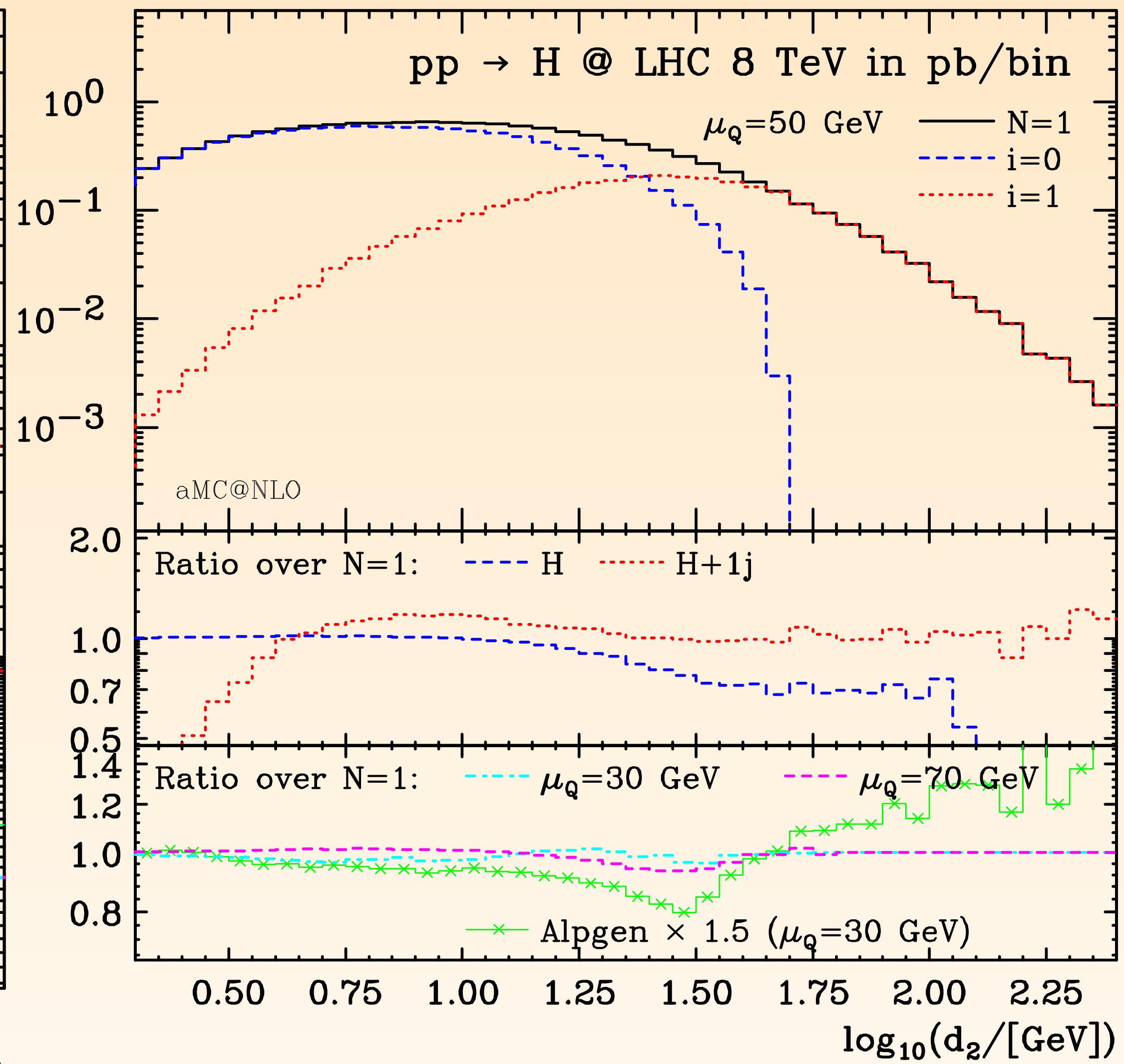


- Transverse momentum of the Higgs and of the 1st jet.
- Agreement with H+0j at MC@NLO and H+1j at MC@NLO in their respective regions of phase-space; Smooth matching in between; Small dependence on matching scale
- Alpgen (LO matching) shows larger kinks

