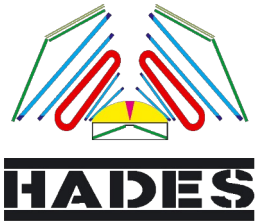




# Hadronic environment for p+p @ 4.5 GeV within JAM/RQMD, GiBUU and SMASH models

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# Motivation

Direct motivation: realistic hadronic background for embedding of Pluto-generated dileptons (see **Iza Ciepał**'s talk)

After Geant → test sample for trigger development for p+p collisions @ 4.5 GeV.

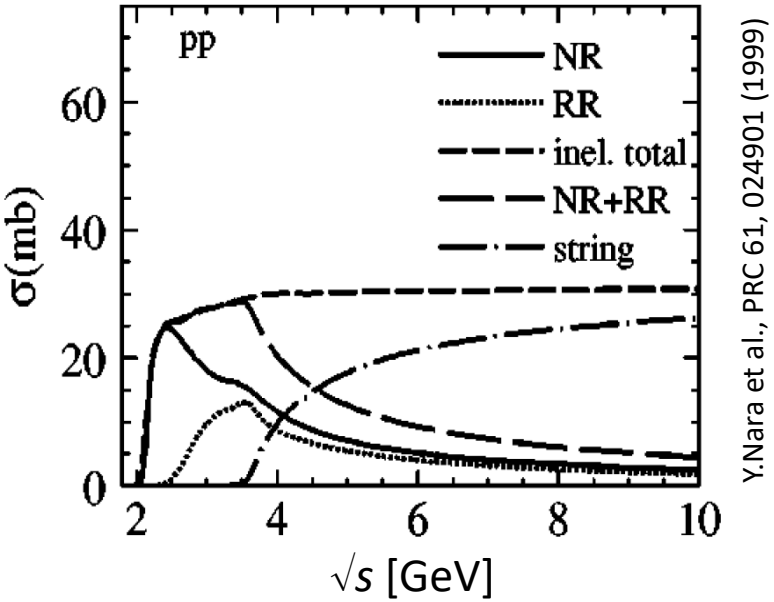
| | Multiplicity | | | $\sigma_{INEL}$ [mb] | | | $\sigma_{INEL}$ [mb] |
|---|---|---|---|---|---|---|---|
| | JAM/RQMD | GiBUU (M.G) | SMASH | JAM/RQMD | GiBUU | SMASH | Experiments |
| Reaction | | | | 30 | 30 | 30 | |
| $\pi^0$ | 0.65 | 0.51 | 0.43 | 20 | 15 | 13 | 20 |
| $\pi^+$ | 1.0 | 0.7 | 0.67 | 31 | 21 | 20 | 30 |
| $\pi^-$ | 0.30 | 0.22 | 0.18 | 9.0 | 6.6 | 5.5 | 8 |
| $\Delta^{++}$ | 0.42 | | 0.35 | 13 | | 11 | |
| $\Delta^+$ | 0.25 | | 0.25 | 7.5 | | 7.5 | 10 |
| $\Delta^0$ | 0.13 | | 0.13 | 4.0 | | 4.0 | 10 |
| $\Delta^-$ | 0.013 | | 0.020 | 0.40 | | 0.60 | |
| $\eta$ | 0.023 | | 0.024 | 0.7 | | 0.72 | 2 |
| $\omega$ | 0.019 | | 0.0095 | 0.56 | | 0.30 | 0.4 |
| $\rho^0$ | 0.045 | | 0.014 | 1.35 | | 0.40 | 0.8 |
| $K^+$ | 0.012 | 0.017 | 0.015 | 0.36 | 0.51 | 0.45 | 0.5 |
| $K^0$ | 0.0062 | | 0.013 | 0.19 | 0.12 | 0.39 | |
| $K^-$ | 0 | 0.00023 | 0.00012 | 0 | 0.0070 | 0.0036 | 0.03 |
| $\Lambda$ | 0.0094 | 0.016 | 0.0054 | 0.28 | 0.48 | 0.16 | 0.2 |
| $\Sigma^+$ | 0.005 | 0.0058 | 0.0100 | 0.15 | 0.17 | 0.30 | |
| $\Sigma^-$ | 0.001 | 0.0021 | 0.0014 | 0.03 | 0.063 | 0.042 | |
| $\Sigma^0$ | 0.0027 | 0.0034 | 0.0047 | 0.08 | 0.10 | 0.14 | 0.1 |

