pp→$t\bar{t}\gamma\gamma$ 23 years after

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in collaboration with
A. Kardos

Zoltan 70, Zürich
May 23, 2014

NEW SZÉCHENYI PLAN

LHCphenOnet

Outline

- Motivation
- Method
- Predictions
- Conclusions

Motivation

First visit to ETH

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- Zoltan's excitement about a clear signal of observing a Higgs-boson of intermediate mass ($70 < m_H\, c^2/\mathrm{GeV} < 140$)
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- … actually achieved by ATLAS and CMS

First visit to ETH

Physics Letters B 271 (1991) 247–255
North-Holland

PHYSICS LETTERS B

Clear signal of intermediate mass Higgs boson production at LHC and SSC

Z. Kunszt, Z. Trócsányi [1]
Theoretical Physics, ETH, CH-8093 Zurich, Switzerland

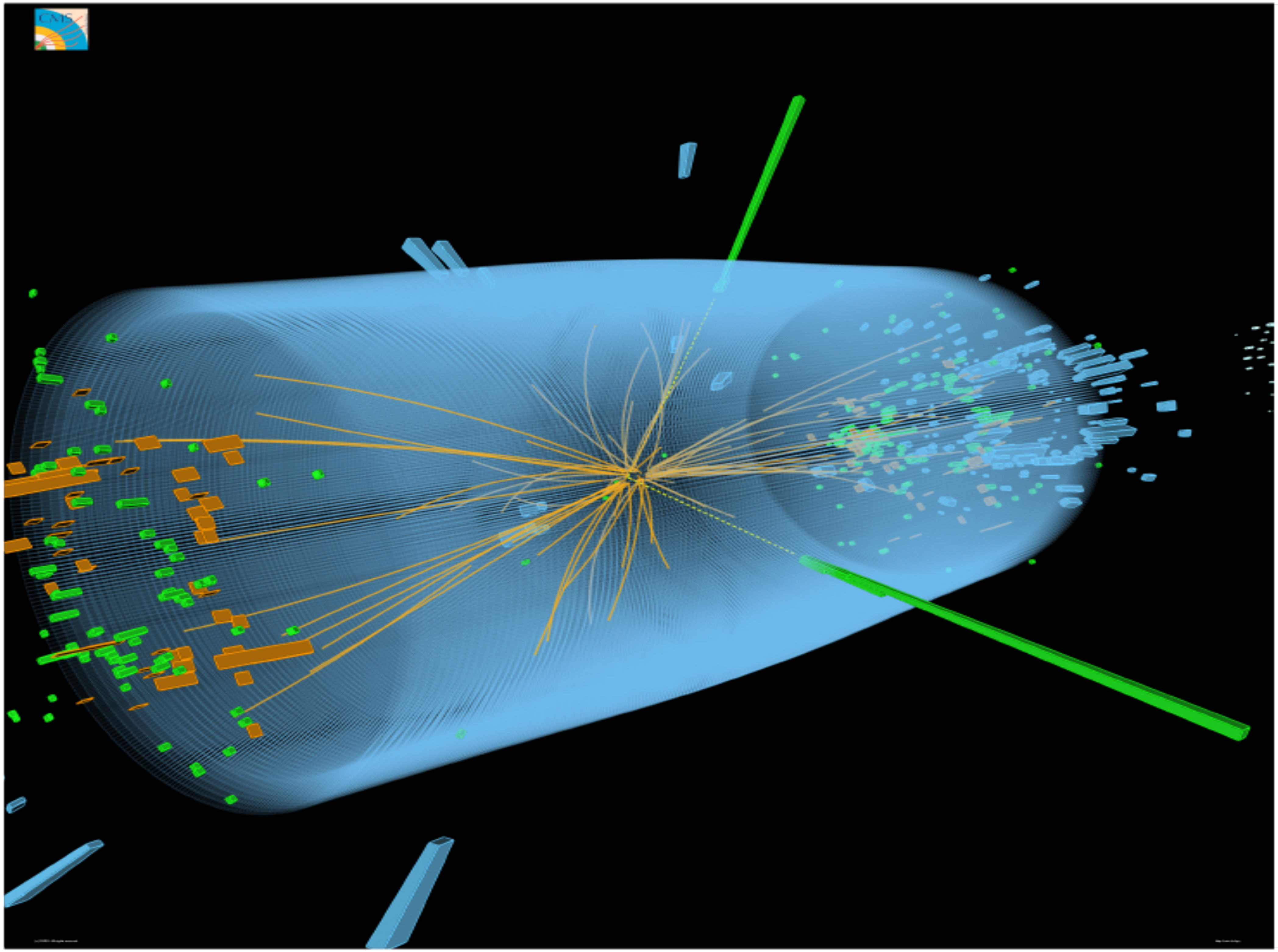
and

W.J. Stirling
Departments of Physics and Mathematical Sciences, University of Durham, Durham DH1 3LE, UK

Received 11 July 1991

We compute the event rates for two potentially important background processes $pp \to t\bar{t}\gamma\gamma X$ and $pp \to b\bar{b}\gamma\gamma X$ to the recently proposed signature for Higgs production of one isolated lepton and two isolated photons in the intermediate-mass range. We find that the background can be suppressed assuming good ($\approx (2-3)\%$) mass resolution in the invariant mass of the two photons, and assuming that the isolation criteria for the lepton and photons can be efficiently implemented experimentally. We reanalyse the signal to background ratios using realistic experimental cuts and find that by measuring the inclusive production of one isolated lepton and two isolated photons at the LHC or the SSC we can obtain a clear experimental signal for the production of the Higgs boson in the mass region $70 < M_H < 140$ GeV.

Higgs boson has been discovered



Higgs boson has been discovered

- m_H [GeV]=125.5±0.2$_{stat}$±0.6$_{syst}$ (ATLAS 2013)
  125.7±0.3$_{stat}$±0.3$_{syst}$ (CMS 2013)

- All measured properties are consistent with SM expectations within experimental uncertainties
  - branching ratios as predicted
  - spin zero
  - parity +
  - couples to masses of W and Z (with c_V=1 within experimental uncertainty)

t-quark: potential tool for discovery

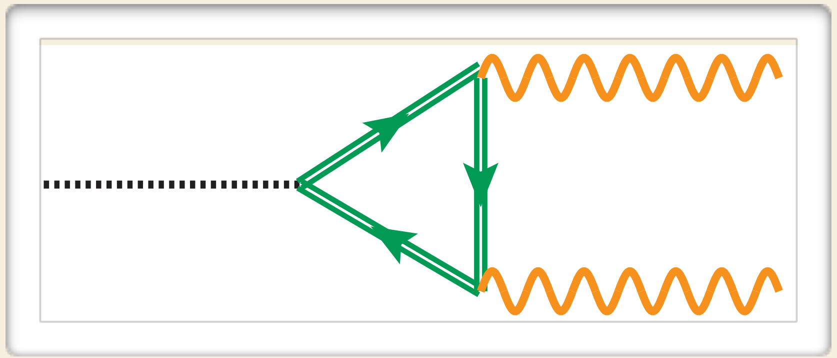
- The t-quark is heavy, Yukawa coupling ~1
  m_t [GeV]=173.34±0.64 (LHC+TeVatron, 2014)
  ($\Rightarrow y_t$=0.997±0.003)

  $\Rightarrow$ plays important role in Higgs physics
  (more tantalizing: $m_t\, m_Z = (125.7\pm0.3)^2$ GeV^2)
- y_t cannot be measured in $H \to t\bar{t}$ decay ($m_t > m_H$)

How to measure y_t?

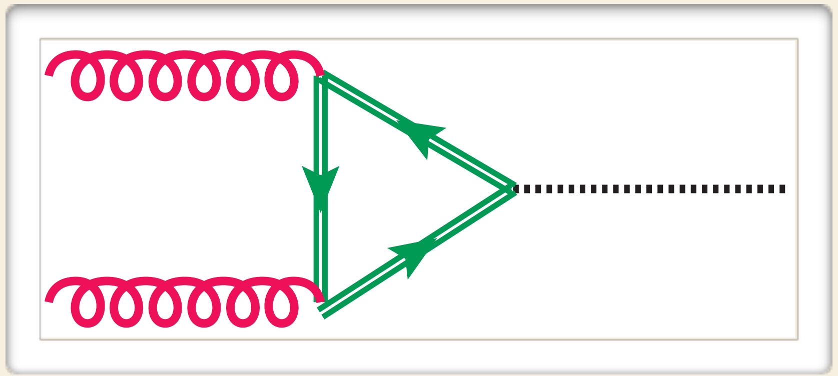
- $H \to \gamma\gamma$ is sensitive to y_t through t-quark loop,

  but rates are small and W loop also contributes



- $gg \to H$ is sensitive to y_t through t-quark loop

  if only SM model particles contribute (so far xsec is consistent with SM)

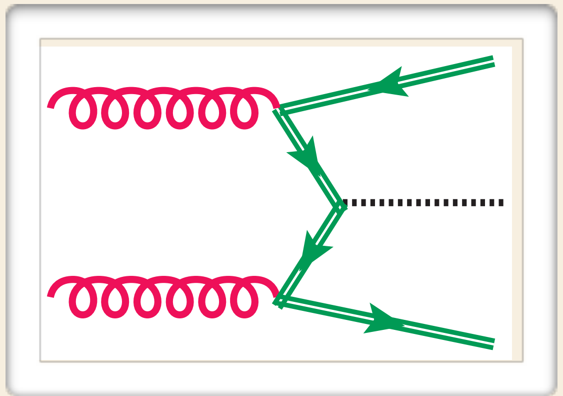


- $gg \to H$ is sensitive to BSM physics

  if y_t is measured separately

tTH hadroproduction

- y_t can be measured in pp $\to$ tTH through many decay channels (all very difficult):



  - hadrons with single lepton: $\mathrm{t} \to \mathrm{b}\ell\nu,\ \bar{\mathrm{t}} \to \bar{\mathrm{b}}jj,\ \mathrm{H} \to \mathrm{b}\bar{\mathrm{b}}$
  - hadrons with dilepton: $\mathrm{t} \to \mathrm{b}\ell\nu,\ \bar{\mathrm{t}} \to \bar{\mathrm{b}}\ell\nu,\ \mathrm{H} \to \mathrm{b}\bar{\mathrm{b}}$
  - hadrons with hadronic tau: $\mathrm{t} \to \mathrm{b}\ell\nu,\ \bar{\mathrm{t}} \to \bar{\mathrm{b}}jj,\ \mathrm{H} \to \tau_h^+\tau_h^-$
  - diphoton with lepton: $\mathrm{t} \to \mathrm{b}\ell\nu,\ \bar{\mathrm{t}} \to \bar{\mathrm{b}}jj,\ \mathrm{H} \to \gamma\gamma$
  - diphoton with hadrons: $\mathrm{t} \to \mathrm{b}\ jj,\ \bar{\mathrm{t}} \to \bar{\mathrm{b}}jj,\ \mathrm{H} \to \gamma\gamma$
  - same sign dilepton: $\mathrm{t} \to \mathrm{b}\ jj,\ \bar{\mathrm{t}} \to \bar{\mathrm{b}}jj,\ \mathrm{H} \to \ell\nu\ell[\nu]$
  - 3 leptons with di, trilepton: $\mathrm{t} \to \mathrm{b}\ell\nu,\ \bar{\mathrm{t}} \to \bar{\mathrm{b}}jj,\ \mathrm{H} \to \ell[\nu]\ell[\nu]$
  - 4 lepton with di, trilepton: $\mathrm{t} \to \mathrm{b}\ell\nu,\ \bar{\mathrm{t}} \to \bar{\mathrm{b}}\ell[\nu],\ \mathrm{H} \to \ell[\nu]\ell[\nu]$

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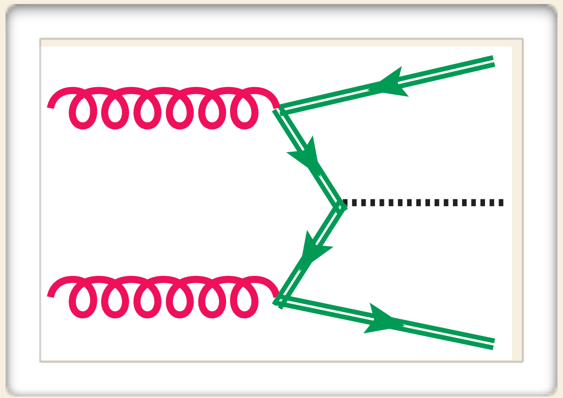

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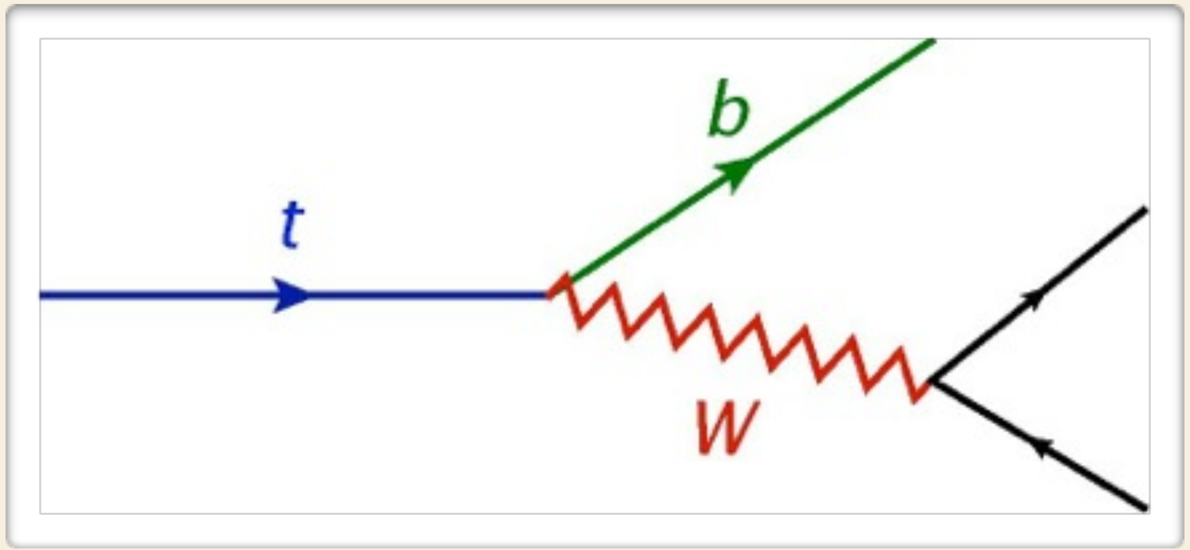
The importance of being top