FxFx merging: Higgs boson production

RF & Frixione, 2012

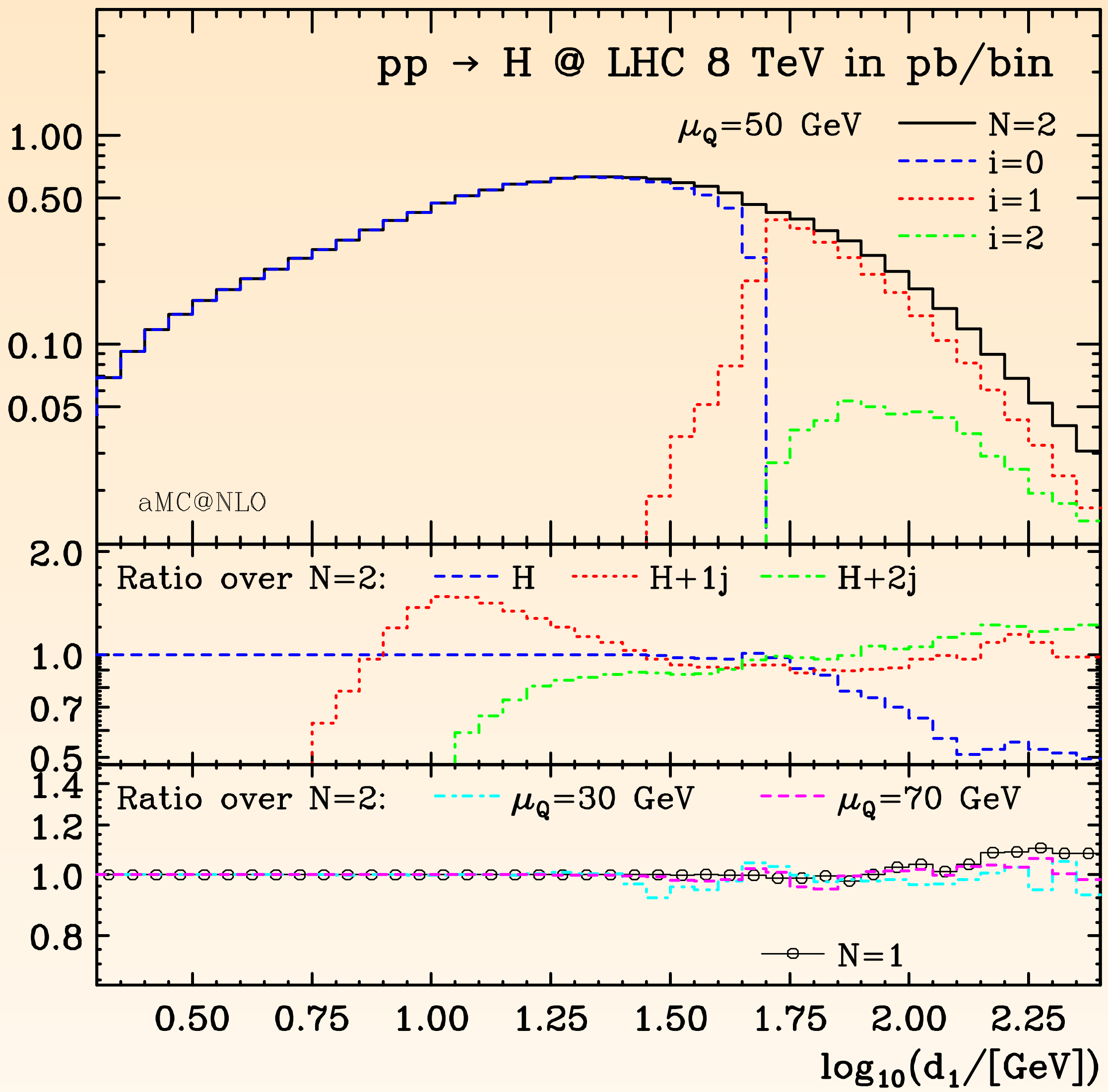


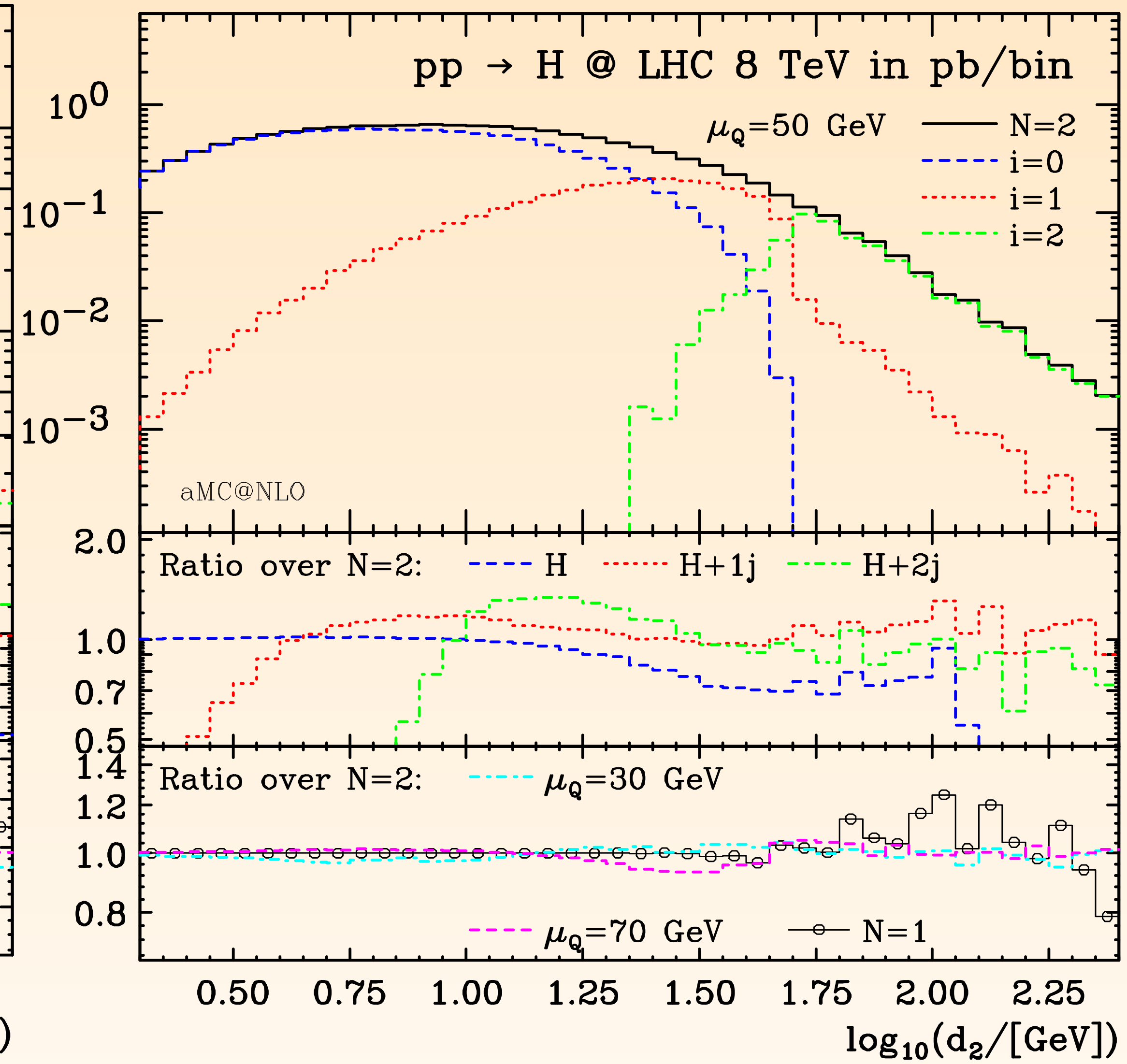