Second motivation: towards understanding of model differences

# Hadron – string transition region

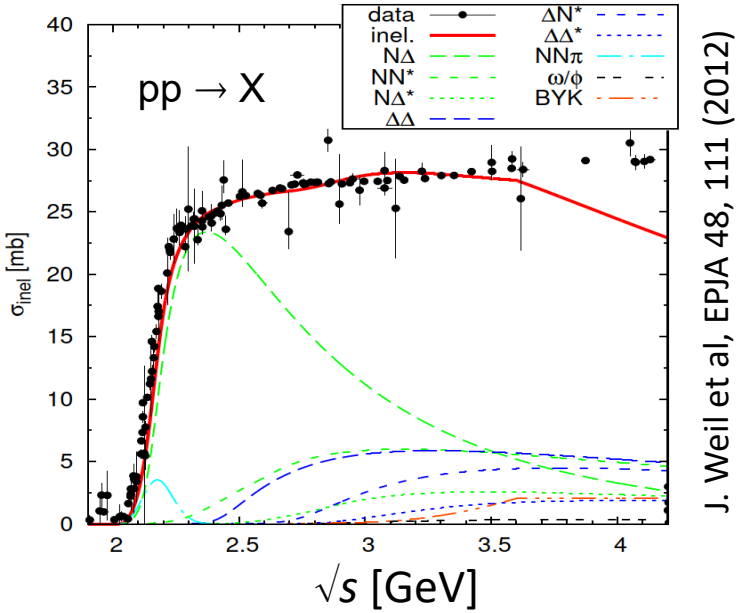
For p+p @ $T_{beam}$ = 4.5 GeV, the energy available in CM is $\sqrt{s}$ = 3.46 GeV.

## JAM/RQMD



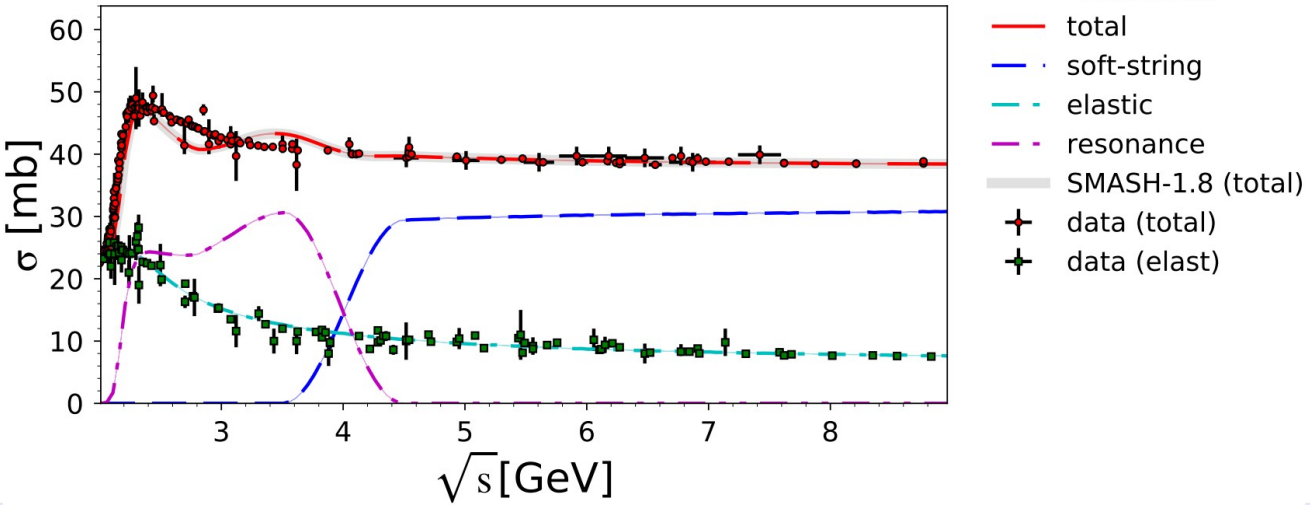

Y.Nara et al., PRC 61, 024901 (1999)