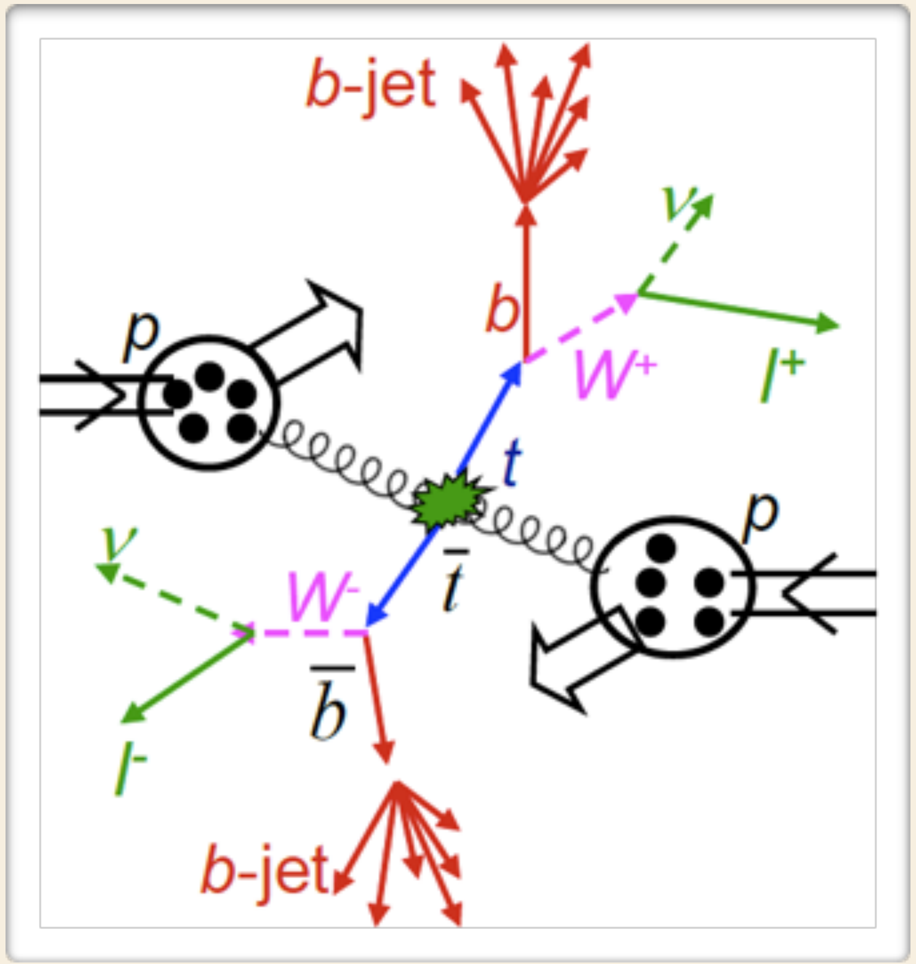
These require precise predictions of distributions at hadron level for

pp →tT+hard X, X = H,W,Z,γ,j,bB,2j...

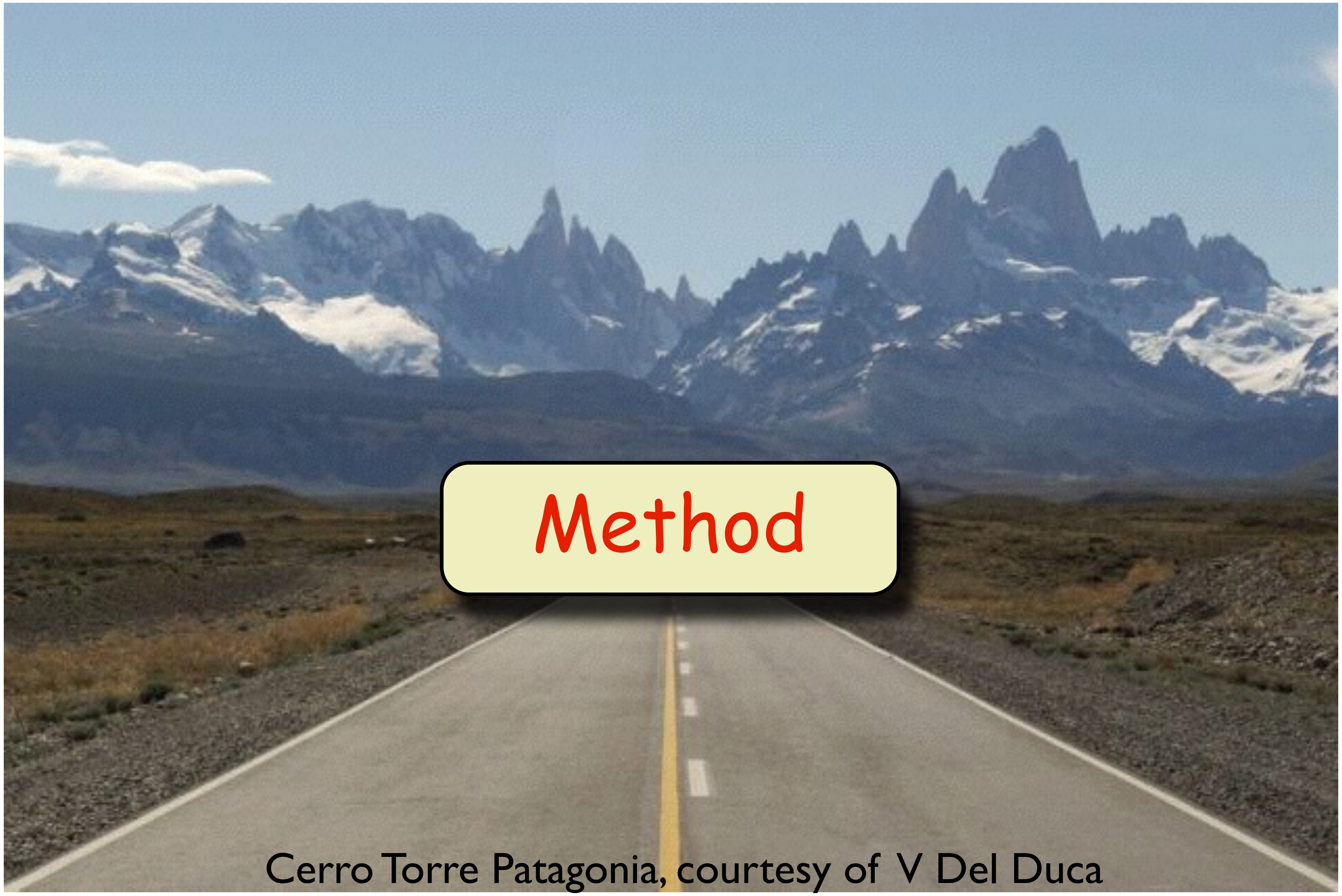
...with decays: the t-quark is not detected because it decays before hadronization

$$|V_{tb}|^2 \gg |V_{ts}|^2,\ |V_{td}|^2$$





...to distributions, full of pitfalls & difficulties



There is a long way from loops and legs...

From standard SMC to POWHEG MC

SMC idea: use probabilistic picture of parton splitting in the collinear approximation, iterate splitting to high orders

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- Standard MC first emission:

$$d\sigma_{\rm SMC} = B(\Phi_n) d\Phi_n \left[\Delta_{\rm SMC}(t_0) + \Delta_{\rm SMC}(t) \underbrace{\frac{\alpha_s(t)}{2\pi} \frac{1}{t} P(z)} \Theta(t - t_0)\, d\Phi_{\rm rad}^{\rm SMC} \right]$$

$$= \lim_{k_\perp \to 0} R(\Phi_{n+1})/B(\Phi_n)$$

$$\int B(\Phi_n) d\Phi_n = \sigma_{\rm LO}$$

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- POWHEG MC first emission:

$$d\sigma = \bar{B}(\Phi_n)d\Phi_n \left[\Delta(\Phi_n, p_\perp^{\rm min}) + \Delta(\Phi_n, k_\perp) \frac{R(\Phi_{n+1})}{B(\Phi_n)} \Theta(k_\perp - p_\perp^{\rm min}) \, d\Phi_{\rm rad} \right]$$

$$\bar{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int \left[R(\Phi_{n+1}) - A(\Phi_{n+1}) \right] d\Phi_{\rm rad}$$

[Frixione, Nason, Oleari arXiv: 0709.2092]

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$$\int \bar{B}(\Phi_n)d\Phi_n = \sigma_{\rm NLO}$$

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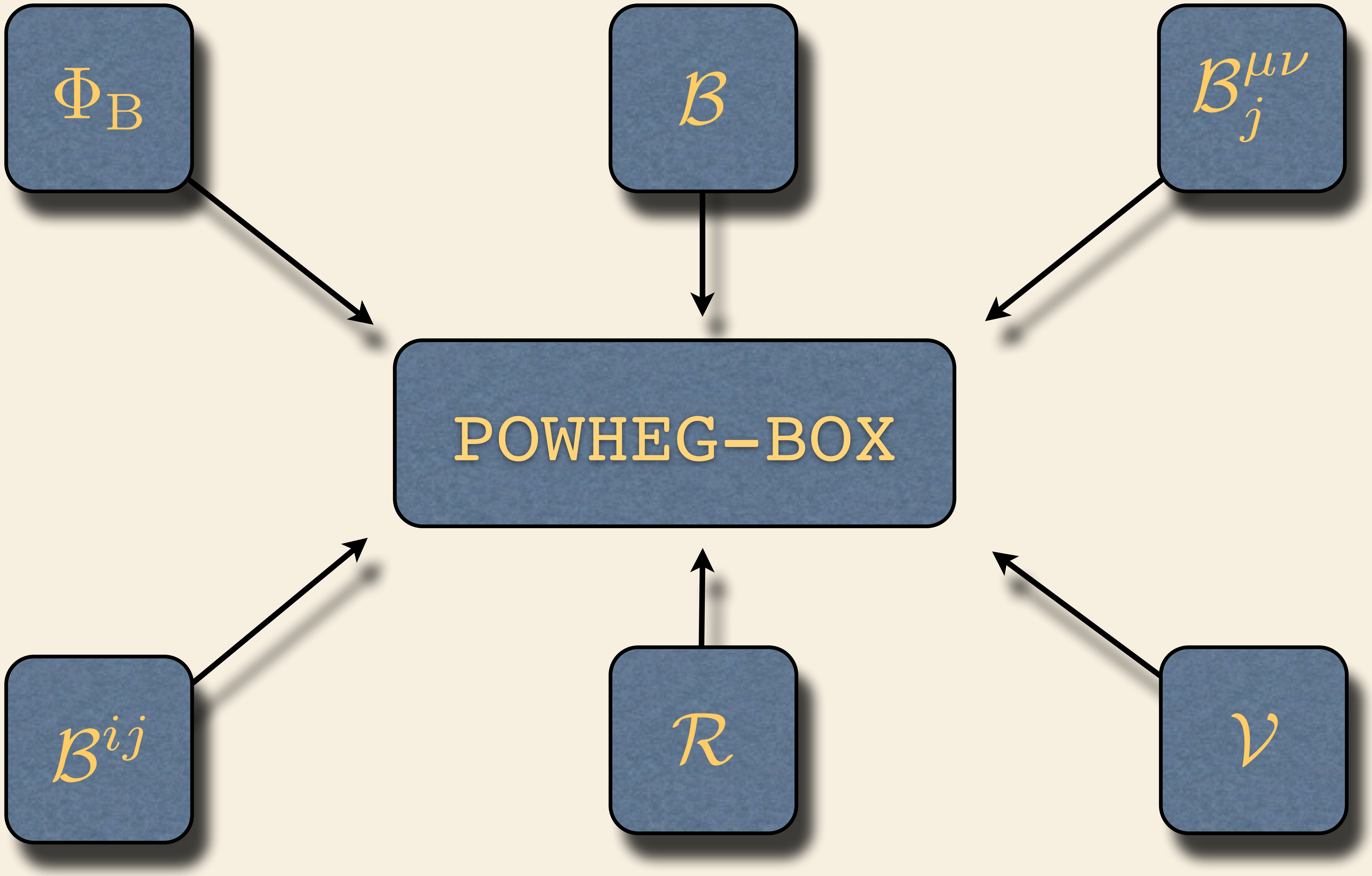
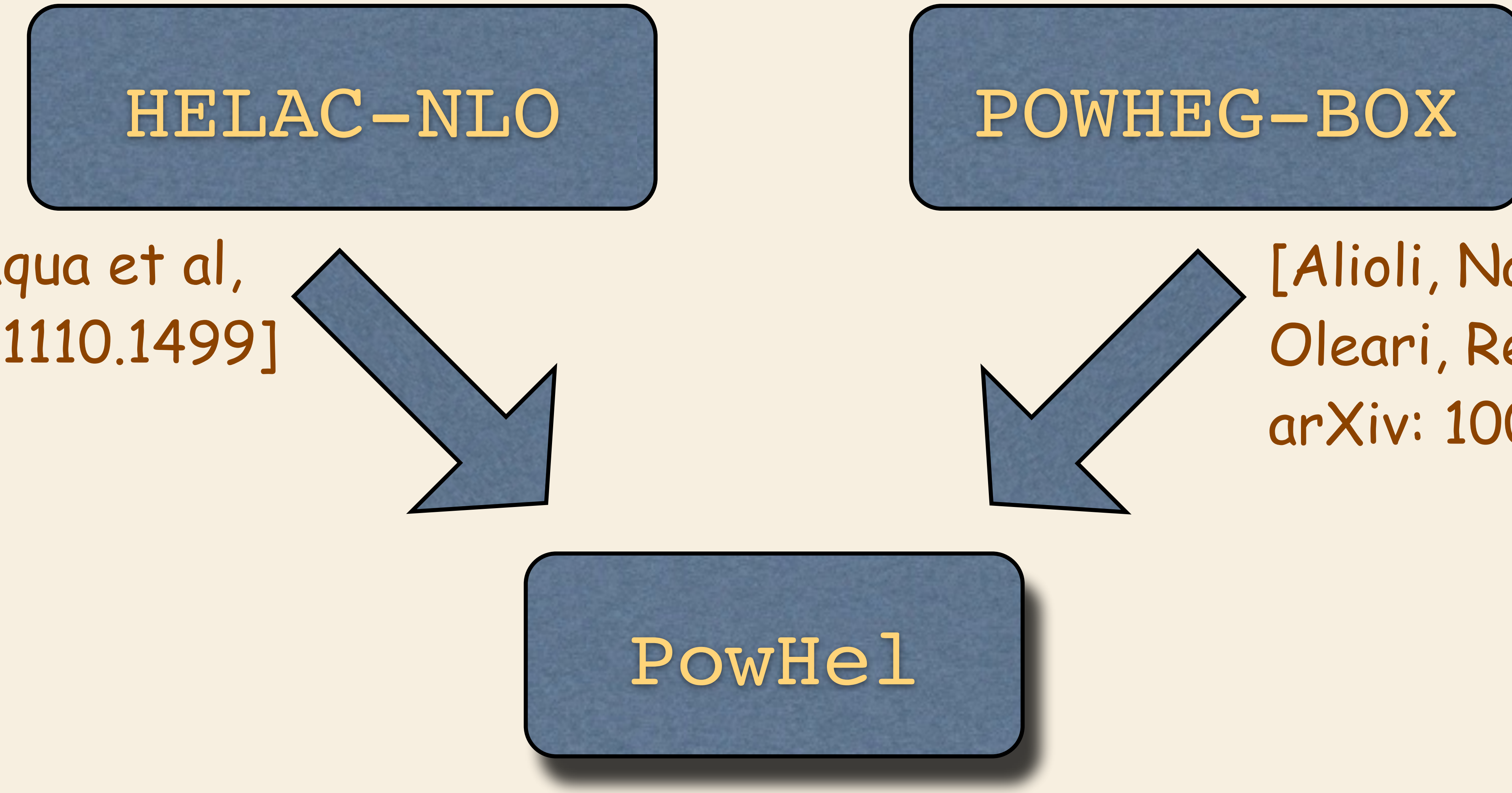
POWHEG-BOX framework