- ✦ Differential jet rates for 1->0 and 2->1

FxFx merging: Higgs boson production

RF & Frixione, 2012

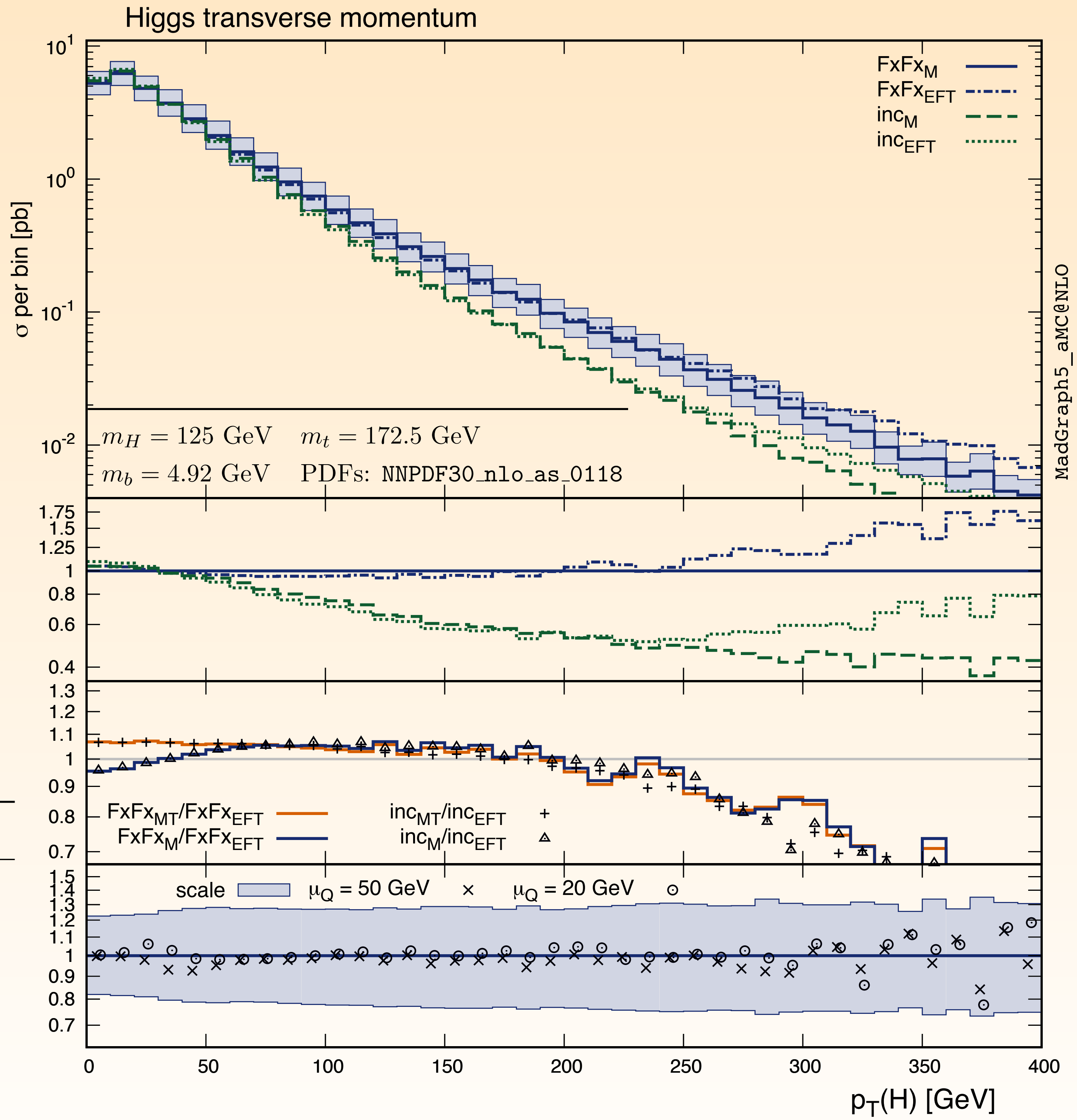




- Differential jet rates
- Matching up to 2 jets at NLO
- Results very much consistent with matching up to 1 jet at NLO