## GiBUU



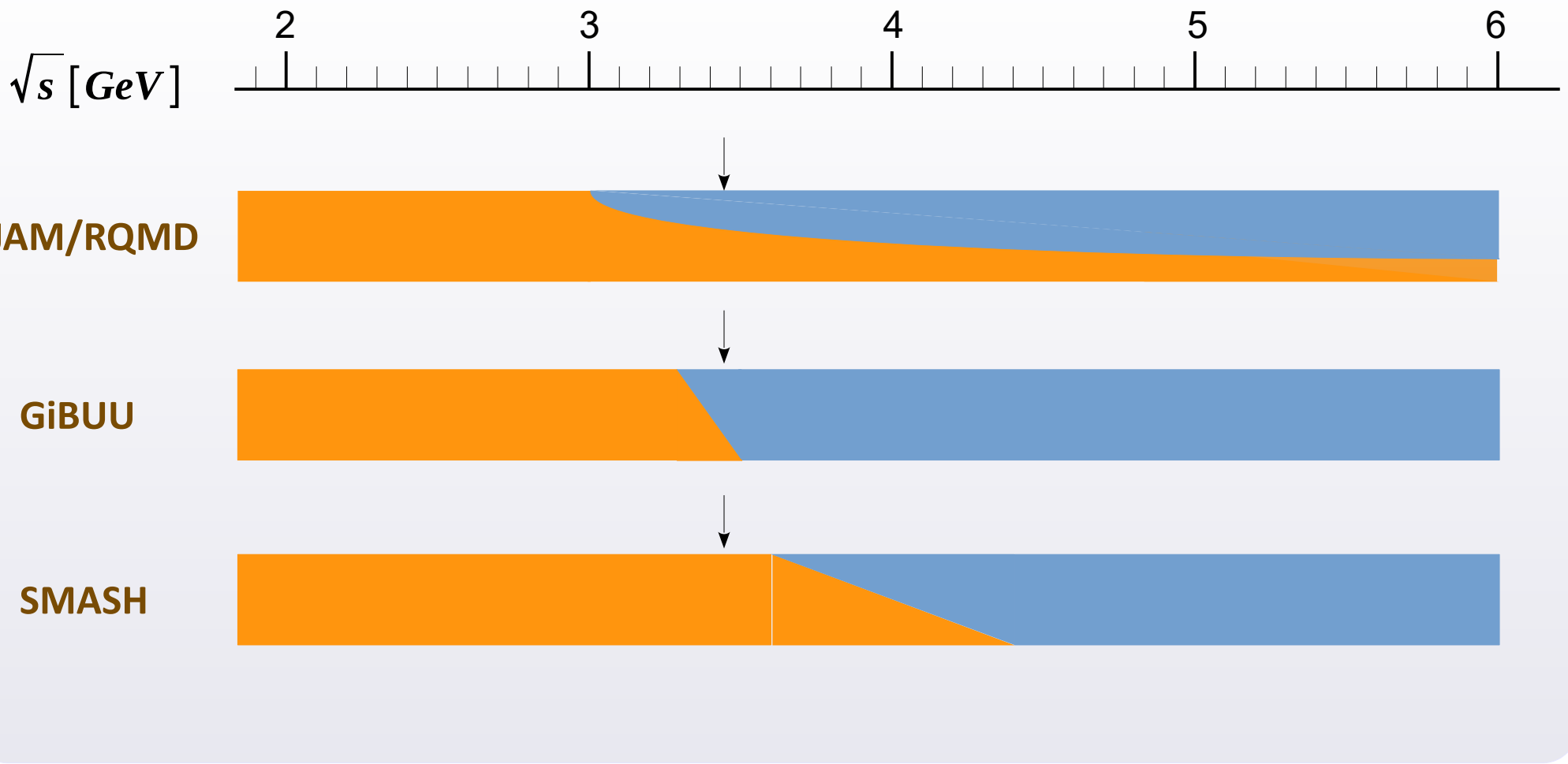

J. Weil et al, EPJA 48, 111 (2012)

## SMASH 2.0 [*url*]



# Hadron – string transition region

For p+p @ $T_{beam}$ 4.5 GeV, the energy available in CM is $\sqrt{s}$ = 3.46 GeV.




Beam energy is in a **sensitive position** with respect to
Hadron ↔ String transition region implemented in different models.

# Implementation in baryonic region

- For p+p collision, we concentrate on vacuum properties.

| | JAM/RQMD | GiBUU | SMASH |
|---|---|---|---|
| $M_{max}$ [GeV] | 2.0 | 2.35 | 2.25 |

- Properties of resonances:

[**GiBUU** & **SMASH**] : Breit-Wigner distributions with energy-dependent widths from *D. Manley, E. Saleski, Phys. Rev. D 45, 4002 (1992)*

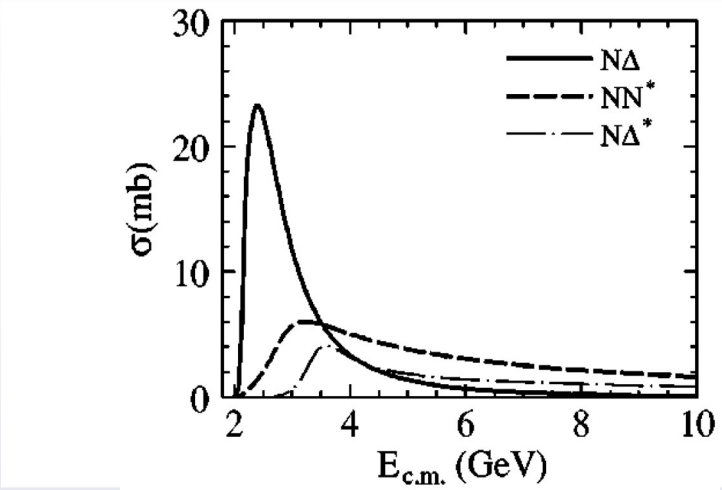
- Non-strange channels of pp interaction: two-body vs three-body channels

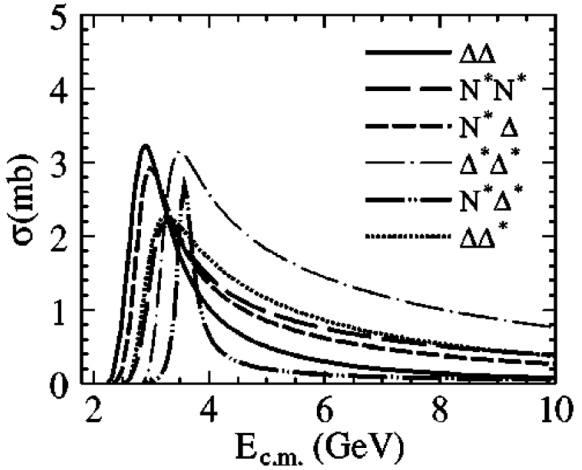
| | JAM/RQMD | GiBUU | SMASH |
|---|---|---|---|
| NN → CD | ✔ | ✔ | ✔ |
| NN → CDE | ✗ | ✔ | ✗ |