PowHel framework



[Bevilaqua et al, arXiv: 1110.1499]

[Alioli, Nason, Oleari, Re, arXiv: 1002.2581]

RESULT of PowHel:

Les Houches file of Born and Born+1st radiation events (LHE) ready for processing with SMC followed by almost arbitrary experimental analysis

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- Hadrons in final state
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...but we deliver the events on request

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- Three solutions:

1. use inclusive photons
2. use smooth isolation

} attractive only theoretically

3. include photon fragmentation — cumbersome theoretically and photon fragmentation is not known well

Second paper with Zoltan

Nuclear Physics B394 (1993) 139–168
North-Holland

NUCLEAR PHYSICS B

QCD corrections to photon production in association with hadrons in e^+e^- annihilation *

Zoltan Kunszt and Zoltán Trócsányi [1]

Theoretical Physics, ETH, Zurich, Switzerland

Received 17 July 1992
Accepted for publication 19 October 1992

Next-to-leading order QCD corrections for inclusive photon production in e^+e^- annihilation are derived. We emphasize that in a well-defined perturbative analysis – with or without isolation – it is always necessary to subtract the photon–quark collinear singularity. The subtraction term is absorbed into the non-perturbative fragmentation functions of the photon. The Q^2-dependence of the photon fragmentation functions is determined by inhomogeneous evolution equations. The modification of the evolution equations due to photon isolation is discussed. We also analyse the validity of the approaches where the non-perturbative contributions are neglected. Using a general purpose next-to-leading order Monte Carlo program, we calculate various physical quantities that were measured in LEP experiments recently.

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- Solution: isolate photon from partons with cone radius decreasing as parton energy inside the cone decreases

$$E_{\perp,\mathrm{had}} = \sum_{i\in\mathrm{tracks}} E_{\perp,i}\Theta\left(\delta - R(p_\gamma, p_i)\right) < E_{\perp,\gamma}\left(\frac{1-\cos\delta}{1-\cos\delta_0}\right)$$

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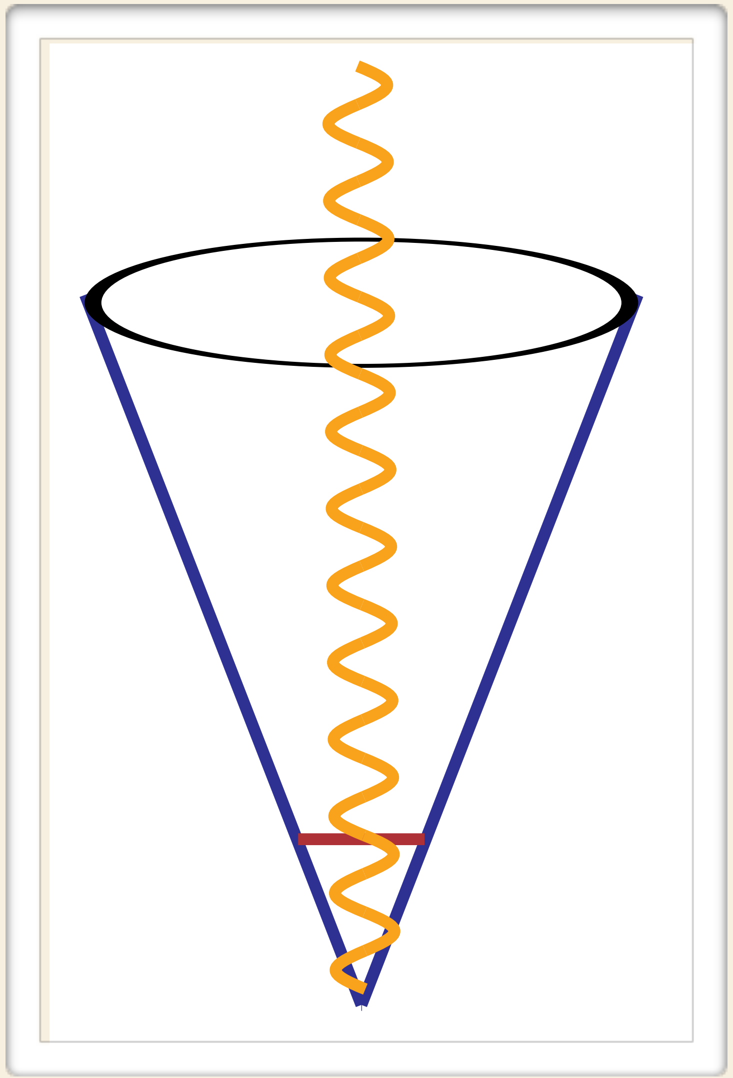
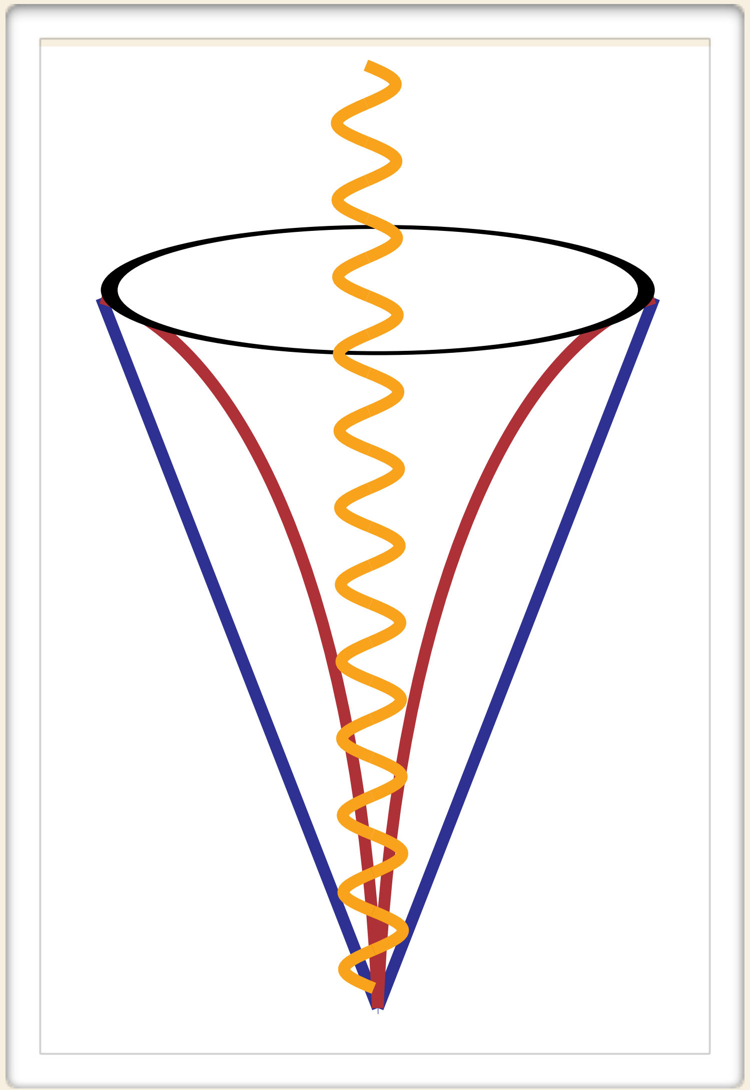
- Experimenters prefer cone with fixed radius, with reduced hadronic activity inside the cone

$$E_{\perp,\mathrm{had}} = \sum_{i\in\mathrm{tracks}} E_{\perp,i}\Theta\left(R_\gamma - R(p_\gamma, p_i)\right) < E_{\perp,\mathrm{had}}^{\mathrm{max}}$$

Experimental cone vs. smooth cone

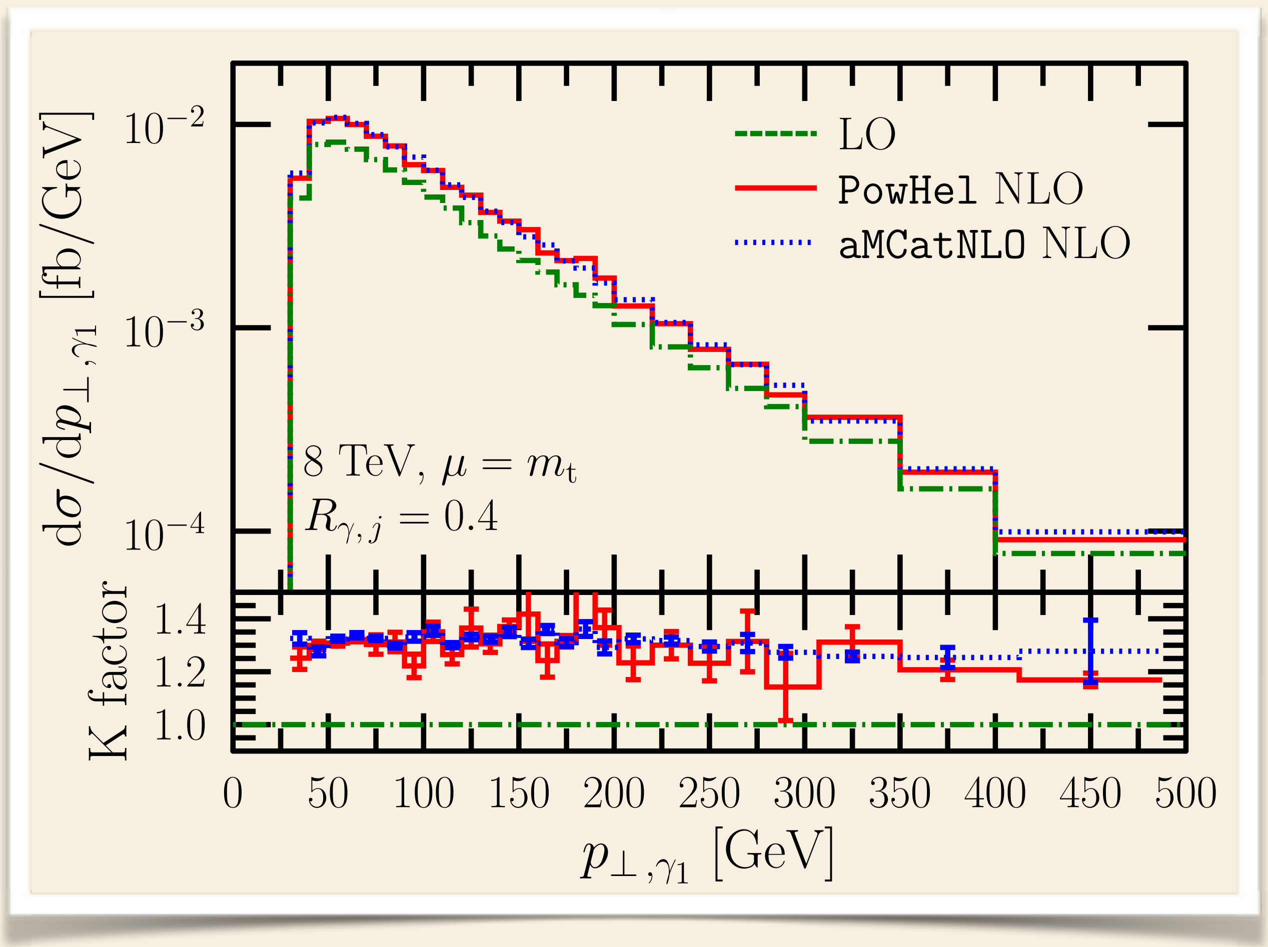


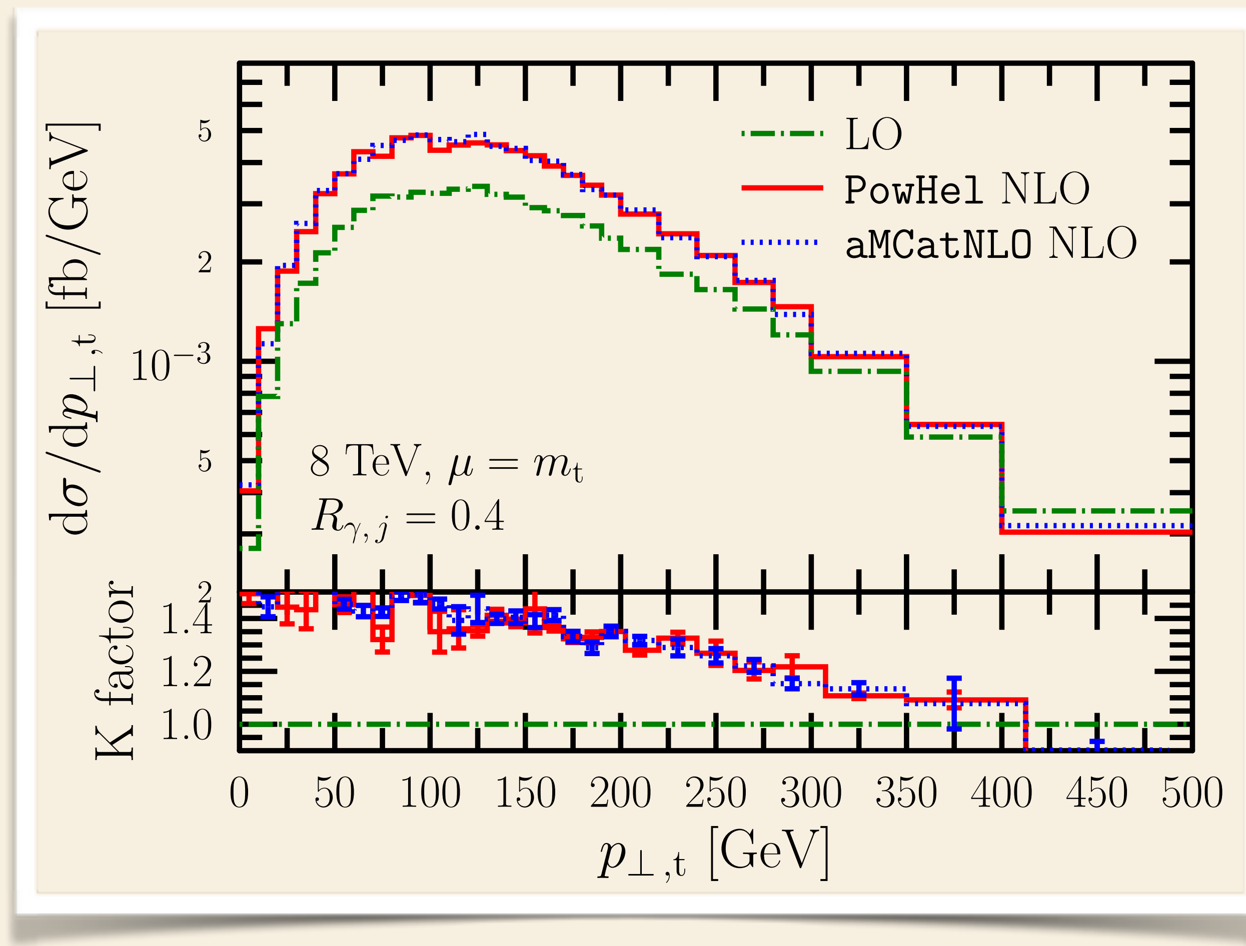


tTγγ hadroproduction at NLO

Preliminary

PowHel can produce distributions at NLO





Cross sections agree with predictions of MadGraph5 if m_b -> 0: (1052±10) pb with given cuts