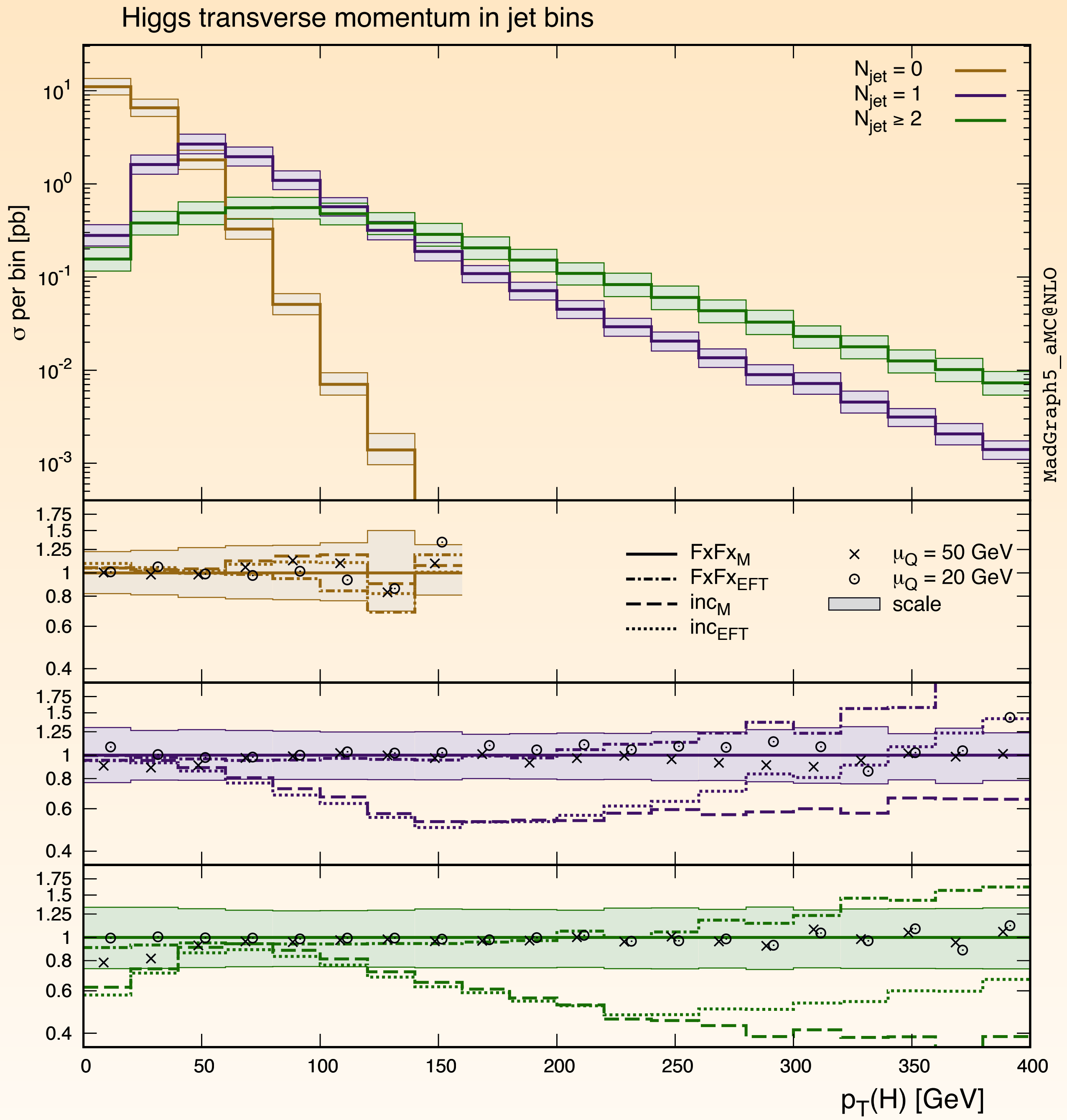
Mass effects

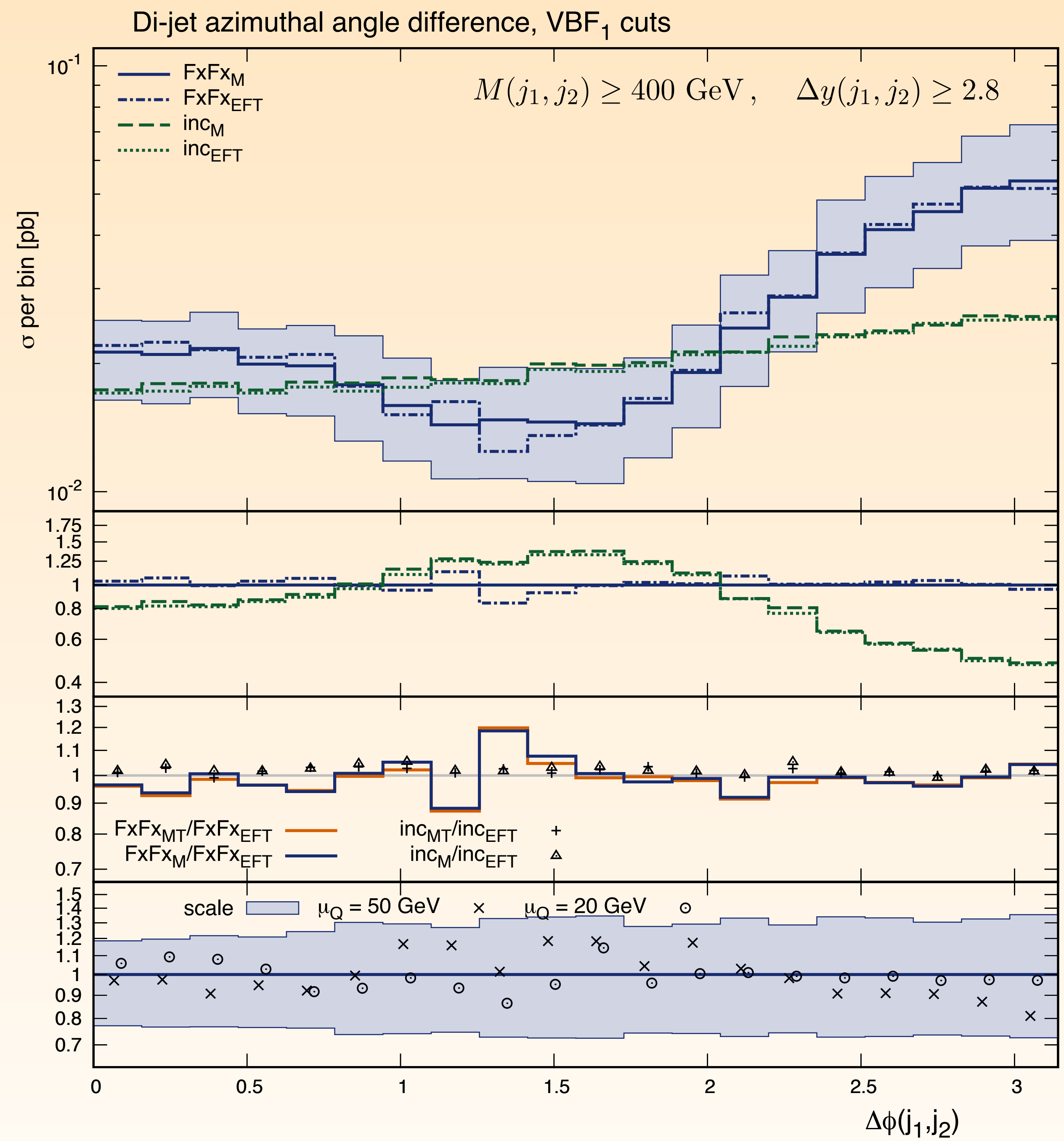
[RF, S. Frixione, E. Vryonidou, M. Wiesemann, 2016]