*(Note: other processes are also possible via string formation and decay)*

# Treatment of inelastic NN → BB

- **JAM/RQMD** has a pre-stage: resonances are joined in 3 groups: Δ(1232) , Δ* and N*. Own parametrization of σ for: NN → NΔ , NN* , NΔ* , ΔΔ , ΔN* , ΔΔ* , N*Δ , N*Δ* , Δ*Δ* . "Macro-channel" is picked first.




Y.Nara et al., PRC 61, 024901 (1999)

- In all the models the specific channel is chosen with Probability ~ σ .

$$\sigma_{NN\to CD} \sim |\mathcal{M}|^2 \cdot \iint |\vec{p}_F| \, \mathcal{A}_C \, dm_C \, \mathcal{A}_D \, dm_D$$

Matrix element of interaction

Momentum of outgoing C (or D) in CM NN

Baryon spectral function (here: in vacuum)

For N: $\mathcal{A}(m) = \delta(m - m_N)$

For res.: $\mathcal{A}(m) = BW(m; m_0, \Gamma)$

# Treatment of inelastic NN → BB

- In all the models the specific channel is chosen with Probability $\sim \sigma$ .

$$\sigma_{NN\to CD} \sim |\mathcal{M}|^2 \cdot \iint |\vec{p}_F| \; \mathcal{A}_C\, dm_C \; \mathcal{A}_D\, dm_D$$

Matrix element of interaction

Momentum of outgoing C (or D) in CM NN

Baryon spectral function (here: in vacuum)

For N: $\mathcal{A}(m) = \delta(m - m_N)$

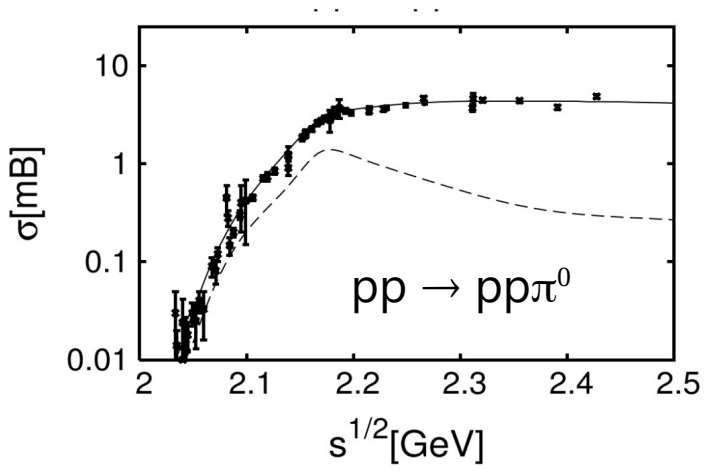
For res.: $\mathcal{A}(m) = BW(m; m_0, \Gamma)$

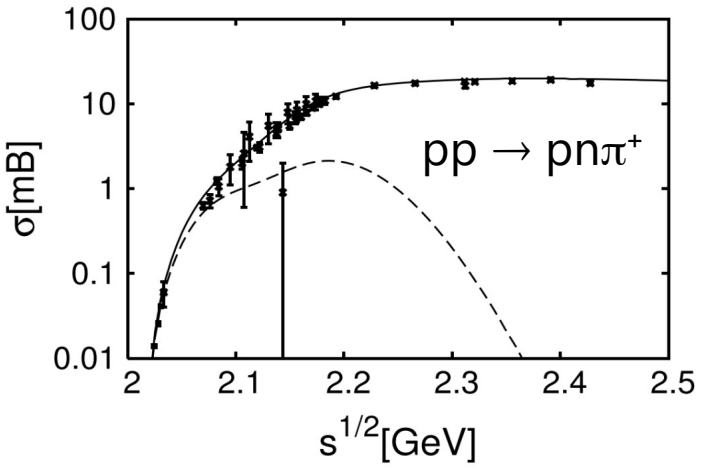
- Matrix element $|\mathcal{M}|^2$

| | JAM/RQMD | GiBUU | SMASH |
|---|---|---|---|
| NN → NΔ(1232) | one common value | f ($\sqrt{s}$) from One Boson Exchange model *V. Dmitriev et al., NPA 459, 503 (1986)* | |
| NN → CD | | constant per given resonance | |
| | | *J.Weil et al., Tab. 1 of EPJA 48, 111 (2012)* | *J.Weil et al., Tab. IV of PRC 94, 054905 (2016)* |