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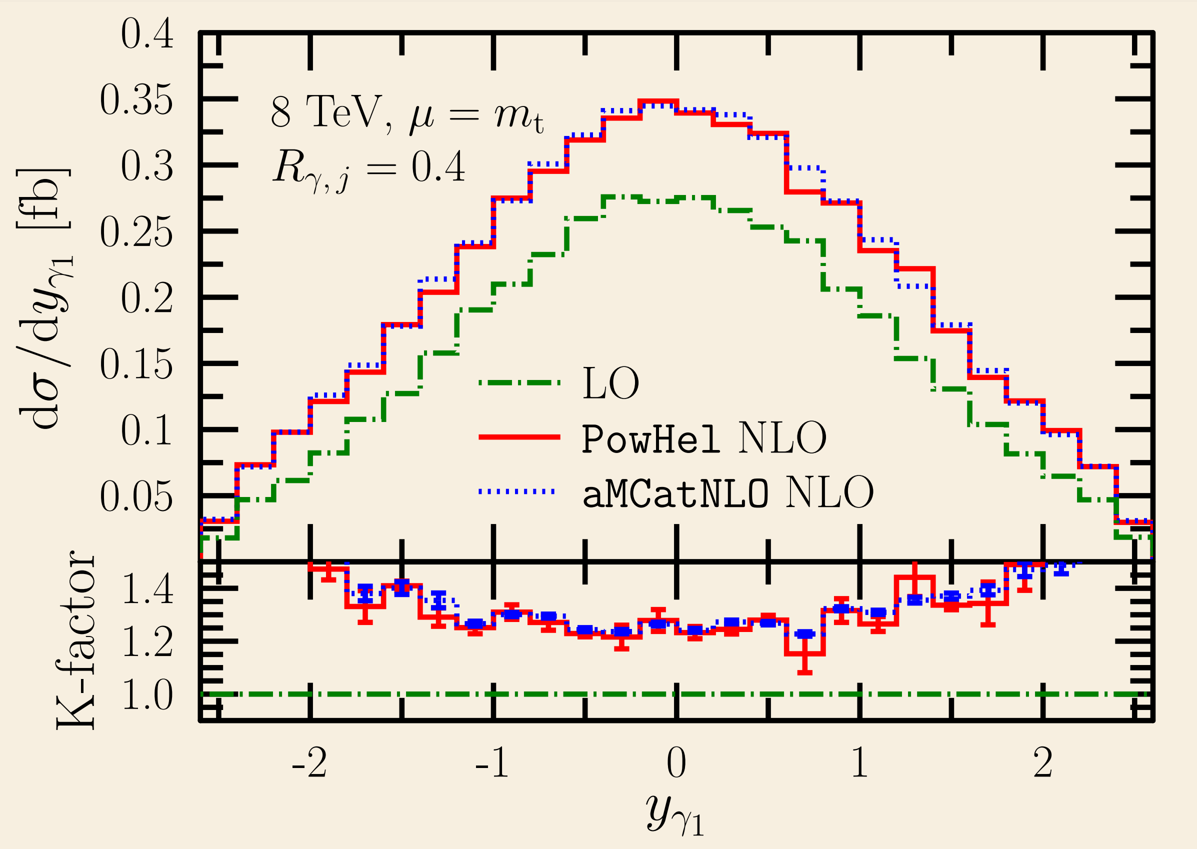

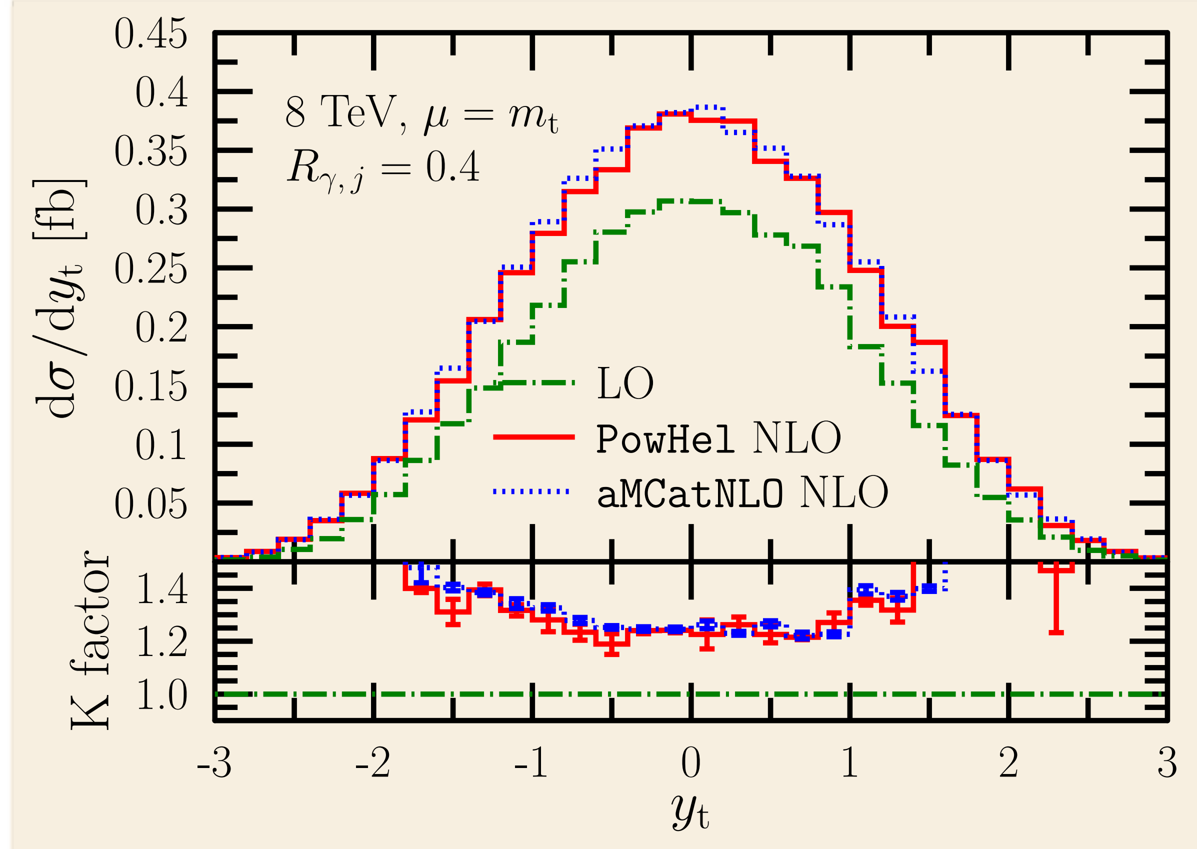

NLO K-factor is in the range 1.2-1.5

for fixed default scale,

improves with dynamic scale

NLO+PS matching makes possible (almost) inclusive event sample with photons

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- Event generation requires generation cuts, chosen much smaller than physical cuts $\Rightarrow$

measurable cross sections are independent of the generation cuts

- Applicable to processes without final-state light patrons in the Born cross section

Formal accuracy of the POWHEG MC

$$\langle O \rangle = \int \mathrm{d}\Phi_{\mathrm{B}} \widetilde{B} \left[\Delta(p_{\perp,\mathrm{min}}) O(\Phi_{\mathrm{B}}) + \int \mathrm{d}\Phi_{\mathrm{rad}} \Delta(p_{\perp}) \frac{R}{B} O(\Phi_{\mathrm{R}}) \right] =$$

...

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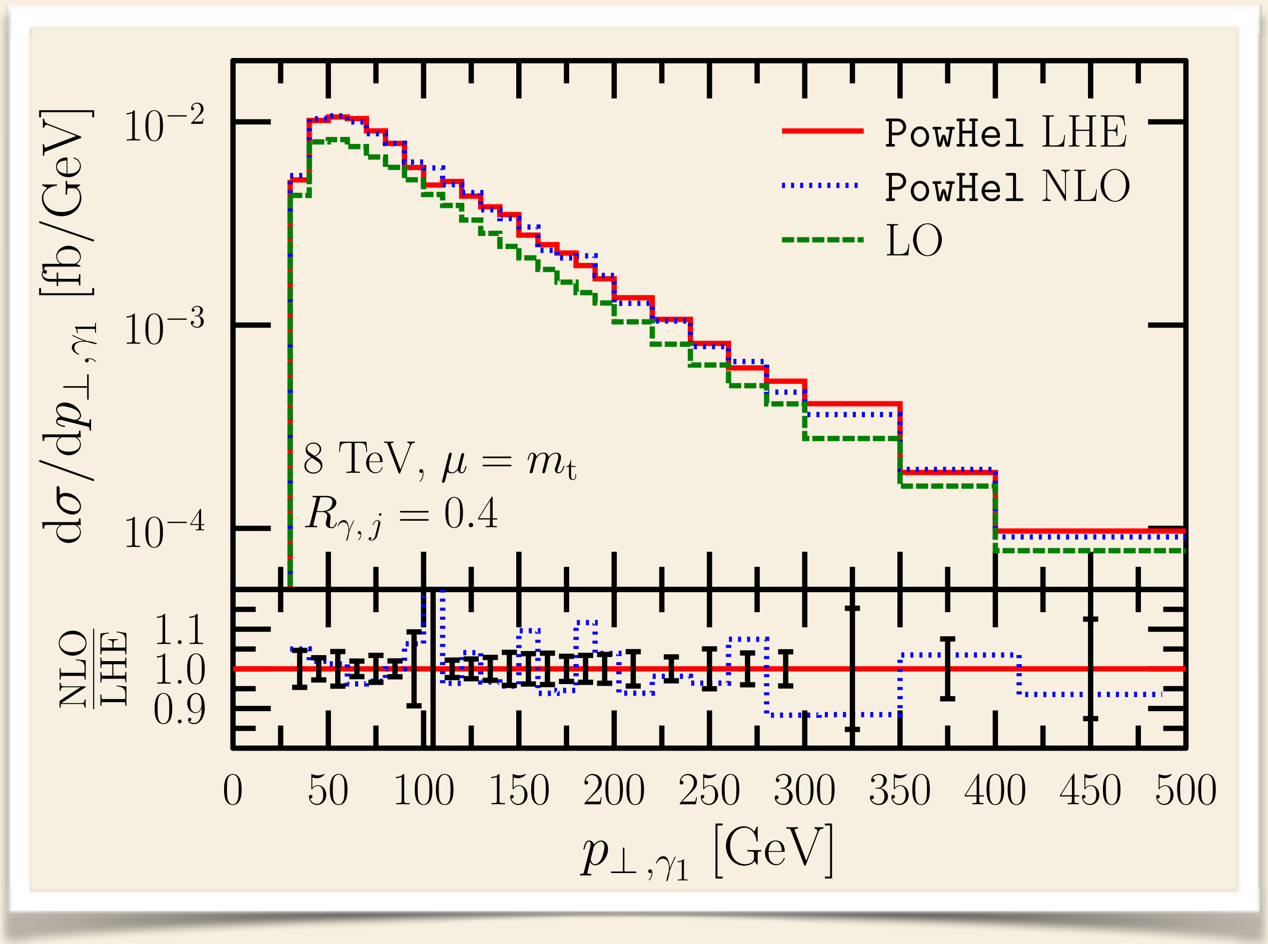
...

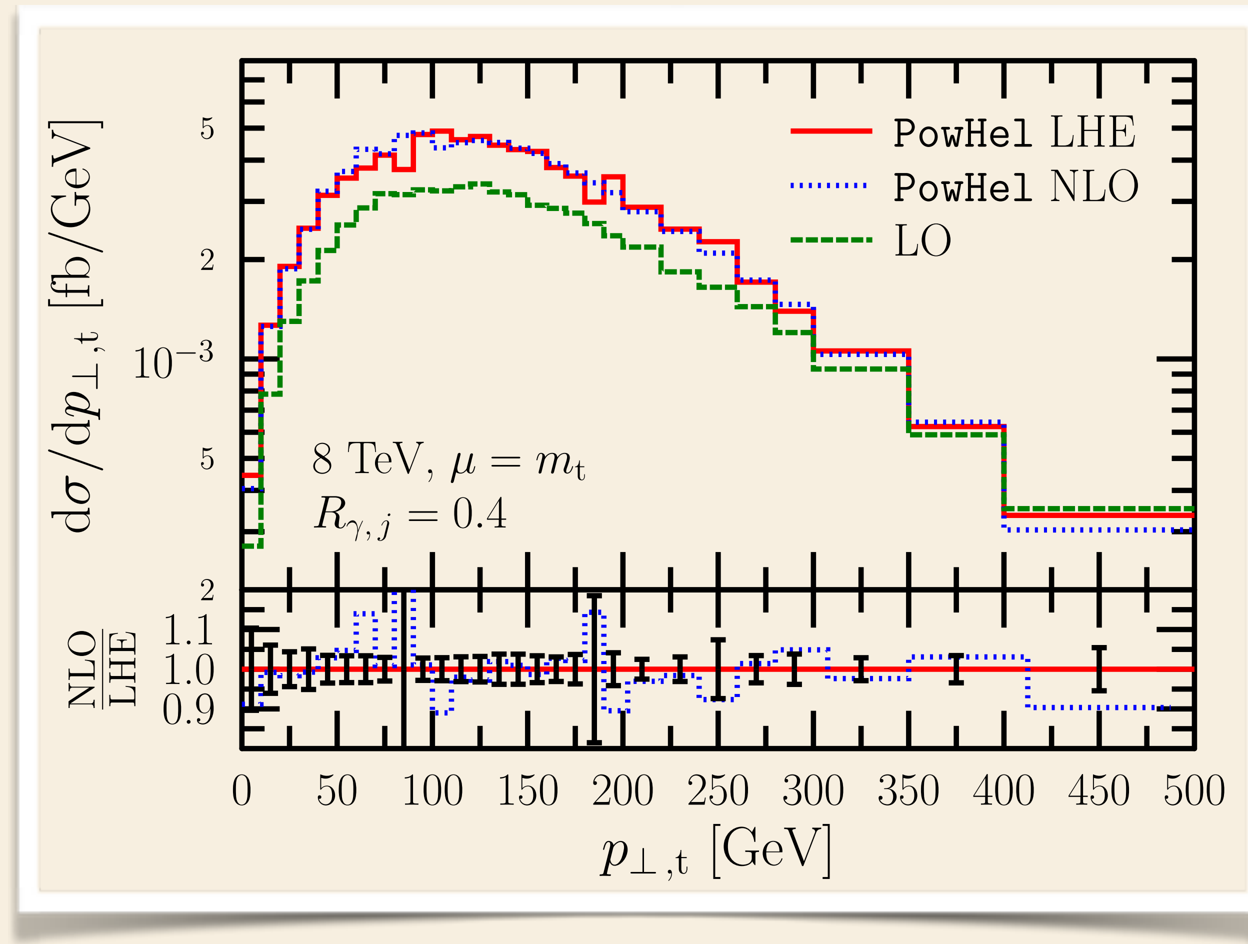
$$= \left\{ \int d\Phi_{\rm B} \left[B + V \right] O(\Phi_{\rm B}) + \int d\Phi_{\rm R} R O(\Phi_{\rm R}) \right\} (1 + \mathcal{O}(\alpha_{\rm S}))$$