- ✦ Reweighting the EFT to include finite top (and bottom) quark mass effects, apart from the two-loop contributions to H+1j and H+2j NLO matrix elements
- ✦ Non-trivial effects in the Higgs boson transverse momentum

	FxFx$_M$	FxFx$_{EFT}$	inc$_M$	inc$_{EFT}$	σ_b
Total	$32.83^{+24.9\%+1.3\%}_{-19.5\%-2.6\%}$	$33.02^{+23.3\%+1.4\%}_{-18.8\%-2.4\%}$	$31.13^{+21.0\%}_{-18.2\%}$	$31.31^{+19.7\%}_{-17.6\%}$	$-2.05^{+2.9\%}_{-8.9\%}$
$N_{jet}=0$	$19.75^{+23.6\%+2.4\%}_{-18.7\%-0.5\%}$	$20.37^{+21.8\%+2.3\%}_{-18.0\%-0.3\%}$	$20.65^{+20.1\%}_{-18.0\%}$	$21.20^{+18.8\%}_{-17.3\%}$	$-1.97^{+5.7\%}_{-11.1\%}$
$N_{jet}=1$	$9.011^{+26.4\%+0.0\%}_{-20.5\%-5.8\%}$	$8.715^{+25.2\%+0.0\%}_{-19.9\%-6.1\%}$	$7.397^{+22.0\%}_{-18.6\%}$	$7.136^{+21.1\%}_{-18.0\%}$	$-0.10^{+27\%}_{-77\%}$
$N_{jet}\geq 2$	$4.061^{+30.4\%+0.0\%}_{-25.0\%-5.7\%}$	$3.935^{+29.7\%+0.0\%}_{-24.8\%-5.7\%}$	$3.083^{+31.9\%}_{-21.7\%}$	$2.972^{+32.1\%}_{-21.8\%}$	0
VBF$_1$	$0.512^{+29.6\%+0.0\%}_{-26.0\%-3.8\%}$	$0.518^{+29.8\%+0.0\%}_{-25.9\%-5.1\%}$	$0.411^{+32.7\%}_{-22.0\%}$	$0.402^{+32.7\%}_{-22.0\%}$	0
VBF$_2$	$0.214^{+29.0\%+0.0\%}_{-26.4\%-2.3\%}$	$0.221^{+30.5\%+0.4\%}_{-26.7\%-5.0\%}$	$0.191^{+32.5\%}_{-21.7\%}$	$0.184^{+32.3\%}_{-21.6\%}$	0





[RF, S. Frixione, E. Vryonidou, M. Wiesemann, 2016]

Multi-jet production in association with an EW boson

[RF, Frixione, Papaefstathiou, Prestel, Torrielli, 2016]

- FxFx merging for W and Z plus up to 2 jets at NLO for LHC 7 TeV

	$\mu_Q = 15$ GeV	$\mu_Q = 25$ GeV	$\mu_Q = 45$ GeV	inclusive	
Z+jets	2.055(−0.9%)	2.074	2.085(+0.5%)	2.012(−3.0%)	HW++
	2.168(+0.8%)	2.150	2.117(−1.5%)	2.011(−6.5%)	PY8
W+jets	20.60(−0.9%)	20.78	20.87(+0.4%)	19.96(−3.9%)	HW++
	21.71(+1.0%)	21.50	21.18(−1.5%)	19.97(−7.1%)	PY8

- FxFx Merged results close to the NLO inclusive cross sections
- Order 1% dependence on the merging scale for total rates
  - slightly smaller for HW++ than for PY8
- Slightly larger cross section for PY8 than for HW++

- For comparisons to data (next slides) no normalisation factors applied: the normalisation of the predictions is as they come out of the code