# Pion production in pp collisions: main channels

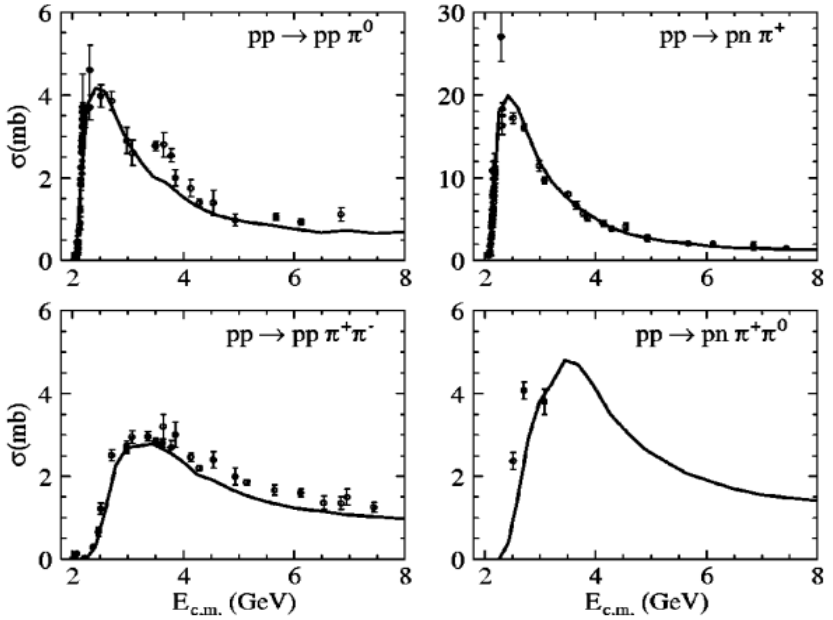
- Within hadronic channels, $2 \to 3$ are realized by **GiBUU** only.
  Therein, direct $pp \to pp\pi$ is important at lower energies (no info @ $\sqrt{s}$ = 3.45 GeV)



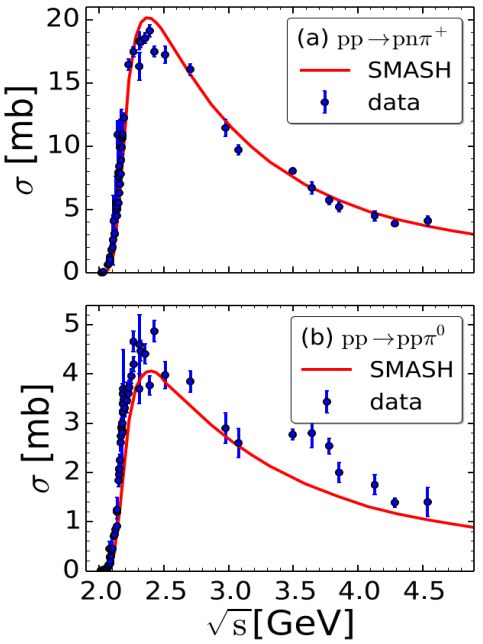

O. Buss et al., PR 512, 1 (2012)

- **JAM/RQMD**. $pp \to pR$, $R \to \pi N$




Y.Nara et al., PRC 61, 024901 (1999)