$\langle O \rangle_{\rm NLO}$

Useful for checking

σ_{LHE} agree with σ_{NLO} w smooth isolation





NLO and LHE predictions agree

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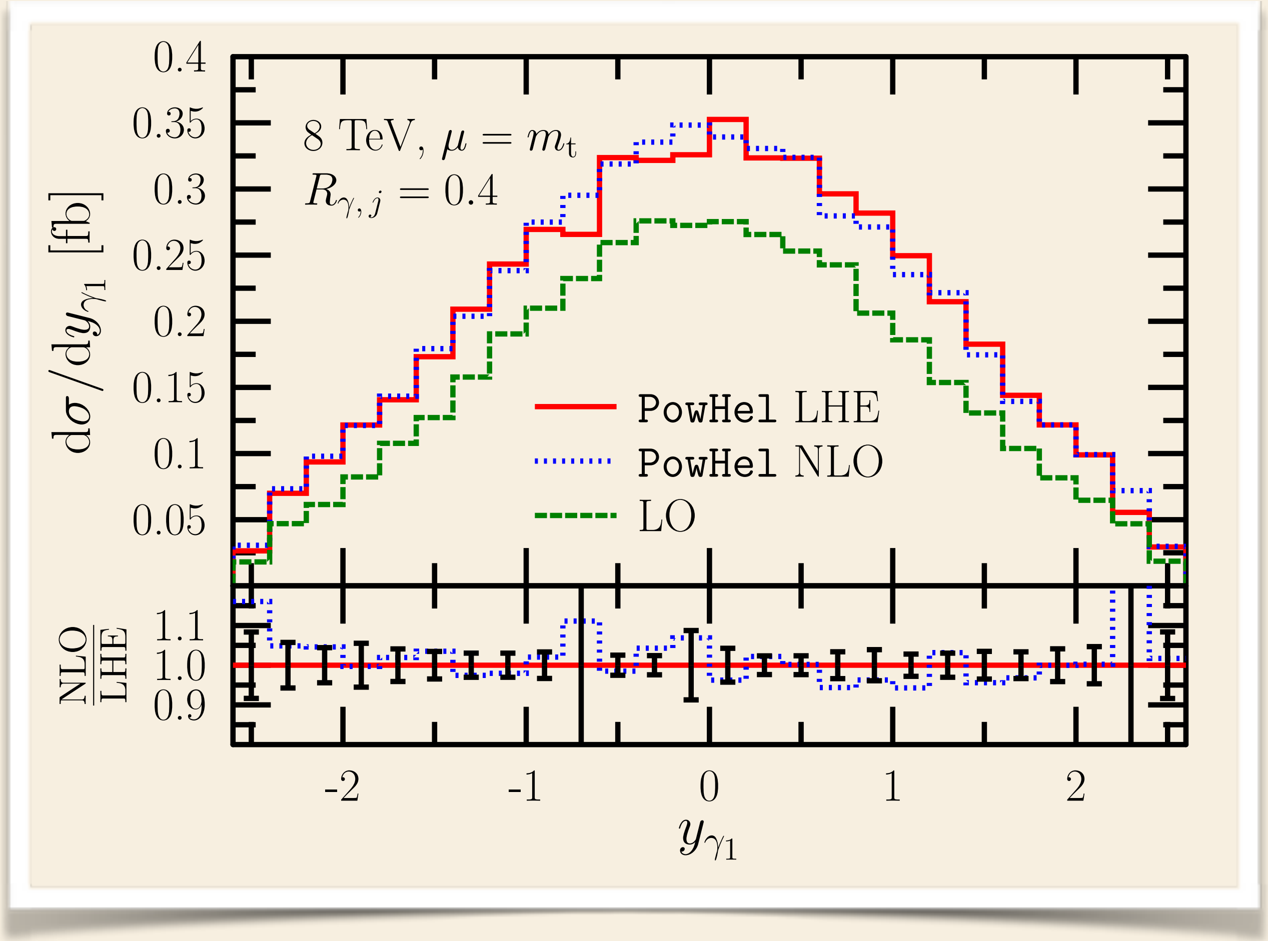

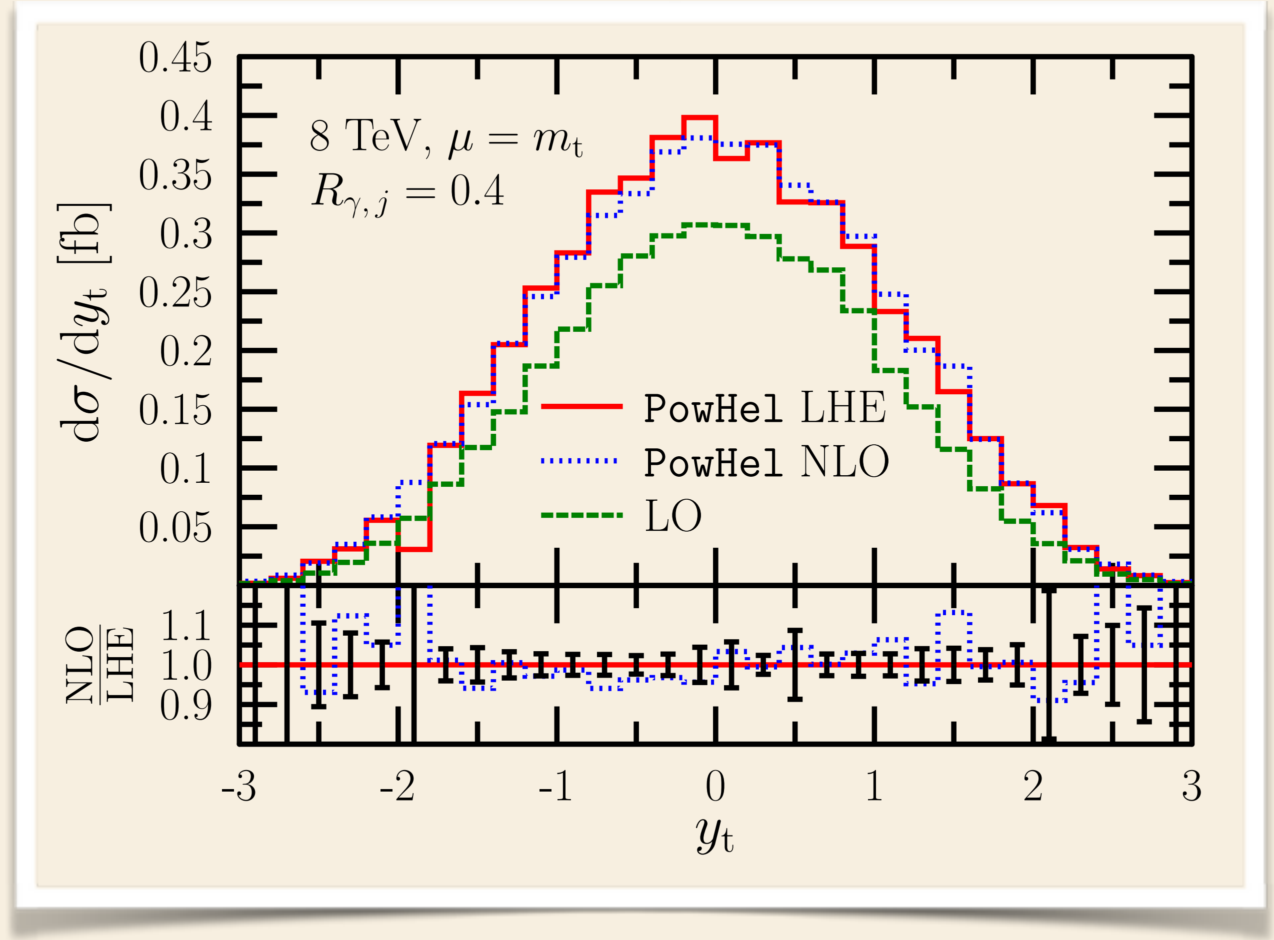

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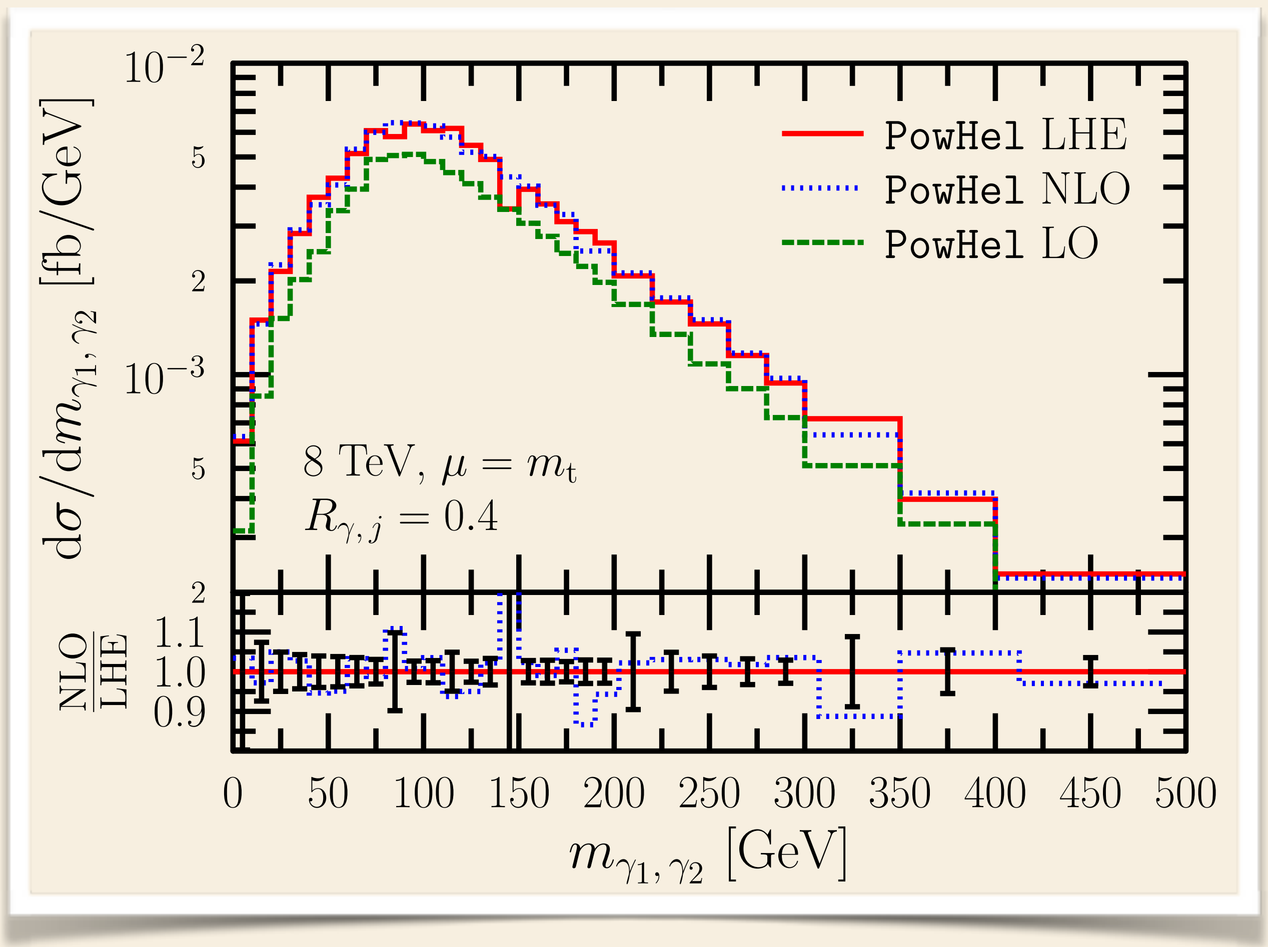

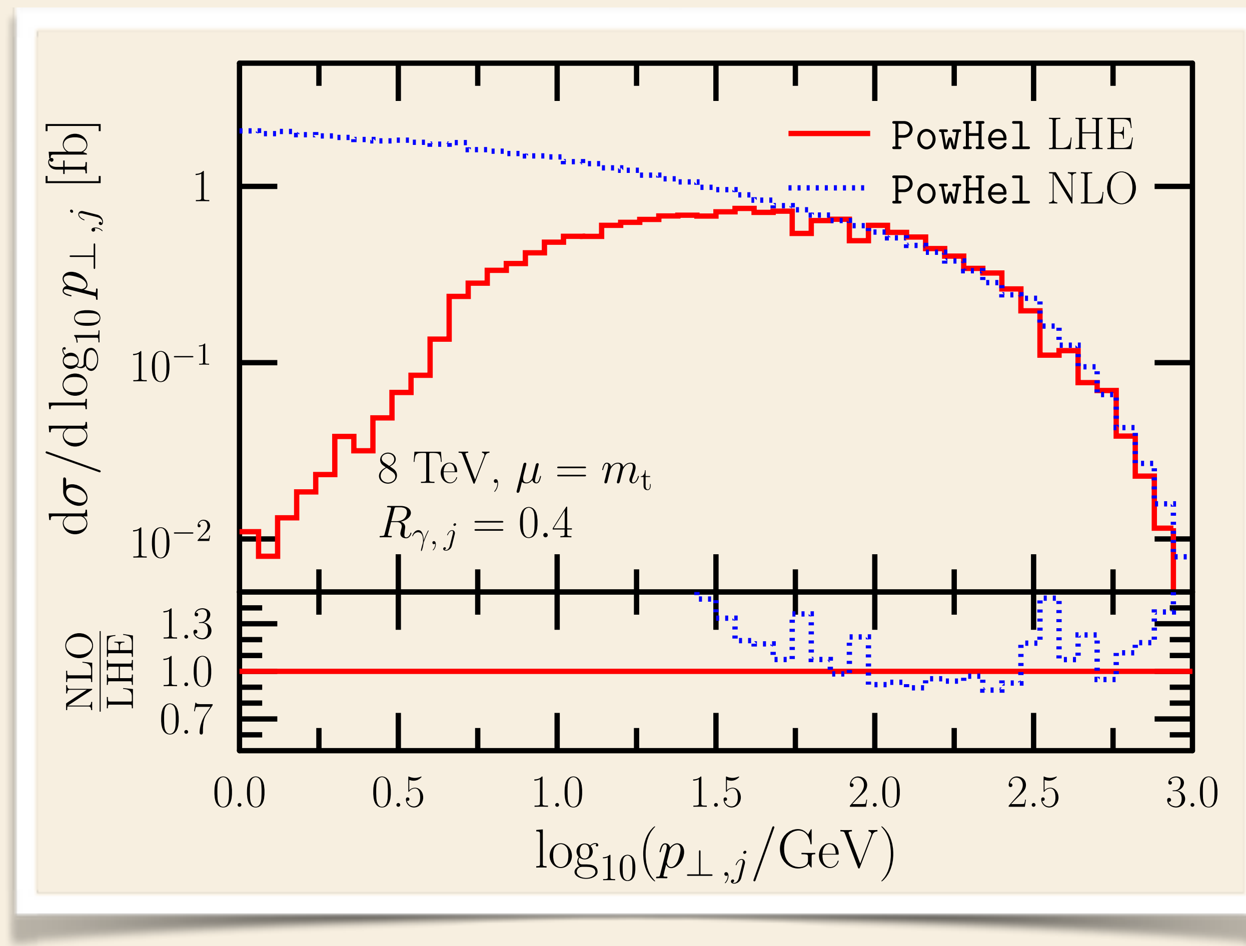

Exception:
Sudakov damping

Message:

we can trust the LHE's, so can make

Predictions

Four possible forms of predictions

LHE: distributions from events at BORN+1st radiation

Decay: on-shell decays of heavy particles (t-quarks), shower and hadronization effects turned off

PS: parton showering (PYTHIA or HERWIG) included (t-quarks kept stable)

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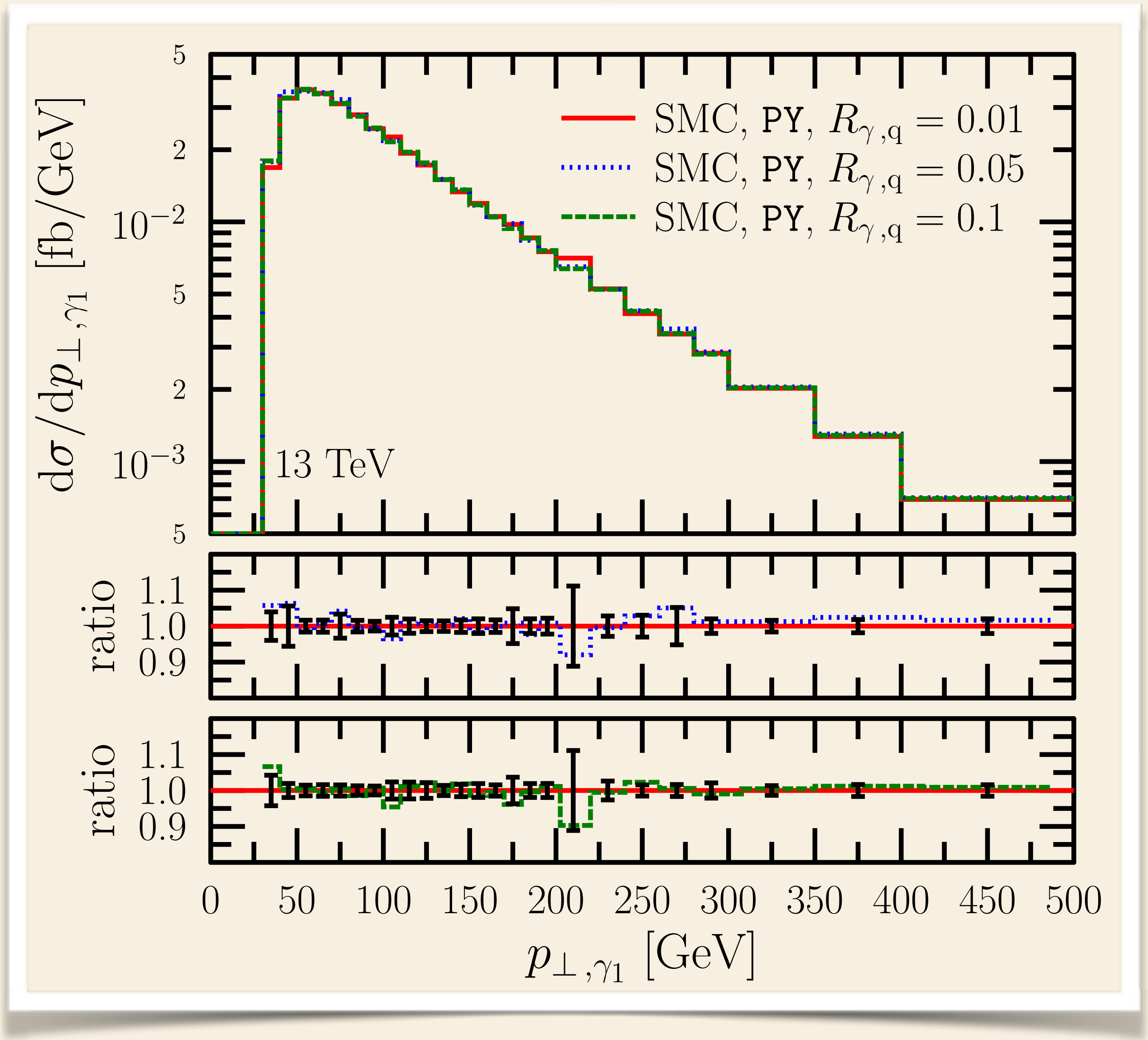
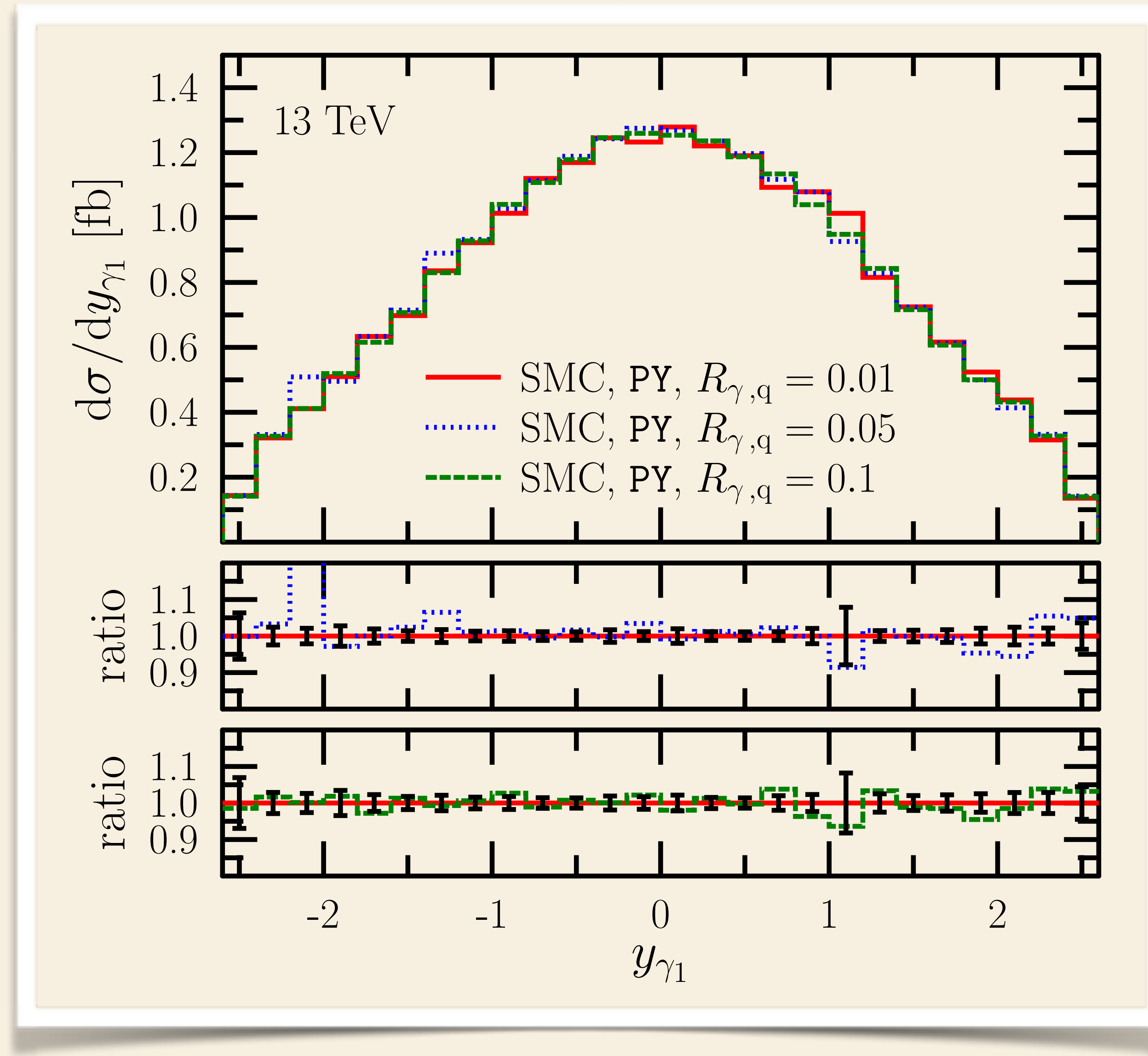
Full SMC: decays, parton showering and hadronization are included by using PYTHIA or HERWIG

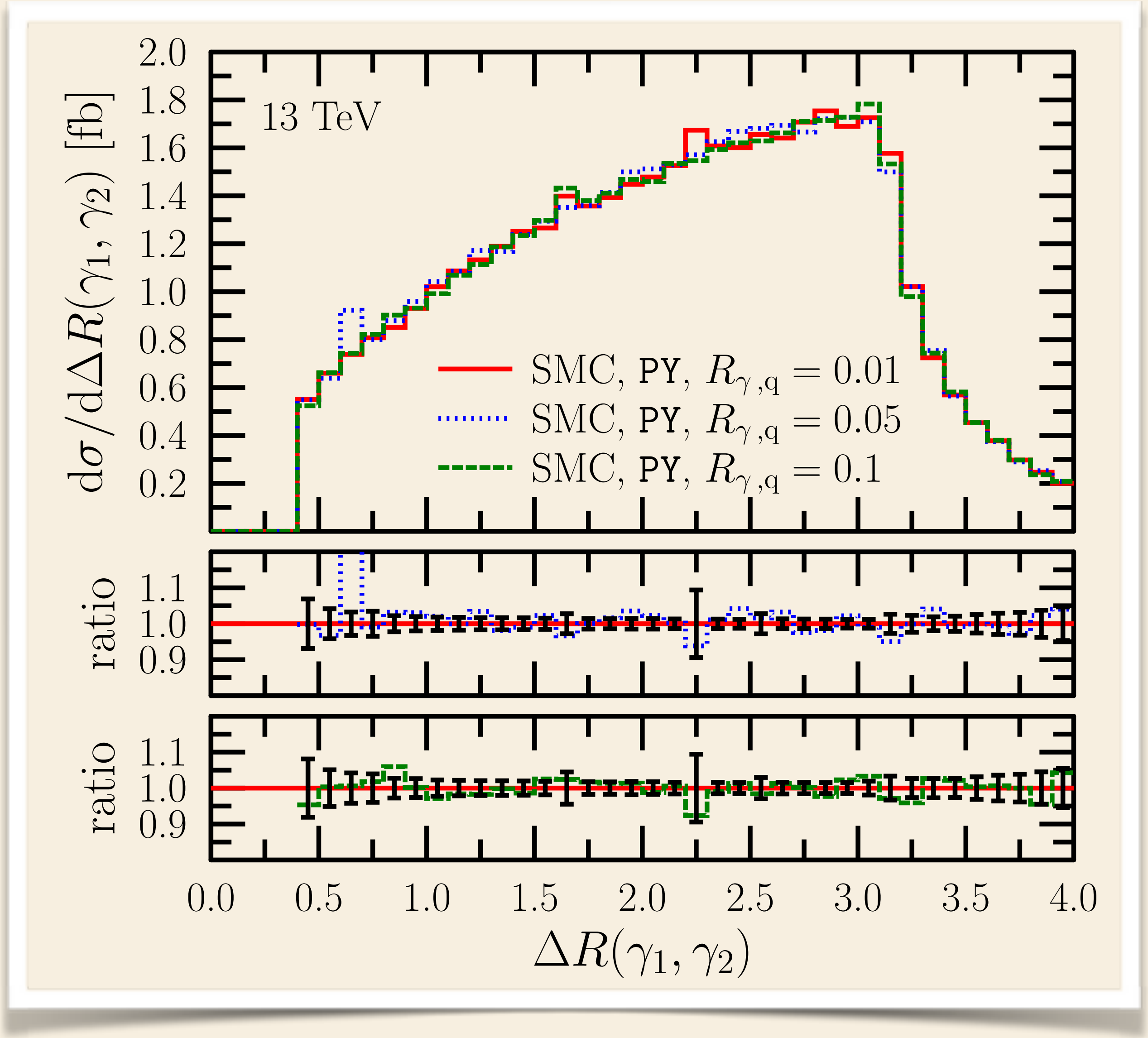
Number and type of particles are very different =>
to study the effect of SMC we employ selection cuts to keep the cross section fixed