- **SMASH**. $pp \to pR$, $R \to \pi N$




J. Weil et al, PRC 94, 054905 (2016)

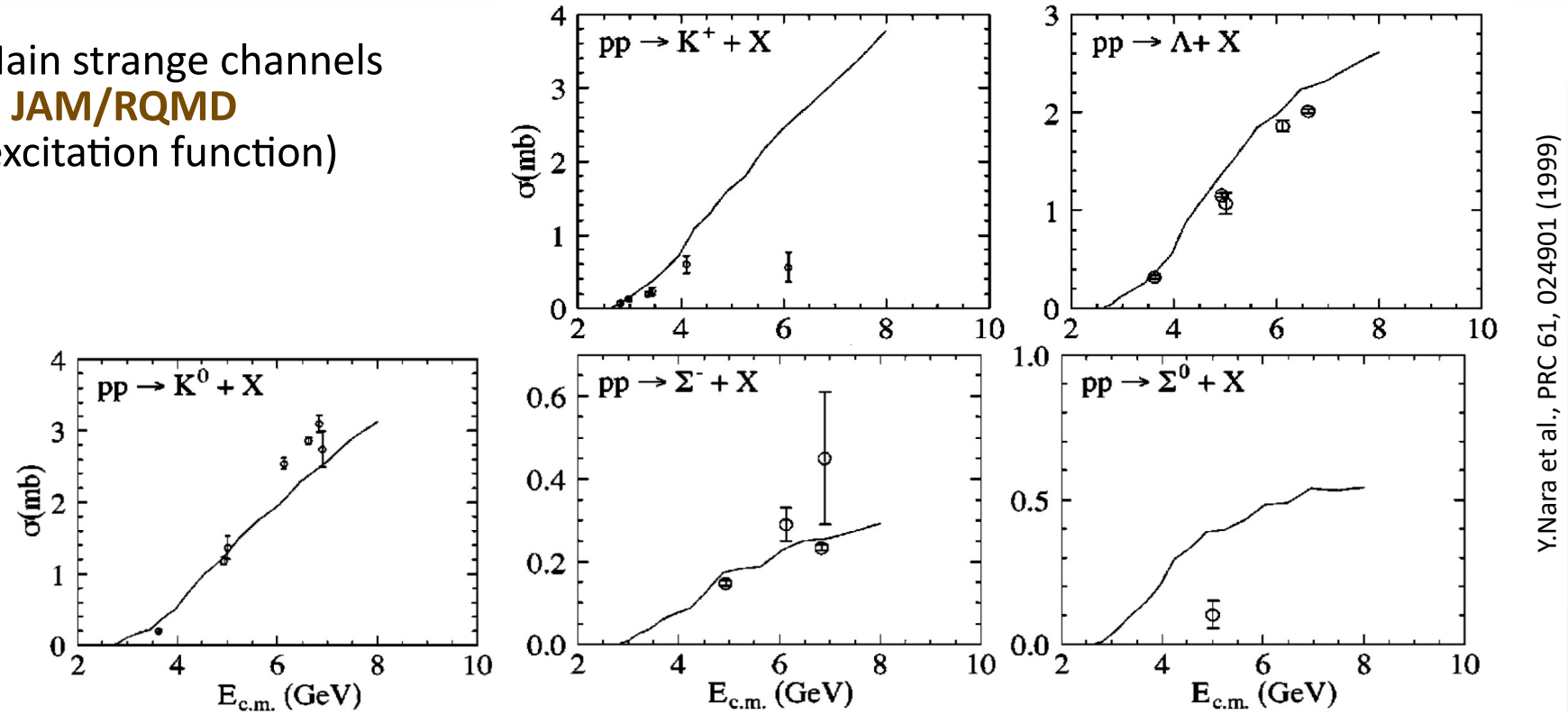
# Strangeness production in pp : main channels

- pp → strangeness. Production of typical strangeness via hadronic channels:

| | JAM/RQMD | GiBUU | SMASH |
|---|---|---|---|
| KY | pp → pR → pKY | pp → pKY | pp → pR → pKY |
| K$\bar{K}$ | | pp → ppK$\bar{K}$ | pp → pR → pp$\phi$ → ppK$\bar{K}$ |
| $\phi$ | | | pp → pR → pp$\phi$ |

*(Note: other processes are also possible via string formation and decay)*

- Main strange channels in **JAM/RQMD** (excitation function)




Y.Nara et al., PRC 61, 024901 (1999)

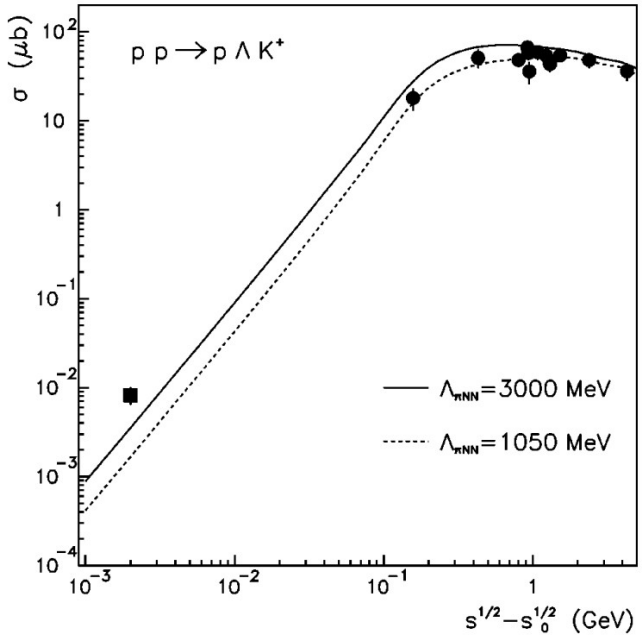
## Main strange channels in **GiBUU**

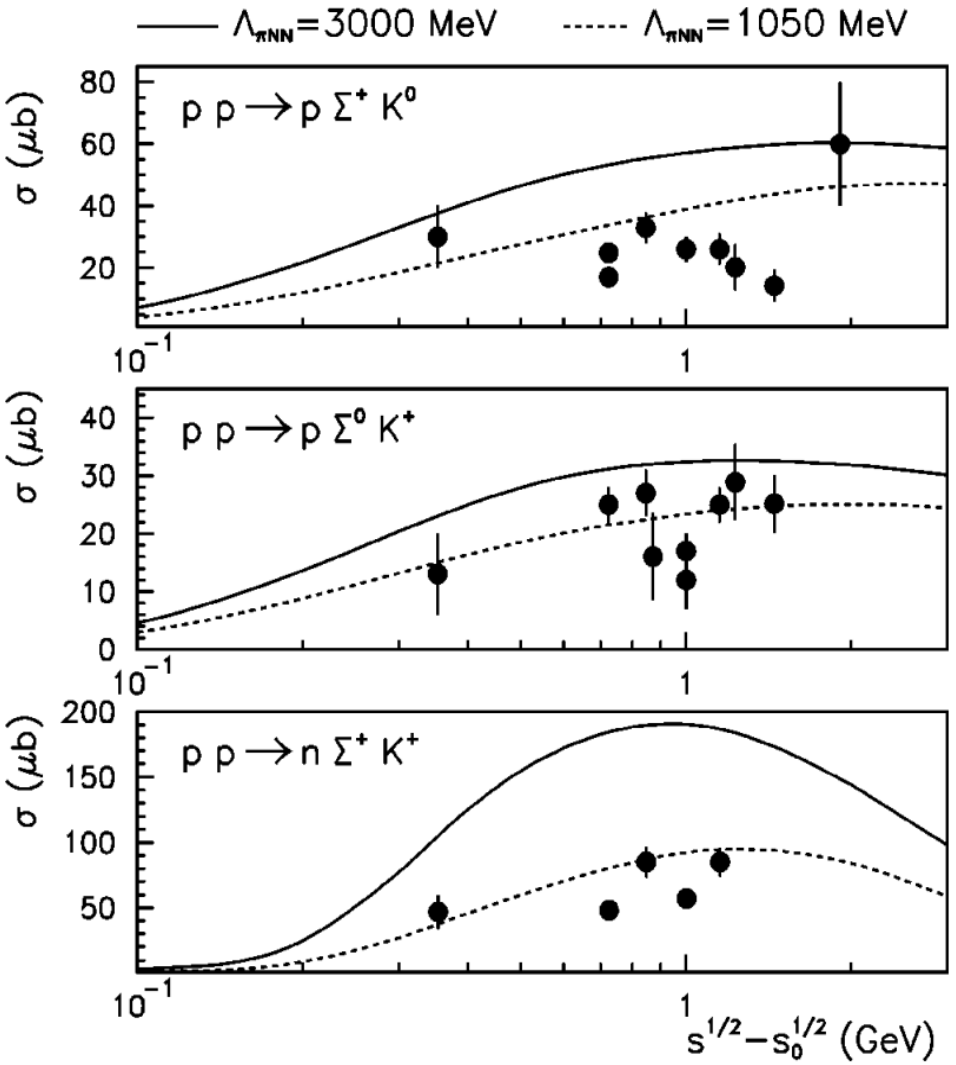
Cross sections are fits to exp. data using Tsushima parametrization:

$$\sigma(BB \to YK) = a\left(\frac{s}{s_0} - 1\right)^b \left(\frac{s_0}{s}\right)^c$$

On the plots, only data points (not curves) are relevant for the applied $\sigma$.

The best-fit parameters are in Table III of *K. Tsushima et al., PRC 59, 369 (1999)*.



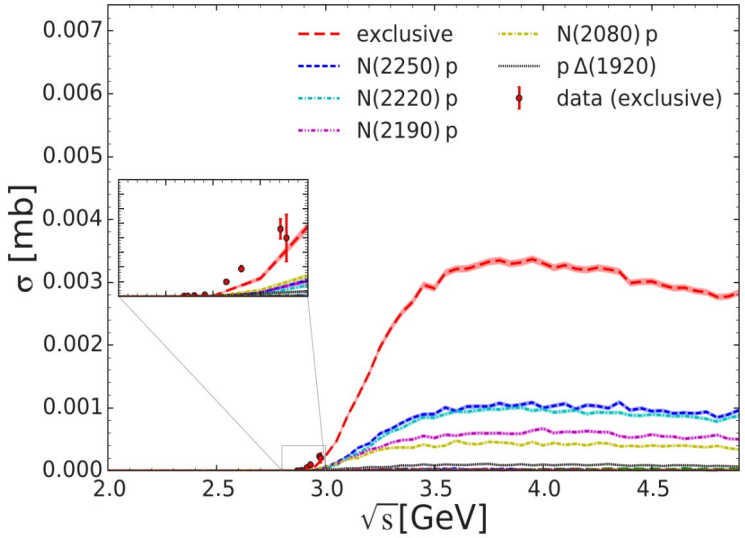

K. Tsushima et al., PRC 59, 369 (1999)

# pp → strangeness in SMASH

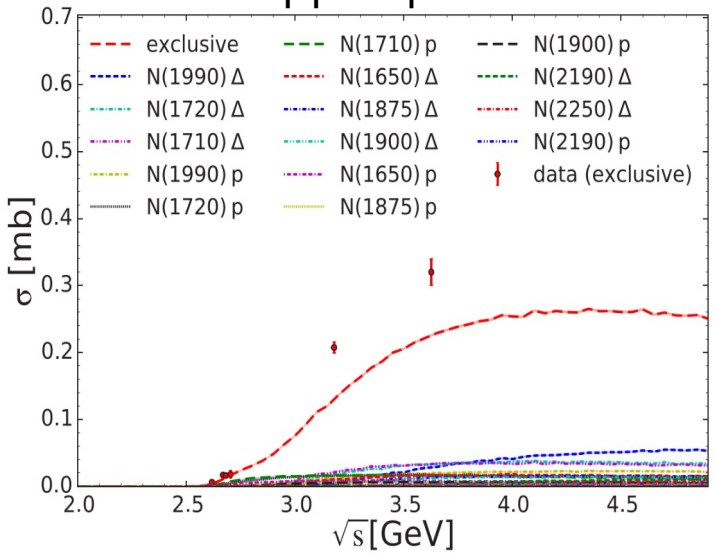
- Main strange channels in **SMASH**

[ *V. Steinberg et al. PRC 99, 064908 (2019)* ]