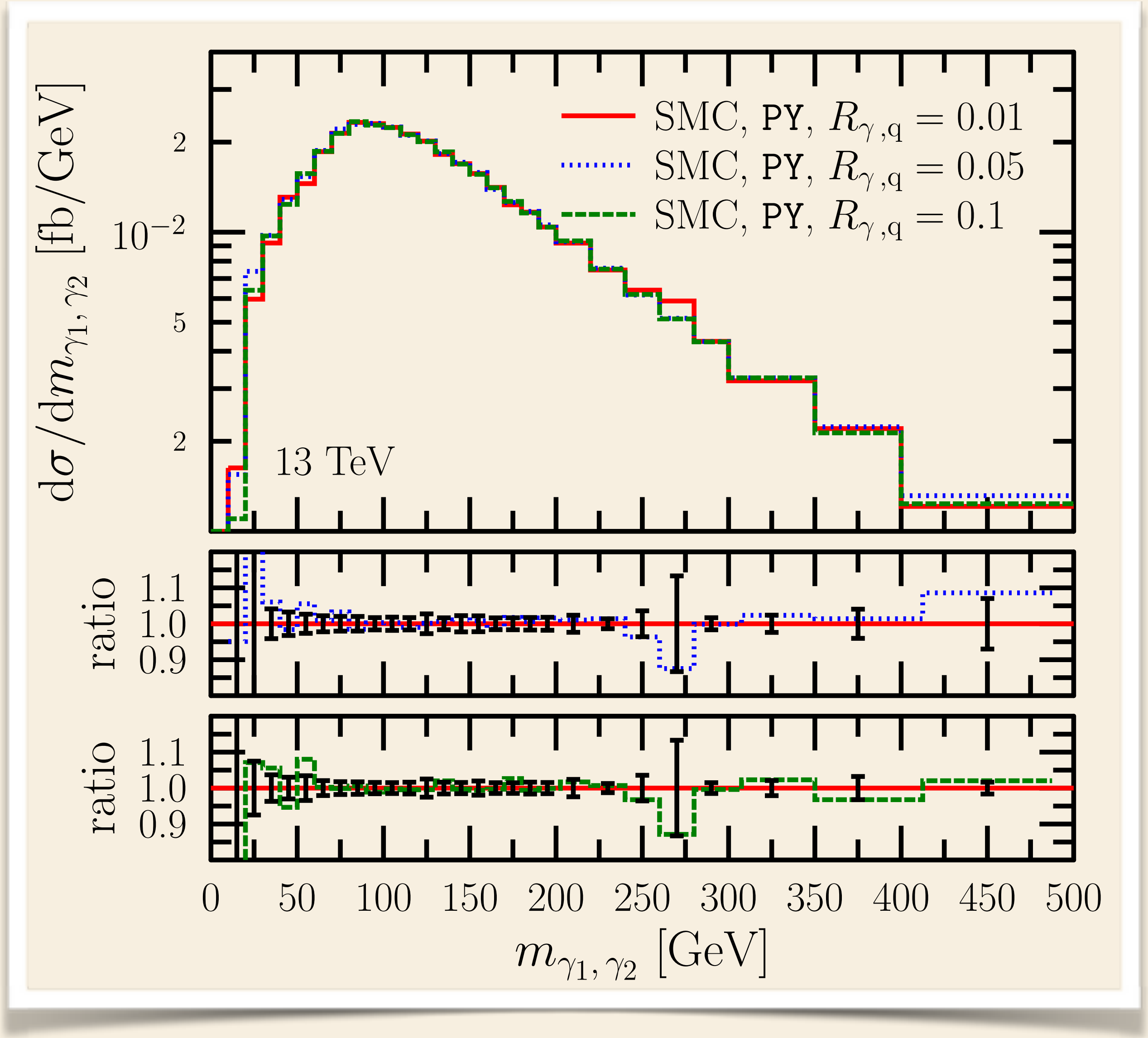
Predictions after full SMC with physical cuts are independent of generation cuts





Predictions after full SMC with physical cuts are independent of generation cuts





Message:

we can trust the (almost) inclusive LHE's,

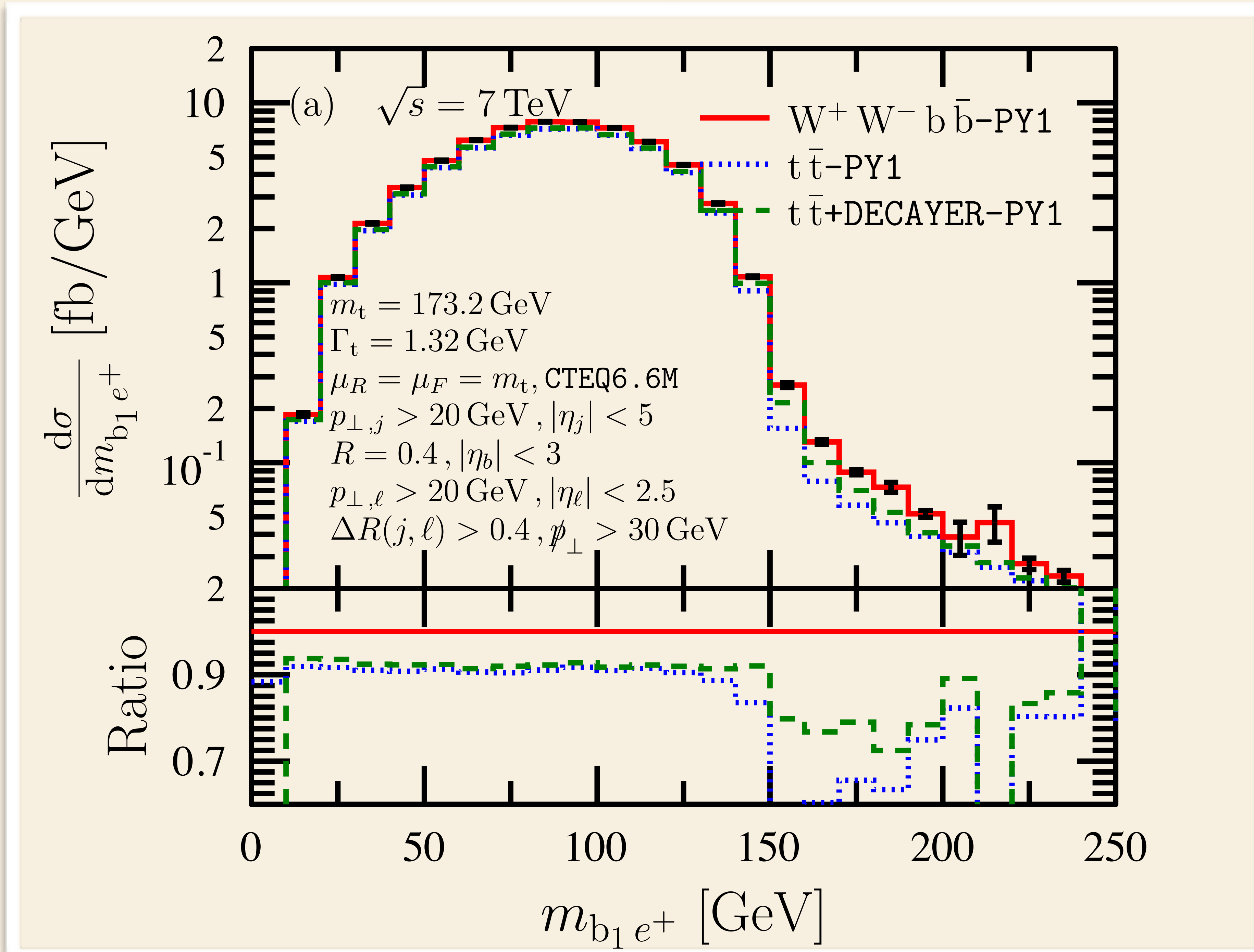
so can use experimental isolation

Conclusions

Conclusions

- First computation of $pp \to t\bar{t}\gamma\gamma$ at NLO + SMC accuracy
- NLO cross sections agree with predictions of public codes
- Experimentally preferred cone isolation is possible on (almost) inclusive event sample
- Effects of parton shower, SMC can be quantified
- LHE event files for $pp \to t\bar{t}$, $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}$jet, $t\bar{t}b\bar{b}$, $t\bar{t}\gamma$, $t\bar{t}\gamma\gamma$, $WWb\bar{b}$ processes available, to put into SMC and perform experimental analyses on events with hadrons

An example: $pp \to t\bar{t} \to W^+W^-b\bar{b}$



details in arXiv:1405.5859

Processes available in PowHel

✓$t\bar{T}$	[Kardos et al, arXiv:
✓tT + Z	1111.0610,1111.1444,
✓tT + W	1208.2665,
✓tT + H/A	1108.0387,
✓tT + j	1101.2672,
✓WWbB	PoS LL2012 057, 1405.5659
✓tT + bB	1303.6291
✓tT + γ	ready to submit
✓tT + γ γ	to be published soon]

Kedves Zoli

Köszönöm az útnak indítást

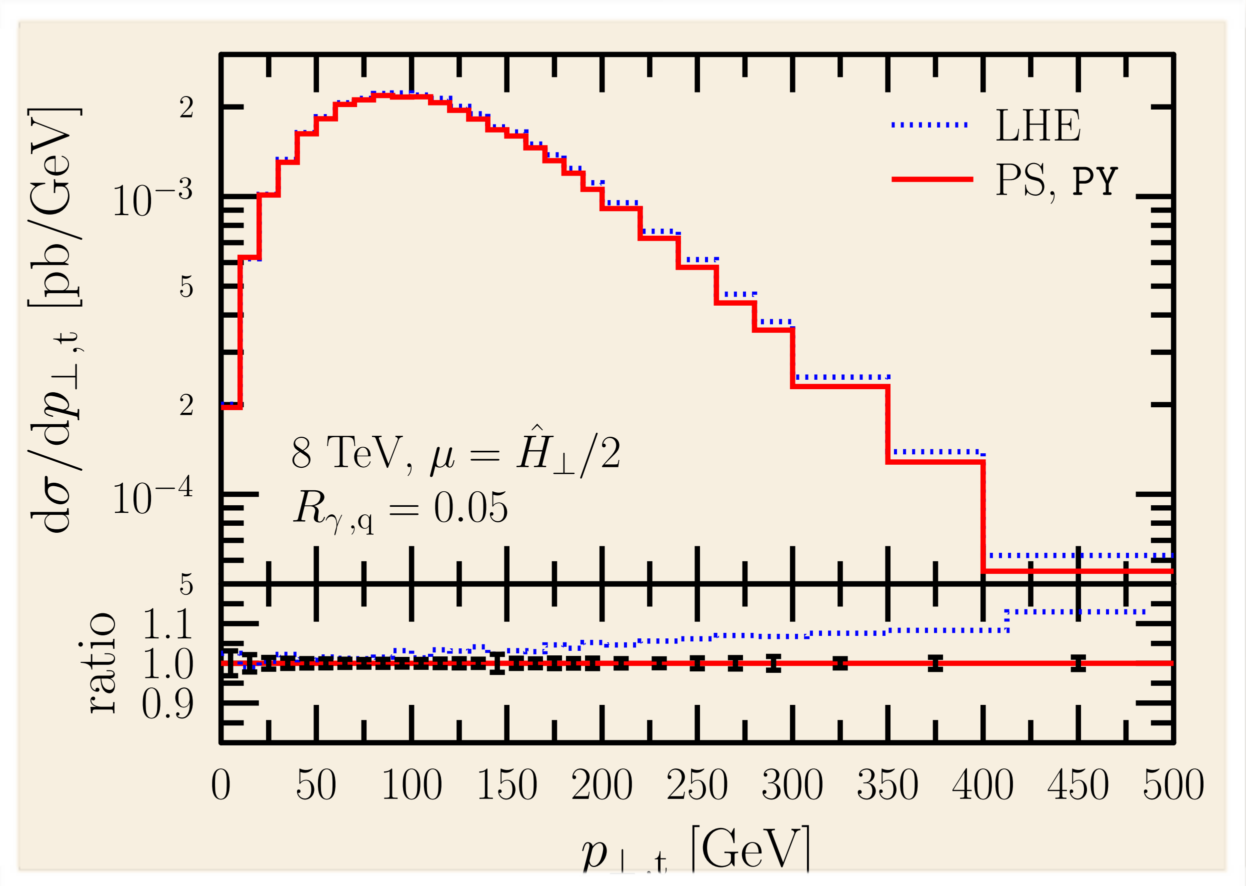
és

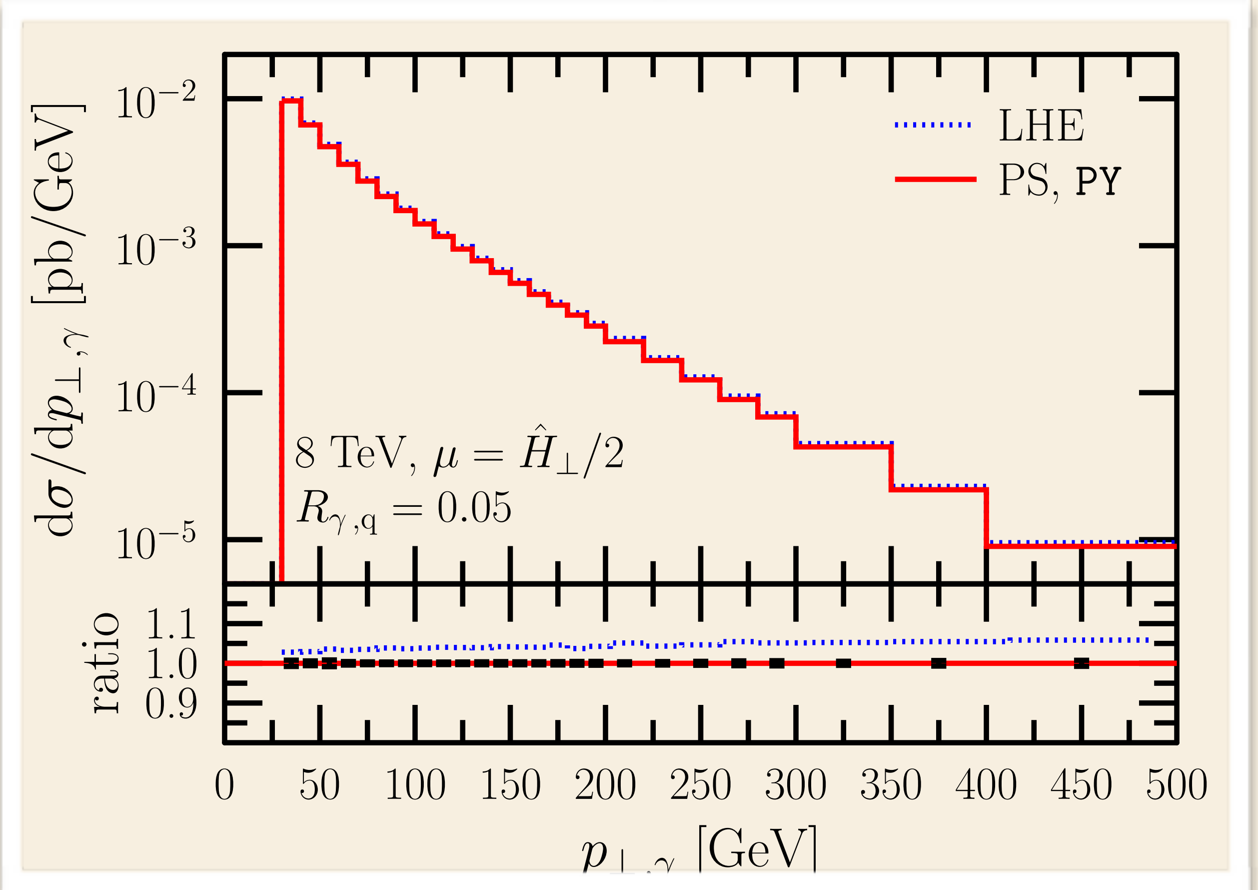
Isten éltessen sokáig erőben, egészségben!

Appendix

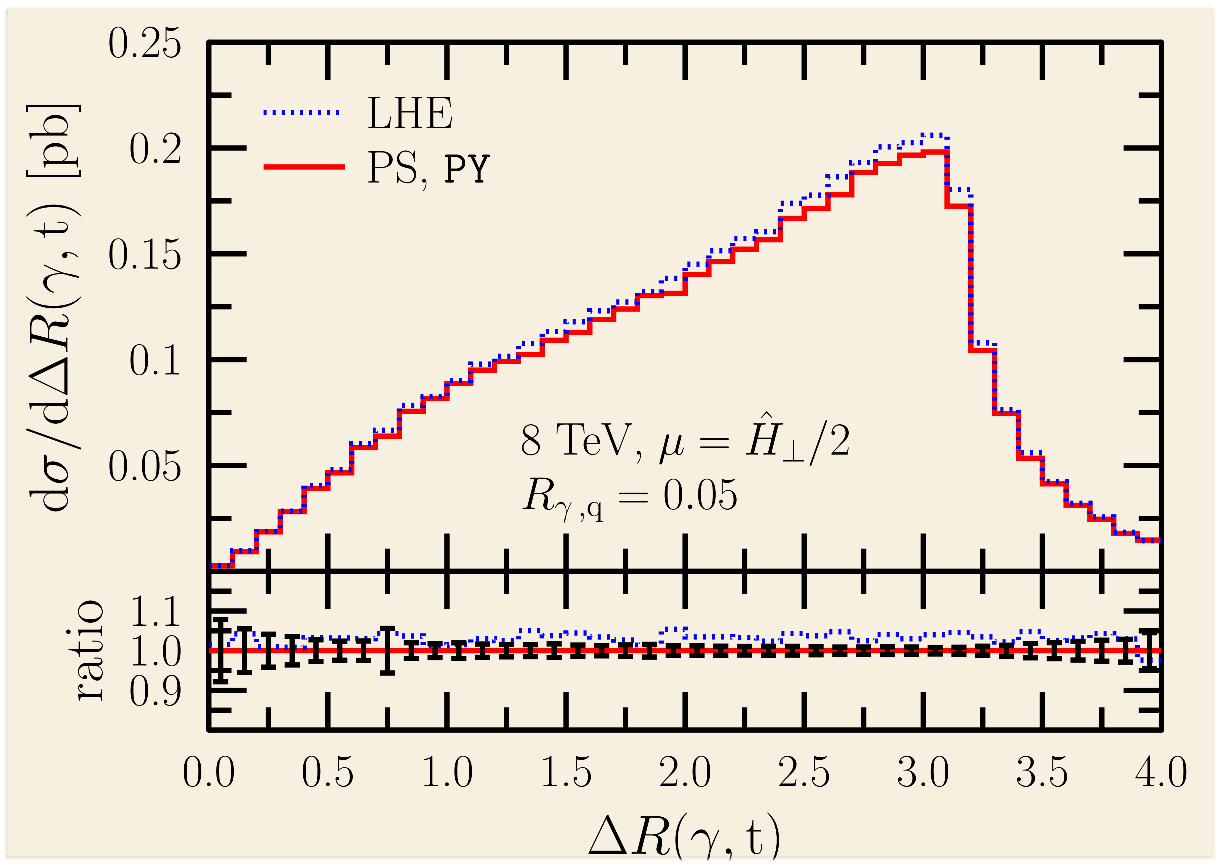
tTγ hadroproduction at NLO

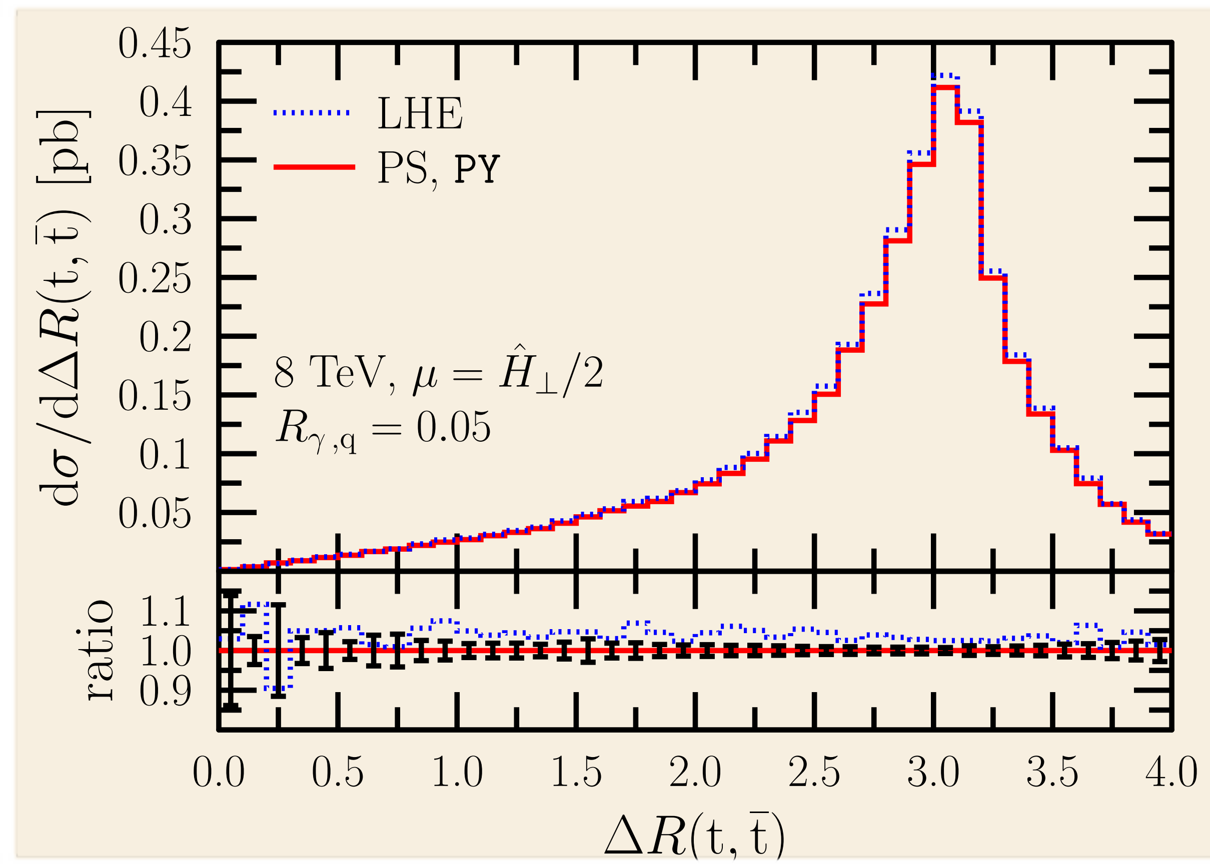
NLO vs. PS at 8TeV, μ = $H_T/2$



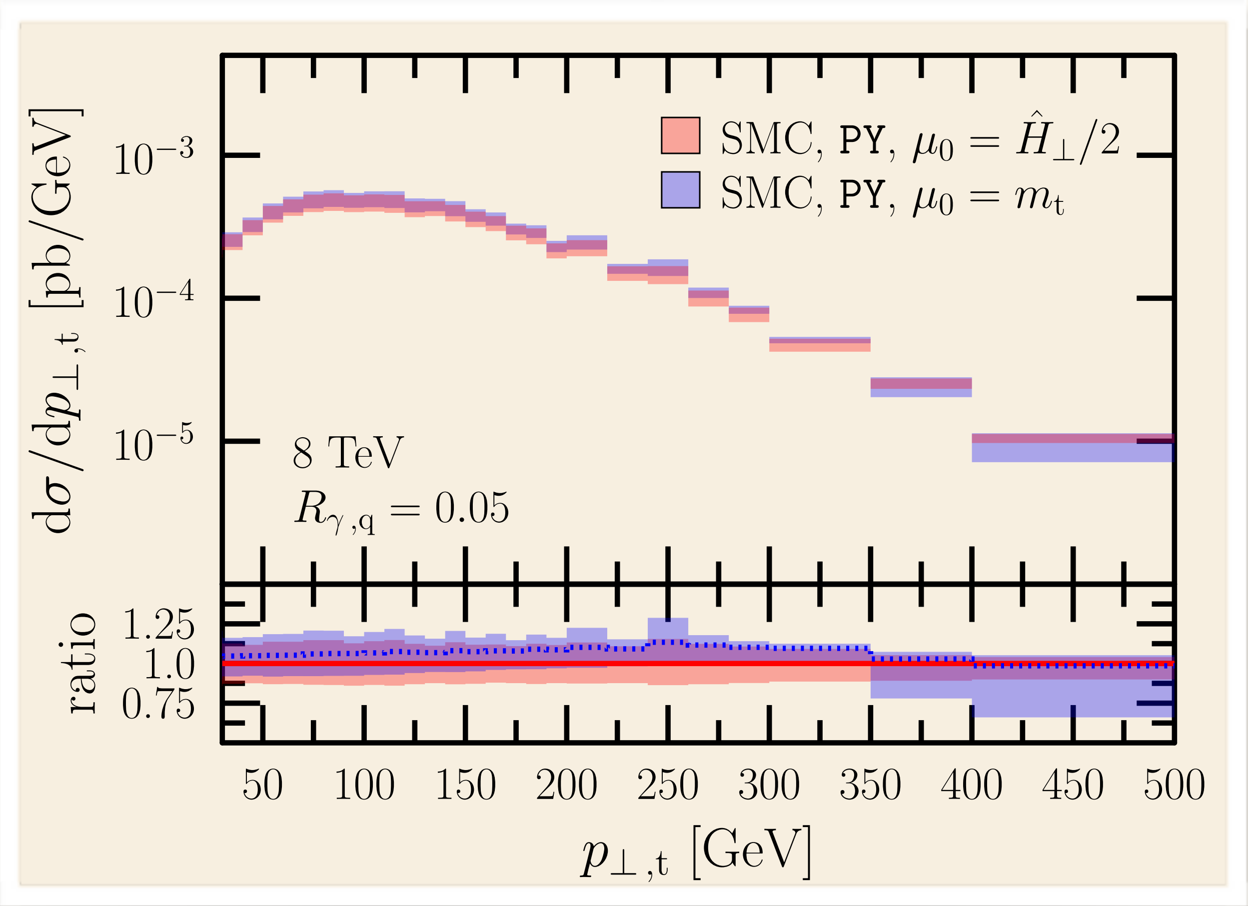


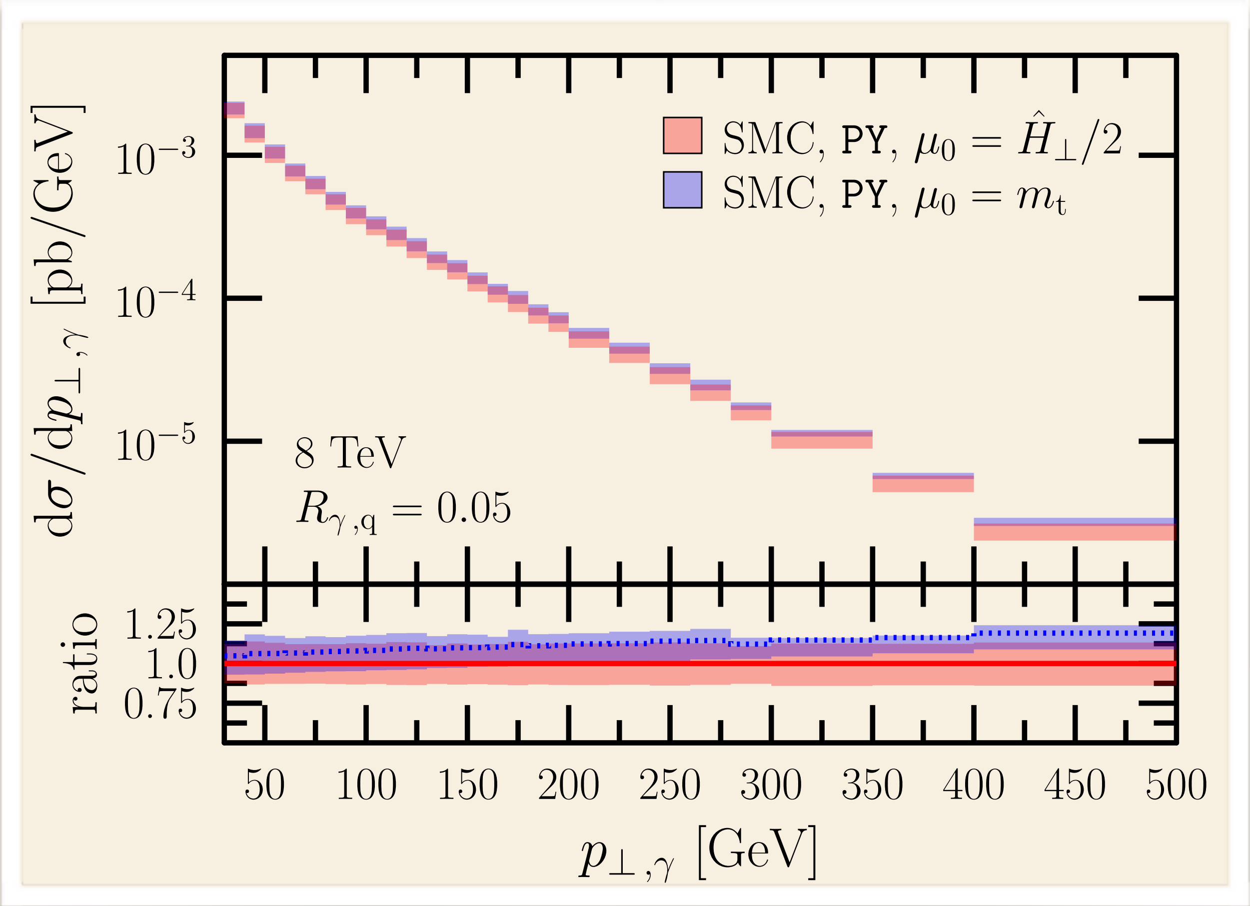
NLO vs. PS at 8TeV, μ = $H_T/2$





Scale dependence after full SMC at 8TeV





Scale dependence after full SMC at 8TeV