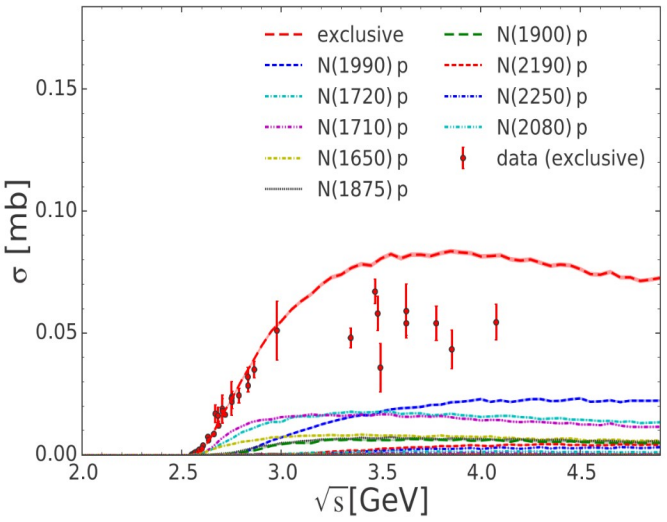
pp → ppKK̄



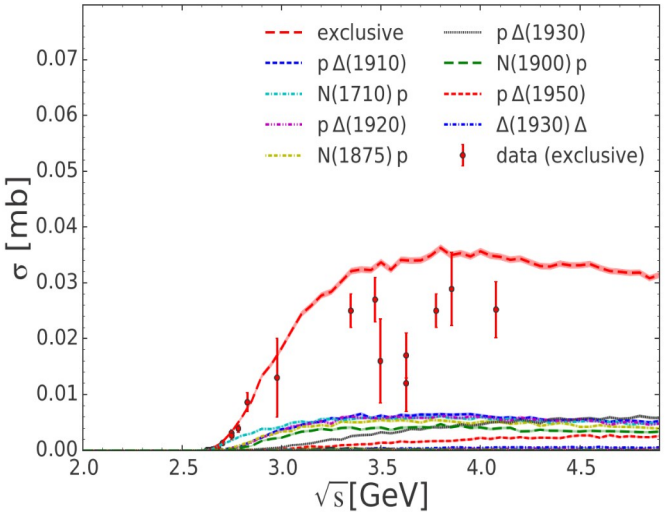

pp → pΛX



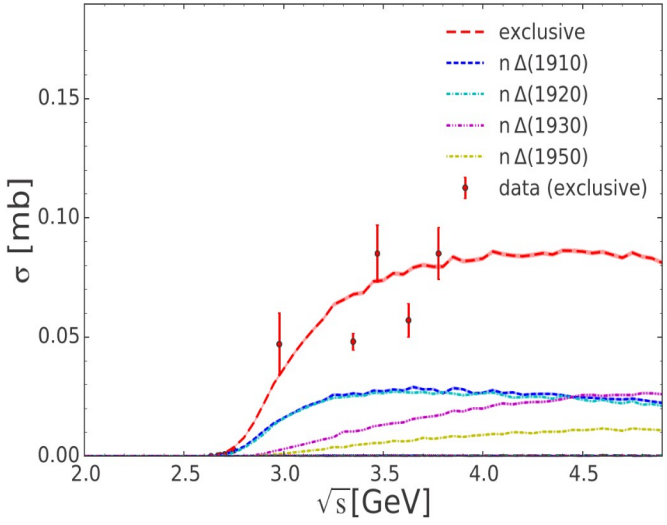

pp → pK⁺Λ




pp → nK⁺Σ⁰




pp → nK⁺Σ⁺



# Summary

Hadronic environment for pp @ $T_{Beam}$ = 4.5 GeV according to JAM/RQMD, GiBUU and SMASH moderately compatible with available data.

… but differences in some channels appear up to factor 3, or even hadron absent.

Structural differences exist between models that could cause it, e.g.:

- Different ways of implementing the transition zone between hadrons and strings
- Within hadronic sector:
  - Direct 2 → 3 channels implemented only in **GiBUU**
  - Resonance excitation in pp collision modelled a bit differently in **JAM/RQMD** vs [**GiBUU**, **SMASH**].
  - To reproduce eg. $\phi$ in **SMASH**, speculative decay channels of massive resonances
  - Channels with ≥4 products mostly missing and may cause underestimation (see e.g. $\Lambda$X)

*Thank You!*